

Performance and emission characteristics of a CNG-Biodiesel dual fuel operation of a single cylinder four stroke CI engine

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Abstract: The introduction of stringent emissions norms like Euro V and Euro VI is diverting the research to develop new technologies to reduce the engines exhaust emissions. Many researchers have adopted different techniques for lowering the tailpipe emissions from the engines where oxides of nitrogen (NO_x) and smoke are mainly formed. In this study a diesel engine having single cylinder is converted into dual-fuel engine to operate with pilot injection of Diesel/biodiesel ethanol blend and Compressed natural gas (CNG). The engine was operated on both single fuel(SF) and dual fuel(DF) mode. The CNG was inducted into the inlet manifold through a gas carburettor on purpose designed for this application. The injection timings was optimized for CNG- biodiesel. The optimum injection timing was 27°BTDC. The pilot fuel injection pressure was maintained at 230 bar. Engine was operated with optimum Compression ratio of 17.5 and CNG flow rate was optimized and found to be 0.5 kg/h. The effect of CNG induction on combustion and emissions characteristics of a compression ignition engine with a dual fuel was studied and compared with single fuel operation. Comparative results revealing the effect of dual fuel combustion on the engine performance, combustion and exhaust emissions. Based on the performance, combustion and emission characteristics it is concluded that, use of CNG in the dual fuel mode in a diesel engine improves the performance and reduces the exhaust emissions from the engine except for HC and NO_x emissions.

1. Introduction

Continuous pressure on emission control through tightened and stringent emission norms is directing the researchers to design new methods to control engine tailpipe emissions. Due to stringent restrictions laid down by government agencies on tail pipe emissions from internal combustion engines and worldwide shortage of fossil fuels, alternative fuels have gained popularity [1-3]. Continued efforts towards reducing pollutant emissions from diesel engines especially particulate matters and nitrogen oxides, many researchers recommended a dual fuel engines for utilising CNG as a partial substitute along with liquid biodiesel [4-6] which paves the way for replacement of neat diesel. In such engines a variety of combination of biodiesel fuels and gaseous fuels have been utilized. In this context natural gas has become a most widely used alternative gaseous fuel for a variety of reasons including its ready availability and its low emissions [7-8].

2. Majority of the transport vehicles are driven by Compression Ignition (CI) engines and they can effectively use variety of fuels that are alternatives to diesel and hence possible to meet stringent emission norms besides conserving energy as well [1, 9-14]. Research on highly efficient diesel engines, using various alternative and renewable fuels has been reported in the literature [10, 15-16]. Different methods have been adopted by researchers for controlling the tailpipe emissions from the engines in order to address smoke and oxides of nitrogen emissions [19-23]. It is possible to convert existing CI engines to run in dual fuel mode with natural gas as primary fuel and diesel/biodiesel as pilot fuel. In



dual fuel engines, injected diesel/biodiesel will auto ignite first then it ignites the compressed CNG [5, 9-11]. However, many initial trails to adopt this technology were crude, leading to excessive diesel/biodiesel usage, over fuelling to achieve acceptable power levels, and unacceptably high emissions [24-25]. The present research is aimed to reduce the emissions from diesel engines by operating the engine in dual fuel mode.

2. Experimental section

2.1. Fuels used

Biodiesel and their blends with ethanol (15%) were used as pilot liquid fuels in the present study. Engine was operated in single fuel and dual fuel mode using same liquid fuels. CNG is supplied as the primary fuel in DF mode. Biodiesels are produced from honge and jatropha oils. Accordingly these biodiesels are called by names HOME and JOME respectively. Table 1 shows the various properties of the diesel and 15% ethanol blended biodiesel. CNG at 2 bar pressure was inducted through the gas carburettor in to the intake manifold. A two stage pressure regulator was used to control the gas pressure. The different properties of CNG are shown in Table 2.

Table 1. Properties of diesel, ethanol blends of HOME and JOME

Sl No	Properties and ASTM standard testing method	Diesel	HOME	JOME	HOME+ 15%	JOME+ 15% Ethanol
1	Viscosity @ 40 °C (cst) (ASTM D445)	3.5	5.4	5.92	3.7	3.25
2	Flash point °C	56	163	163	32	33
3	Calorific Value in kJ / kg (ASTM D5865)	45000	36010	35200	35550	33060
4	Density kg / m ³	830	890	880	----	----
5	Cetane Number	45-55	40-42	40-45	----	----

Table 2. Properties of CNG [5]

