Development of a Single Cylinder CNG Direct Injection Engine and Its Performance, Emissions and Combustion Characteristics

ABSTRACT

This study presents experimental test results of a compressed natural gas (CNG) direct injection (DI) engine, which has been developed by modifying a single cylinder diesel engine. The major modifications are (a) modification of components such as cylinder head, piston etc. and (b) development and deployment of electronic fuel injection system and (c) installation of a capacitive discharge ignition system. Tests were conducted at constant fuel injection pressure and engine speed to investigate the performance, emission and combustion characteristics of a CNG DI engine under different fuel injection timings (Start of injection; SOI) and varying engine load (Brake mean effective pressure; BMEP). Based on the experimental results, it was found that moderate engine loads (BMEP) lead to faster and more complete combustion and improved engine performance with relatively lower emissions for specific injection timings. Advanced fuel injections improve engine performance (lower BSFC, higher BTE); reduce engine emissions and produce faster and superior combustion whereas retarded injections show completely opposite trends for every engine load.

Keywords: Compressed natural gas; Direct Injection; Manifold injection; Engine performance; Emission characteristics; Combustion Characteristics.

INTRODUCTION

With emerging stringent pollution legislations and limited availability of liquid fossil fuels, demand for improving fuel efficiency and reduction of harmful emissions has become the prime thrust for the present engine researchers. Petrol engine have the advantage of higher power-to-weight ratio compared to its diesel counterparts, but they suffer from the issue of relatively lower thermal efficiency due to unavoidable throttling and engine knock. Diesel engine has higher thermal efficiency; however, the emission of NO_x and particulate matters still remain a major concern. In recent years, direct injection gasoline engine has emerged to fulfill the need of improve fuel economy but still suffers from the problem of harmful PM emissions [1, 2].

With the plentiful availability of natural gas and low emissions due to its favorable (H: C) ratio, Natural gas has emerged as one of the most promising and clean alternative fuels for engine applications. Furthermore, its high octane rating allows high compression ratios leading to higher thermal efficiency however CNG suffer from the problems of very low energy density. There are many CNG engine technologies used worldwide, which differ in the way the fuel is introduced into the cylinder e.g. carburetor technology, port injection, duel fuel technology, etc. To utilize the full potential of CNG in engine applications, concept of direct injection (DI) has been investigated under various engine operating conditions by varying fuel injection timings, equivalence ratio, cyclic variations, spark timings etc.

Richards et al. [3] reported that CNG DI engine have higher power output and higher thermal efficiency compared to a conventional spark ignited natural gas engine due to higher compression ratio, and lower pumping losses at the part load conditions. Ikeda et al. [4] found in their study that an eight cylinder CNG DI engine had twice the brake mean effective pressure as compared to conventional spark ignited CNG engine (port fuel injected). Caley et al. [5] performed a comparative study on manifold CNG injection, manifold gasoline injection and CNG DI system and discovered that manifold CNG operation leads to a performance reduction of 9-13% compared to manifold gasoline operation whereas performance with DI CNG is within 3% of stoichiometric gasoline performance at low engine speeds and within 7% at higher engine speeds. Direct injection of CNG with late injection improves air flow upto 10% over manifold CNG operation, which in turn increases engine performance upto 10% at lower engine speeds but at higher speeds, only 4% improvement in engine performance due to reduction in mixing duration. Yuichi Goto [6] investigated the influence of injection timings and spark timings on the combustion and exhaust emission characteristics of a single cylinder diesel engine and demonstrated that when λ is close to 1.0 (Stoichiometric mixture), combustion becomes stable by more advanced injection and when λ is more than 2.0, retarded injection provides more stable combustion. Zeng et al. [7] showed that with advanced fuel injection timings, HC emissions decrease but NO_x emission increase due to adequate fuel-air mixing and complete and faster homogeneous combustion, whereas retarded injection lead to opposite trends. Liu et al. [8] investigated the influence of fuel injection timings and spark timings on combustion and emission characteristics of a spark ignited CNG DI engine and reported that advanced fuel injections lead to better air-fuel mixtures, promoting formation of flame kernel and thus reducing initial combustion duration, however, the rapid combustion duration is prolonged slightly. Huang et al. [9, 10] investigated the basic behavior of CNG DI combustion in a spark ignited rapid compression machine (RCM) with different injection modes and showed the same level of unburned HC as that of homogeneous combustion. CO increased steeply with the increase in equivalence ratio, when equivalence ratio was greater than 0.8 and NO_x emission peak shifts to the region of lower equivalence ratio. Results also showed that heat release pattern of early injection showed a slower combustion in the initial stages and a faster combustion in the later stages, which is similar to that of premixed gas. Whereas for late CNG injection, the heat release pattern showed faster combustion in the initial stage and slower combustion in the later stage, which is similar to diesel combustion. Early injection leads to a longer duration of initial combustion, whereas late injection leads to a longer duration of the late combustion. Most of the CNG DI researches are performed in RCM and provide some useful insight, however, the real in-cylinder gas flow and combustion between them makes it difficult to understand the effect of fuel injection timing on CNG DI combustion. Therefore, a systematic experimental study on the effect of fuel injection timing into an IC engine is worth investigating. The objective of the present study is to experimentally investigate the combustion behavior at varying loads and injection timings in a direct injection natural gas engine in order to develop better understanding of CNG DI engine.

EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in Figure 1. A single cylinder, four-stroke, naturally aspirated, water-cooled diesel engine was modified into CNG DI engine. The specifications of the modified engine are given in Table 1.

Table1: Test engine specifications after modifications

Make	Kirloskar, India
Model	DM-10
Bore	102 mm
Stroke	115 mm
Displacement	1000 cc
Compression ratio	9.5
Combustion chamber	Bowl shape
CNG Injection pressure	50 bars
Ignition source	Spark Plug

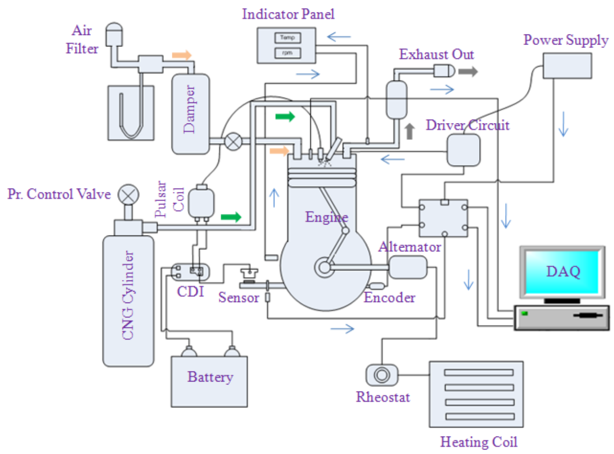

Figure 1: Schematic of the experimental setup

The major modifications done on the test engine are (a) cylinder head machining to accommodate both spark plug and CNG injector in their respective optimized positions, (b) modifications in piston bowl in order to reduce the compression ratio, (c) installation of capacitive discharge ignition system for the spark plug and (d) development and deployment of electronic fuel injection system. A gasoline direct injection injector (GDI) injector (Model: DIM1000G E7T05071, Mitsubishi, Japan) was procured and used to supply CNG directly into the engine combustion chamber at 50 bar pressure and the opening, closing of the injector and injection duration was controlled by a custom made electronic circuit, which uses TDC signals from a proximity sensor (GLP18APS, TAP). The calibration of the fuel quantity injected with the injector pulse width was carried out in the laboratory. An ignition system having pickup coil, capacitive discharge ignition (CDI) coil and a long tip spark plug was installed onto the engine. An alternator was coupled with the engine to apply load on the engine. The air flow rate into the engine intake manifold was measured using an orifice plate and U-tube manometer installed cross an air box. CNG mass flow meter was used to measure the CNG mass flow rate into the engine. A piezo-electric pressure transducer (6613CQ09-01, Kistler Instruments, Switzerland) was mounted flush with cylinder head and the in-cylinder pressure data vis-a-vis crank position signals from a shaft encoder (ENC58/6-720AB, Encoders India) was acquired by a high-speed combustion data acquisition system (Synergy, Hi-Techniques, USA). For the analysis for combustion characteristics, average data set of data acquired for 100 consecutive cycles was used. Raw exhaust emissions were measured using exhaust gas emission analyzer (444 Digas, AVL, Austria) and smoke opacimeter (437, AVL, Austria). The engine was operated in steady-state condition with wide open throttle (WOT) at constant engine speed of 1500 rpm and spark ignition angle was fixed at 31^0 BTDC. Four different fuel injection timings were selected for investigation in this study and engine loads were varied from 1- 3 kW with 0.5 kW step size. Fuel injection pressure was kept constant at 50 bars.

RESULTS AND DISCUSSION

INJECTION STRATEGIES

The start of fuel injection (SOI) timing and injection duration for four different cases are shown in figure 2. Due to relatively long injection duration for natural gas injection and in order to complete the injection before the ignition, the starting of the fuel injection is done before intake valve closing (IVC).

