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Characterization of Engine Performance, Combustion Process and Emission of Diesel/CNG Dual Fuel Engines with Pilot Injection Timing Variation at Low Load

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Abstract. The use of CNG on dual fuel diesel engines causes a decrease in engine performance, combustion and increased emissions, especially at low loads, which is affected by the addition of ignition delay period so that the maximum of peak combustion away from the top dead center (TDC). Pilot injection timing acts as an ignition delay controller. This research was carried out using an experimental method on diesel/CNG dual fuel engine a single-cylinder to determine the engine performance, combustion process and emissions characteristics with a variation of pilot injection timing from 11^0 to 19^0 BTDC with an interval of 2^0. The results showed an increase in thermal efficiency of 3.006%, maximum cylinder pressure up to 4.78 MPa, maximum heat release rate of up to 52.05 kJ /m^3/^{0}CA, and decrease hydrocarbons (HC), carbon dioxide (CO) and particulate matter (PM) emissions at pilot injection timing 17^0 BTDC under low load. Likewise, combustion performance has increased marked by a reduction in combustion duration and maximum of peak combustion approaching TDC by advancing the pilot injection timing on diesel/CNGdual fuel engine.

Keyword. Engine performance, combustion process, emissions, diesel/CNG dual fuel, pilot injection timing, ignition delay period

1. Introduction

The dual fuel engine operates using two fuels that are burned simultaneously. Alternative fuels become the main fuel while diesel fuel as a pilot diesel[1]. One of alternative fuel that is widely used in dual fuel diesel engine is compressed natural gas (CNG)[2][3]. This is because CNG has the characteristics of high auto-ignition temperature (± 650^0C)[4][5], so it can be used on engine that have a high compression ratio. The combustion process that occurs in dual fuel diesel engines is in sequence, where diesel fuel is used as a flame to burn CNG. This is because CNG cannot burn by itself. Moment a diesel fuel is injected, a mixture of diesel fuel and air-CNG mixture is called the ignition delay period. The ignition delay period occurs in two phases, physical delay and chemical delay phases. Both of these phases will affect the duration or shortness of ignition delay. The dual fuel diesel engine has a longer ignition delay period compared to single fuel diesel engines. This is due to a decrease in partial pressure from oxygen and the intake temperature of the CNG-air mixture so that it affects the pressure and temperature of the compression stroke[6][7]. The addition of ignition delay time causes a decrease in combustion performance and an increase in HC and CO emissions in dual fuel diesel engines[8]. Prolong ignition delay causes the maximum of peak pressure away from the position of the TDC so that combustion tends to occur at the step of the business which results in a decrease in engine performance, especially at low loads [4]. Several studies related to dual fuel diesel engines to overcome these problems have already been carried out. Yuvenda and Sudarmanta[9], analyze the pressure reducer by optimizing the strength of the spring as a pressure reducing gas and supplying CNG fuel to the combustion chamber and they find that by increasing the spring constant at the pressure reducer can increase the amount of CNG gas supply into the combustion chamber on the diesel dual fuel engine so that it can increase CNG gas substitution as the main fuel. Sayin, et al.[10] investigate the effect of pilot injection timing on the performance and emissions of diesel dual fuel engines under low and high load and they found that by advancing the pilot injection timing it increases thermal efficiency and decreases CO and HC emissions under low load but, moment pilot injection timing further advances the decrease in thermal efficiency. Liu, et al.[11] investigated the effect of pilot injection timing and diesel pilot quantity on dual fuel diesel exhaust emission characteristics under low, medium and high load and they found that by advancing the pilot injection timing and increasing diesel pilot quantity can reduce NO_x and PM emissions significantly but HC and CO emissions increased slightly in all loading. Yang, et al.[12][13] investigated the effect of pilot injection timing on combustion performance and reduction of emissions especially HC and CO emissions on diesel dual fuel engines at low loading and they found that by advancing the pilot injection timing it could increase cylinder pressure and heat release rate as well as significantly reduce HC and CO emissions but NO_x emissions increase. Wang, et al.[14] investigate the effect of pilot injection timing on combustion and emissions characteristics on dual fuel diesel engines under low load, and they found that by advancing the pilot injection timing can increase cylinder pressure, heat release rate and thermal efficiency and significantly reduce HC emissions but NO_x emissions increase, but if it is further advanced the injection time of the diesel pilot then it reduces the performance of the diesel dual fuel engine. Guerry, et al.[15] investigated the effect of pilot injection timing on combustion performance and emissions of diesel dual fuel engines with the method of low temperature combustion (LTC) under low and high loads, and they found that by advancing the injection time of diesel pilots can increase cylinder pressure and the rate of heat release and reduce emissions of HC and CO, but if the pilot injection time of diesel is further promoted further reduce combustion performance and increase exhaust emissions under low load. Papagiannakis, et al.[16] investigated the effect of pilot injection timing on combustion performance and emissions on dual fuel diesel engines at low loading and they found that by advancing the pilot injection timing increased cylinder pressure and heat release rate and reduced exhaust emissions on dual diesel engines fuel under low load. Shu, et al.[17] investigated the effect of pilot injection timing on thermodynamics, combustion and emissions on diesel dual fuel engines at low speed and load, and they found that by advancing the pilot injection timing can increase cylinder pressure and heat release rates and thermal efficiency while NO_x and HC emissions also increase. Based on the research that has been done above, it can be concluded that the timing of pilot injection timing can affect engine performance, combustion and emissions on desel/CNG dual fuel engines under low load. This study aims to correlate engine performance, combustion and exhaust emissions by optimizing the pilot injection timing of diesel/CNG in dual fuel engines under low load.

