Design and Development of Electronic Fuel Injection Control System Program for Single Cylinder Diesel Engine

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Abstract

This research aimed to evaluate mainly on engine-out emission of a single cylinder diesel engine on two conditions of fuel injection system: mechanically and electronically controlled fuel injection system. The research engine was modified to have changeable fuel injection system. The in-house built PECU was capable of producing 3 consecutive injection pulses. Fuel pressure was adjusted between 500 bar to 1100 bar. Engine with electronically controlled fuel injection system produced less NOx than original engine approximately 50%. However, as the result of higher injection pressure HC and CO were increased due to fuel impingement on combustion chamber.

Keywords*: Electronically controlled fuel injection system, Common Rail fuel injection system, Single cylinder diesel engine, Multiple injection*

1 Introduction

Diesel engines usage has been highly demand compared to spark ignition engines in order to simplicity, cost and performance [1]. Conventional diesel engines generally employ the conventional mechanically fuel controlled injection systems. The engine's air to fuel ratio (A/F ratio) and fuel injection timing are not precisely controlled under operating conditions, therefore; desired engine performance, break specific fuel consumption (BSFC), and emissions level (e.g. nitrogen oxide, particulate matter) can hardly be achieved [2].

In additions, the growing concern regarding to the global warming and the depletion of fossil fuel resource, the demand of diesel engine has gradually increased due to the better fuel economy, higher durability and wider range of renewable fuel (e.g. biodiesel). The researches on fuel injection strategies have been developed to improve the engine performance. Common Rail (CR) fuel injection system is one of electronically controlled fuel injection system that has become the main feature for CI engine nowadays. The system is able to provide various and flexible control of injections [3,4] such as injection event, injection pressure, injection rate and injection number in a cycle of operation.

Electronically controlled fuel injection system has proven to be the major improvement of diesel engine that is able to achieve reduction in both aspects of fuel consumption rate and engine-out emission [5]. Operating noise from the engine is also reduced, due to the use of high pressurised fuel atomiser and sophisticated control of injections pattern. The trend of diesel technology has been focused on increasing injection pressure and injection strategies, which achieved the higher combustion efficiency and lower emissions [5,6].

CR system has been employed for multi cylinder diesel engine for passenger cars and trucks. Although there is no single cylinder diesel engine with electronically controlled fuel injection system commercialised in the market. The major advantages of CR system can be referred in terms of improvement in the thermal efficiency and fuel economy compared to mechanism injection system diesel. Also, the lower fuel economy and the controlled emission in order to keep within the current limits and meet forthcoming scheduled stringent emission standards (e.g. Euro 6, Tier 4, Low Emission Vehicle III (LEV III)). Therefore, the introduction CR system in single cylinder diesel engine should be an interesting method. However, the high cost implement is the main disadvantage in this small system.

There are several factors contributed in order to have a fully controlled in fuel injection such as fuel injection pressure, injection timing, dwell time, and amount of fuel injected [7]. Fuel injection pressure is the main advantage of CR system as it can be controlled independently from engine speed [8] that results in designable injection pressure at any engine conditions. Sophisticated control of injection pressure in the rail is needed to optimise with the variation of pressure drop between each injection event [9] which affects actual fuel amount injected. Dwell time is a crucial parameter that has the very impact on combustion process [5]. Previous studies showed the various length of dwell time utilised between 0.5 – 1.8 ms [5, 7, 8, 10, 11]. The reduction of dwell time is mainly development with fuel injector by having faster method of actuation. The approaches to 0 μs of dwell time capable of producing close couple multiple injection or injection trains [3] which enable more advance combustion.

In this study, a preliminary work was to design and install electronically controlled fuel injection system into single cylinder agriculture diesel engine. The experiment on engine performances and engine-out emission were carried out for both conditions of engine before and after modification.

2 Experimental procedure and apparatus

2.1 *Apparatus*

This experimental research was carried out on a YANMAR TF DI 90, four stroke single cylinder naturally aspiration diesel engine which is modified and equipped with conventional Common Rail fuel injection system (Figure 1, 2 and 3). The CR control injection period and fuel pressure are controlled using in house microcontroller based software. Combustion chamber geometry was kept unchanged. The engine specifications are given in table 1. A PC programmable electronic control unit was designed to split fuel injection into multiple injections (i.e. pre-injection, main-injection, and post- injection) with adjustable fuel pressure up to 2000 bar.

