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# Effects of Different Injection Timings on the Performance and Emission Characteristics of the Direct-Injection Compressed Natural Gas Engine

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## Abstract

The primary objective of this research is to investigate the effects of different injection timings such as early, partial and late fuel injection timings on the performance and emission characteristics of the direct injection compressed natural gas (DI-CNG) engine. The research was conducted by experiment using single cylinder four stroke spark-ignition direct injection CNG engine at stoichiometric mixture, wide open throttle (WOT) and different injection timings. The results showed that by advancing the injection timing (early injection timing) produce a better brake torque across all engine speed compared to the other injection timing under the same operating conditions. While, partial injection timing gives out the lowest brake specific fuel consumption as it produces the least friction mean effective pressure inside the cylinder during the combustion process which lowered the amount of work done by the piston. At lower engine speed (up to 3000 rpm), BSNOx emission was notably lower at late injection timing. Drastic reduction in BSCO emissions was observed as more complete combustion process occurred at the operating condition under consideration. As the speed was increased above 3000 rpm, there is increase in BSCO emission. Early injection timing recorded the lowest BSUHC emission as homogeneous fuel mixture provides a complete combustion process which reduces the BSUHC emission. In addition, late injection timing increases the BSNOx and BSUHC emissions because of the lower quality of combustion process at that operating condition. From the foregoing, it is reasonable to say that the use of late injection timing to control BSNOx and BSUHC emission concentrations in DI-CNG engine is greatly discouraged. Thus it can be concluded that, the implementation of early and partial injection timing in DI-CNG engine is a viable approach towards realizing high performing internal combustion engine and curbing global warming by drastically reduce the emission of BSNOx, BSCO and BSUHC in DI-CNG engine.

**Keywords:** Injection Timings, Direct Injection Compressed Natural Gas Engine, Performance Characteristics, Emission Characteristics, Wide Open Throttle (WOT), and Stoichiometric Mixtures.

## INTRODUCTION

World's today is basically runs on fossil fuel such as the petroleum and diesel. Gasoline is a transparent liquid that was obtained from the distillation process and was mixed with some additive that typically consists of four to eight carbon atoms [1-2]. Diesel fuel also was produced by fractional distillation of crude oil which typically consists of eight to twenty carbon atoms per molecule. Combustion from the fossil fuel engines such as those which burn gasoline and diesel fuel is causing permanent damage to the environment. Carbon monoxide is not the only carbon by-product from the exhaust. Carbon dioxide is also is given off by the exhaust fumes and one of the leading cause of the breakdown in the ozone layer which is leading to global warming. The reason why these conventional fuel become dominant is because of their high energy content and availability. However, the utilization of these fuel poses threat such as, environment hazards due to its high emission and high pollutant emission (i.e. NOx and CO), unstable energy price and last but not least the non-renewability of the fuel [2-5].

In view of these problems pose by the conventional fuel, investigating another fuel to be utilized in internal combustion fuel become highly imperative. Compressed natural gas (CNG) is the best alternative fuel because it is cheap, cleaner burning characteristics and renewability which can be found naturally in decaying organic materials [5-7]. CNG offers many advantages over conventional petroleum products. Compressed Natural Gas (CNG) represents almost a 50% savings over petroleum products such as gasoline and diesel fuel. Vehicles powered by CNG have lower maintenance costs than other hydrocarbon fueled vehicles. Using CNG makes the engine cleaner and more efficient. Unlike gasoline, CNG minimizes harmful carbon deposits when combusted. This results to a cleaner and more efficient engine as well as longer lasting spark plugs. Oil changes are also minimized because of carbon deposits that contaminate the oil is eliminated [7].

