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Original Research Article

Effect of CNG Manifold Injection on the Performance, Combustion and Emission Characteristics of a CNG-Biodiesel Dual Fuel Operation

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Abstract

Energy demand at a global level is increasing day by day and fossil fuel resources are on the verge of becoming extinct. The drastic increase of the oil prices in the global oil market and the increased pollution levels created an interest to find renewable, sustainable and alternative fuels. Natural gas (NG) is considered as a most prominent alternative fuel due to its many advantages including its ready availability and its low emission levels. A diesel engine was converted to operate in dual fuel engine mode in which compressed natural gas (CNG) was injected using a specially developed electronic control unit (ECU) into the intake manifold while injected pilot biodiesel auto ignites and it becomes a source of ignition for CNG. Experimental investigations were conducted over a single cylinder water cooled four stroke dual fuel CI engine test rig operated using diesel, honge methyl ester (HOME), jatropha methyl ester (JOME) and their blends with 15% ethanol as injected pilot fuels and CNG as injected primary fuel. ECU was used for varying the injection timings and injection durations for CNG injection while the optimum injection timing for diesel/biodiesel was maintained at 27°bTDC. The pilot fuel injection pressure was maintained at 230 bar. Engine was operated with constant compression ratio of 17.5 and CNG flow rate was maintained at 0.5 kg/h. The experimental results showed that an injection timing of 5ºbTDC and injection duration of 60º CA for CNG injection was found to be optimum based on the improved performance, combustion and emission characteristics. The brake thermal efficiency for manifold injected CNG-diesel/biodiesel-ethanol blended dual fuel operation at 80% load was found to be 27.1%, 26.2% and 25.2% for diesel-ethanol blend, HOME-ethanol blend and JOME-ethanol blends respectively. The carbon exhaust emissions and smoke emissions were found to be lesser in CNG injected dual fuel operation compared to CNG inducted dual fuel operation.

Keywords: CNG; Combustion; Dual fuel engine; Injection strategies; ECU; Injector.

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1.Introduction

The restriction on vehicular emissions and worldwide continuous depletion of fossil fuels, alternative fuels like biodiesel and CNG have gained more popularity[1-2]. Natural gas is considered as a most prominent alternative fuel because of its lower emissions and ready availability. The poor efficiency due to pumping losses with intake throttling the spark-ignited NG engines cannot match the brake thermal efficiency of diesel engines. Existing diesel engines may be converted readily to operate primarily on natural gas, using pilot injection of diesel/biodiesel to achieve ignition [3-6]. However, earlier attempts to implement this method were crude, lead to excessive diesel/biodiesel usage, over fuelling to achieve acceptable power levels, and unacceptably higher emissions. The injected diesel/biodiesels inside the combustion chamber will undergo combustion first which in-turn would assist to ignite the CNG. CNG injection assisted dual fuel engines show significant potential matching diesel engines part and full load efficiency and is equally aimed at reducing the emissions from diesel engines through dual fuel conversion by adopting different CNG injection strategies [7-11].

The studies on use of alternative fuels in diesel engines have been undertaken by many researchers since most of the vehicles used in public transport and stationery power plants use diesel engines as prime movers [7, 12-15]. Hence research has been focused more on diesel engines to reduce exhaust emissions and to improve thermal efficiency [7, 12, 16-18]. The problem associated with diesel engines are higher NOx and smoke or particulate matter (PM) due to governing combustion mechanisms of diesel engine [3, 7, 9-11, 19-20]. The higher hydrogen-to-carbon ratio of natural gas provides reduced carbon dioxide emissions and is becoming more promising alternative fuel than gasoline and diesel [4, 7, and 21]. According to the current oil market survey, cost of CNG is cheaper than gasoline and diesel due to its vast deposits available throughout the world. The shorter carbon chains in CNG results in cleaner exhaust gas emissions and reduced greenhouse gas emissions [10, 15, 22-25].

Non-toxic CNG is lighter than air and diffuses quickly if any leakage occurs, provides an advantage of safety. The higher octane number of CNG permits it to be utilized in high compression diesel engines. The higher auto-ignition temperature of CNG (923K) requires either a spark plug or pilot injection to achieve ignition [7, 16, 18]. Therefore, CNG would be best utilized in diesel engine under dual fuel mode with diesel/biodiesel pilot injection as an ignition source. Dual fuel combustion (DFC) of CNG in diesel engine presents promising prospects as it results in improved thermal efficiency and reduced the exhaust emissions without much engine modifications. NOx and PM levels in are significantly lower than that of traditional diesel engines. Combustion, performance and emission characteristics of DFC using diesel and CNG have been reported [5, 7].

Lower smoke, lower peak cylinder pressure and equivalent thermal efficiencies were reported in DFC for the majority of operating conditions while some researchers claim higher efficiency than single fuel (diesel) mode. Poor part load efficiency due to lean homogenous charge was also reported for dual fuel engine operation [4-5, 7, 25]. Accumulation of premixed CNG with the intake air in the combustion chamber crevices during the compression stroke in DFC leads to increased HC emissions in the engine exhaust was reported[7, 9, 16, 26]. Several methods of improving the poor low load characteristics, including throttling, EGR, increased inlet air temperature, or switching over to diesel mode was reported [7]. Lower brake thermal efficiency (BTE) for diesel-CNG DFC than diesel specific fuel consumption (SFC) was reported with a modified diesel engine at part and low torque conditions. Use of micro-pilot injector to reduce exhaust emissions in DFC systems have been reported [4, 11, and 27]. Studies on diesel-CNG DFC systems have been conducted by many researchers. Few studies on the use of biodiesel as pilot fuel for DFC systems have been reported [7, 27-30]. Higher boiling point of biodiesel makes it easy and safe to handle. Shorter ignition delay due to higher cetane number and higher specific gravity of biodiesel are encouraging the biodiesel as a prominent alternative fuel for CI engines. In addition, it is eco-friendly fuel with lower smoke emissions [31-33].

2. Fuel used for the study

Biodiesels produced from honge and jatropha oils blended with ethanol (15% by volume) was used as pilot fuel and CNG was used as the main fuel in this study. CNG was supplied to the gas injector provided in the intake manifold during the suction stroke at a constant pressure of 2 bar. The pulse signals generated from an electronic control unit (ECU) controls the amount of CNG. The important properties of natural gas used are shown in Table 1. Table 2 shows the properties of various liquid fuels used in this study. The governor system of the engine regulates and varies the pilot fuel supply with respect to increase in engine load and thus keeping the speed constant.

2.1. CNG as an alternative fuel

Major component of a natural gas is Methane. Primarily natural gas (NG) is contains more than 90% methane (CH_4), trace amounts of carbon dioxide, propane, ethane, nitrogen, hydrogen sulphide and water vapour [30, 34-35].In many respect natural gas is safer than gasoline and its ignition temperature is higher than gasoline and diesel [35]. Additionally, natural gas is lighter than air and will dissipate upward rapidly if a rupture occurs. Gasoline and diesel will pool on the ground, increasing the danger of fire. Compressed natural gas is non-toxic and if spilled it will not contaminate groundwater. The main sources of natural gas are gas wells or tied in with crude oil production. Natural gas can be compressed, and hence can be stored in tanks and used as CNG. CNG requires a much larger volume to store the same mass of natural gas and requires the use of very high pressure at about 200 bar [34-38]. Advanced CNG engines promises considerable advantages over other conventional engines. CNG is a form of fossil energy and therefore non-renewable. The octane number of natural gas is about 130; hence engines could operate at compression ratio of up to 16:1without any knock or detonation [5, 7, 34, 39].With encouraging CNG application policy many of the automotive manufacturers use natural gas fuelling system and ECU controlled gas injection system as consumer do not have to pay for the cost of conversion kits and required accessories [40-41]. Most importantly, because of simple chemical structures (primarily methane-CH_4) which contain one carbon compared to diesel ($C_{15}H_{32}$) and gasoline (C_8H_{18}), natural gas significantly reduces CO_2 emissions by 20-25% [42-43].Natural gas composition varies considerably over time and from location to location [7, 35, 43-45]. Natural gas exists as gas at atmospheric pressure and temperature and has lower density. Since the volumetric energy density is so low, natural gas is often stored in a compressed state at high pressure and stored in pressure vessels.

3. Methods of CNG utilization in compression ignition engines

CNG supply system plays a very vital role in its utilization especially for compression ignition engines. Different techniques of CNG supply include carburetion, continuous/timed manifold injection, sequential/multipoint injection and high pressure direct cylinder injection [34-35, 39].