Boiling range (K @101325Pa)	147	Flame Speed (cm/s)	33.80
Density (kg/m ³) at 1 atm. & 15° C	0.77	Net Energy Content (MJ/kg)	49.5
Flash Point (K)	124	Auto Ignition Temperature (K)	923 (650°C)
Flammability Limits Range-Rich, Lean	0.5873	Stoichiometric A/F (kg of air/kg of fuel)	17
	1.9695	Octane Number	130

2.2. Experimental set-up and methodology

Fig. 1 shows an experimental test rig having provision to run the engine in both single fuel and dual fuel mode. A single cylinder, 4-stroke water cooled direct injection CI engine was operated at a rated speed of 1500 rpm. The static injection timing of 23° before top dead center (BTDC) and an injector opening pressure (IOP) of 205 bar were maintained for diesel fuel operation. A CNG Flow rate from 0.25 to 1 kg/h and the pilot fuel injection timings in between 19° and 27° BTDC were employed with diesel, HOME and JOME along with CNG fuel combinations.



Figure 1. Engine test rig with ethanol mixing tank

3 Results and discussion

The experimental investigations were conducted on a four stroke water cooled single cylinder CI engine test rig to operate on both SF and DF mode. In the present study, engine was operated in single fuel (SF) using ethanol blends of diesel, HOME and JOME at optimised parameters. Further engine tests were performed with DF using CNG and Biodiesel for 80% load and 100% load conditions to optimize pilot fuel injection timing and CNG flow rate for dual fuel operations.

3.1. Performance of DF Operation with Diesel, HOME, JOME with different CNG flow rates

In the current investigations, engine operating parameters namely IOP, CR and IT were kept constant as 230 bar, 17.5 and 23° BTDC respectively for HOME and JOME and CNG flow rate was varied from 0.25kg/h to 1 kg/h. Engine was operated at 80% and 100% load conditions.

3.1.1. Performance characteristic

3.1.1 Brake Thermal Efficiency

Brake thermal efficiency (BTE) of dual fuel engine for selected fuel combinations at different CNG flow rates are represented in figure 2. Higher BTE was observed for CNG-diesel DFC mode followed by HOME and JOME with CNG DFC operation at all loads. The lower energy content and higher viscosity of injected ethanol blended biodiesels leads to lower BTE. The increase in CNG flow rate from 0.25 to 1.0 kg/h, resulted in drop in volumetric efficiency inturn reduces BTE. At higher liquid fuel pilot quantities CNG fuel utilization improves [23]. This is because of the availability of stronger ignition source and also due to increased temperature which reduces substantially gaseous fuel escaping combustion. CNG flow rate of 0.25 kg/h results in higher BTE for both 80% and 100% loads. Engine starts knocking severely at CNG flow rate beyond 1 kg/h. For the same CNG flow rate, HOME-CNG operation resulted in better performance compared to JOME-CNG operation. It could be attributed to comparatively lower viscosity and higher energy content of HOME. BTE values at 80% load for Diesel-CNG, HOME-CNG and JOME-CNG operation with 0.5 kg/h flow rate of CNG were found to be 24, 25.5 and 21.6% respectively.