Apart from the fuel, there are other important parameters that can control the internal combustion engine for higher performance and low engine out emission. One of such parameter is injection parameter. Injection parameters are the parameters that control the injection necessary to ensure efficient fuel delivery in internal combustion engine. The parameters include fuel injection rate, fuel injection pressure and fuel injection timing [1]. However, for the purpose of this study, attention will be focused on the effects of the fuel injection timings. Fuel–Injection timing essentially controls the crank angle at which the combustion starts. While the state of air into which the fuel is injected changes as injection timing varied, and thus ignition delay will vary, these effects are predictable [1-4]. A lot of researches have been done to study the effects of injection timings in internal combustion engine. Sequera, Parthasarathy, & Gollahalli, 2011[8] conducted an investigation on the 'effect of fuel injection timing in the combustion of biofuels in a diesel engine. Their research focus on the use of biodiesel in a diesel engine where they found that by advancing injection by 8°CA increased peak pressure by approximately 20%, whereas retarding injection by 11° CA reduced peak pressure by about 10%. It was found that retarded injection could be used to reduce the CO and NO emissions. On the other hand, advanced injection resulted in an increase in the CO and NO emissions. These changes in the exhaust emissions were attributed to the interaction of the start of injection and the ignition delay. The shorter ignition delay of biofuels allowed combustion to start earlier in the cycle; however, this effect was compensated by the retarded injection, making the combustion start and end closer to the optimal time of combustion of the cycle. Nwafor et al., 2000 [9] also conducted a study to investigate injection timing in their research titled "Effects of advanced injection timing on the performance of rapeseed oil in diesel engines". Their research focus more on the advanced injection timing tended to reduce performance, relative to standard injection timing test on rapeseed oil where the advanced injection timing produced highest exhaust temperatures with appreciable reduction in carbon monoxide (CO) and carbon dioxide ($CO_2$) exhaust emissions. They come to a conclusion that plant oil fuels exhibited longer ignition delay with slower burning rates. The test results also showed that each alternative fuel requires injection advance appropriate to its delay period. The delay period was to be influenced by the engine load, speed and the system temperature. At the engine speed of 2400 rpm, there seems to be a significant increase in brake thermal efficiency when running on rapeseed oil fuel with standard injection timing. Mechanical efficiency was observed to be reduced with advanced timing compared to the standard timing test results at 2400 rpm. The engine ran smoothly with advance of 3.58° CA as compared to the standard timing. A further 1.58°CA advance tended to produce erratic behaviour of the engine. There seems to be a significant reduction in CO and $CO_2$ emissions with advanced timing for the speeds tested. A moderate injection advance is recommended for operations at low engine speeds. The overall results indicate that vegetable oils exhibit longer combustion duration with moderate rates of pressure rise, unlike petroleum derived fuels. Desantes, Benajes, Molina, & González, 2004 [6] also investigated the modification of the fuel injection rate in heavy-duty diesel engines. The study focus on the effects of injection rate shaping on the combustion process and exhaust emissions of a direct-injection diesel engine and evaluation of the effective changes produced in the injection rate at different engine operating conditions, when the engine rotating speed and the total fuel injected were changed. They found that there are significant reduction in NOx emissions, which is greater as the boot length is increased or the boot pressure is reduced. On the other hand, since the injection time is increased by taking these actions, BSFC and dry soot emissions increased the latter being more sensitive to these factors. The relative increase in dry soot with respect to the decrease in NOx emissions is worse at medium engine load. This prove that the injection system is able to produce flexible rate shaping, and in particular, boot-type injections with different lengths and pressures at different engine operating modes. Parlak et al., 2005 [10] concentrated on the impact of infusion timing on the NOx outflows and BSFC of a low heat rejection (LHR) indirect injection diesel engine using diesel as fuel. The tests were led with variable loads at engine speeds of 1000, 1400, 1800 and 2000 rpm and the static injection timing of 38°, 36°, 34° and 328° crank angle (CA). After the load tests were conducted for original diesel engine, same test order was adopted for the LHR engine. When the LHR engine was operated with the injection timing of the 388° CA before top dead centre (BTDC), which is the optimum value of the original engine, it was shown that NOx emission increased about 15%. Till date, communication gap still exists on the effects of injection timings in the direct injection compressed natural gas (DI-CNG) engine. Therefore, the purpose of this research is to study the effects of different injection timings such as early, partial and late injection timings in the direct injection compressed natural gas (DI-CNG) engine and clarify the engine behavior under the influence of different injection timings.

## EXPERIMENTAL PROCEDURES

The schematic of the experimental set up is given in Figure 1 below. The specifications of the test engine are listed in Table 1. A four stroke single cylinder research engine was used to investigate the effects of different injection timings on the performance and emission characteristics of the direct injection compressed natural gas (DI-CNG).