3.1. Electronically controlled CNG port/manifold injection

The natural gas injection strategy provides improvements towards regulating exhaust emissions and improved engine performance than carburetion method. An ECU-controlled fuel injector to introduce fuel into a mixer within the intake system provides more accurate control of fuel quantity to be injected [35, 39]. The robust design of ECU controls the start of injection (injection delay) and injection duration (on-time) with quicker response leads to better control of mixture formation to operate under high speeds and changing load conditions. Thus, it offers the opportunity to minimize the negative effects on the engine performance compared to carburetor-type induction method. The skip-firing strategy of manifold injection system enables fuel to be delivered precisely at low loads which provides even more efficient use of the fuel, further lowering fuel consumption and unburned hydrocarbon [34]. Manifold injection system is able to diminish the cyclic variations and enhance the limit of lean operation of the engine. It also offers the potential advantage of improved performance, lowered emissions and lesser fuel consumption [34-39, 48]

Table 1 Characteristics of test fuels [13, 27, 33]

Sl No	Properties	Diesel	Honge oil	Jatropha oil	HOME	JOME	Ethanol	HOME+ 15% Ethanol	JOME+ 15% Ethanol	ASTM Standards
1	Viscosity @ 40 °C	4.59	56	50.73	5.60	4.84	1.20	3.70	3.25	ASTM D445
2	Flash point °C	56	270	240	163	192	13.50	32	33	ASTM D93
3	Calorific Value in	45000	35800	34000	36010	35200	27300	35550	33060	ASTM D5865
4	Density kg / m^3	830	930	918	890	880	780	----	-----	ASTM D4052
5	Cetane Number	45-55	40	45	40-42	40-45	----	----	----	ASTM D613
6	Type of oil	Fossil fuel	Non edible	Non edible	Non edible	Non edible	----	----	----	

Table 2 Properties of Natural Gas [15, 34]

Property	CNG
Boiling point (K @1atm)	147
Density (kg/m^3@1 atm,150C)	0.77
Flash point (K)	124
Octane number	130
Flammability limits range	5.0-15.0
Flame speed (cm/s)	33.8
Net energy content (MJ/kg)	49.5
Auto ignition temperature (K)	923
Combustion energy (kJ/m^3)	24.6
Stoichiometric A/F ratio (kg air/kg fuel)	17

3.2. CNG Injector

In principle, for smooth and reliable operation with lesser fuel consumption and desired power output the optimal design of air-fuel mixture is required [34-35]. Electronic pulse-width-modulated sequential port injection (SPI) system uses sequentially timed individual injections at each intake port in multi-cylinder engines. A transient gas jet exhibits potential core region in which gas was injected and gas fuel gets mixed with air in the mixing flow region while in the dilution region, the gas fuel and air mixture occurs [40, 43]. Core region is considered as the main jet region and contains the bulk of the unmixed fuel. Turbulent vortices are generated as a result of shear forces exerted by the ambient air in the chamber on the periphery of the jet core [35, 38]. A significant amount of work has undertaken on the fuel-air mixing process and less information has been reported on the structure of the fuel spray from SPI injectors [38].

A 12 V battery supplies constant power supply to the CNG solenoid injector. The specifications of the CNG injector used in the study are given in Table 3. The CNG injector is fitted to the inlet manifold along perpendicular axis of the intake valve. CNG injector with rail and ECU showing circuit diagram is shown in Fig. 1.

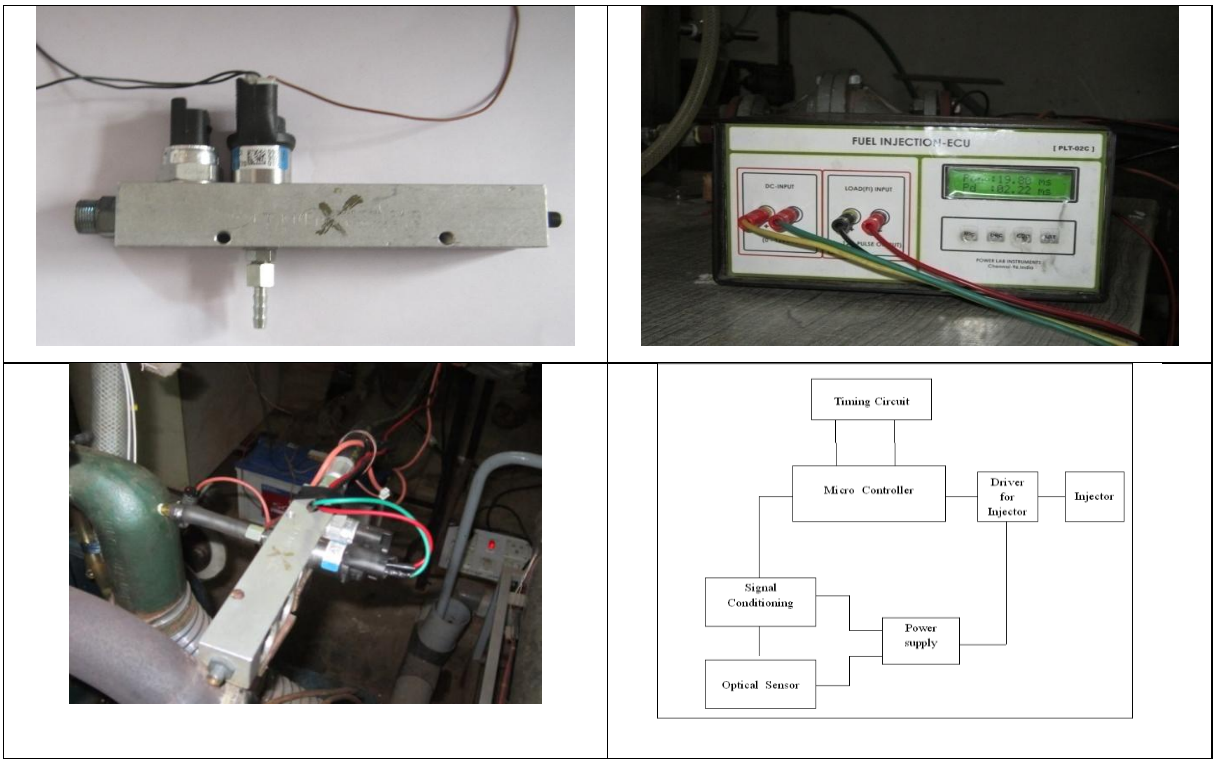


Fig. 1CNG injector with rail and ECU showing circuit diagram

Table 3 The specifications of CNG injector

Make	BRC Italy
Supply voltage	8–16 V
Peak current	4 A
Holding current	1 A
Flow capacity	0.8 g/s at 4 bar
Working pressure	103–552 kPa
Max. rail pressure	4bar

4. Accuracy of measurements and uncertainty analysis

In order to ensure accuracy in measurements made, all instruments used in this study were calibrated before the experimentation. To maintain the accuracy of the measured values, after completion of the work on a selected test condition, the gas analyzers were purged and then calibrated before the next measurement. The smoke meter was also adjusted to its zero point before each measurement. The values reported for all measured parameters are time averaged at each test condition. The consumption rate of the pilot fuel injection was averaged over 6 measurements to account for the cycle-to-cycle variations. The cylinder pressure for combustion analysis was averaged for100 cycles at each experimental condition. To examine the accuracy of measurement and the limiting errors associated with each measured parameter, comprehensive uncertainty analysis was conducted. The uncertainty of the measured parameters could be estimated with confidence limits of ±2σ (95.45% of the measured data lie within the limits of ±2σ around the mean). The percentage uncertainty of the measured parameters can be estimated using the following relation:

$$\Delta xi = \frac{2\sigma x_i}{\bar{x}_i} \times 100 \text{ -------(1)}$$

Where,

σ_{xi} = Standard deviation

Δ_{xi}=Difference between readings

$\bar{X_i}$ = Mean difference in reading

5. Engine operating method and test conditions

In this study combustion, performance and exhaust emission characteristics of a dual fuel engine were investigated with CNG-diesel blended with 15% ethanol and CNG-Biodiesel blended with 15% ethanol combinations. Static injection timing was set to 27° bTDC and compression ratio of 17.5 was maintained throughout the experiment. Engine was operated at a constant speed of 1500 rpm and pilot fuel injection pressure was maintained constant at 230 bar for biodiesels and 205 bar for diesel respectively. Cooling water temperature was maintained at 70 ± 2 0C throughout the work. Fig. 2 shows a valve timing diagram representing the CNG injection timing and injection duration. Fig. 3 shows a schematic line diagram of the experimental set up.

The injection timings and durations for the CNG injection were controlled through ECU. The electronic control unit acquires the signal from an infrared sensor that indicates the crankshaft position [51]. The injection timings of the CNG injector were varied from 10°CA before top dead centre (bTDC) to 10°CA after top dead centre (aTDC) in steps of 5°CA. The trigger point was set to 5°CA before top dead centre. The injection duration was varied from 30°CA to 90°CA in steps of 30°CA. Optimized timings for CNG injection was then determined.