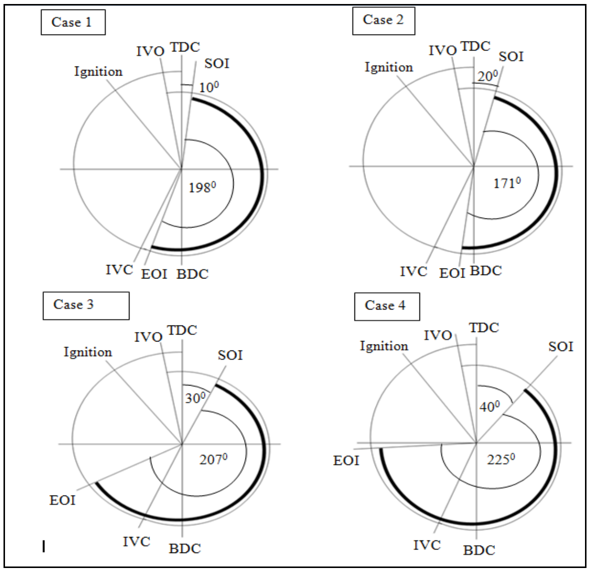

Fig 2: Various injection events and schemes on the valve timing diagram

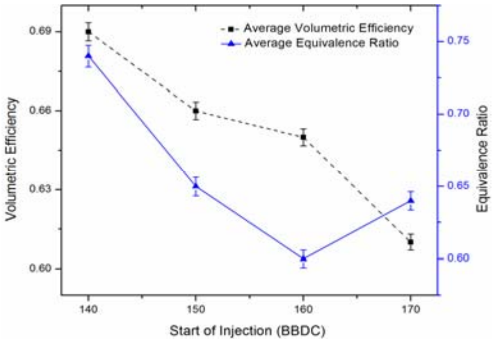

Fig 3 : Volumetric efficiency and equivalence ratio vs. start of injection timings

PERFORMANCE CHARACTERISTICS

The performance of the engine with respect to volumetric efficiency, brake thermal efficiency, specific fuel consumption and exhaust gas temperature were investigated in this study under various engine operating conditions. Figure 3 shows the effect of start of injection timings on volumetric efficiency and equivalence ratio of CNG DI engine. It is seen that the average volumetric efficiency of CNG DI engine decreases with advancing start of fuel injection timing. This is due to displacement of higher air quantity by natural gas as the intake valve remains open during advanced fuel injection.

Figure 4 presents various engine performance curves with engine load i.e. brake mean effective pressure (BMEP) under different fuel injection strategies at constant speed and fuel injection pressure. The figure indicates that the start of injection timing has a great influence on engine performance characteristics.

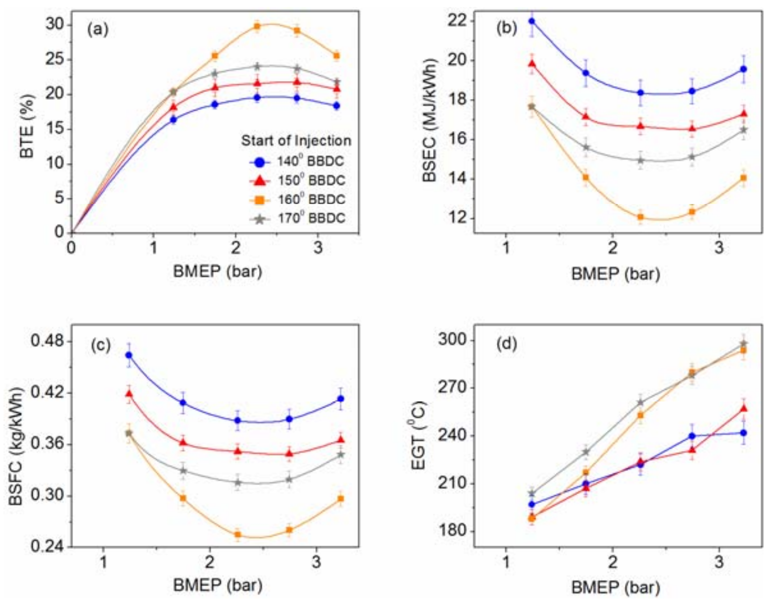

Figure 4: Engine performance characteristics curves (a) BTE vs. BMEP (b) BSEC vs. BMEP (c) BSFC vs. BMEP (d) EGT vs. BMEP