2. Experimental apparatus ang procedure

2.1. Test engine

The diesel engine used in this study is a Diamond DI 800 single-cylinder using a water cooling system. The engine specifications used in this study are shown in Table 1. This engine is modified into diesel/CNG dual fuel engine by adding CNG as the main fuel as shown in Figure 1. CNG is injected

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through the port channel that is controlled using an electrical control unit (ECU) whereas diesel fuel is injected directly into the combustion chamber using a conventional system. CNG is injected at 45^0 ATDC at the suction stroke, while the standard diesel pilot injection timing is 13^0 BTDC at the end of the compression stroke.

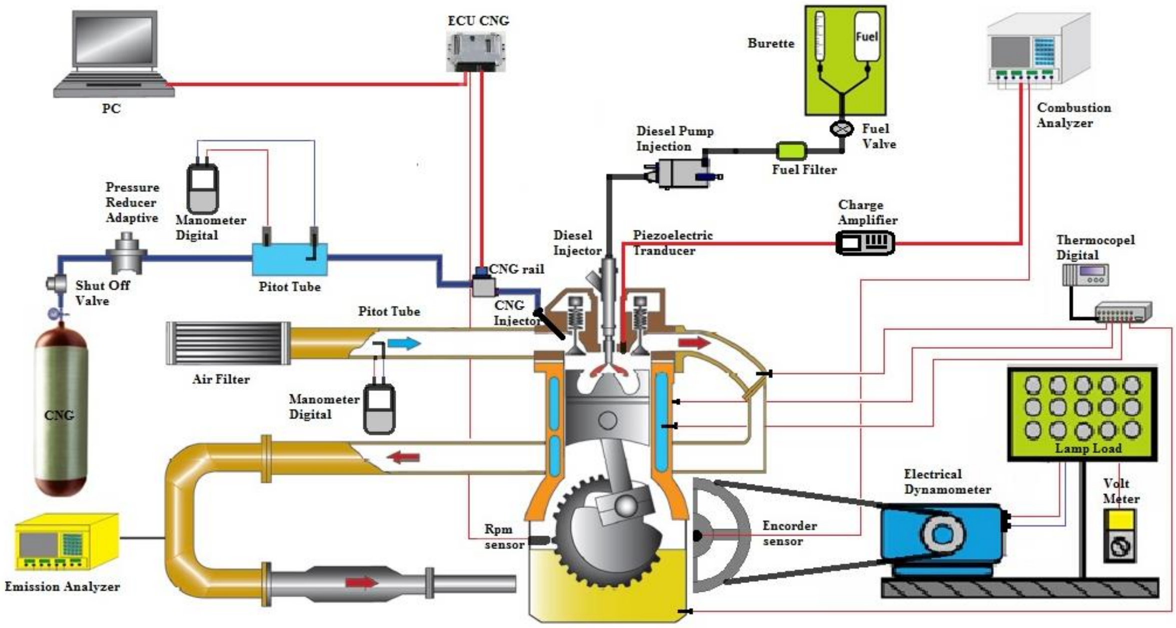

Figure 1. Experimental setup

2.2. Fuel and supply system

In this study, diesel fuel is used as a pilot for diesel while CNG is the main fuel for diesel/CNG dual fuel engine. The diesel fuel and CNG properties used in this study are shown in tables 2 and 3 below[18]. Experimental research on diesel/CNG dual fuel engines using a dual fuel system. Diesel fuel uses conventional fuel systems that already exist on the engine. CNG fuel is supplied from a gas tank that has a pressure of 250 bar which is equipped with a safety valve, then the pressure is lowered using an adaptive reducer pressure[19] to a working pressure of 2 bar. CNG is injected into the intake port using a CNG injector.

Table 1 The poperties of fuel.

Fuel Properties	Diesel	CNG
Low heating value (MJ/kg)	42,8	48,6
Cetane number	52,5	-
Octane number	-	130
Auto-ignition temperature (^{0}C)	316	650
Stoichiometric air–fuel ratio (kg/kg)	14,69	17,2
Carbon content (%)	87	75

Table 2 Composition of natural gas.

Fuel Poperties	Volumetric concentration (%)
Methane	96.160
Ethane	1.096
Butane	0.136
Iso-Butane,n-butane	0.021
Iso-Pentane, n-pentane	0.006
N2	0.001
H2S	0.0002
H2O	0.006

2.3. Instrument arrangement and data acquisition
Diesel/CNG dual fuel engine coupled with an electrical generator used for loading the engine. Kistler piezoelectric pressure sensors are mounted on the cylinder head to measure cylinder pressure and heat release rate with a 0.20 crank angle (CA) resolution. CNG mass flow rate and air are measured using a digital manometer with an accuracy of ± 0.001. The machine is given a low load using a lamp with a capacity of 1500 watts (33.3%) connected to an electric generator. The consumption of diesel fuel is measured using a burette meter with an accuracy of 1 ml. The gas star 898 emission analyzer is used to measure HC and CO exhaust emissions while the PM is measured using a smoke opacity meter parallel to the emission analyzer.