A double stage pressure regulator was suitably used to reduce high-pressure (260 bar) CNG to 2 bar respectively. CNG was admitted into the intake manifold through rota meter and digital mass flow controller for controlling the known gas supply to the engine. To suppress possible flash back and fire hazards in the fuel line wet flame trap and dry type flame arrestors were used [7, 9, 12, 49-50]. The CNG was injected by using a solenoid operated gas injector placed in the inlet manifold. The engine was operated with diesel/biodiesel as pilot fuel and CNG as main fuel [51]. The pictorial view of the experimental set up is shown in Fig. 4 with gas supply arrangements used. The specifications of the exhaust gas analyzer, smoke meter and piezo pressure sensor are given in the table 4, 5 and 6 respectively.

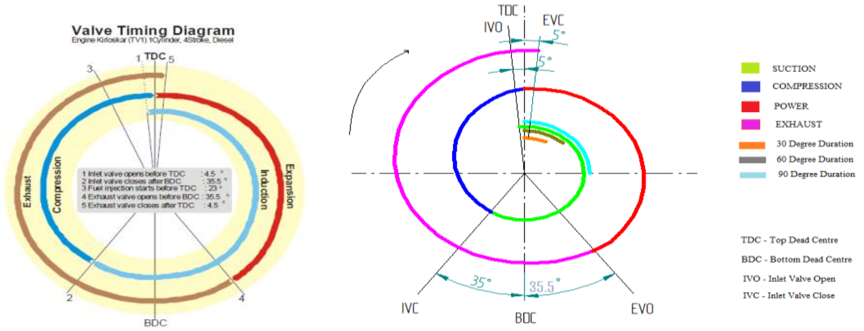
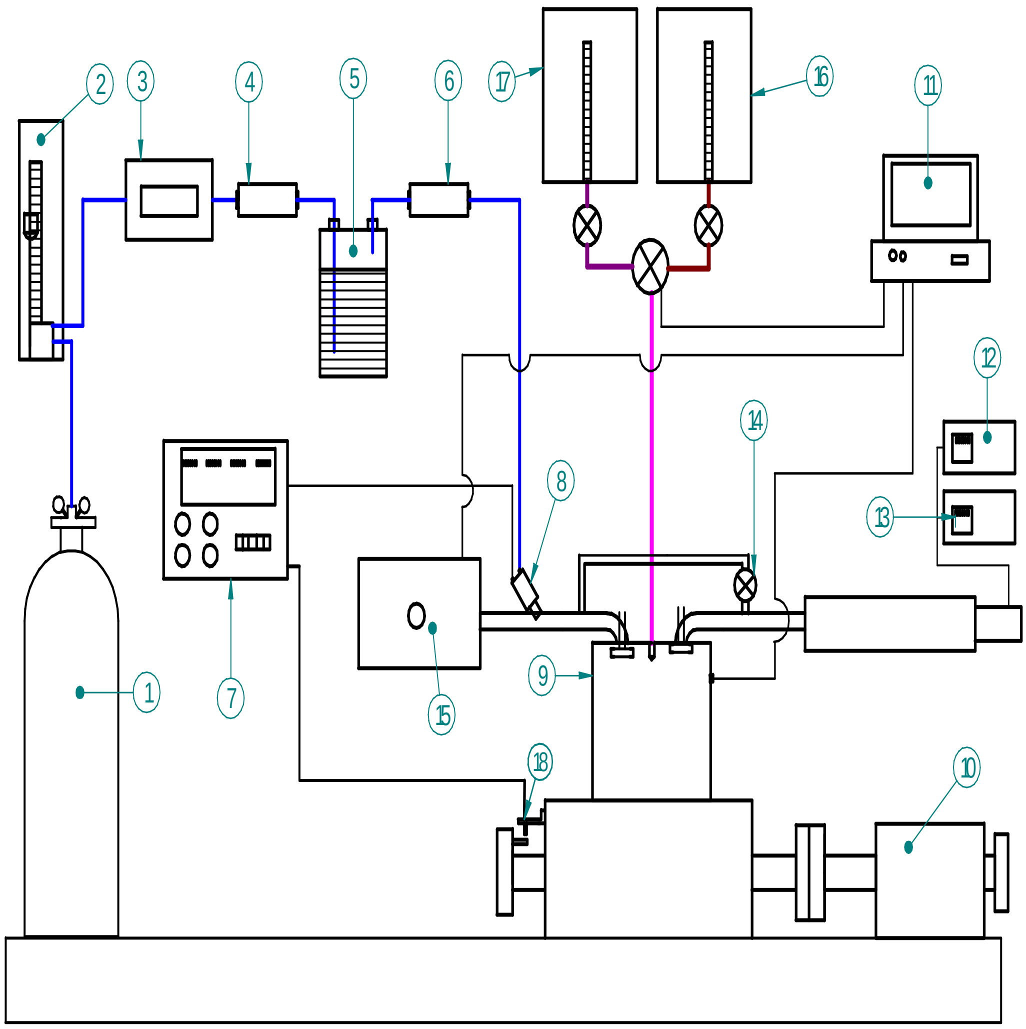


Fig.2 Valve timing diagram of single cylinder diesel engine for different CNG injection timings



01. CNG Cylinder	10. Eddy Current Dynamo Meter
02. CNG Rota meter	11. PC Interfaced to Engine
03. Gas Flow Meter	12. Exhaust Gas Analyzer
04. Dry Flame Arrester	13. Smoke Meter
05. Wet type flame trap	14. EGR Valve
06. Dry Flame Arrester	15. Air Box
07. Electronic Control Unit	16. Bio Diesel Tank
08. CNG Injector	17. Diesel Tank
09. Diesel Engine	18.Proximity sensor

Fig. 3 Schematic view of the experimental set up

Table 4 Specifications of the exhaust gas analyzer

Type	**DELTA 1600S**
Object of Measurement	Carbon monoxide (CO), Carbon Dioxide (CO_2) Hydrocarbons (HC),Oxygen(O_2) and Nitric Oxide (NO_X)
Range of Measurement	HC = 0 to 20,000 ppm as C_3H_8 (Propane), CO = 0 to 10%,CO_2 = 0 to 16%, O_2 = 0 to 21% NO_X = 0 to 5000 ppm (as Nitric Oxide)
Accuracy	HC = +/- 30 ppm HC, CO = +/- 0.2% CO, CO_2 = +/- 1% CO_2, O_2 = +/- 0.2% O_2, NO_X = +/- 10 ppm NO
Resolution	HC = 1 ppm, CO = 0.01% Vol., CO_2 = 0.1% Vol., O_2 = 0.01% Vol., NO_X = 1 ppm
Warm up time	10 min. (self-controlled) at 20^0C
Speed of Response Time	Within 15 sec. for 90% response
Sampling	Directly sampled from tail pipe
Power Source	100 to 240 V AC / 50Hz
Weight	800 g
Size	100 mm x 210 mm x 50 mm

Table 5 Specifications of the smoke meter

Type	HARTRIDGE SMOKEMETER-4
Object of Measurement	Smoke
Measuring range opacity	0 – 100 %
Accuracy	+ / -2 % relative
Resolution	0.1 %
Smoke length	0.43 m
Ambient Temperature Range	-5^0 C to + 45^0 C
Warm up time	10 min. (self-controlled) at 20^0C
Speed of Response Time	Within 15 sec. for 90% response
Sampling	Directly sampled from tail pipe
Power Supply	100 to 240 V AC / 50HZ 10 – 16 V DC @15 amps
Size	100 mm x 210 mm x 50 mm.

Table 6 Specifications of the piezo-pressure sensor

Make	PCB Piezotronics
Model	HSM111A22, Piezoelectric
Measurement range	0 to 344 bar
Sensitivity	0.145 mV / kPa
Resolution	0.69 kPa
Non - Linearity	$\leq$ 2.0 % FS
Temperature Range	-73 to + 135^0C

Fig. 4 Pictorial view of the experimental set up

6. Results and discussion

Earlier studies reported by the authors highlighted that advancing the injection timing of pilot fuel from 19^o to 27^{o}bTDCimproved the biodiesel-CNG performance [15, 27]. In the present work, CNG injection delay and on-time were optimized based on the improved performance and emission characteristics of the dual fuel engine keeping pilot injection timing of 27^o bTDC, compression ratio of 17.5 and pilot injection pressure of 230bar. The heat release rate of the fuel causes a variation of gas pressure and temperature within the engine cylinder, and strongly affects the fuel economy, power output and emissions of the engine [27]. It provides a good insight into the combustion process that takes place in the engine. The optimum heat release rate is particularly important in engine research and for this a computer program was developed to obtain the heat release rate from the ensemble pressure crank angle history. The heat release rate at each crank angle was calculated by using a first law analysis of the average pressure versus crank angle variation obtained from 100 cycles using the following expression [4, 19-20].