Figure 4 (a) shows the variation of BTE with engine BMEP at various SOI timings. It is seen from the figure that the brake thermal efficiency increases with increasing engine load (BMEP), and reaches a maximum value (which is also lowest BSFC point also in figure 4(c)) and then starts decreasing with further increase in BMEP. Among these four SOI timings, 160° BBDC gives the highest BTE at all engine loads. Figure 4(b) shows BSEC versus engine BMEP under different fuel injection timing. Figure 4 (c) shows the variation of BSFC with the engine BMEP at constant speed (1500 rpm) under different fuel injection strategies. It is observed that BSFC is relatively high, both at high and low loads [13, 14] and it is lowest at loads slightly lower than rated load. At high engine loads, the requirement of enriched mixture so as to increase engine torque increases fuel consumption whereas increased pumping work at low engine loads reduces brake power, which in-turn increases specific fuel consumption. Lowest BSFC obtained at 2.5

bars BMEP (injection case 2) is 0.26 kg/kWh. Figure 4(d) shows the exhaust gas temperature variation with engine load (BMEP) under different fuel injection timings. The result shows that the EGT increases with engine load and attains maximum value of 298^{0}C for 170°. Advanced SOI timings produce relatively lower BSFC and higher BTE and EGT and vice versa. Advanced SOI timings lead to availability of higher fuel-air mixing time therefore making the mixture more homogeneous, which finally results in improved combustion. This also reduces pumping losses during intake. These factors play an important role in improving the engine performance. On the other hand, retarded fuel injection timings reduce the time available for the fuel-air mixing and decreases the fuel jet penetration distance for later part of the injected fuel after the intake valve closing, resulting in poor combustion and relatively inferior engine performance.

EMISSION CHARACTERISTICS

Emissions of hydrocarbons mainly occur due to poor and incomplete combustion, possibly from incomplete mixing of fuel and air. Figure 5 shows the same data of HC emissions in terms of raw emissions and mass emission with varying engine load (BMEP) and equivalence ratio respectively under different fuel injection strategies.

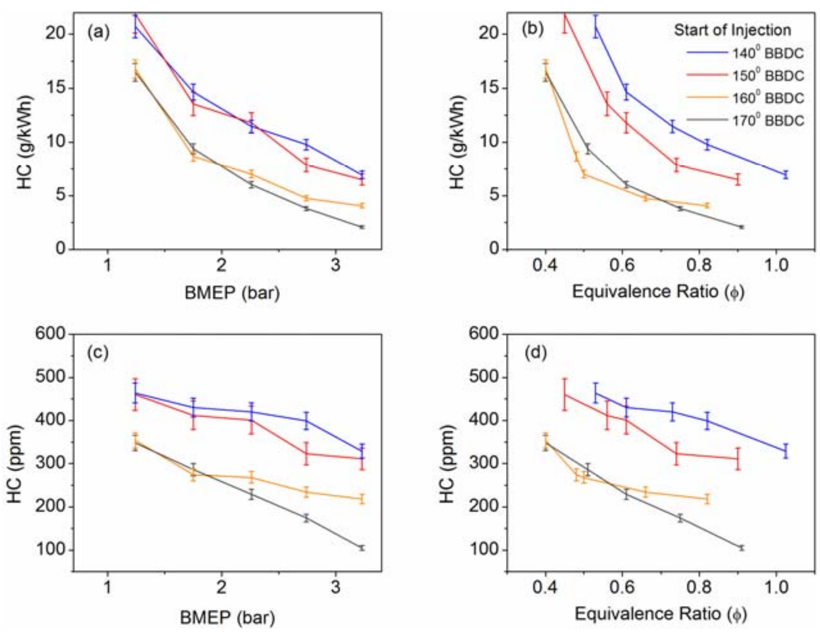

Figure 5: Unburnt hydrocarbon emissions (a, b) Mass emissions of HC vs. BMEP and equivalence ratio (c, d) Raw emissions of HC vs. BMEP and equivalence ratio

The results show that at lower BMEP (lower equivalence ratio), HC emissions are higher, and they decrease with increasing BMEP and then starts increasing with further increasing BMEP (higher equivalence ratio). At lower engine loads, combustible mixture is too lean to burn completely due to relatively lower flame propagation speeds, making HC emissions high. On the other hand, lack of oxygen in richer combustible mixture at higher engine loads increases HC levels in the exhaust. The range of HC emissions emitted from the CNG DI engine over the entire load range vary from 2 to 20.7 g/kWh. It is also observed that late injection timing increases fraction of unburnt fuel (HC) in the exhaust compared to advanced fuel injection timings because of insufficient fuel-air mixing time available and relatively inferior combustion.

Figure 6 presents NO emission vs. BMEP and equivalence ratio for various SOI timings at constant speed and fuel injection pressure. It is found that at lower BMEP i.e. low equivalence ratio, NO emission is lower, increases rapidly with increasing equivalence ratio (up to 0.9) and then the trend reverses. At lower engine load (BMEP), relatively lower combustion temperatures dominate over high oxygen concentration, resulting in lower NO levels. However, at higher BMEP with equivalence ratio in the range of 0.8 to 0.9, high combustion temperature and sufficient excess oxygen availability produces high NO emissions. Test results show that NO emissions obtained from CNG DI engine is in the range of 12- 42 g/kWh. It is also seen that NO is higher for advanced fuel injection due to relatively faster and more complete combustion. Similarly decreased combustion temperatures due to slower combustion with retarded injection reduce NO levels in the exhaust.