2.4. Test procedure and conditions
The test engine is heated for 30 minutes until it reaches a temperature of ± 80^0 at ambient temperature of 25^0. Experiment testing is carried out on dual fuel diesel engines at low, medium and high loads at rotation 1500. The test is divided into two stages, first, testing the engine with standard fuel as control variable. Second, testing the engine using two fuels with a variation on the time of injection of a diesel pilot. Pilot injection timing is advanced from 110 BTDC to 190 BTDC. Advancing the pilot injection timing is done by reducing the thickness of the shim plate on the diesel injection pump holder. Reducing the thickness of the shim plate 0.1 mm can advance the pilot injection time of 1^0 CA.

3. Results and discusstions
This discussion analyzes engine performance, combustion process and emissions in diesel/CNG dual fuel engines under low loads with varying pilot injection timing. Power, specific fuel consumption (SFC) and thermal efficiency are engine performance while the combustion process includes cylinder pressure, heat release rate (HRR), ignition delay and combustion duration, then emissions include HC, CO and PM. Combustion include cylinder pressure, heat release rate, ignition delay, combustion duration, while. Ignition delay is defined as the start of the pilot injection until the start of combustion while the duration of combustion is the start of combustion (SOC) to the end of combustion (EOC). Generally, the ignition delay period on a diesel/CNG dual fuel engine is longer than a single fuel engine[6] while the duration of combustion is affected by the quality of premix combustion and diffusion of diesel/CNG fuel. The combustion process in diesel/CNG dual fuel engines has three stages. The first stage of combustion is premix from diesel fuel and a small part of the gas that starts to mix with diesel fuel, the second stage is premix combustion of CNG and the third stage is the combustion of diffusion from diesel fuel and CNG [13].