$$Qapp = \frac{\gamma}{\gamma - 1}[PdV] + \frac{1}{\gamma - 1}[Vdp] + Qwall \text{ ---- (2)}$$

Where,

Q_{app} - Apparent heat release rate (J)

γ - Ratio of specific heats $C_p/(C_p - \bar{R})$

$\bar{R}$ - Gas constant in (J / kmol-K)

C_p - Specific heat at constant

pressure (J / kmol – K)

V - Instantaneous volume of the cylinder (m^3)

P - Cylinder pressure (bar)

Q_{wall} - Heat transfer to the wall (J)

For this above calculation the contents of the cylinder were assumed to behave as an ideal gas (air) with specific heats dependent on temperature. The specific heat was calculated using the equation below.

$$Cp = [3.6359 - \frac{1.33736T}{1000} + \frac{3.29421T^2}{1\times10^6} - \frac{-1.91142T^3}{1\times10^9} + \frac{0.275462T^4}{1\times10^{12}}]\,R \quad \text{---- (3)}$$

for T < 1000 ^{0}K

$$Cp = [3.04473 + \frac{1.338056T}{1000} - \frac{0.488256T^2}{1\times10^6} + \frac{0.0855475T^3}{1\times10^9} - \frac{0.00570127T^4}{1\times10^{12}}]\,R \text{---- (4)}$$

for T > 1000 ^{0}K

The heat transfer was calculated based on the Hohenberg equation given below and the wall temperature was assumed to be 723^{0}K.

$$Qwall = h \times A \times [\,Tg - Tw\,] \,(5)$$

$$h = C1V^{-0.06}\;P^{0.8}\;T^{-0.4}\;(\,V_P + C_2\,)^{0.8} \quad (6)$$

h-Heat transfer coefficient in W/m^2 K

C_1& C_2-Constants, 1.3 & 1.4

V-Cylinder volume in m^3

P-Cylinder pressure in bar

T-Cylinder gas temperature in K

V_P-Piston mean speed in m/s

A-Instantaneous Area (m^2)

6.1. Performance Characteristics

The results of investigation in dual fuel mode of operation for different CNG injection timings and injection durations were discussed in this section. Engine tests have been carried out on a single cylinder, DI engine operating in dual fuel mode with diesel/biodiesel blended with 15% ethanol as pilot fuel and CNG as injected main fuel with the aim of obtaining comparative measures of brake thermal efficiency.

6.1.1. Brake thermal efficiency

Figure 5 shows the variation of brake thermal efficiency (BTE) of a dual fuel engine fuelled with diesel, HOME, JOME and their blends with ethanol with CNG injection at 80% load. HOME and JOME and 15% ethanol blends obviously will have reduced calorific value and higher viscosity and therefore perform poorly when compared to the diesel. CNG being common for all the fuel combinations, the properties of the injected liquid blend combinations is responsible for the observed trends. Higher brake thermal efficiency of 27.1%, 26.2% and 25.2% were observed with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG manifold injections when CNG injection delay timing of 5^{o}bTDC and injection on-time of 60°CA was used. The increased BTE is mainly due to better combustion CNG due to timed manifold injection. The optimum injection timing and injection duration of CNG in manifold injection resulted in smoother combustion. Better mixing of CNG with air and the higher calorific value may be the reason for the improvement in performance. Complete burning of the injected liquid fuel as well as injected gaseous fuel leads to better combustion. Supplying gas to the intake manifold through injectors at appropriate timing provides proper air/fuel mixture available for combustion [25,36, 51-52].

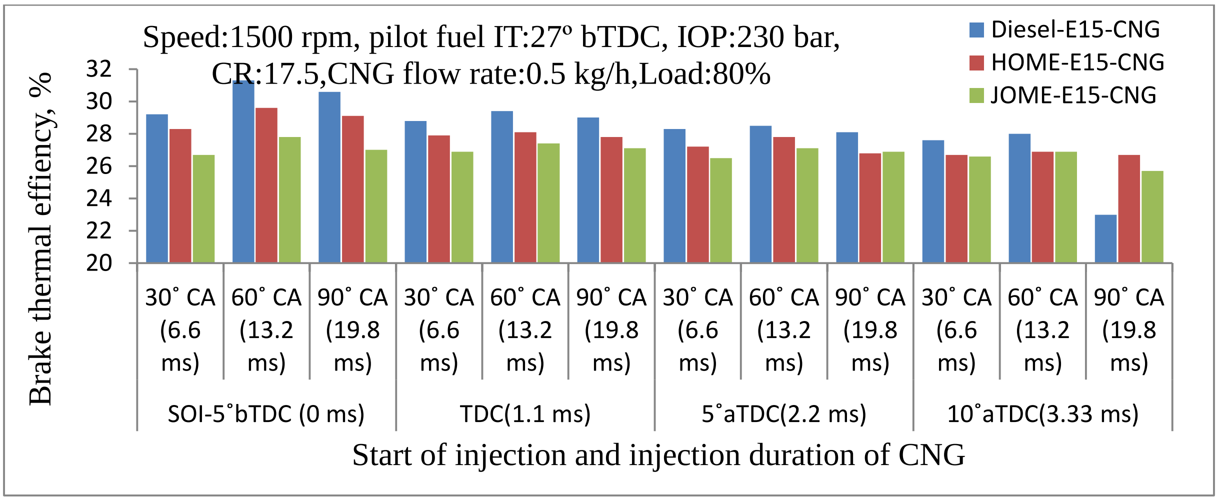


Fig. 5 Variation of BTE with CNG injection timing and injection duration

6.2. Emission characteristics

6.2.1 Smoke Opacity

The variation of smoke with injection timing and injection duration for different selected fuel combinations under dual fuel operation at 80% load are shown in figure 6. It is a known fact that dual-fuel operation with CNG remarkably reduces smoke emission as CNG has no carbon–carbon bonds and with high hydrogen to carbon ratio, it leads to lower sooting tendencies [43-52 46]. Higher viscosity (nearly twice the diesel) of the injected HOME and JOME with ethanol combinations is responsible for the observed trends of higher smoke emissions. The heavier molecular structure of the biodiesels used results into improper fuel air mixtures compared to diesel and this can be effectively reduced using 15% ethanol blending. The smoke levels decreased with increased CNG injection duration. The smoke levels for diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG manifold injection dual fuel operation when engine was operated with CNG injection timing of 5ºbTDC and injection duration of 60º CA were found to be 44, 54 and 58 HSU respectively. Moreover, smoke produced in DFC is mainly due to the pilot injection of diesel/biodiesels used for combustion initiation and combustion of CNG produces no particulates [27].

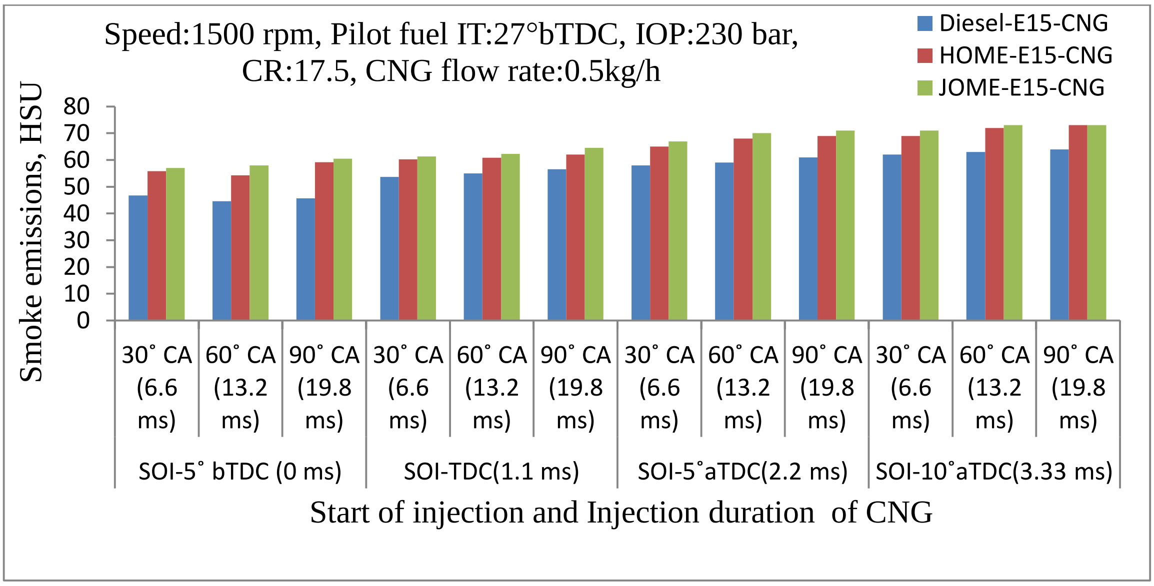


Fig.6 Variation of Smoke with CNG injection timing and injection duration

6.2.2. Hydrocarbon emissions

Figure 7 shows the variation of HC with injection timing and injection duration for CNG-diesel, CNG-HOME and CNG-JOME with15% ethanol blended dual fuel operation for 80% load respectively. The higher HC emissions were observed during DFC for both the biodiesel-ethanol and CNG fuel combinations. For DFC, it can be seen that there is no noticeable trend of HC in variation of pilot injection timing [3, 12]. Accumulation of mixture in the crevices of the combustion chamber results into flame quenching due to low temperature of the mixture near the combustion chamber walls. Hence the mixture is too fuel-lean for combustion to propagate throughout the charge and are the main reasons for higher HC emissions in DFC system [12, 21].The lower BTE of the biodiesel and ethanol blends due to higher viscosity and lower volatility could be responsible for the increased HC emissions compared to diesel with CNG injection in both versions. The HC emissions with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG dual fuel operation with manifold injection when engine was operated with CNG injection timing of 5^{o}bTDC and injection duration of 60°CA were found to be 58, 62 and 66 ppm respectively.