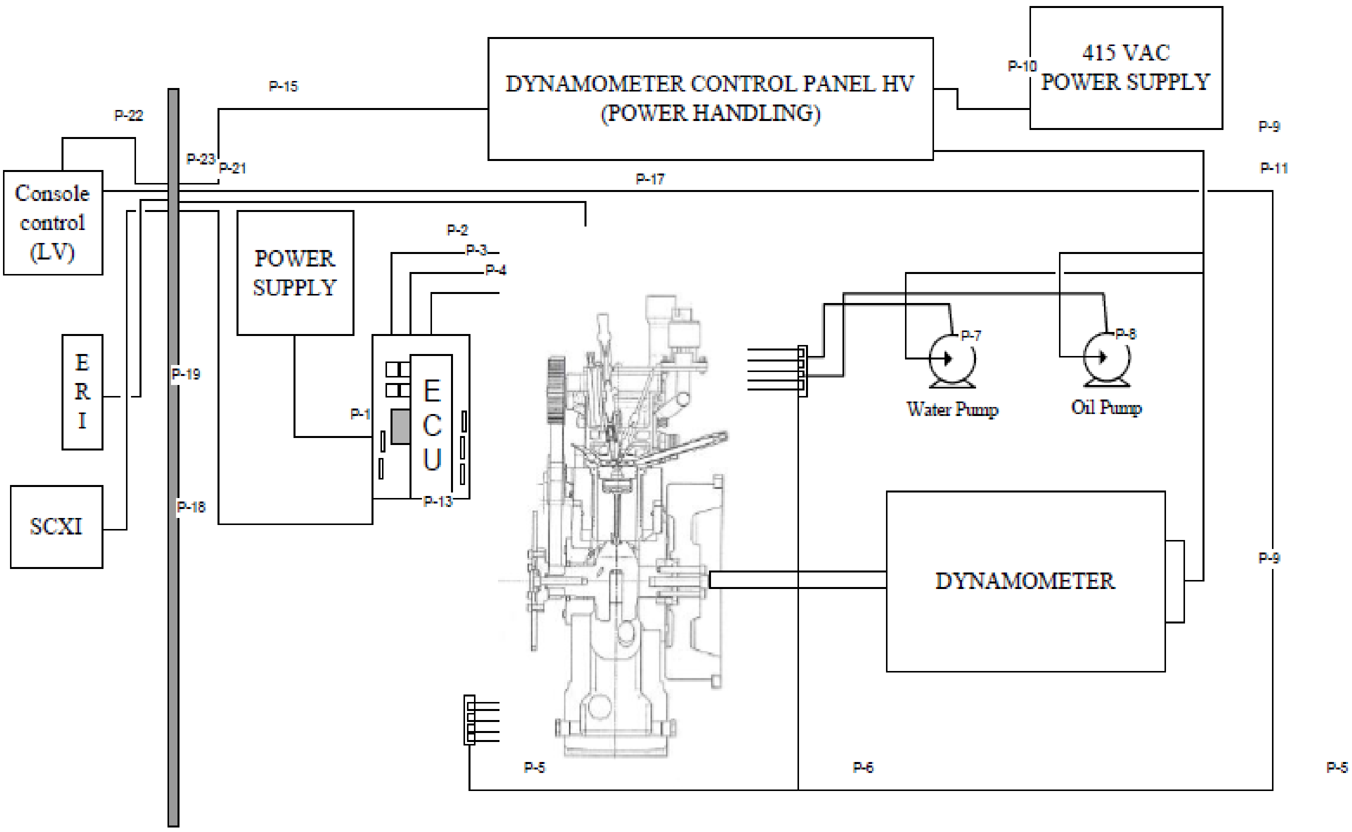


**Figure 1:** Schematic diagram of the experimental setup

**Table 1:** Engine Specification

| **Engine Properties** | |
|---|---|
| Displacement Volume | 399.25 $cm^3$ |
| Cylinder Bore | 76 mm |
| Cylinder Stroke | 88 mm |
| Compression Ratio | 14 |
| Exhaust Valve Open | BBDC 45° |
| Exhaust Valve Closed | ATDC 10° |
| Inlet Valve Open | BTDC 12° |
| Inlet Valve Closed | ABDC 48° |
| Dynamometer | Eddy current with maximum reading of 50 Nm |
| ECU | Orbital Inc |