Table 1: Experiment engine details.

Engine specification	Before Modification	After Modification
Model	YANMAR TF-DI 90	
Number of cylinders	1	
Cylinder-head	2 valve, Over Head Valve	
Combustion system	Direct Injection-DI	
Bore/stroke	85 mm/87 mm	
Displacement volume	493 cm^3	
Compression ratio	16.6:1	
Cont. Rating Output (kW)	5.9@ 2400rpm	
Max. Output (kW)	6.6@ 2400rpm	
Injection system	Bosch Type Mechanically Fuel injection system	Electronically controlled fuel injection system
Fuel pump mounting	Engine mechanically driven	Electrically driven

Horiba MEXA-584L gas analysis included measurement of CO_2, CO by non-dispersive infrared (NDIR), O_2 by magnetopneumatic method, NO_X by chemiluminescence detection (CLD) and total unburned hydrocarbons by flame ionisation detector (FID). H_2 concentrations were measured by gas chromatography. For all the conditions, engine out, measurements of NO_X, CO and HC were recorded.

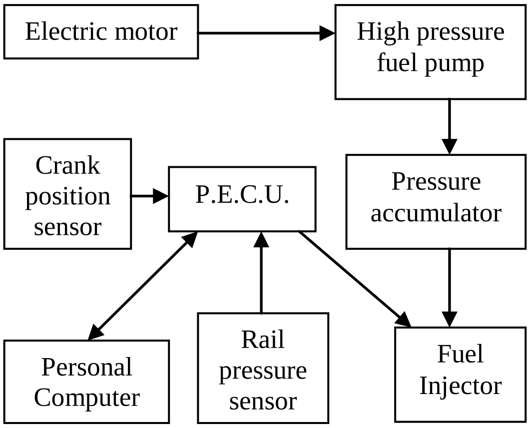

Figure 1: CR system diagram for modified engine

Figure 2: Fuel Injection Equipment Unit

Figure 3: CR injector mounted on modified cylinder head

2.2 *Procedure*

The experimental were carried out on a engine test rig equipped with external cooling system and an in-house built fuel consumption meter. Tests with injection system were performed at 3 different injection patterns are describe in table 2. To note that mode 0 represented standard injection with conventional mechanically controlled fuel injection system and mode 1 through mode 9 represented CR electronic fuel injection system.

The combustion of conventional diesel fuel injection system with standard injection timing at 20^{o}bTDC and with CR injection system setup were examined under a constant engine speed of 1500 rpm with an engine load of 75% of maximum engine load.

Table 2: Engine Test Injection Strategies

Mode	Inj. Pressure	Inj. Pattern		
	(Bar)	Pilot	Main	Post
0	200		✓	
1	500		✓	
2	500	✓	✓	
3	500	✓	✓	✓
4	800		✓	
5	800	✓	✓	
6	800	✓	✓	✓
7	1100		✓	
8	1100	✓	✓	
9	1100	✓	✓	✓

In the case of engine after modification which fuel pump was driven by external electric motor, external energy as pumping work must be taken in account using equation (1). W_{pump} was obtained during experiment as the product of positive area of voltage and current from electric motor.

$$\eta_t = \frac{W \times 1000}{\left[\left(\frac{BSFC \times W \times HHV}{3.6 \times 10^6}\right) + W_{pump}\right]} \times 100\% \qquad (1)$$

Where

η_t = Thermal efficiency

W = Brake work from engine (kW)

BSFC = Brake Specific Fuel Consumption (g/kW.h)

HHV = High Heating Value of fuel (MJ/kg)

W_{pump} = Work required by fuel pump (W)

3 Results and discussion

3.1 *Fuel injector test*

The experiment on fuel injector at various injection patterns as shown in table 3 and injection pressure intended to observe the in-house built control unit capability to manipulate both fuel injection pressure in the pressure accumulator (rail) and injection event. Fuel amount injected was under validation with standard injector test bench Bosch model: H-S/EFEP 130. Fuel injection waveform and rail pressure were recorded for further investigations.