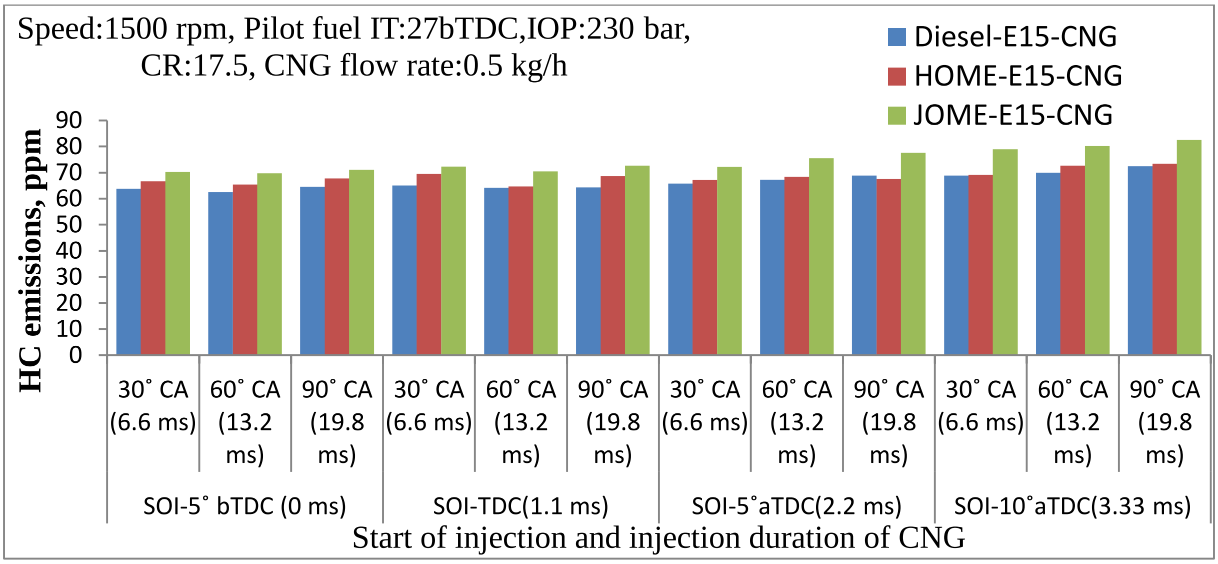


Fig.7 Variation of HC with CNG injection time and injection duration

6.2.3. CO emissions

Figure 8 shows the effect of CNG injection delay timing and injection duration on CO emissions for ethanol blends of diesel/biodiesel-CNG in DFC mode. The lower combustion rates of DFC due to increased area of quenching inside combustion chamber, the CO emissions were found to be higher for ethanol blended biodiesel-CNG fuels over the range of operating conditions [21]. The lower BTE of the biodiesel and ethanol blends could be responsible for the increased CO emissions compared to diesel with CNG injection in both versions. The higher viscosity and lower volatility of the biodiesel blends could also be responsible for the increased HC emissions. The CO emissions with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG dual fuel operation with manifold injection when engine was operated with CNG injection timing of 5^{o}bTDC and injection duration of 60°CA were found to be 0.132, 0.15 and 0.18% respectively. The incomplete combustion in the fuel over rich region due to sudden lack of oxidant leads to higher CO formation. However, in the fuel lean region, when the combustion temperature was under 1450K which is limited temperature of the flame extinction a large number of CO was generated [21,40].

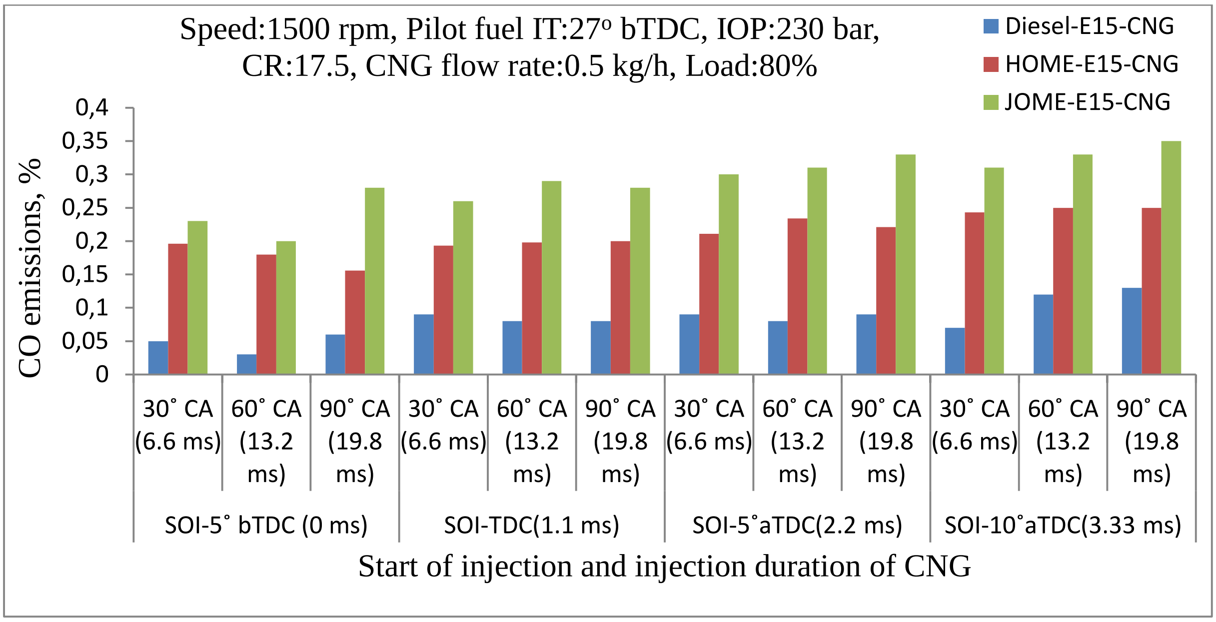


Fig.8 Variation of CO with CNG injection timing and injection duration

6.2.4 NO_x emissions

Figure 9 shows the variation of NOx with injection delay timing and injection duration for CNG- diesel+E15, CNG-HOME+E15 and CNG-JOME+E15 blended fuel dual fuel operation for 80% load respectively. The combustion of CNG anddiesel-E15 blend leads to higher NOx compared to CNG-biodiesel-E15 fuel combination [53-54]. In DF operation, higher peak combustion temperatures (above 2000 K)prevailing inside the cylinder and longer residence time leads to formation of NOx in greater quantity [12].However this can be controlled with the introduction of suitable exhaust gas recirculation(EGR). The double bonds contained in biodiesel are likely to result in higher levels of certain radicals that promote the prompt NOx emissions [47]. The NOx emissions with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNGdual fuel operation with manifold injection when engine was operated with CNG injection timing of 5°bTDC and injection duration of 60°CA were found to be 745, 765 and 830 ppm respectively.

6.2.5. Exhaust gas temperature (EGT)

Figure 10 shows the variation of EGT with injection delay timing and injection duration for dual fuel operation with diesel-E15-CNG, HOME-E15-CNG, JOME-E15-CNG fuel combinations for 80% load respectively. EGT is found to be marginally higher for the biodiesel-E15-CNG blend operation compared to diesel-E15-CNG blend. The hotter environment due to more complete combustion in diffusion combustion phase of CNG increased the exhaust gas temperature. The EGT with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG dual fuel operation with manifold injection when engine was operated with CNG injection delay timing of 5°bTDC and injection duration of 60°CA were found to be 295, 343 and 405°C respectively.

6.3. Combustion characteristics

This section covers the various combustion aspects of the dual fuel engine operation using the selected biodiesel and ethanol fuel combinations.