The supply system of the experiment consists of pressure gauge, fuel line and flowmeter. The engine was ran before conducting the experiment until the oil and coolant reached 60°C and 70°C respectively to make sure it is stable. The experimental works started by injecting CNG into the engine cylinder. The engine control unit (ECU) was used to control the engine operating parameters such as the injection timings, the air-fuel ratio, WOT and engine speeds. Fuel pressure regulator was used to control the fuel rail pressure and stabilized the injector pressure. The fuel rail deliver the CNG to the engine from the fuel tank. Flowmeter control the flow rate of the CNG to ensure the flow rate is fixed. Pressure regulator was used to regulate the pressure of the CNG. Eddy current dynamometer was used to measure the performance characteristics of the engine such as the brake-torque (BT) and brake-power (BP) and brake specific fuel consumption (BSFC). The exhaust gas from the engine was measured with the aid of the Gasmet gas analyser which analysed the emission characteristics data of the engine such as nitric oxide (NOx), unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions.

## STOICHIOMETRIC COMBUSTION STRATEGY

The combustion equation representing CNG from which the various stoichiometric air-fuel ratio utilized for this experiment was calculated is given below:

$$CH_4 + a\,(O_2 + 3.76N_2) \longrightarrow xCO_2 + yH_2O + zN_2$$

Where:

a represents mole number of air

x represents mole number of carbon dioxide

y represents mole number of water

z represents mole number of Nitrogen gas

## RESULTS AND DISCUSSION

### Introduction

The results from the experiments performed on the direct-injection single cylinder four-stroke engine for maximum load operating condition are shown below. The injection timings utilized for this experimental is set at 300°CA (Early Injection Timing), 180° CA (Partial Injection Timing) and 120° CA (Late Injection Timing) respectively. Finally, results were analyzed and discussed for performance characteristics such as brake torque (BT), brake specific fuel consumption (BSFC) and various emission characteristics such as brake specific carbon monoxide emission (BSCO), brake specific nitric oxides emission (BSNOx) and brake specific unburned hydrocarbon emission (BSUHC) against different engine speeds.

### Performance Characteristics

#### *Brake Torque*

Figure 2 shows the relationship between the brake torque against the engine speed at various injection timings (early, partial and late injection timing). The experiment was conducted at WOT using stoichiometric mixture. From the graph, it can be seen that brake torque for early and partial injection timing increased from 2000 rpm to 3000rpm. This is due to the increase in burning velocity occasioned by enhanced turbulence in the engine cylinder as the engine speed was increased to 3000 rpm. While, the brake torque for early and partial injection timing decreased from 3000 rpm to 5000 rpm. This is so, as the friction power increase rapidly with increasing engine speed, the brake torque of the engine will decrease. More so, brake torque for late injection timing from 2000 rpm to 3000 rpm experienced a slight decrease. This is because as the in-cylinder pressure is increased; the intake velocity of the engine will reduce which subsequently reduce the amount of air entering the cylinder. It is also clear from the graph that for late injection timing there is no data available for engine speed above 3000 rpm. This is because at that operating condition, the engine become unstable due to the high cycle by cycle combustion variation occasioned by variation in mixture composition. By comparing the various injection timings under consideration, the maximum brake torque occurs at early injection timing. This is because of the homogeneous air-fuel mixing that consequently leads to a more complete combustion process in the engine cylinder. Consider the brake torque at engine speed of 2000 rpm and 5000 rpm for early and partial injection timing. For early injection timing at 2000 rpm and 5000 rpm, the brake torque are 23.68 Nm and 20.45 Nm respectively. While for partial injection timing under the same operating condition, the brake torque respectively are 26.04 Nm and 19.90 Nm. This shows approximately 14% and 24% decrease in brake torque respectively. From the foregoing, it is obvious that more reduction in brake torque is occurring at partial injection timing. This is largely due to the composition mixture being neither homogeneous nor stratified. Good agreement is found between the experiment results and [1, 11].

