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Effects of Advancing the Pilot Injection Timing on The Engine Performance, Combustion and Emissions on Diesel dual fuel Engine at High Load

Bambang Sudarmanta^{1, a}, Atok Setiyawan¹, Ary Bachtiar K P¹, Dori Yuvenda^{1,2, b}, and Jose da Silva¹

¹ Department of Mechanical Engineering, Faculty of Industrial Technology, Institut Teknologi Sepuluh Nopember, Kampus ITS, Sukolilo, Surabaya 60111, Indonesia

² Department of Automotive Engineering, Faculty of engineering, Universitas Negeri Padang. Kampus UNP Air Tawar Barat, Padang 25171, Indonesia

^a bsudarmanta@gmail.com, ^b doriyuvenda@ft.unp.ac.id

Abstract. Pilot injection timing is a very important parameter at the start of ignition which will affect engine performance and emissions on diesel dual-fuel engines, especially at high loads. This research was carried out on the Diamond DI 800 diesel engine, a single-cylinder that was modified into a dual fuel engine with the aim to determine the effect of advancing the pilot injection timing (PIT) on engine performance, combustion and emissions under high loads with variation pilot injection timing (11°, 13°, 15°, 17° and 19° BTDC). The cylinder pressure, heat release rate (HRR), combustion duration, ignition delay, power, SFC and brake thermal efficiency (BTE), as well as carbon monoxide (CO), hydrocarbon (HC) and particulate matter emissions, were analyzed. The results showed that advancing the pilot injection timing increased the maximum cylinder pressure by 69.52 bar; the heat release rate was 117.79 kJ/m³/°CA, brake thermal efficiency was 25.17% and significantly reduced HC, CO and PM emissions at the pilot injection timing 17° BTDC. Improved combustion performance occurs when the combustion duration is reduced even though the ignition delay period occurs by adding pilot injection timing under high load.

1. Introduction

Currently, alternative fuels are the solution to the scarcity of fuels such as ethanol fuel on gasoline engine [1]–[4], while diesel engine use CNG [5] and biodiesel fuels [6]. The use of CNG fuel in a diesel engine is better known as diesel dual fuel (DDF). Diesel dual fuel engine still causes problems related to engine performances and emissions [7]–[9]. Where the use of pure diesel fuel (100%) is replaced in part by CNG fuel, causing a decrease in combustion performance which affects the decrease in engine performance [10][11]. Besides that, CNG utilization causes an increase in emissions of carbon monoxide (CO) and hydrocarbons (HC)[12][13], although the addition of CNG can reduce nitrogen oxide (NO_x) and particulate matter (PM) emissions[14].

The problem with diesel dual fuel engine is that there is a decrease in engine performance and increased emissions compared to a standard diesel engine, especially high load[15][16]. The reason is that at high load the engine consumption large amounts of fuel to produce maximum power in offsetting the load, so that the mixture of fuel and air is richer, allowing combustion to become imperfect. Besides that, it



is also affected by the addition of the ignition delay, resulting from a decrease in the partial pressure of the oxygen and the intake temperature of the air-gas mixture[15].

Research related to diesel dual fuel engine in improving combustion performances and emissions at high load includes Singh, et al. [17] investigate the effect of the pilot injection timing, pilot quantity and intake temperature on performances and emissions on diesel/natural gas engine at medium and high loads, and they found that by advancing the injection timing of pilot increased fuel conversion efficiency and decreased NO_x, CO and HC emissions at high load. Kerdsurwan, et al. [18] investigate the effect of advancing the pilot injection timing on engine performance on diesel dual fuel engine using diesel fuel and producer gas at low, medium and high loads, and they found that by advancing the pilot injection timing can improve BTE, fuel substitution, SFC and decreased HC, CO and soot emissions except for NO_x emission for all engine loads.

Zhou, et al.[19] investigate the effect of the pilot injection timing and pilot quantity on combustion and particle emission characteristics on diesel/natural gas engine under low, medium and high loads, and they conclude that by advancing the pilot injection timing improves combustion duration, start of combustion (SOC) and decreases HC and CO emissions significantly, but NO_x emissions slightly increase under high load. Liu, et al.[20] investigate the effect of pilot diesel quantity on emission characteristics on diesel dual fuel engine by optimizing the injection timing of pilot under medium and high loads, and they found that by advancing the pilot injection timing can reduction of CO and PM emission under high load.