6.3.1. Peak pressure

Figure 11 shows variation of peak pressure with different modes of dual fuel engine operation. Peak pressure and maximum rate of pressure rise were higher with CNG injection timing of 5°bTDC and injection duration of 60°CA for diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG dual fuel operation for 80% load respectively. Lower rate of pressure rise was observed in dual fuel operation with above fuel combinations as compared to single fuel operation [53]. A dual fuel operation in which CNG being common, injected ethanol blended biodiesels having lower cetane number and lower calorific value results to lowered peak pressure when compared to diesel-E15-CNG fuel combination. The peak pressure with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG dual fuel operation with manifold injection when engine was operated with CNG injection timing of 5^{o}bTDC and injection duration of 60°CA were found to be 69.21, 66.83 and 61bar respectively.

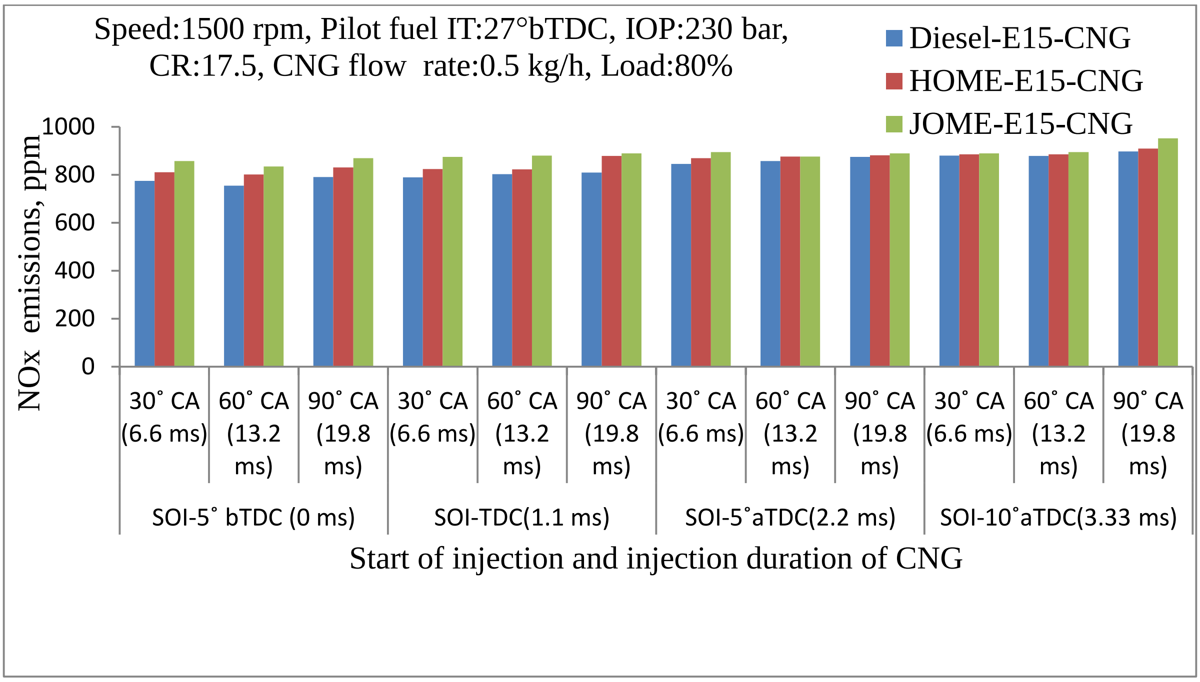


Fig.9 Variation of $NO_x$with CNG injection timing and injection duration

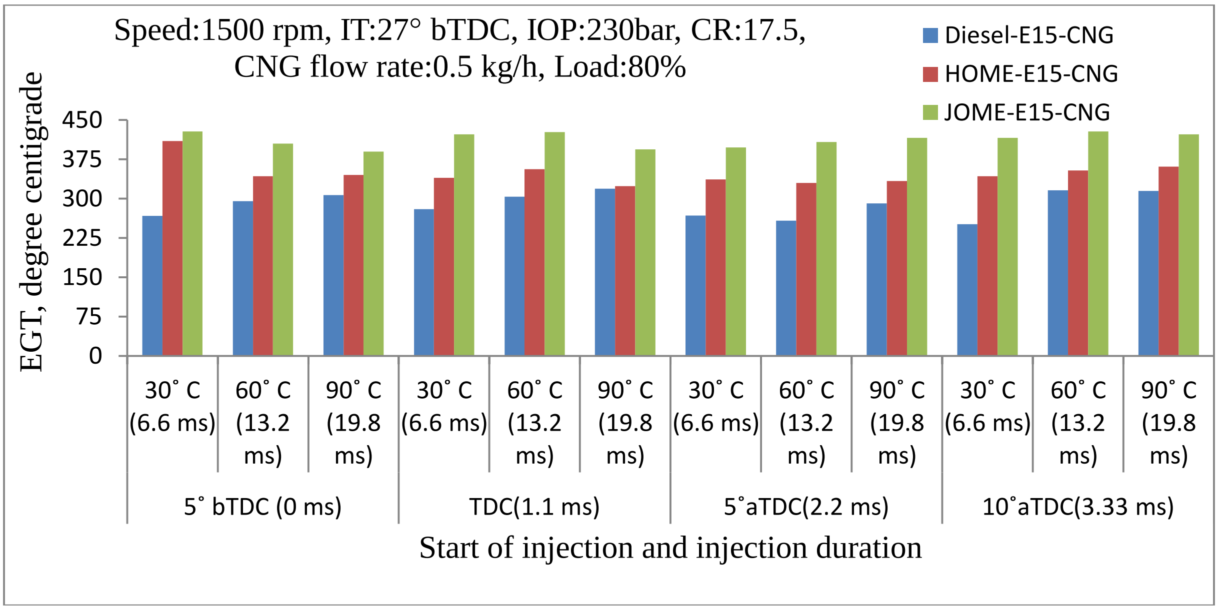


Fig.10 Variation of EGT with CNG injection timing and injection duration

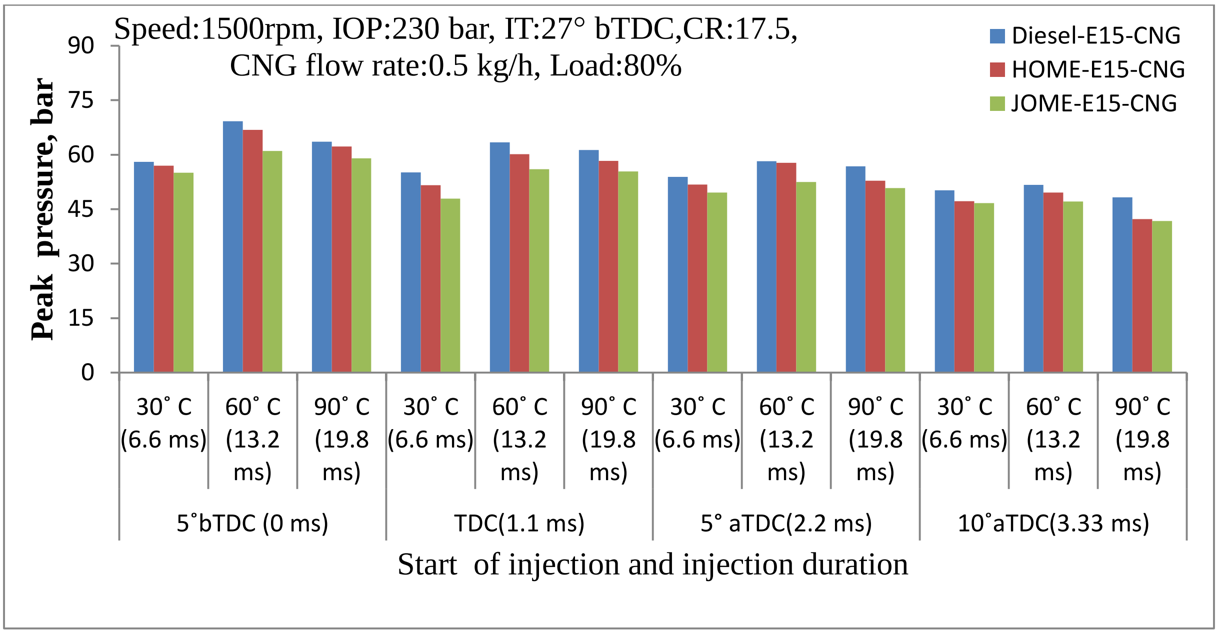


Fig.11 Variation of peak pressure with CNG injection timing and injection duration

6.3.2. Ignition delay

Figure 12 shows the variation of ignition delay with injection timing and injection duration for diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG dual fuel operation for 80% load respectively. The time difference between the start of injection and ignition is termed as ignition delay in CI engines. Higher auto ignition temperature of CNG, leads to more ignition delay. Once the CNG ignites, further mixture ignites without any difficulty. Due to its high auto ignition temperature, initially at zero loads and part load it takes more time to ignite. But at full load the ignition delay for CNG enriched fuel is found to be lower because of the high heating value of CNG. Higher viscosity and lower cetane number of the biodiesel and ethanol blended fuel combinations shows higher ignition delay when compared to diesel. The ignition delay found to be lesser for all fuel combinations when engine was operated with CNG injection timing of 5^{o}bTDC and injection duration of 60°CA. At 80% load the ignition delay was 12.1, 11.3 and 10.6°CA with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG fuel combination respectively.