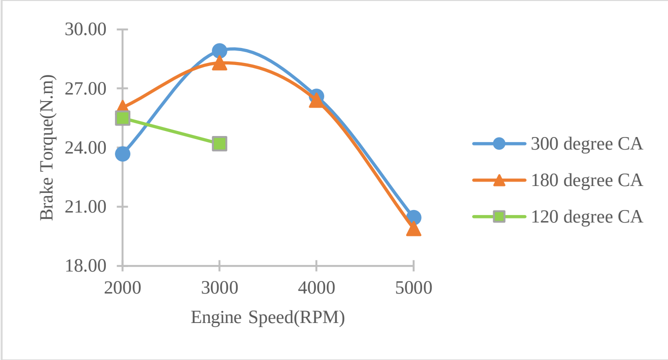


**Figure 2:** Brake-torque against engine speed at various injection timings

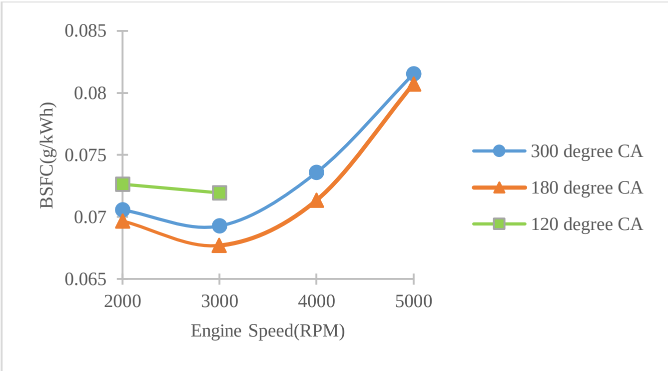


**Figure 3:** BSFC against engine speed at various injection timings

#### *Brake Specific Fuel Consumption*

Figure 3 shows the relationship between the BSFC against the engine speed at various injection timings (early, partial and late injection timing). The experiment was conducted at WOT using stoichiometric mixture. From the graph, it can be found that the BSFC is approximately constant at engine speed of 2000 rpm to 3000 rpm. This is because at lower engine speed, the friction mean effective pressure might not have a big influence over BSFC thus resulting in a constant graph trend at the operating condition. From 3000 rpm to 5000 rpm, the BSFC shows an increase for the early and partial injection timing. This is mainly due to the increased in friction mean effective pressure(FMEP) and decreasing importance of heat losses per cycle on efficiency. It is also clear from the graph that for late injection timing there is no data available for engine speed above 3000 rpm. This is because at that operating condition, the engine become unstable due to the high cycle by cycle combustion variation due to variation in mixture composition. Minimum BSFC occurs at the partial injection timing. This is because of the lower friction mean effective pressure as the engine speed increased as well as better air fuel mixing at this operating condition. Consider the BSFC at engine speed of 2000 rpm and 5000 rpm for early and partial injection timing. For early injection timing at 2000 rpm and 5000 rpm, the BSFC are 0.0705 g/kWh and 0.0815 g/kWh respectively. While for partial injection timing under the same operating condition, the BSFC are 0.0715 g/kWh and 0.0807 g/kWh. This shows approximately 16% and 13% increase in BSFC respectively. The result obtained here is in line with what is obtained in [1, 12].

## Emission Characteristics

### *Brake Specific Nitric Oxide (BSNO)*

Figure 4 shows the relationship between the BSNOx emission concentrations against the engine speed at various injection timings (early, partial and late injection timing). The experiment was conducted at WOT using stoichiometric mixture. The graph clearly shows a decreasing trend at 2000 rpm to 3000 rpm. Decrease in BSNOx emission concentrations as the engine speeds increase is due to the lack of oxygen which causes less oxygen to reacts with the nitrogen. While, BSNOx emission concentrations for late injection timing shows an increase from 2000 rpm to 3000 rpm. This is so because the combustion quality deteriorates as the engine speed was increased. It is also clear from the graph that for late injection timing there is no data available for engine speed above 3000 rpm. This is because at that operating condition, the engine become unstable due to the high cycle by cycle combustion variation caused by variation in mixture composition. Consider the BSNOx emission concentrations at engine speed 2000 rpm and 5000 rpm for early and partial injection timing. For early injection timing at 2000 rpm and 5000 rpm, the BSNOx emission concentrations are 216.37 ppm/kW and 67.56 ppm/kW respectively. While for partial injection timing under the same operating condition, the BSNOx emission concentrations are 245.26 ppm/kW and 61.83 ppm/kW. This shows approximately 69% and 75% decrease in BSNOx emission concentrations respectively. Thus, by comparing various injection timing, we can generally conclude that late injection timing is not a viable injection timing to control the BSNOx emission concentrations in DI-CNG engine. The result obtained here is in line with [9, 14 and 15].