Ryu,[21] , investigated the effect of diesel pilot injection timing on combustion characteristics and emissions on dual fuel diesel engines with biodiesel and CNG under high loads, He found that b,y advancing the pilot injection timing can increase cylinder pressure, heat release rate and improve start of combustion. Likewise, HC and PM emissions are decreasing a significant, but CO and NO_x emissions increased under high load. Sun, et al.[22] conducted a study on the analysis of combustion performance and stability of dual fuel gas engine with variations in pilot injection timing and pilot quantity under low, medium and high loads, and they found an increase in cylinder pressure, heat release rate, specific energy consumption and reduce HC emission, but NO_x emission slightly rise under high load. Likewise, the stability of a dual diesel engine by advancing the pilot injection timing under high load can be accepted; this is marked by the coefficient of variation (CoV_{IMEP}) value under 4%.

Papagiannakis, et al. [23] investigate the effect of pilot injection timing and the mass ratio of diesel/gas to performance and emissions on dual fuel diesel engines with experimental and theoretical methods under load variations, and they found an increase in cylinder pressure, heat release rate and decrease in CO and smoke emissions despite an increase in NO_x emissions under high load. Likewise, the duration of combustion becomes shorter when the pilot injection timing was advanced at high load.

Based on the research that has been done above, it can be concluded that advancing the pilot injection timing can improve engine performance and combustion as well as emissions on diesel dual-fuel engines under high load. This study aims to optimize the pilot injection timing to improve engine performance and combustion and reduce emissions in diesel dual fuel engine under high load.

2. Methodology of research

2.1. Test engine

This research use Diamond DI 800 diesel engine, a single-cylinder using a water cooling system cylinder that was modified into a diesel dual fuel engine with diesel and CNG fuel as shown in figure 1. The engine characteristics used in this study are shown in table 1.

Table 1 The engine specification.

No	Item	Specification
1	Merk	Diamond diesel

2	Type	DI 800	
3	Model	1 cylinder, 4 stroke	
4	Bore x Stroke	82 mm x 78 mm	
5	Displacement	411 cc	
6	Max. Power	8 HP (6 KW) / 2400 rpm	
7	Continuous Power	7 HP (5.22 KW)/2200 rpm	
8	Compression Ratio	18:1	
9	Cooling sistem	Hopper/ Condenser	
10	Lube capacity	1,8 liter	
11	Pilot injection timing	13 ⁰ BTDC	
12	Valve timing	Opening	Closing
	Intake	30 ⁰ BTDC	50 ⁰ ABDC
	Exhaust	55 ⁰ BBDC	35 ⁰ ATDC

CNG with low pressure is injected through the intake, which is controlled using an electrical control unit (ECU) while diesel fuel uses a conventional system. CNG is injected at 45⁰ ATDC at the suction stroke, while the injection timing of the standard pilot is 13⁰ BTDC at the end of compression stroke.