Figure 7 describes the variation of CO in the exhaust vs. engine load (BMEP) and equivalence ratio at constant engine speed and different SOI timings. Emission of CO is strongly related to fuel-air mixture strength. The results show that for lower BMEP (i.e. low equivalence ratio) due to leaner mixture, CO emissions are very low (due to availability of excess oxygen); however they increase with increasing equivalence ratio because of formation of richer fuel zones (where sufficient oxygen is not available) leading to relatively incomplete combustion. Different fuel injection strategies show small variations in CO emissions in the range of 0.05- 0.1% (v/v), which is quite low compared to typical gasoline engine emissions. Due to inferior combustion, retarded injections generate slightly higher CO levels.

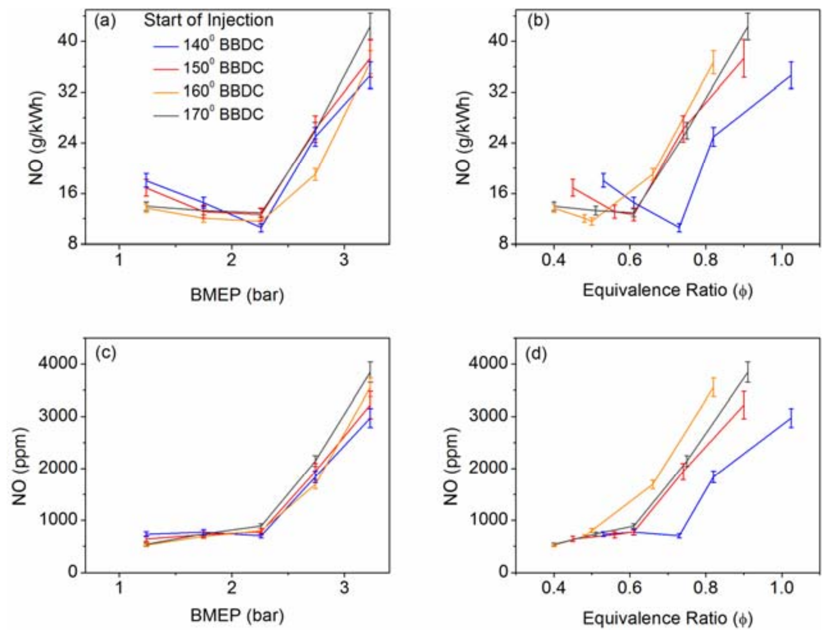

Figure 6: NOx emissions (a, b) Mass emissions of NO vs. BMEP and equivalence ratio (c, d) Raw emissions of NO vs. BMEP and equivalence ratio

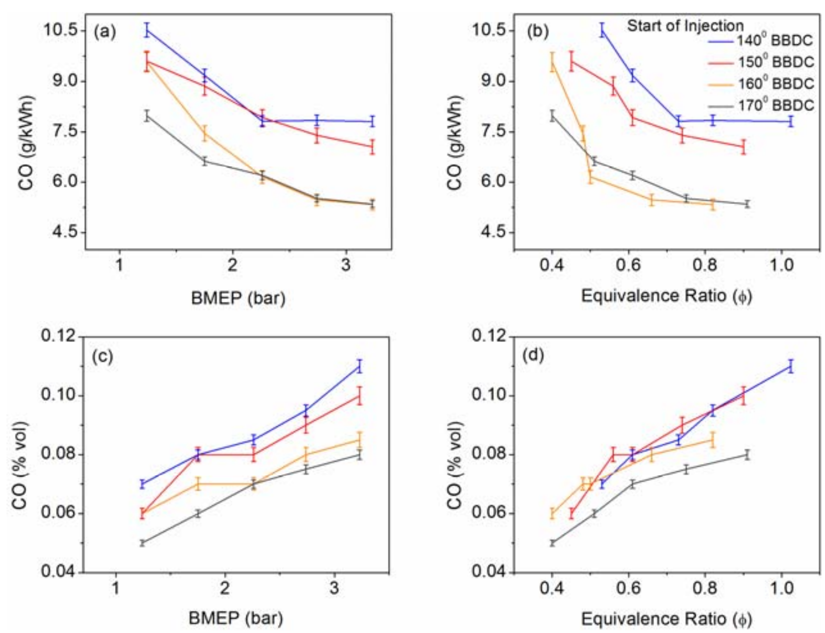

Figure 7: CO emissions (a, b) Mass emission of CO vs. BMEP and equivalence ratio (c & d) Raw emissions of CO vs. BMEP and equivalence ratio