6.3.3. Combustion duration

Figure 13 shows the variation of NOx with injection time and injection duration for CNG-diesel, CNG-HOME and CNG-JOME with15% ethanol blend dual fuel operation for 80% load respectively. The combustion duration was calculated based on the duration between the start of combustion and 90% cumulative heat release. The combustion duration is found to be more for HOME-E15-CNG and JOME-E15-CNG compared to diesel-E15-CNG dual fuel operation. This could be due to the higher viscosity and lower calorific value of the biodiesels used. The Combustion duration found to be short for all fuel combinations when engine was operated with CNG injection timing of 5^{o}bTDC and injection duration of 60^{o}CA. At 80% load the combustion duration was 50, 53 and 58°CA with diesel-E15-CNG, HOME-E15-CNG and JOME-E15-CNG fuel combinations respectively.

6.3.4. In-cylinder pressure

Figure 14 and 15 shows the variation of in-cylinder pressure with crank angle for a CNG-HOME+E15 dual fuel operation for different CNG injection duration and CNG injection timings. The rate of pressure rise is higher with CNG injection time of 5°bTDC and injection duration of 60^{o}CA. It is observed that the peak in-cylinder pressure for HOME-CNG DFC is slightly lower than diesel-CNG dual fuel combustion. The injection of CNG during the suction process reduces the in-cylinder temperature and hence causing the primary fuel combustion to be unstable. This is primarily as a result of HOME's low lower heating value relative to that of regular diesel fuel. Similar trend was observed with JOME-E15-CNG dual fuel mode operation. The peak pressure developed inside the engine cylinder is found to be higher for CNG- diesel-E15-CNG followed by HOME-E15-CNGfuel combinations respectively. The increased injection duration allows more quantity of CNG in to the engine cylinder leading to fuel-rich mixture and decreased combustion efficiency results in to decrease in in-pressure.

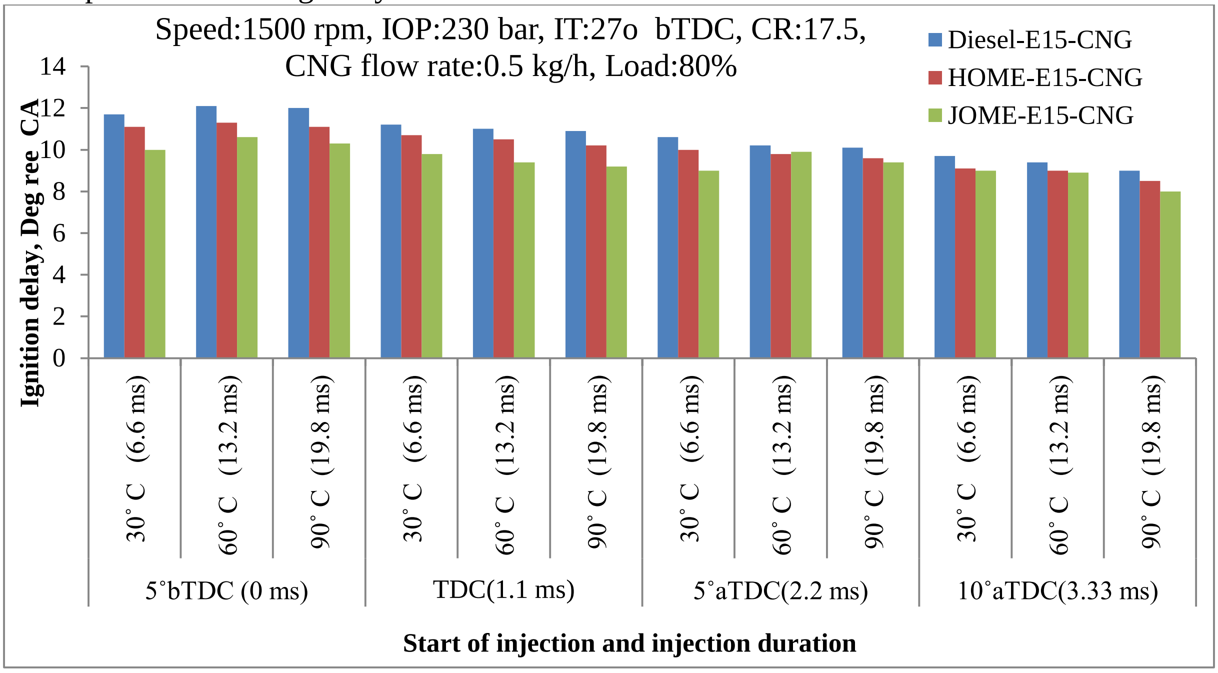


Fig.12 Variation of Ignition delay with CNG injection timing and injection duration

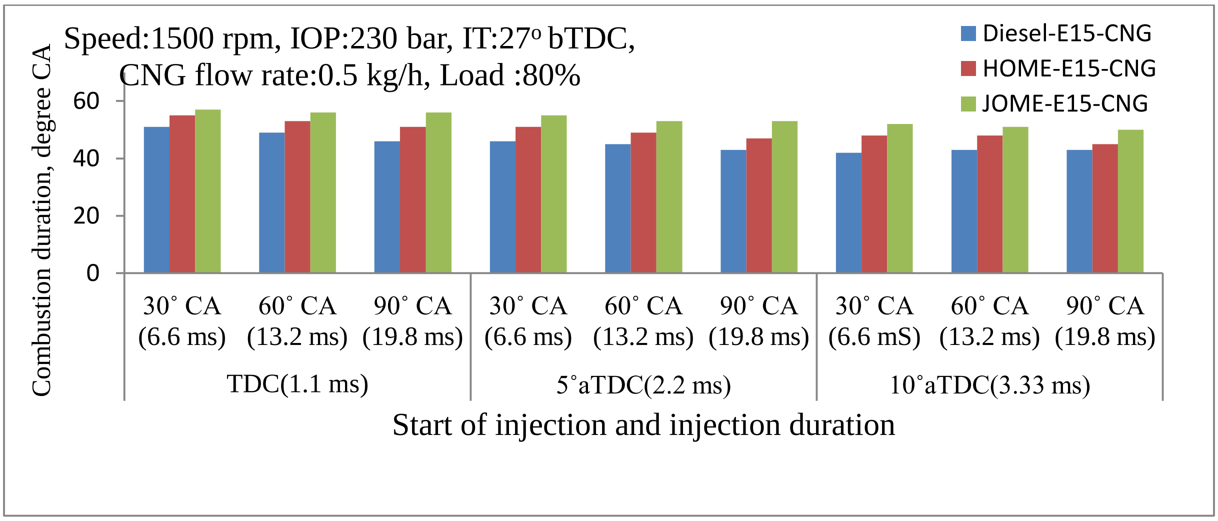


Fig.13 Variation of combustion duration with CNG injection timing and injection duration

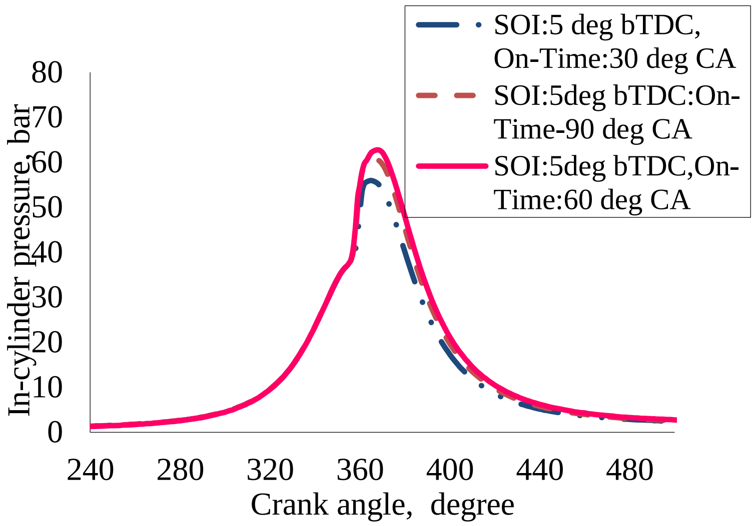


Fig.14 Variation of in-cylinder pressure with crank angle at different CNG injectiondurations