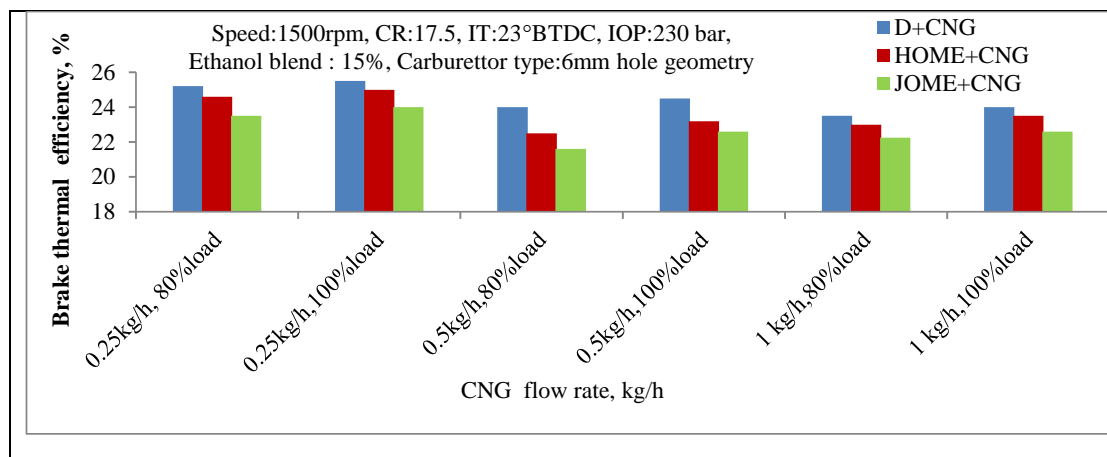


Figure 2. Variation of BTE with load for different CNG flow rates

3.1.2 Smoke Opacity

The smoke opacity for dual-fuel operation for selected fuel combinations are represented in figure 3. Diesel-CNG dual fuel operation have lower smoke levels compared to HOME and JOME fuels with inducted CNG. Ethanol blended biodiesel pilot fuels produced higher smoke emissions. The increase in CNG quantity increases the heat output which leads to rise in in- cylinder temperature results in reduced smoke levels. At 80% load, Smoke emission levels for diesel-CNG, HOME-CNG and JOME-CNG dual-fuel operation with a CNG flow rate of 0.5 kg/h were found to be 55, 67 and 68 HSU respectively.

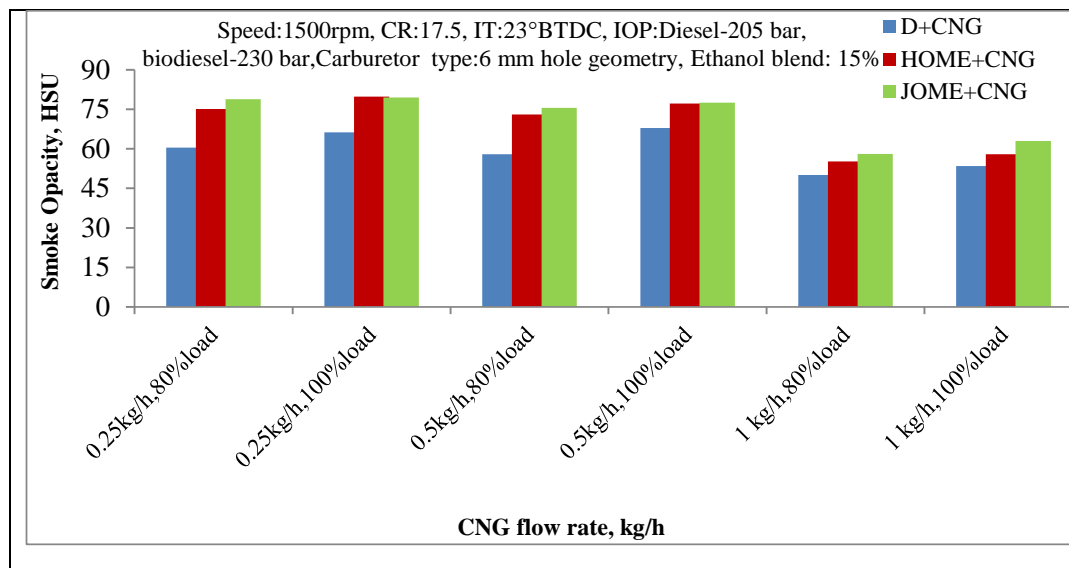


Figure 3. Smoke variation for different CNG flow rates

3.1.3 HC emissions

Hydrocarbon emissions were found to be higher throughout the load range for the injected biodiesel-CNG dual fuel combinations compared to diesel-CNG (Figure 4). The overall HC emissions levels using DFC is higher due to the CNG charge, which causes lean, homogeneous, low-temperature combustion, resulting in less complete combustion. This is because small amount of pilot fuel cannot propagate fast and far enough to ignite the whole premixed fuel mixture. This is due to the increase of burnt gas temperature, which promotes the oxidation of unburned hydrocarbons. Under dual fuel operation, the filling of the crevice volumes with unburned mixture of air and gaseous fuel during compression and combustion is an important source dominating the formation of HC emissions [23]. HC emissions of JOME-CNG operation are found to be higher than HOME-CNG and diesel-CNG dual fuel operation. HC emission levels for diesel-CNG, HOME-CNG and JOME-CNG dual-fuel operation at 0.5 kg/h flow rate of CNG were found to be 61, 65 and 69 ppm respectively at 80% load.