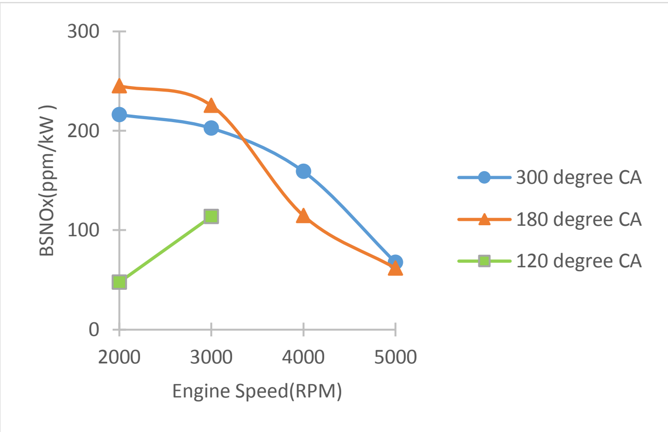


**Figure 4:** BSNOx against engine speed at various injection timings.

### *Brake Specific Carbon Monoxide (BSCO)*

Figure 5 shows the relationship between the BSCO emission concentrations against the engine speed at various injection timings (early, partial and late injection timing). The experiment was conducted at WOT using stoichiometric mixture. It is obvious from the figure 4.4 below that BSCO emission concentrations decreased from 2000 rpm to 3000 rpm. This is resulted from a more complete combustion process occurred which causes a leaner combustion process at lower engine speed. Subsequently, the BSCO emission concentrations shows an increasing trend with engine speed above 3000 rpm for the early and partial injection timing. This is because at a higher engine speed, oxygen concentrations decrease which results in incomplete combustion process as well as insufficient time for the complete combustion to take place as the combustion process occur at a higher speed. It is also clear from the graph that for late injection timing there is no data available for engine speed above 3000 rpm. This is because at that operating condition, the engine become unstable caused by the high cycle by cycle combustion variation which is caused by variation in mixture composition. The lowest emission of BSCO concentration occurs at the partial injection timing. This might due to the enhanced turbulence inside the engine cylinder resulting in a better and complete combustion process. Consider the BSCO emission concentrations at engine speed of 2000 rpm and 5000 rpm for early and partial injection timing. For early injection timing at 2000 rpm and 5000 rpm, the BSCO emissions concentration are 3174.71 ppm/kW and 1630.36 ppm/kW respectively. While for partial injection timing under the same operating condition, the BSCO emission concentrations are 3359.15 ppm/kW and 1199.24 ppm/kW. This shows approximately 48% and 64% decrease in BSCO emission concentrations respectively. Good agreement was achieved between the experiment and [8, 16].