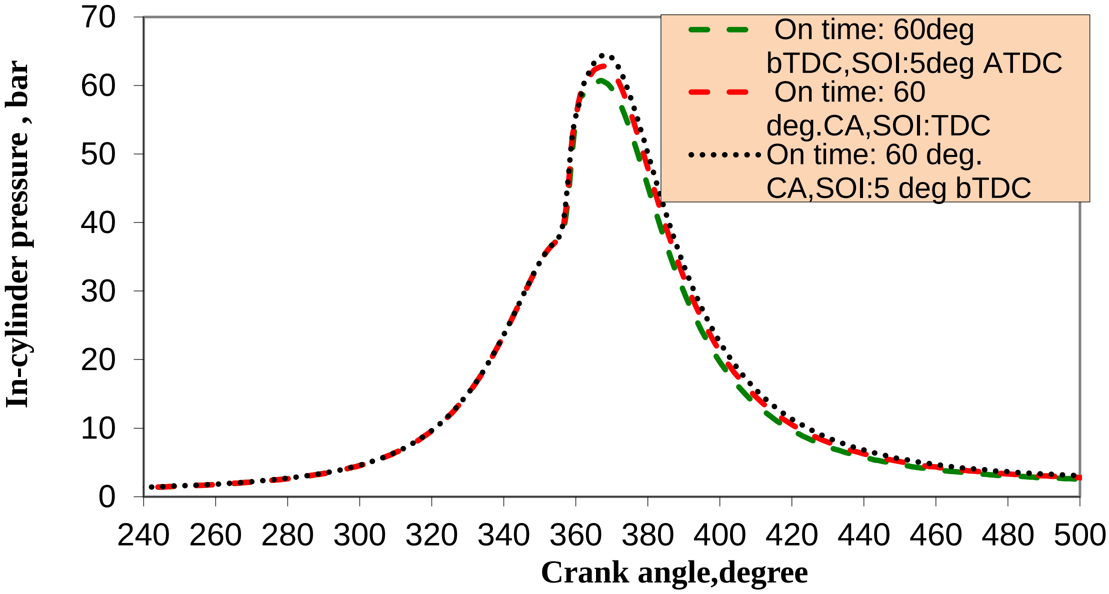


Fig.15 Variation of In-cylinder pressure with CNG injection timing

6.3.5. Heat release rate

Figure 16 and 17 shows the comparison of rate of heat release rate (HRR) for HOME-E15-CNG dual fuel engine operation when operated at different CNG injection duration and CNG injection timings. It is observed that heat release rates for CNG is premixed type combustion, in contrast to typical diffusion type combustion of liquid fuel operation. The reduced premixed combustion observed with biodiesel and ethanol combinations could be responsible for the reduced HRR when compared to diesel operation. CNG being common the properties of the injected liquid fuel combinations could be responsible for the observed HRR rates. The similar trend of HRR was also observed with JOME-E15-CNG dual fuel operation. HRR for HOME-E15-CNGmanifold injection dual fuel operation with CNG injection timing of 5^{o}bTDC and injection duration of 60^{o} CA was found to be 89.32 J/CA respectively.

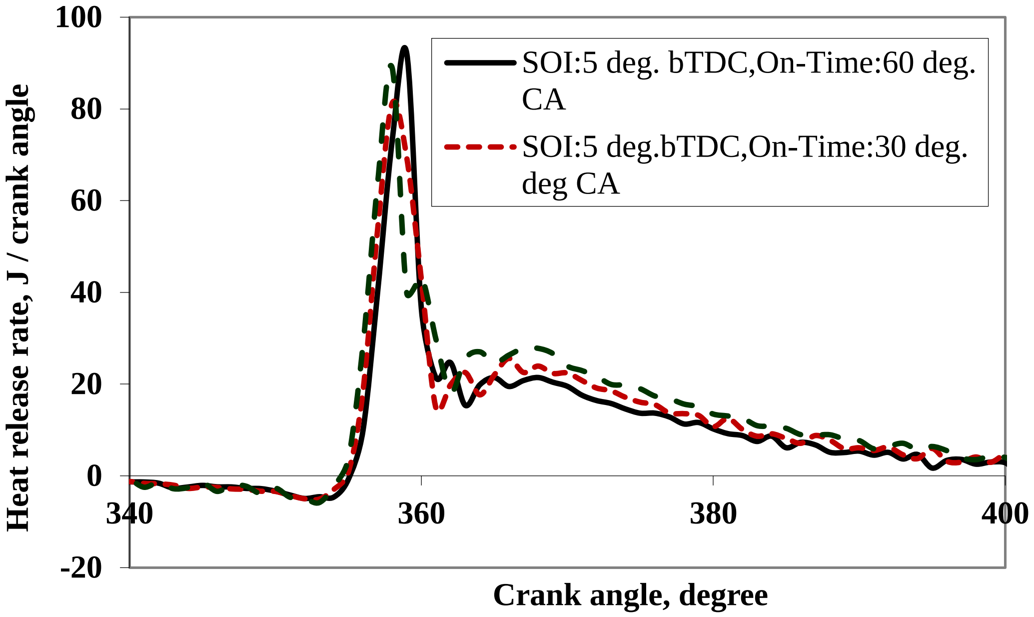


Fig.16 Variation HRR with crank angle at different CNG injection durations

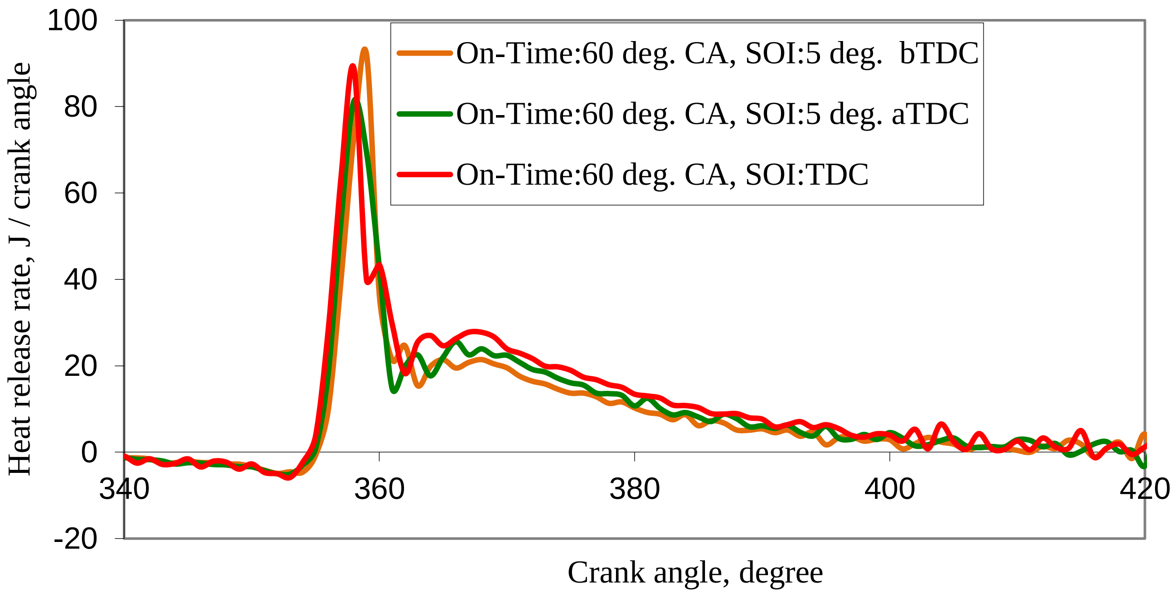


Fig.17 Variation of HRR with crank angle at different CNG injection timing

7. Conclusions

Electronically controlled gaseous fuel injection system is considered to be the most viable technology to reduce emissions in CNG dual fuel engines. This approach helps to achieve a homogeneous mixture of air and fuel before the air stream splits in the intake manifold. It is observed that CNG manifold injection causes turbulence and charge stratification, particularly at engine part load operations and is able to diminish the cyclic variations and enhance the limit of lean operation of the engine. The gas pulse timing offers the potential advantage of lower emissions and lesser fuel consumption. The experimental results showed that an injection timing of 5^{o}bTDC with injection duration of 60^o bTDC was found to be optimum based on the improved performance, combustion and emission characteristics. Use of renewable fuels of HOME, JOME and ethanol blends can partially eliminates use of fossil fuels and this ensures sustained energy security for the developing countries like India. The brake thermal efficiency in manifold injected CNG-diesel/biodiesel-ethanol blend dual fuel operation for 80% load was 27.1%, 26.2% and 25.2% for diesel- ethanol blend, HOME-ethanol blend and JOME-ethanol blends respectively. Reduced smoke emissions and carbon monoxide (CO) were obtained with the optimized CNG injection timings. The use of CNG manifold injection in the dual fuel mode in the modified CI engine improves the performance and reduces the exhaust emissions from the engine except for HC and NO_x emissions. However NO_x can be effectively controlled with suitable EGR arrangement.

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