3.1. Engine performance characteristics of diesel/CNG dual fuel engine
In figure 2, shows the power, SFC and thermal efficiency under variations in pilot injection timing at low loads. Figure 2. It is seen that thermal efficiency has a significant difference with the variation of pilot injection timing compared to power and SFC. Advancing the pilot injection time from 11^0 to 19^0

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BTDC can increase thermal efficiency with a maximum value of up to 14.03% at pilot injection time 17^0 BTDC under low load. This is because by advancing the pilot injection timing prolongs the mixing time of diesel fuel with CNG-air mixture so that the mixture is more homogeneous, so that it initiates a large number of hotspots around the combustion chamber which influence the premix combustion speed so as to improve diffusion combustion quality better and cause an increase in thermal efficiency. However, if the pilot injection timing is further advanced, the efficiency decreases slightly. This is because the pilot injection timing is too fast in the compression stroke with the pressure and temperature that is still low so that the combustion performance decreases which affects the decrease in thermal efficiency. This proves that the pilot injection timing affects the thermal efficiency so that optimization is needed to get the right pilot injection timing. In figure 2, also displays the power and SFC on diesel/CNG dual fuel engine under different pilot injection timing. Pilot injection timing does not have a significant effect on power and SFC, this is due to the given load and constant engine speed (1500 rpm) so that the voltage and current generated by the electricity generator are the same, as well as the engine fuel consumption.