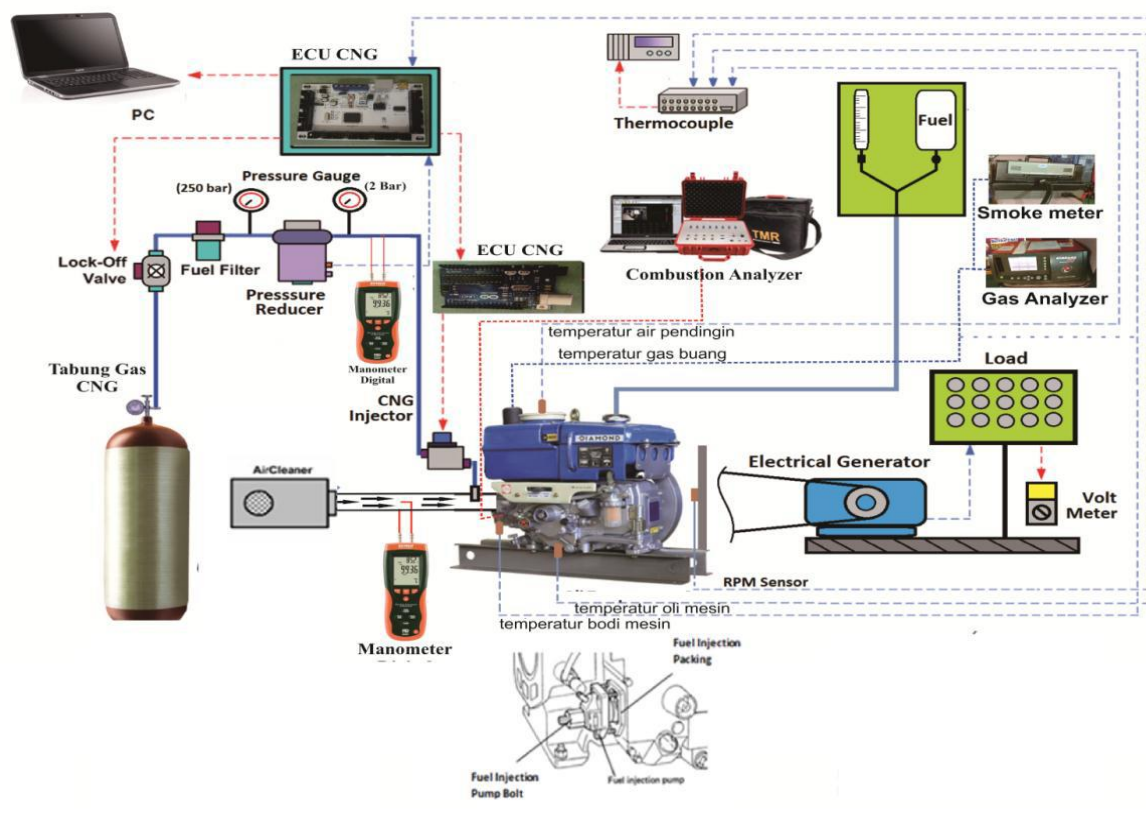


Figure 1. Experimental setup

2.2. The fuel of dual fuel system

This research uses diesel fuel as a pilot and CNG as the main fuel in diesel dual fuel engine. The diesel fuel and CNG properties used in this study are shown in tables 2 and composition of CNG at tables 3 below. The research method uses experimental methods on diesel dual fuel engine that are tested at high load. The converter kit consists of several components that work integrated to reduce the high pressure

in a CNG tank by 250 bar to a working pressure of 2 bars through the inlet port [24]. CNG is injected into the intake port using a CNG injector controlled by the ECU.

Table 2 The fuel properties[25].

Fuel Properties	Diesel	CNG
Low heating value (MJ/kg)	42,8	48,6
Cetane number	52,5	-
Octane number	-	130
Self ignition temperature ($^{\circ}\text{C}$)	316	650
A/F _{stoic} (kg/kg)	14,69	17,2
Carbon content (%)	87	75

Table 3 The composition of CNG[25].

Fuel Properties	Volumetric concentration (%)
Methane	96.160
Ethane	1.096
Butane	0.136
Iso-Butane, n-butane	0.021
Iso-Pentane, n-pentane	0.006
N ₂	0.001
H ₂ S	0.0002
H ₂ O	0.006

2.3. Instrument arrangement and data acquisition

Diesel dual fuel engine is connected to an electric generator as a load. The loading of the engine is carried out with a high load using a lamp with a capacity of 4000 watts. Kistler piezoelectric pressure sensors are installed in the cylinder head which is used to measure cylinder pressure and heat release rate with a 0.20 crank angle (CA) resolution. CNG and air mass flow rate are measured using a digital manometer with an accuracy of ± 0.001 . Diesel fuel consumption using a burette meter with 1 ml accuracy. The star gas 898 emission analyzer to measure HC and CO emissions, while PM emissions use a smoke tester.