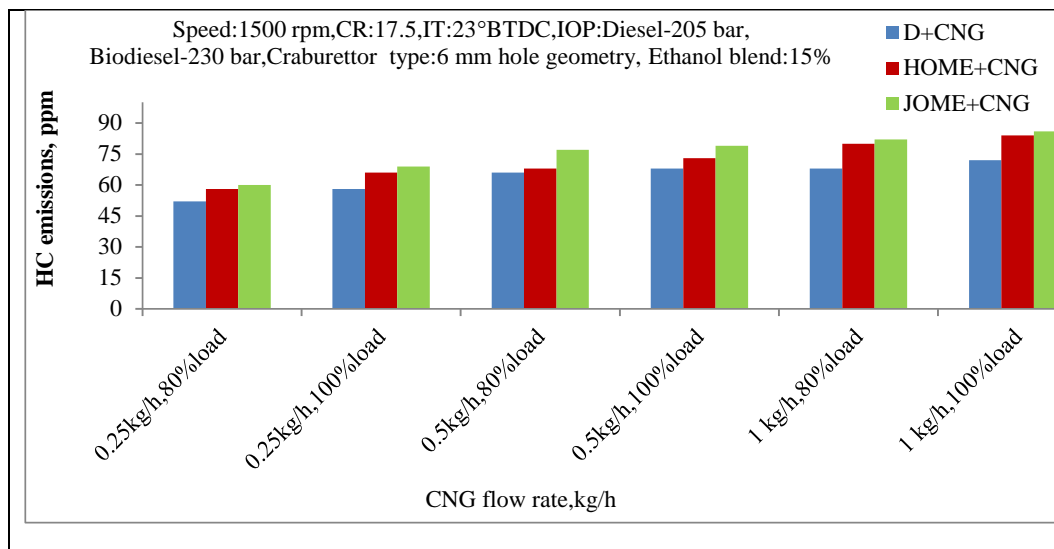


Figure 4. HC emissions for different CNG flow rates

3.1.4 CO emissions

The carbon monoxide variation for various CNG flow rates are represented in figure 5. For CNG-diesel fuel combinations, the exhaust emissions of CO were lower compared to pilot fuels such as HOME and JOME along with CNG respectively. Higher heat release rate at premixed burning phase, resulted in lower CO for CNG-diesel mixture. The rich air-fuel ratio relative to stoichiometric invariably produces CO. The CO levels are observed to be minimum for lower CNG flow rate. As CNG flow rate increases CO emission and later on these begin to decrease. Poor engine performance was noticed as CNG flow rate is increased beyond 1 kg/h. The severe onset knock is encountered at higher CNG flow rate more than 1 kg/h. CO emission levels for diesel-CNG, HOME-CNG and JOME-CNG dual-fuel operation at 0.5 kg/h flow rate of CNG were found to be 0.13, 0.15 and 0.18% respectively at 80% load.

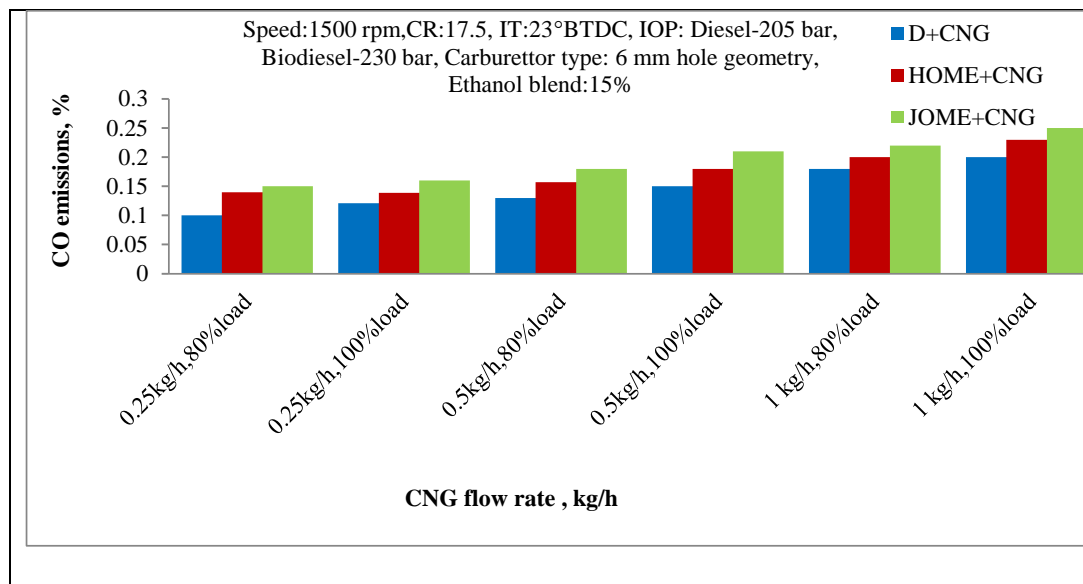


Figure 5. CO variation with CNG flow rates

3.1.5 NO_x emissions

The NO_x variation for different CNG flow rates are shown in figure 6. The NO_x formation in CI engine is mainly because of more oxygen supply and higher charge temperature inside the cylinder. For CNG–diesel DFC operation, NO_x emissions were higher followed by biodiesel-CNG fuel combination. The lower calorific value and heavier molecular structure of injected biodiesels in dual fuel operation leads to higher NO_x emissions. As gas flow rate increased for all the DFC combinations the NO_x emissions levels increased. NO_x emission levels with diesel-CNG, HOME-CNG and JOME-CNG dual-fuel operation at 0.5 kg/h flow rate of CNG were found to be 910, 800 and 760ppm respectively at 80% load.