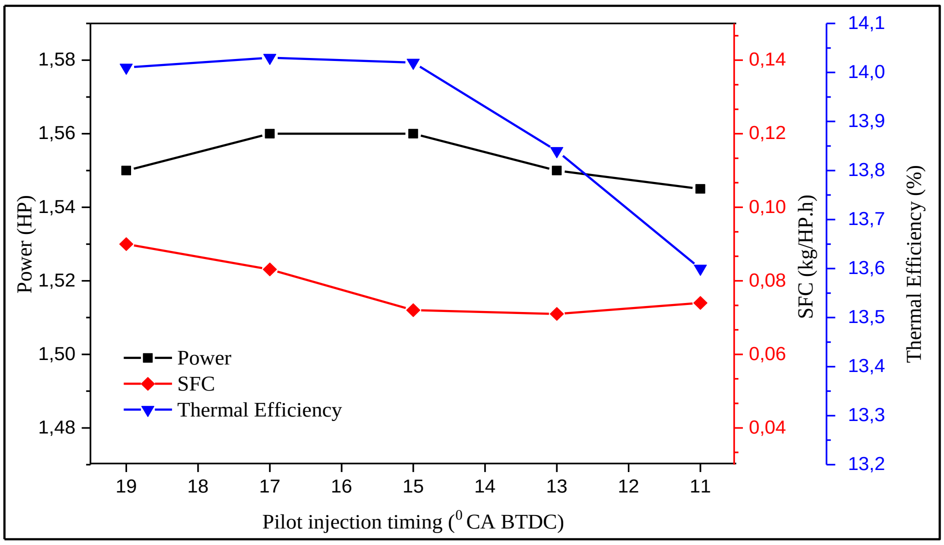

Figure 2. Engine performance versus pilot injection timing under low load

3.2. The cylinder pressure and heat release rate characteristics of diesel/CNG dual fuel engine

In figure 3, shows cylinder pressure and HRR below the variation of diesel pilot injection timing at low loads. Figure 3 explains that the cylinder pressure has two peaks, the first peak of which is the premix combustion of diesel and CNG while the second peak is the diffusion combustion of diesel fuel and CNG. Advancing the diesel pilot injection timing can increase cylinder pressure and also the cylinder pressure curve tends to lead to one peak. A significant increase occurred at the pilot injection timing of 17^0 BTDC with a value of 4.87 MPa compared to other variations. The peak of diffusion combustion occurs at an angle of 12^0 ATDC near TDC at the pilot injection timing of 17^0 BTDC. This shows that by burning the peak near TDC will produce maximum cylinder pressure. However, moment the pilot injection timing is further advanced at 19^0 BTDC there is a decrease in cylinder pressure. This is due to the injection that is too early at compression pressure and the temperature is too low so that the combustion of the fire speed that develops becomes slow. Likewise with pilot injection timing retard there is a decrease in combustion pressure, especially at the second peak in diffusion combustion. This is affected by a long ignition delay period on dual fuel engines so that maximum combustion occurs at the expansion stroke away from TDC. Figure 3. Also explains the rate of heat release (HRR) affected by pilot injection timing under low load. Advancing the pilot injection timing causes an increase in HRR, especially at pilot injection timing of 17^0 BTDC with a maximum value of 52.05 $kJ/m^3/^0CA$. Peak heat release rate occurs during diffusion combustion. This is because the cylinder pressure and high

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temperature due to the energy released at the compression step increases so that the peak heat release occurs at TDC. Likewise, advancing the pilot injection timing causes the ignition delay period to be longer so that mixing between the pilot fuel and the CNG-air mixture becomes more homogeneous[13]. Thus the number of ignition kernel will form more in the area of the combustion chamber so that the propagation of the fire becomes faster, resulting in increased premix and diffusion combustion. However, if the pilot injection timing is further promoted causing a decrease in HRR, due to compression pressure and the temperature is still low so that the combustion quality decreases. Besides that, by pilot injection timing retard too far there was a decline in HRR, especially during the pilot injection timing of 11^0 BTDC. This is affected by the ignition delay on the diesel/CNG dual fuel engine for longer so that the maximum of peak cylinder pressure away from the TDC so that diffusion combustion occurs more in the expansion stroke. This is indicated by the high heat release rate in the expansion stroke.

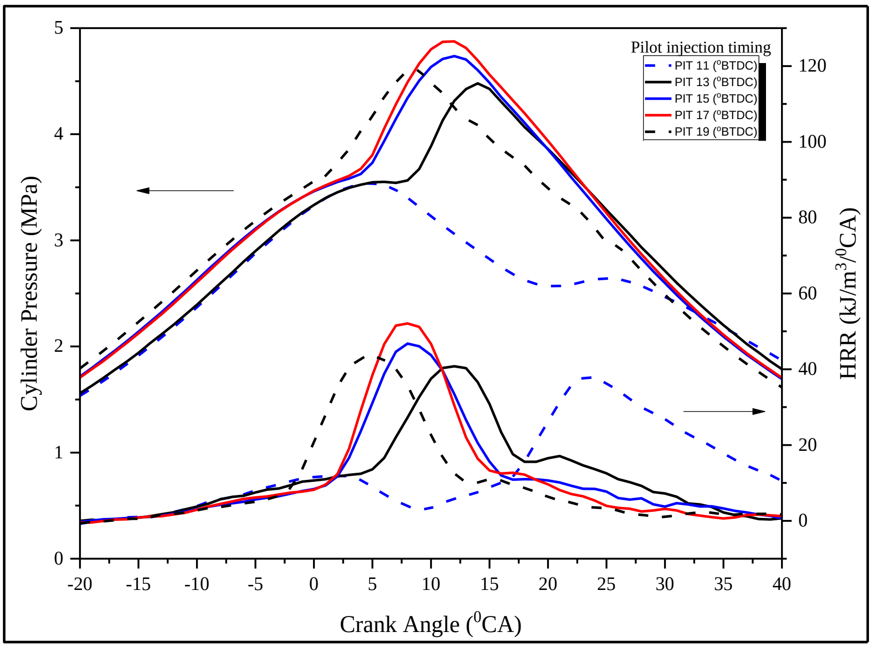

Figure 3. The cylinder pressure and HRR versus pilot injection timing under low load