Table 3: CR Injector Test Conditions

Strategy	Inj. Duration (ms)		
	Pilot	Main	Post
1	0	0.1	0
2	0	0.5	0
3	0	1	0
4	0.27	0.1	0
5	0.27	0.5	0
6	0.27	1	0
7	0.27	0.1	0.1
8	0.27	0.5	0.2
9	0.27	1	0.3

Fuel injection rate from fuel injector has non-linearity characteristic in the beginning of injection event as shown in figure 4. It should be noted that the amount of fuel injected under lowest excitation duration (100µs) has no significant effect for all injection pressure conditions. As solenoid actuator requires certain amount of time to gain sufficient electromagnetic force to lift the pressure balanced valve in the injector [3]. However, the longer injection duration (500 µs) shown the linearity characteristic compared to the 100 µs injection duration to actually start the injection. The dwell time of 1.8 ms was used for investigated fuel injection strategies during experiments. The higher injection pressure and longer injecting duration resulted in increasing fuel amount injected. It can be clear that the linear change of fuel injection amount for strategy 2 and 3 (Figure 4).

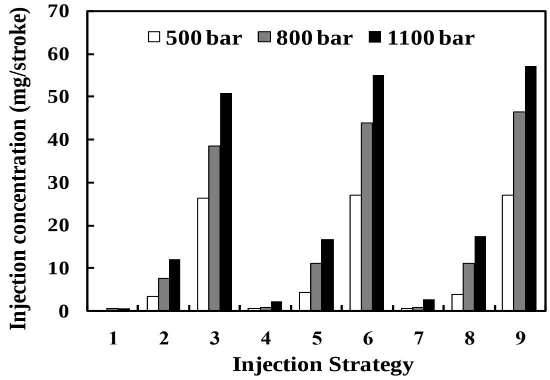

Figure 4: CR Injector characteristics

Injection waveforms in figure 5 show the pattern of instantaneous fuel pressure drop of all injection strategies at injection pressure of 800 bar. During double injections and triple injections, pattern of pressure drop were uniform. They occurred at the end of injection almost the same time at falling edge of injection waveform. These instantaneous pressure drop [9] were caused by the effect of fuel in pressure accumulator (rail) begin to compensate the absence of pressure during the control piston moving down to close injector needle. This simultaneously happens when pressure balanced valve [3] is closing. The rail pressure is rising again as the result of pressure balanced value fully closed as prove of the actual end of injection. The result demonstrates the potential to reduce dwell time between pilot- main injections and main-post injection down to tens of microsecond (µs) which leads to the potential for sophisticated injection strategies.

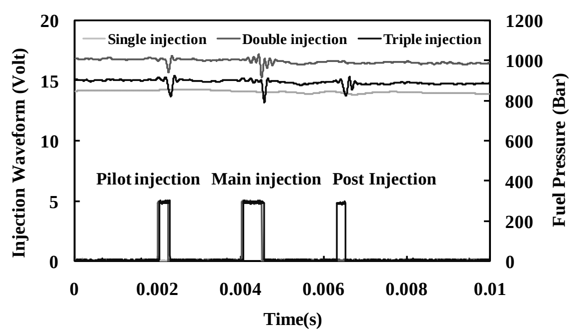

Figure 5: Injection waveforms against rail pressure at various injection strategies.

It can be noticed that the rail pressure utilised in double consecutive injection mode was higher than other testing mode due to the overshooting with high gain value of proportional control system. The pressure overshooting can be seen distinctively when longer time domain is active. This fuel pressure fluctuation can be as much as 200 bar during transient operating conditions.

3.2 *Engine test*

Brake specific fuel consumption (BSFC)

The results showed BSFC of all injection modes in comparison as shown in figure 6. The advantage of utilising higher fuel injection pressure contributed with multiple injection of CR system lead to reduce BSFC level of that engine compared with conventional fuel injection system. Especially, the engine after modification equipped with CR fuel injection system was able to significantly reduced BSFC using double injection (Injection mode 2) as shown in figure 6. This is due to optimisation by increasing the rate of air-fuel mixture before combustion process as shown in figure 6.

The high injection pressure (800 bar and 1100 bar) in CR system shown very poor fuel economy compared to the conventional fuel injection system. Furthermore, the comparison results of engine in CR mode at the same strategy found that BSFC increased as injection pressure increased due to the effect of fuel impingement caused via high penetration of high injection pressure. This trend of phenomena was confirmed by previous study [3].