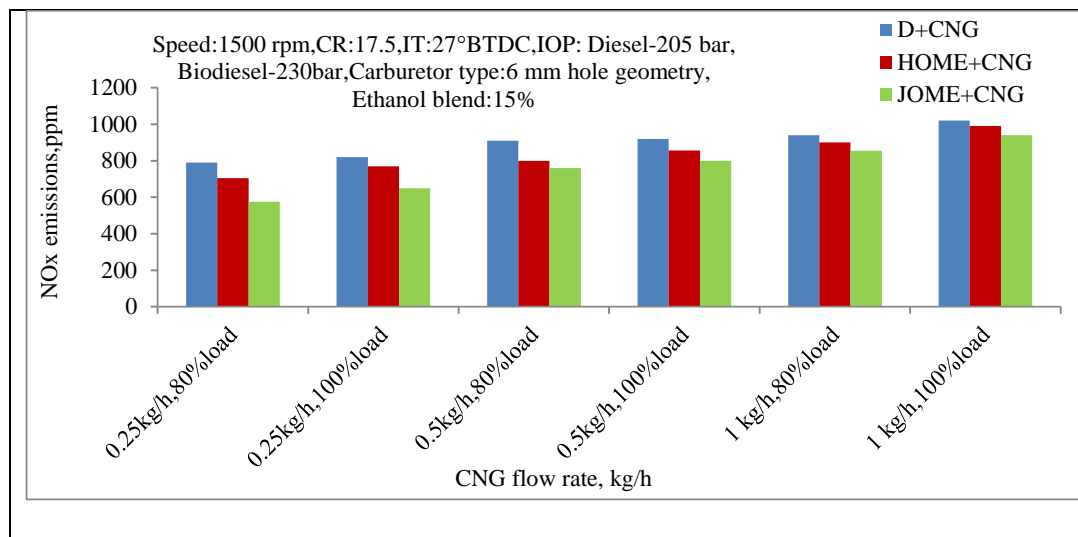


Figure 6. NO_x variation for different CNG flow rates

3.2 Effect of injection timing for Diesel-CNG, HOME-CNG and JOME-CNG dual fuel operation

To study the effect of injection timing (IT) on the performance of CNG-diesel, CNG-HOME and CNG-JOME fuelled dual fuel engine operation, the engine was operated by keeping the compression ratio of 17.5, a carburettor with a hole geometry of 6 mm to mix CNG and air, an injector nozzle opening pressure of 230 bar was maintained for biodiesel and 205 bar for diesel combination combination. 0.5 kg/h CNG was supplied during the experiment.

3.2.1 Brake Thermal Efficiency

At higher loads for different fuel combinations the BTE variation with pilot fuel injection timing during are shown in figure 7. BTE increased with the advancement of pilot fuel injection timing from 19° to 27° BTDC. The reason for this increased BTE is that more time will be available for CNG fuel burning and these results in better performance with improved brake thermal efficiency. The smooth operation of the engine was observed with advanced IT with slight increased fuel consumption [20]. By advancing the IT, an improvement in BTE was achieved. BTE values for diesel, HOME and JOME with CNG dual-fuel operation at 27° BTDC injection timing were found to be 24.5, 23.2 and 22.1% respectively at 80% load.