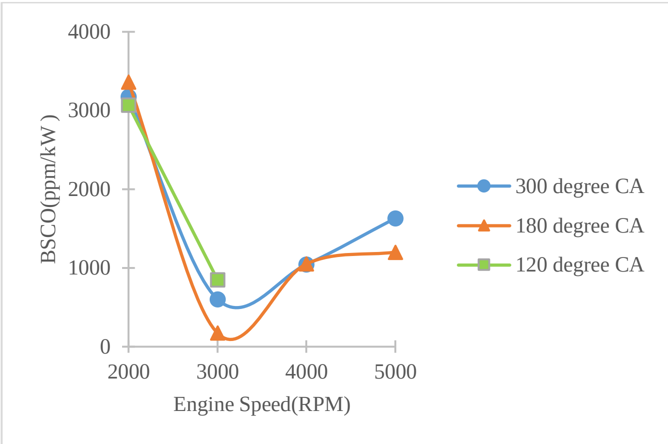


**Figure 5:** BSCO against engine speed at various injection timings

### *Brake Specific Unburned Hydrocarbon (BSUHC)*

Figure 6 shows the relationship between the BSUHC emission concentrations against the engine speed at various injection timings (early, partial and late injection timing). The experiment was conducted at WOT using stoichiometric mixture. It is obvious from the figure 4.5 below that increasing the engine speed from 2000 rpm to 3000 rpm drastically reduce the BSUHC emission concentrations. As the engine speed is increased, the combustion become faster thus reducing the BSUHC emission. More so, it can be observed that above 3000 rpm, the trend line for BSUHC emission concentrations is approximately constant. This is because of the reduced significance of heat transfer per cycle at higher engine speed. It is also clear from the graph that for late injection timing there is no data available for engine speed above 3000 rpm. This is because at that operating condition, the engine become unstable due to the high cycle by cycle combustion variation occasioned by variation in mixture composition. Lowest BSUHC emission concentrations occurred at early injection timing. This is caused by the homogeneous mixture of the fuel and air that contribute to a better combustion process. Consider the BSUHC emission concentrations at engine speed of 2000 rpm and 5000 rpm for early and partial injection timing. For early injection timing at 2000 rpm and 5000 rpm, the BSUHC emission concentrations are 217.43 ppm/kW and 95.59 ppm/kW respectively. While for partial injection timing under the same operating condition, the BSUHC emission concentrations respectively are 232.18 ppm/kW and 132.61 ppm/kW. This shows approximately 56% and 42% decrease in BSUHC emission concentrations respectively. It is obvious from the figure 4.5, that using late injection timing to reduce BSUHC emission concentrations in DI-CNG engine should be avoided (as it increases BSNOx and BSUHC emission concentrations). Good agreement is achieved between these experimental results and [17, 18].

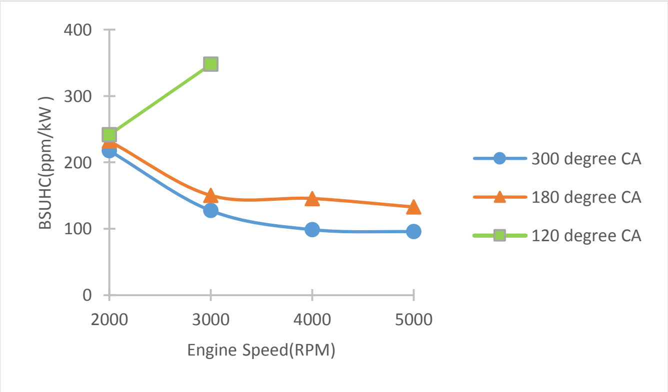


**Figure 6:** BSUHC against engine speed at various injection timings.

## CONCLUSIONS

An experimental study has been conducted to study the effect of different injection timings (early, partial and late injection timings) on the performance and emission characteristics of the DI-CNG engine and the vital findings from the results are outlined below:

- Advancing the injection timing (early injection timing) produce a better brake torque across all engine speed compared to the various injection timing under the same operating conditions. This is because of the homogeneous mixture of the air and fuel which promotes a better combustion quality.
- Partial injection timing gives out the lowest brake specific fuel consumption as it produces the least friction mean effective pressure inside the cylinder during the combustion which lowered the amount of work done by the piston.
- At lower engine speed (up to 3000 rpm), BSNOx emission concentration was notably lower at late injection timing. This is due to the stratified air-fuel mixture which results in more turbulence in the cylinder. However, as the engine speed was increased, partial injection timing shows a better BSNOx emission concentration compared to the various injection timings under consideration.
- Drastic reduction in BSCO emission concentration was observed from 2000 rpm to 3000 rpm for all the injection timing under consideration as more complete combustion occurred during the lower engine speed operation. As the speed was increased above 3000 rpm, there is increase in BSCO emission concentration. This is because oxygen concentration decreases which results in incomplete combustion process. Partial injection timing shows the lowest BSCO emission concentration across various engine speed.
- Early injection timing recorded the lowest BSUHC emission concentration as homogeneous fuel mixture provides a complete combustion process which reduces the BSUHC emission concentration. Engine speed above 3000 rpm shows a constant BSUHC emission concentration. However, it must be noted that the use of late injection timing should be avoided for BSNOx and BSUHC emission concentration as it increases their emission concentrations in DI-CNG engine. Figure 4.3 and 4.5 support this claim.

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