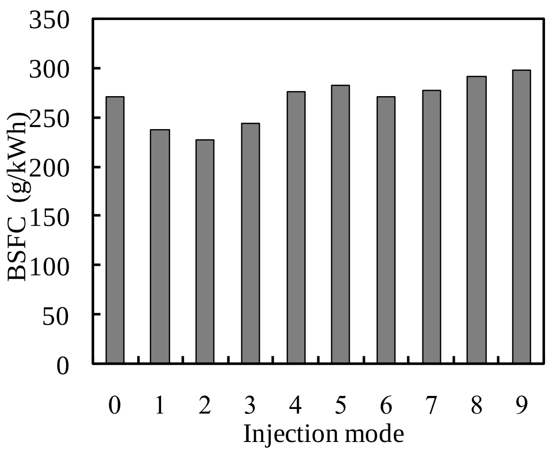

Figure 6: The effect of fuel injection strategies on Brake Specific Fuel Consumption

Thermal efficiency

Figure 7 illustrated the CR system could be improve engine thermal efficiency compared to conventional fuel injection system. In additions, the fuel pressure of 500 bar (Injection mode 2) result in higher thermal efficiency compared to the fuel pressure of 800 and 1100 bar. As the result of fuel impingement accumulated on cylinder wall and piston head when utilised high injection pressure. The higher injection pressure also increased the rate of in-cylinder pressure build up which can enhance the amount of knock, thus the lowering thermal efficiency.

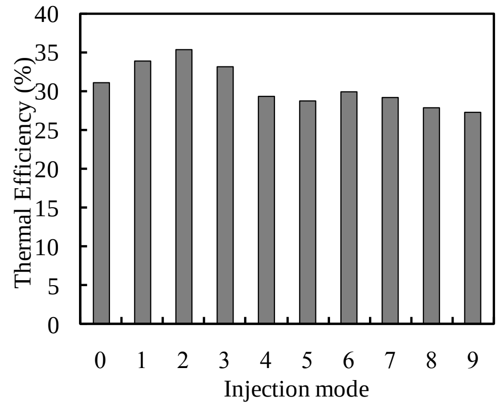

Figure 7: The effect of fuel injection strategies on thermal efficiency

Nitrogen oxides (NO_x)

The engine with conventional fuel injection system produced higher NO_x emission level compared with engine after modification. This is thought to be due to fuel impingement on combustion chamber which caused incomplete combustion that led to lowering combustion temperature.

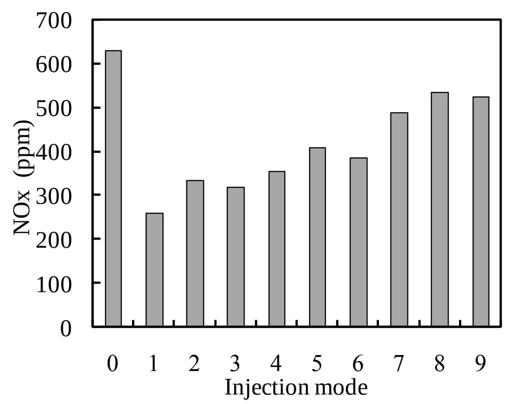

Figure 8: The effect of fuel injection strategies on NO_x concentration

Although, in CR mode, raising injection pressure led to increasing of NO_x as it produced smaller and fine fuel droplet lead to improve combustion rate and combustion temperature [5]. On the other hand, the highest NO_x level for each injection pressures were observed with introduced double fuel injection as shown in figure 8. It should be noted that single injection strategy for all injection pressures (mode 1, 4 and 7) resulted in low NO_x level compared with other injection strategies at the same injection pressure. This concluded that single injection with high injection pressure led to poor combustion process, therefore, NO_x was lowered. NO_x is expected to sharply decrease with high level of exhaust gas recirculation employed while compromising NO_x-smoke trade off.