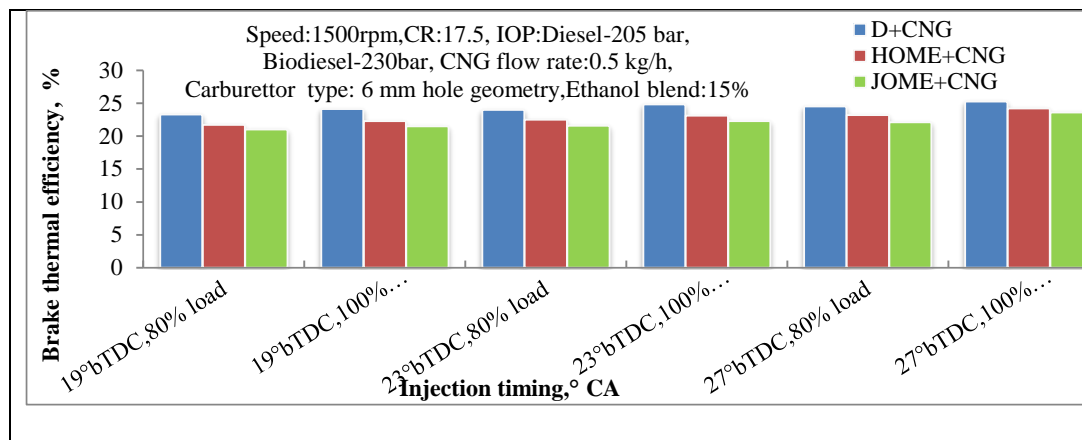


Figure 7. Variation of BTE with injection timing

3.2.2 Smoke Opacity

From figure 8 it is evident that the amount of smoke in the engine exhaust reduced with increased in injection timing for all the fuel combinations tested in DFC mode. This is because of better combustion prevailing inside the engine cylinder. As engine load increases, the smoke emissions increase slightly. Further, the smoke opacity for biodiesel-CNG operation found to be more compared to diesel-CNG combination. Smoke levels for, HOME-CNG and JOME-CNG dual-fuel operation at 19, 23 and 27°BTDC injection timing were found to be 55, 67 and 69 HSU at 27°BTDC respectively at 80% load.

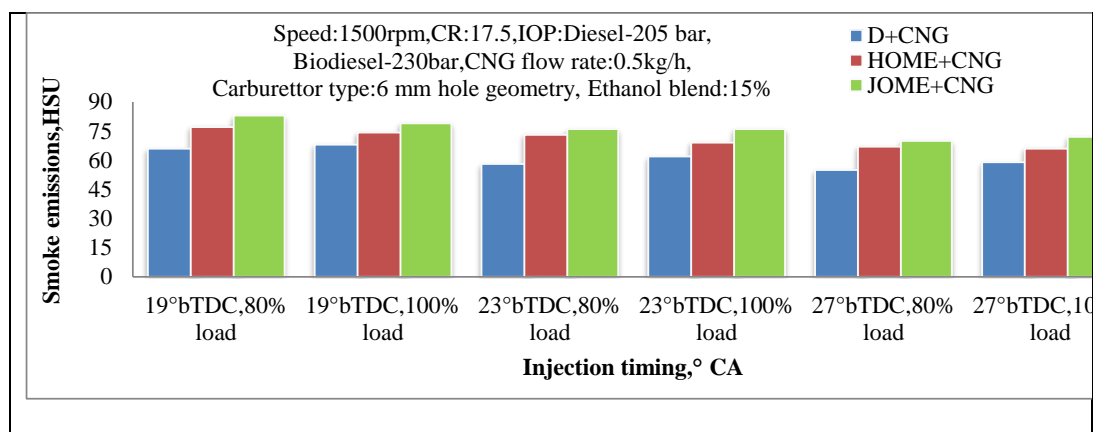


Figure 8. Smoke opacity for different injection timings

3.2.3 HC emissions

The amount of hydrocarbon in exhaust emissions for different injection timings for different fuel combinations at higher loads are shown in figure 9. HC emission observed to be decreased as pilot fuel injection timing is advanced for different fuel combinations tested. The improved combustion and higher heat release in premixed combustion stage may leads to increased thermal efficiency and reduced hydrocarbon emissions. HC emission levels for DFC mode with diesel-CNG, HOME-CNG and JOME-

CNG dual-fuel operation at 19, 23 and 27°bTDC injection timing were found to be 61, 65 and 69 ppm at 27°bTDC respectively at 80% load.