3.3. Combustion performance characteristics of diesel/CNG dual fuel engine

The combustion performance described in this study is ignition delay period and combustion duration both under low load. Figure 4, shows ignition delay period and duration of combustion with different pilot injection timing under low load. Advancing the pilot injection timing increases the ignition delay period. The results show an ignition delay with a pilot injection timing of 19^0 BTDC longest compared to other variations. The addition of ignition delay period is affected by physical and chemical delay. Physical delay process is caused by the process of atomization, evaporation and mixing of fuel, while chemical delay is caused by chemical reactions that occur in the formation of ignition kernel. CNG fuel input causes a decrease in charger temperature due to the high specific heat ratio of CNG-air mixture and partial pressure reduction from oxygen, so the chemical delay process becomes long[6], and when the pilot injection timing is advanced, the delay becomes even longer. However, this addition gives a positive value for mixing the pilot fuel with the CNG-air mixture in the combustion chamber, so that the pilot fuel mixture with gas-air becomes more homogeneous and increases the formation of ignition kernel, thus increasing premix combustion from diesel fuel. On the other hand it gives a negative effect if the pilot injection timing is further advanced, where the pilot fuel is injected too early at low temperatures and pressures so that the flame propagation speed becomes slower so the diffusion combustion becomes lower. However, if the pilot injection timing is delayed the CNG-air mixture density in the combustion chamber becomes higher so that the atomization process becomes disrupted which results in fewer ignition kernel which appear. The consequence is the peak of combustion away from the TDC that occurs in the expansion stroke. In Figure 4, it also shows that the duration of combustion on diesel/CNG dual fuel engines under low load has a different phenomenon. The results show that by advancing the pilot injection timing 17^0 BTDC it can accelerate the duration of combustion so that it affects the rate of heat release. This is because the energy burned is more at the maximum cylinder pressure and also the peak position of the cylinder pressure is at TDC so that the combustion temperature is still high. Likewise with a more homogeneous mixture state produces more fire points appear in each area of the combustion chamber so that the time needed to burn the mixture of fuel and air becomes less. However, if the injection time is further advanced there is an additional duration of combustion due to the initial injection on the pressure and low temperature. Another phenomenon, moment the pilot injection timing is retard at the pilot timing injection 11^0 BTDC there is a significant increase in the duration of combustion. This is affected by the peak of the cylinder pressure that occurs at the expansion stroke so that the duration of combustion becomes longer.