2.4. Test procedure and conditions

The engine is heated to a working temperature by ± 80 . Engine testing is carried out under high load with a constant engine speed of 1500 rpm. The test is divided into two stages: the first stage, testing the engine with standard fuel as a control variable. Second stages, testing the engine using dual fuel by advancing the pilot injection timing from 11 $^{\circ}$ BTDC to 19 $^{\circ}$ BTDC. Advance the injection timing of the pilot with reducing the shim plate at the injection pump holder. Each reduction of shim plate of 0.1 mm can advance injection timing of 1 $^{\circ}$ CA.

3. Results and discussions

This discussion analyzes the effect of advancing the pilot injection timing on engine performance and combustion and emissions on a diesel dual fuel engine. Engine performance parameters include power, SFC and thermal efficiency and combustion performance including cylinder pressure, heat release rate, ignition delay, combustion duration and emissions including CO, HC, and PM. Ignition delay is defined

at the start of pilot diesel to be injected to the start of combustion (SOC), while the duration of combustion is the start of combustion (SOC) to the end of combustion (EOC).

3.1 The engine performances with variations in pilot injection timing

In figure 2, shows the effect of pilot injection timing on engine performance including engine power, SFC and thermal efficiency on diesel dual fuel engine under high load. Figure 2, the thermal efficiency and power of the engine showing the same graph trend as the different pilot injection timing. The effect of advancing the pilot injection timing is more significant on thermal efficiency, while the engine power is not significant.

Increased maximum thermal efficiency occurs at pilot injection timing of 17° BTDC of 25.17% at constant engine speed. This is due to advancing the pilot injection timing can extend the period of ignition delay, so that the gas-air mixture can mix with the pilot fuel more homogeneously, resulting in more fire points. Thus the premixed combustion of diesel fuel is faster and triggers the diffusion of gas and diesel fuels so that thermal efficiency also increases under high load.

Figure 2, also shows that the SFC value is optimal with the pilot injection timing of 17° BTDC by 0.8063 kg/HP.h. This is due to greater power so that the engine is more effective at consuming fuel, characterized by increased thermal efficiency.

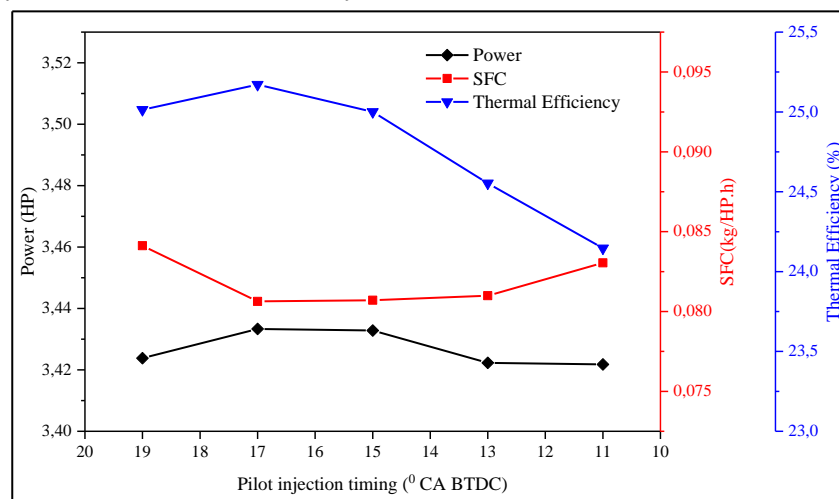


Figure 2. Engine performance with different pilot injection timing

3.2 The Cylinder pressure and heat release rate with variations in pilot injection timing

In Figure 3, shows the effect of pilot injection timing on cylinder pressure and heat release rate (HRR) under high loads. Figure 3, explains that there is a significant increase in cylinder pressure by advancing the pilot injection timing of 17° BTDC to 69.52 bars. This is because injection of diesel fuel is slightly accelerated so that the period of ignition delay is advanced, so the initial combustion is faster, and results in cylinder pressure peaks leading to the top dead center (TDC).

Besides that, the cylinder pressure graph at pilot injection timing of 11° CA BTDC, where the maximum cylinder pressure away from TDC. This is due to the longer ignition delay period in dual fuel diesel so that the pilot injection timing that is too late causes a delay in the initial ignition of combustion so that the maximum pressure occurs in the expansion stroke, so resulting in a pressure drop under high load. However, if the pilot injection timing is too early (PIT 19° BTDC), there is a decrease in cylinder pressure. This is because the pressure and temperature of the cylinder are low.