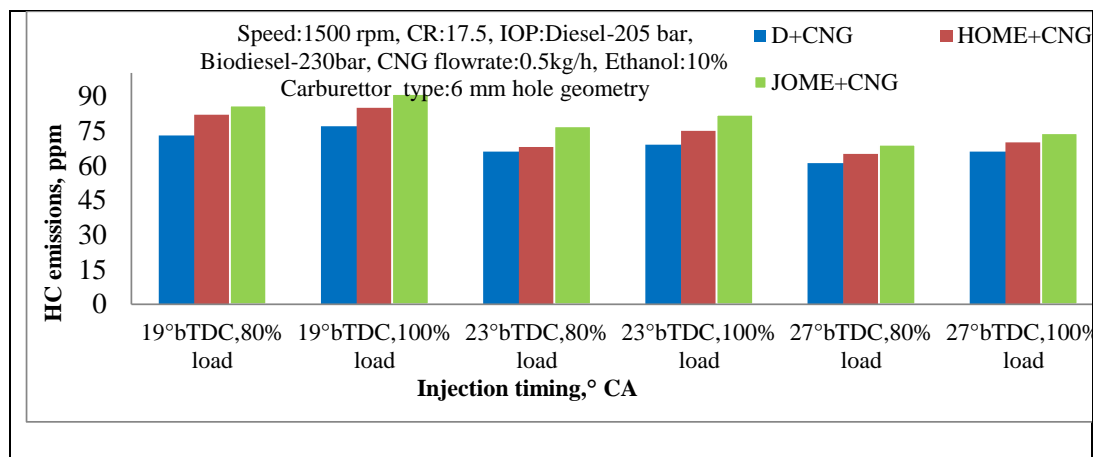


Figure 9. Variation HC emissions for different injection timings

3.2.4 CO emissions

Figure 10 represents the variation of carbon monoxide(CO) with increase in IT of the pilot liquid fuel for higher loads respectively. During the DFC mode with CNG- ethanol blended diesel/ biodiesel, the CO emission increased with increase in load and found to be higher for CNG-biodiesel combination. Higher amount CO is mainly due to incomplete combustion. The emission of CO greatly depends on the air-fuel ratio relative to stoichiometric proportions. CO emission reduced for advanced IT from 19° BTDC to 27° BTDC as seen in the figure. Partial oxidation and better combustion reactions at advance IT helps to minimise CO emissions and an improvement in BTE is noticed. CO emission levels for diesel-CNG, HOME-CNG and JOME-CNG dual-fuel operation at 19, 23 and 27°bTDC injection timing were found to be 0.13, 0.15 and 0.18% at 27°bTDC respectively at 80% load.

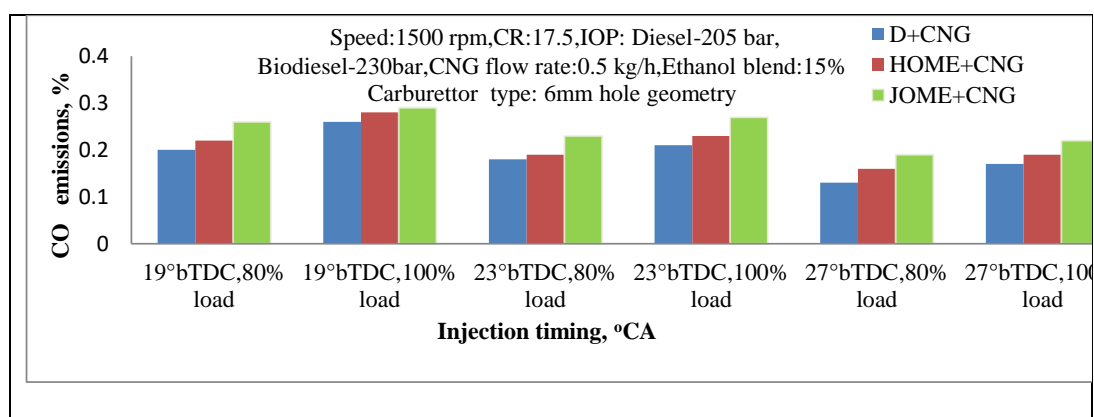


Figure 10. Variation of CO with injection timing

3.2.5 NO_x emissions

The effect of injection timings on NO_x emissions while operating the engine in DFC mode for different fuel combinations for higher loads are represented in figure 11. NO_x levels increased advanced injection timings(IT) for all fuel combinations in DF mode. The improved combustion and higher HRR during premixed combustion may leads to formation of higher NO_x [24]. These higher NO_x levels are possible to control by adopting EGR technique. The changes in adiabatic flame during combustion also leads to higher NO_x emissions. The advanced IT of 27° BTDC for CNG-diesel/biodiesel DFC resulted in higher NO_x levels where as at 19° BTDC, NO_x levels were found to be lower. NO_x levels are increased with the advance of pilot injection timing. NO_x emission levels for diesel-CNG, HOME-CNG and JOME-CNG dual-fuel operation at 19, 23 and 27° BTDC injection timing were found to be 910,800 and 760ppm at 80% 27° BTDC respectively at 80% load.