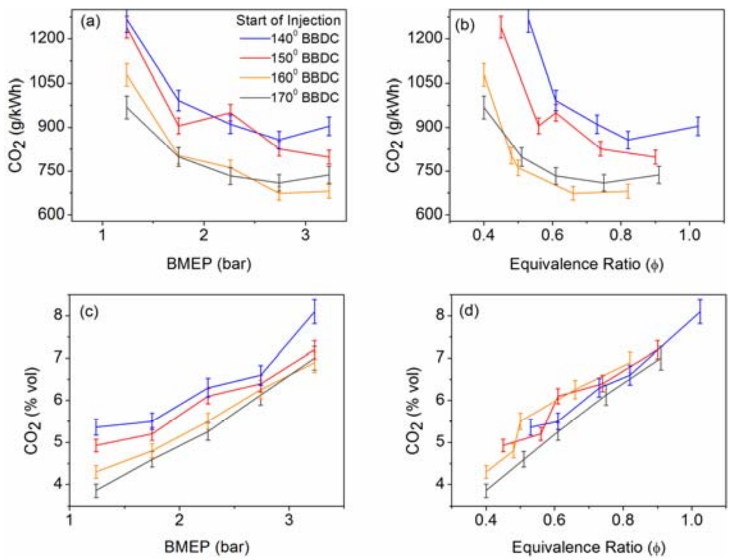

Figure 8: CO_2 emissions (a, b) Mass emissions of CO2 vs. BMEP and equivalence ratio (c, d) Raw emissions of CO_2 vs. BMEP and equivalence ratio

Figure 8 shows variation of CO_2 with engine load (BMEP) and equivalence ratio under different SOI timings at constant speed. It is found that CO_2 emissions increase with increasing BMEP and varies from 4- 8% (v/v). By comparing this value with typical gasoline SI engine emissions, it can be seen that CNG DI engines produce about 20% lesser CO_2 emissions [14] and this is due to lower carbon to hydrogen ratio of natural gas (1:4) compared to gasoline (typically ~ 2.3:1). The results also show that CO_2 increases with retarded injection inspite of its inferior combustion characteristics. The possible reason may be that the mass of fuel required for meeting a particular load is higher in late injection strategy compared to an advanced injection.

COMBUSTION CHARACTERISTICS

In a spark ignition engine, cylinder pressure depends on the in-cylinder combustion. Cylinder pressure characterizes the ability of the fuel-air mixture to burn and release heat. High peak pressure and maximum rate of pressure rise correspond to large amount of charge burned in homogeneous combustion. The cylinder pressure-crank angle history is obtained at different loads for CNG at various SOI conditions. Peak pressure and maximum rate of pressure rise are obtained at different loads from these measurements. Figure 9 shows in-cylinder pressure vs. crank angle diagram for various fuel injections strategies for different engine loads (BMEP).

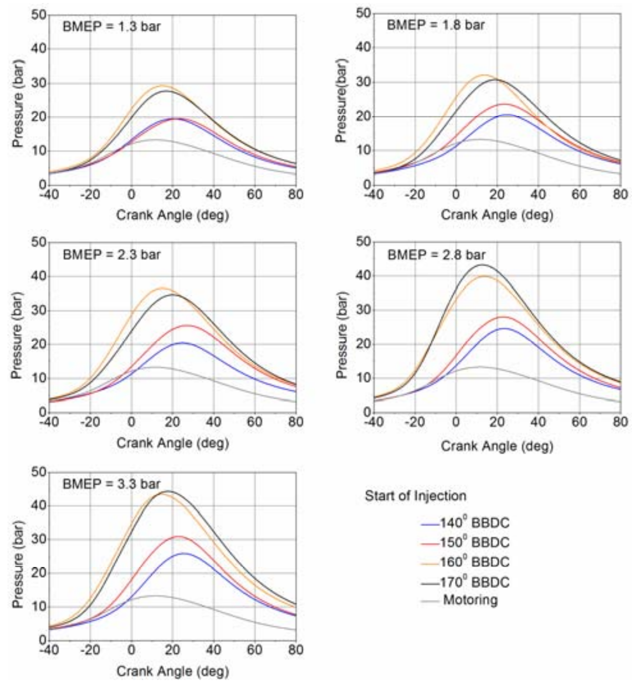

Figure 9: In-cylinder pressure vs. crank angle for different BMEP

The results show that in-cylinder pressure has an increasing trend with increasing engine load (BMEP) for all injection strategies. Increasing CNG quantity is injected into the cylinder at higher loads and improved volumetric efficiency results in superior and faster combustion leading to rise in peak in-cylinder pressure. In-cylinder peak pressure and crank angle at which this peak pressure occurs at different BMEP are shown in figure 10.