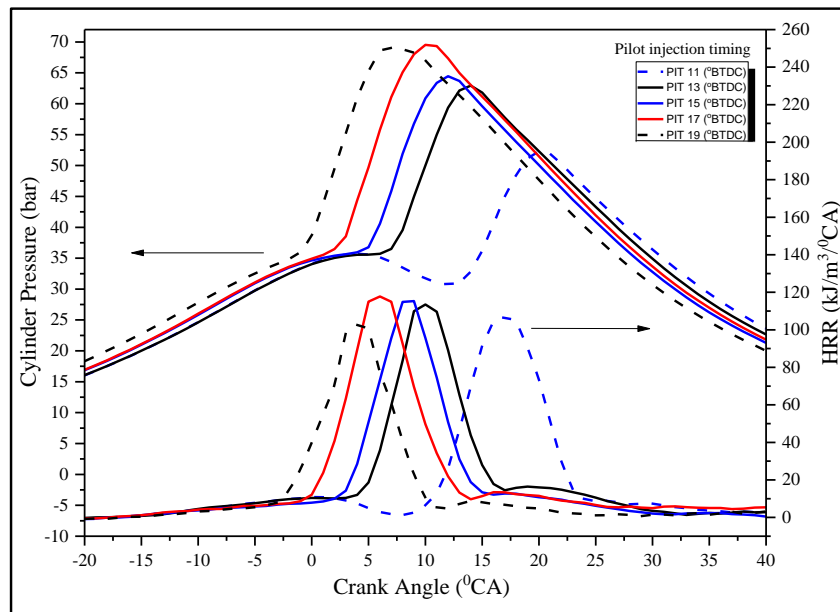


Figure 3. Cylinder pressure and HRR with different pilot injection timing

Figure 3, also shows the heat release rate (HRR) increases the significance of the pilot injection timing of 17° BTDC by 117.79 kJ/m³/deg with a percentage increase of 12.41%. This proves that the increase in cylinder pressure and temperature can cause greater combustion so that the energy released becomes more abundant. The heat release rate of maximum occurs in diffusion combustion from diesel and CNG fuels, where both fuels burn optimally.

However, when the injection timing of the pilot is forwarded too early or rewind too slowly, the heat release rate (HRR) drops. Due to pressure and temperature, the cylinder is still low when the pilot injection timing is too early, while the diesel injection is too slow the pressure and cylinder temperature are too high, allowing knocking of CNG fuel and more heat being wasted through the exhaust manifold because combustion occurs at the expansion stroke.

3.3 The combustion performance with variations in pilot injection timing

Figure 4, shows the ignition delay period and duration of combustion under variations in diesel pilot injection timing on diesel dual fuel under high load. The period of ignition delay increases along with advancing the pilot injection timing. The pilot injection timing of 19° BTDC has a period of ignition delay that is too long at 20° CA. The reason is the pressure and low cylinder temperature so that the chemical delay process is longer. The advantage of a slightly longer ignition delay is to provide the opportunity for air and CNG to mix more homogeneously. However, when injection timing of pilot is slowed down, there is a significant decrease in the ignition delay period, due to the high cylinder pressure and temperature which shorten the chemical delay process, so that firing point is formed faster.

Figure 4, also shows the duration of combustion under variations in the pilot injection timing on diesel dual fuel under high load. The duration of combustion is shorter with the injection time of 15° BTDC pilots of 33° CA. This is influenced by faster combustion speeds so that combustion is completed more quickly. When the pilot injection is advanced too early the duration of combustion increases significantly because the cylinder pressure and temperature are still low.