Total hydrocarbons (THC)

Engine on test with conventional fuel injection system emitted high level of THC as expected from the mechanical injection technology. However, engine with CR system also produced notably high THC level, especially when single injection strategy was introduced as shown in figure 9. This occurred as effect of incomplete combustion process due to the higher injection pressure that caused cylinder wall fuel adhesive or fuel impingement [3,5]. Fuel compounds are also absorbed into oil layers on the cylinder liner under the high injection pressure strategy. The cause was from inappropriate injection timing as very advance injection timing was employed in this experiment. This resulted in inability to improve both HC and CO emission while NO_x was reduced.

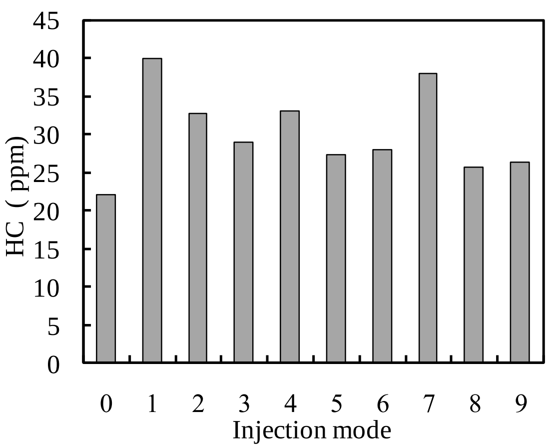

Figure 9: The effect of fuel injection strategies on hydrocarbons

The comparison between the results of the engine on test with CR fuel injection setup (Injection mode 1 through 9) with various injection strategies revealed that raising injection pressure and multiple injection were able to reduce THC as shown in figure 9. Furthermore, utilising double injection and triple injection strategies achieved THC reduction significantly in order to improvement in mixing process and reducing in fuel impingement by fuel penetration reduction [3]. This also contributed by the use of relatively long dwell time compared with previous study [5] that assisted combustion process yielded in less THC in exhaust gas.

Carbon monoxide (CO)

The CO level emitted from engine via conventional fuel injection system was lower of that from engine with CR system as illustrated in figure 10. This can be explained that the conventional injection system utilised lower injection pressure, which has lower range of fuel penetration. Therefore fuel adhesive to piston and cylinder liner was less than of that engine modified with CR fuel injection system. Although the CR system was expected to be result better in all test range, but resulted poorly for all injection strategies under high injection pressure. High injection pressure was thought to be the cause of longer fuel spray penetration which resulted in fuel impingement accumulated on combustion chamber. However, the result from injection mode 9 showed significant CO reduction which might be contributed to triple injection strategy that high combustion temperature was expected. This trend could be confirmed by the fact that NO_x level rose while HC level decreased.

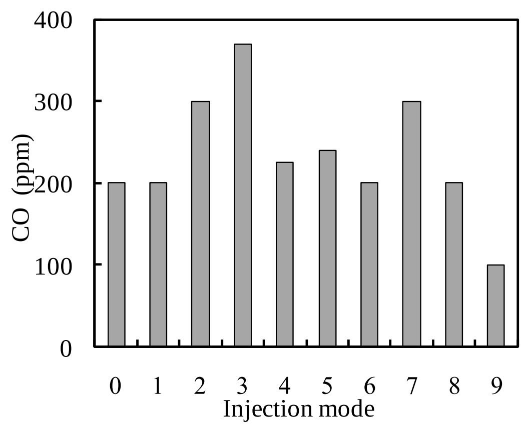

Figure 10: The effect of fuel injection strategies on carbon monoxide

4 Conclusions

The development in-house PECU for high electronically controlled fuel injection system was able to achieve the control over both multiple injection and injection pressure for a single cylinder diesel engine operation. Utilising injection strategies is a major advantage of electronically controlled fuel injection system which yields in improvement of overall engine-out emission and also output power at high load condition. Multiple injection and controllable high fuel pressure confirmed that emission and fuel consumption can be reduced. Using double injection and injection pressure of 500 bar (Injection mode 2) is the optimum strategy for this experiment considering both fuel consumption and engine-out emission.

This system has potential to improve single cylinder diesel engines to operate with higher thermal efficiency and lower fuel economy which will enable agriculture single cylinder diesel engines to operate in cleaner manner. However the optimisation of the CR fuel injection strategies (i.e. fuel quantity injected, dwell time, injection pressure) for different engine operating conditions are still required in order to achieve fuel injection mapping that can cope with transient operation in real applications.

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