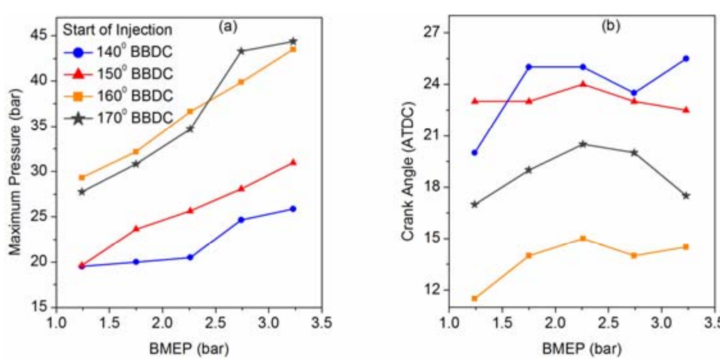

Figure 10: (a) Maximum pressure Vs. BMEP (b) Crank angle at maximum pressure Vs. BMEP

Advanced fuel injection timings (160 and 170° BBDC) produce higher in-cylinder pressures, while late fuel injection timings (140 and 150° BBDC) produce relatively lower in-cylinder pressures for all engine loads (BMEP). Superior homogeneous mixture formation due to advanced injection helps in improved combustion and hence relatively higher pressure rise curves. Up to 2.3 bars BMEP, case 2 shows highest in-cylinder peak pressures over the entire range of injection timings and on increasing the engine load further, case 1 delivers highest peak in-cylinder pressure. Lowest peak in-cylinder pressures are observed for case 4. It can be noticed from figure 10 (b) that crank angle corresponding to the peak in-cylinder pressure shifts towards TDC for higher engine loads due to shorter combustion duration. Crank angle corresponding to peak in-cylinder pressures also retard with further later injections. Slower flame development during the late injection cases may be a possible reason for this.

Figure 11 shows the variation of heat release rate for different BMEP at different SOI timings. Heat release rates increase with increasing engine load (BMEP) for all injection strategies. This is due to higher quantity of CNG injected and faster burn rates of combustible mixtures at higher BMEP.

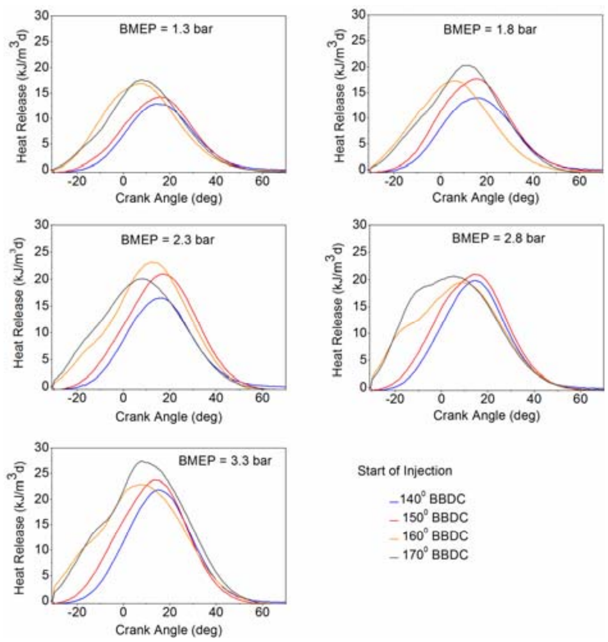

Figure 11: Heat release rate curves for different BMEP

The results also show that for most engine loads, advanced injections (160, 170° BBDC) give higher heat release rates as compared to their retarded counterparts but at some engine loads, both advanced and late injections give more or less equal heat release rate inspite of higher time available for fuel-air mixing and longer jet penetration for advanced injection strategies. Also, at all engine loads, the crank angle, at which, maximum heat release rate occurs is closer to TDC for advanced injection strategies as compared to the retarded ones, resulting in maximum pressure rise at the start of expansion stroke. This points towards possibly higher flame speeds and faster combustion as a result of adequate time availability for fuel-air mixing in case of advanced injections. Figure 12 shows the crank angle for 5% mass burn fraction (MBF), 50% MBF and 90% MBF at different engine loads for various fuel injection strategies. Figure 12 shows that for advanced injections, combustion starts earlier, and retarded injections result in delayed start of combustion.