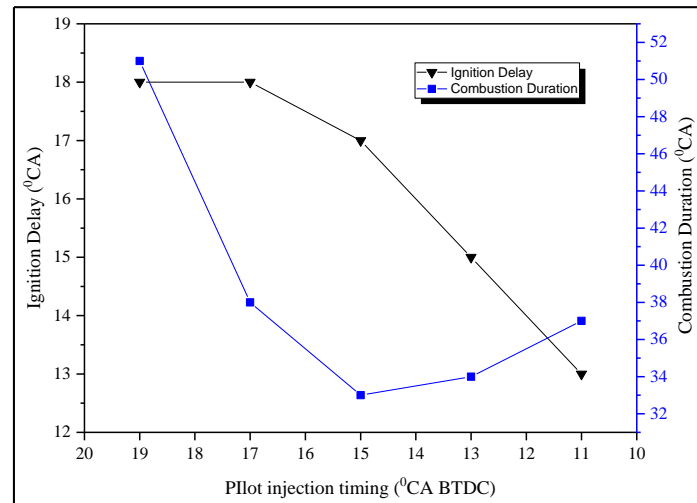


Figure 4. Combustion performance with different pilot injection timing

3.4 The emissions with variations in pilot injection timing

Figure 5, shows the effect of pilot injection timing on HC, CO and PM emissions on diesel dual fuel engine under high load. Figure 5, shows the pilot injection timing of 17°BTDC obtaining value optimal of CO, HC and PM emissions. A decrease in CO emission of up to 0.026%, marked by an increase in cylinder pressure and heat release rate, resulting in high temperatures so that it can help oxidized CO emissions to form CO_2 [25]. Besides, with a peak of combustion approaching TDC so that the time available for the oxidation process is longer.

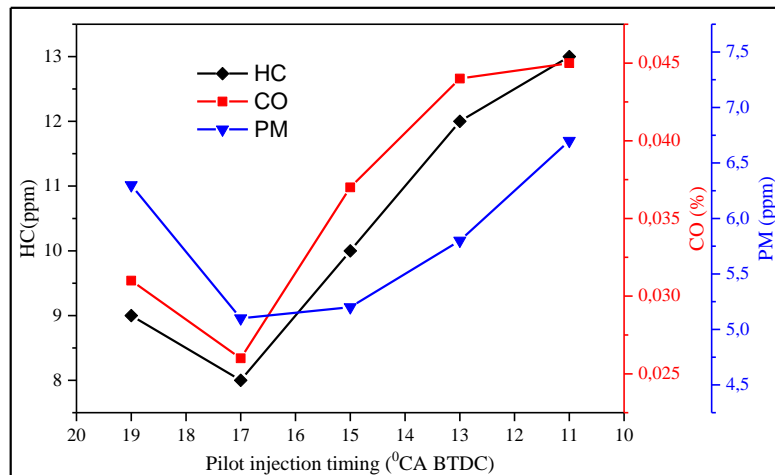


Figure 5. Emission with different pilot injection timing

Figure 5, also shows a decrease in HC emission by 8 ppm with the pilot injection timing of 17°BTDC , this is due to earlier burning so that the pilot fuel burns more. Likewise, advancing the injection timing of pilot increases the cylinder pressure and heat release rate so that the remaining diesel fuel can be burned in diffusion combustion. Figure 5, also shows a reduction in PM emission by 5.1 ppm with the pilot injection timing of 17°BTDC . Two factors, namely cause the reduction in PM emission: first, diesel fuel replaced by CNG does not have soot content, so the possibility of lower PM emissions is formed. Second, by advancing the pilot injection timing of the initial combustion initiation so that diesel fuel burns more because it mixes more with air during the ignition delay period.

4. Conclusion

In general, diesel dual fuel engine the ignition delay period is longer than that of a single fuel diesel engine, thus affecting the engine performance, combustion process, and emissions under high load. The effort taken is to set pilot injection timing so that it can control the ignition delay period that occurs. Advancing the pilot injection timing affects the maximum pressure cylinder pressure up to 69.52 bar, the maximum heat release rate up to 117.79 kJ/m³/°CA under high load. Increased combustion performance is also characterized by a reduction in the duration of combustion despite the addition of an ignition delay period by advancing the pilot injection timing under high load. Likewise, advancing the pilot injection timing can reduce emissions of HC by 8 ppm, CO by 0.026 % and PM by 5.1 ppm on diesel dual fuel engine under high load.

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