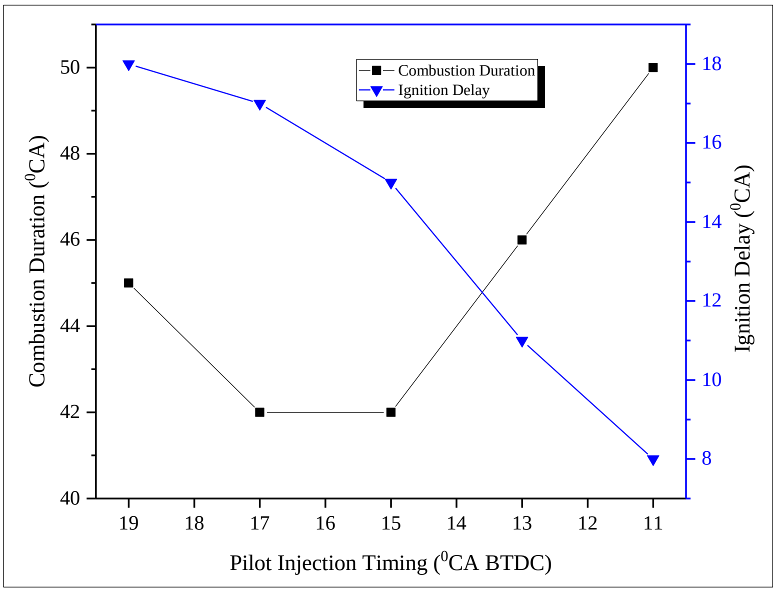

Figure 4. Combustion performance versus pilot injection timing under low load

3.4. Emissions characteristics of diesel/CNG dual fuel engine

In Figure 5, shows emission characteristics on diesel/CNG dual fuel engines at various pilot injection timing under low load. Figure 5, shows that HC, CO and PM emissions have the same chart trend under different pilot injection timing. The results show that the pilot injection timing can significantly reduce HC and CO emissions. One of the causes of CO emissions is incomplete combustion due to low cylinder pressure and temperature. Especially under low pressure and temperature loads are more likely to be lower than medium and high loads. By advancing the pilot injection timing increase the cylinder pressure and the temperature to be higher so that the combustion becomes more perfect. Likewise with HC emissions on diesel/CNG dual fuel engines more likely to increase under low load. HC emissions in 80% from diesel/CNG dual fuel are caused by unburned of CNG. The results show that by advancing the pilot injection timing can prolong the fuel and air mixture to become more homogeneous so that the unburned fuel decreases and also when the ignition starts earlier so that the fuel will burn on TDC with high temperature conditions. Moment the pilot injection timing is retard the combustion occurs more in the expansion stroke so that the pressure and temperature drop so that the fuel is more unburned and wasted through the exhaust manifold. Figure 5, also shows that PM emission has a significant decrease by advancing the pilot injection timing, because by advancing the high cylinder pressure and temperature and homogeneous mixture so that the PM emission is reduced.

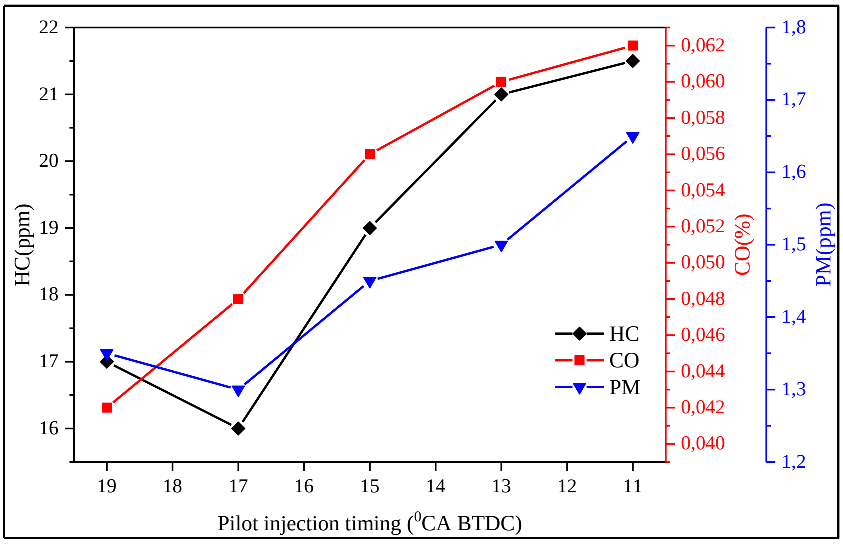

Figure 5. Emission diesel/CNG dual fuel versus pilot injection timing under high load

4. Summary

This study investigates the characteristics of engine performance, combustion and emissions of diesel/CNG dual fuel engine with varying pilot injection timeing under low load at constant speed. The Cylinder pressure, heat release rate, ignition delay and combustion duration were measured using a combustion analyzer, while emissions of HC, CO and PM were measured by using four gas analyzers. Engine performance includes power, SFC and thermal efficiency calculated by the voltage and current data obtained from the electrical generator. Based on the parameters that have been analyzed, we can conclude that the engine performance, proses pembakaran and emissions on diesel/CNG engine dual fuel is affected by the pilot injection timing under low load. Advancing the pilot injection timing of can increase cylinder pressure up to 4.87 MPa, heat release rate up to 52.05 kJ/ $m^3/^0$CA and reduce emissions of CO, HC and PM. Likewise, combustion performance has increased marked by a reduction in the duration of combustion and the maximum of peak combustion approaching TDC by advancing the pilot injection timing.

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