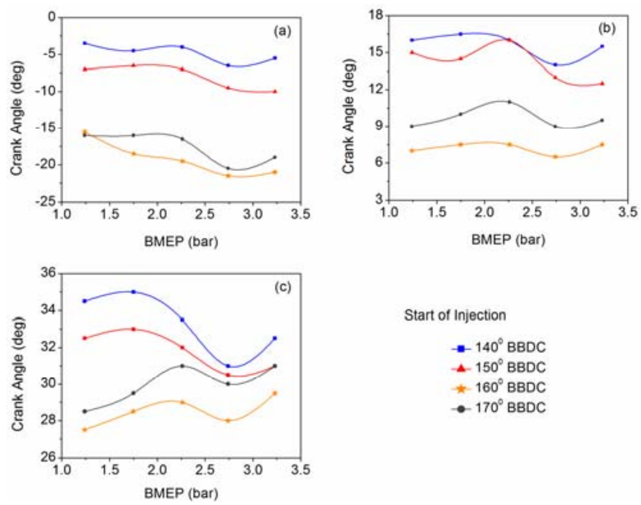

Figure 12: Mass burn fraction vs. BMEP (a) 5% MBF, (b) 50% MBF, (c) 90% MBF

Figure 12b and 12c indicate that both 50% and 90% mass fraction combustion takes longer time (in terms of crank angles) for retarded injections and shorter time for advanced injections, suggesting higher combustion duration for late injection strategies. These results indicate towards the presence of homogeneous mixture and high flame speeds for advanced injections as compared to retarded injections.

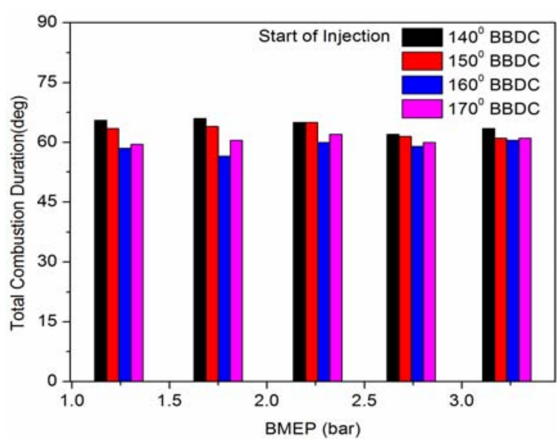

Figure 13: Combustion duration vs. BMEP

Figure 13 shows the variation of combustion duration for different engine loads for different SOI timings. It can be noticed that for all engine loads, late injections lead to longer combustion duration, whereas advanced injections lead to shorter combustion duration. This further confirms the results obtained in earlier sections. In case of retarded injections, the mixture in-homogeneity and lower jet penetration for the later part of the injected fuel (due to ambient pressure) slows down the flame kernel growth, and flame propagation, thus prolonging the combustion duration. There is a slight increase in combustion duration for 170° BBDC SOI timing than 160° inspite of its advancement. It is possibly due to slightly higher fuel consumption at 170^0 BBDC SOI timing (case 1).

CONCLUSIONS

Experimental investigations of performance, emission and combustion characteristics of a CNG DI engine under different fuel start of injection (SOI) timings were carried out and the following conclusions are drawn:

1. Volumetric efficiency decreases with relatively advanced SOI timings. Advanced SOI timings (170, 160° BBDC) produce lower BSFC/ BSEC, higher BTE and higher EGT compared to retarded SOI timings (150, 140° BBDC) for all engine loads. This may be due to relatively superior mixture homogeneity for advanced injection cases. Advanced injection cases result in relatively lower HC and higher NO emissions and vice-versa. CO_2 emissions were higher for retarded injection timings possibly due to the requirement of higher fuel quantities.
2. At very low and very high BMEP, performance characteristic curves display relatively higher BSFC, and lower BTE whereas intermediate BMEP exhibits lowest BSFC and highest BTE for all SOI conditions. HC emissions decrease with increasing engine load upto an equivalence ratio of 0.9 whereas NO and CO2 increase in this zone for all fuel injection strategies. Both CO and smoke opacity displayed marginal variations in the lean zone however the variations increased for richer mixtures at higher BMEP.
3. In-cylinder pressure, rate of pressure rise and heat release trends show lower values for retarded injection strategies compared to advanced ones. Slower and inferior combustion due to lower jet penetration and relatively lower flame propagation speeds may be the possible reasons for this in case of late injections strategies. Crank angle for the peak in-cylinder pressure and maximum heat release rates occur close to TDC for advanced fuel injection strategies, suggesting relatively shorter combustion durations. Moreover, mass burn fraction curves and total combustion duration curves exhibit relatively longer combustion durations for retarded injection strategies and shorter combustion durations for advanced injection strategies.

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ABBREVIATIONS

CNG	Compressed Natural Gas

BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
EGT	Exhaust Gas Temperature