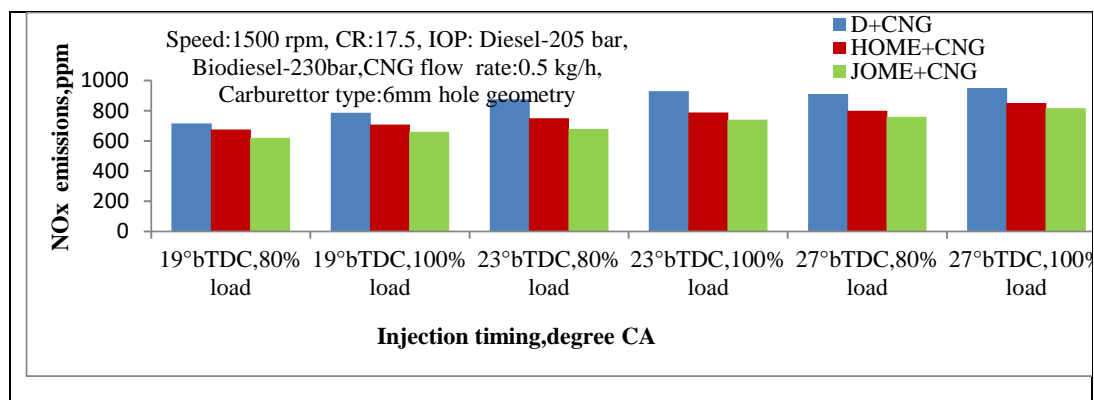


Figure 11. Variation of NO_x with injection timing

3.3 Overall Comparison of the different Modes of Engine Operation

The results obtained with different modes of engine operation using different fuel combination in which diesel and biodiesel are blended with 15% ethanol was used as the injected liquid fuel and CNG as inducted/injected fuel in modified CI engine to operate in dual fuel mode. The comparison has been made at 80 % load condition of the engine. The engine has been operated in single fuel and dual fuel modes with following fuel combinations.

- Single fuel mode of operation with Diesel, HOME and JOME with 15% ethanol.
- Dual fuel operation with CNG as inducted and ethanol blends of diesel, HOME and JOME as the injected pilot fuel. 10% EGR is also inducted during the experimentation.

3.3.1 Brake Thermal Efficiency

The BTE variation for the ethanol blends of diesel/biodiesel in single fuel mode (SFC) and dual fuel mode (DFC) with CNG are shown in figure 12. SFC performs better compared to DFC. Lower BTE was observed for HOME, JOME and their ethanol blends as compared to diesel. The lower energy content of biodiesel are attributed to lower BTE and more biodiesel is consumed for the same power output in SFC mode. Higher viscosity of HOME and JOME brought difficulty in the mixture formation leads to poor combustion than diesel in SFC mode[6]. Higher BTE was observed for CNG-diesel dual fuel mode of operation as compared to ethanol blended biodiesel-CNG combination. The properties of

the injected fuels has a major effect on the engine performance in DFC mode even though CNG being common inducted gaseous fuel,

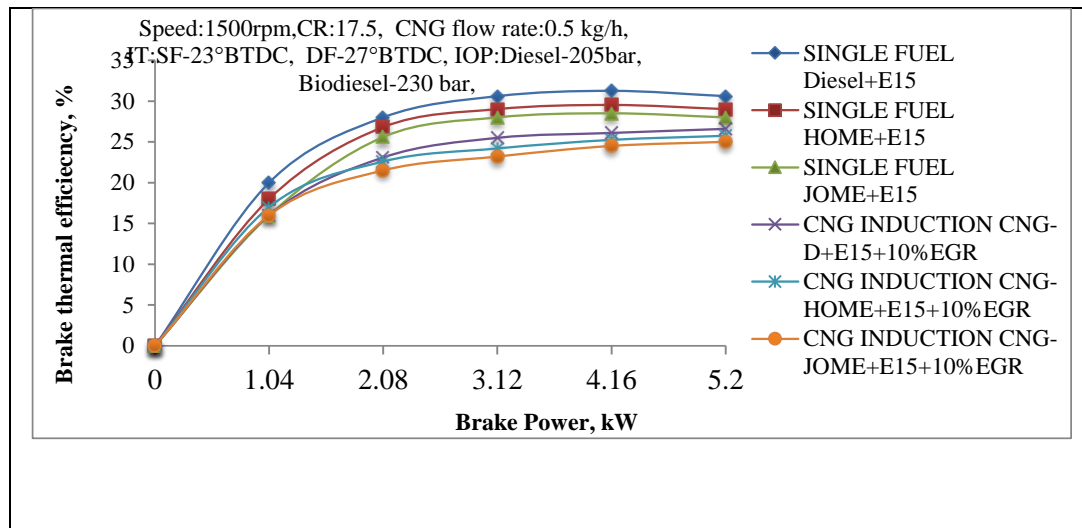


Figure 12. Variation of BTE with BP

3.3.2 Smoke opacity

The variation of smoke with different fuel combinations in SFC and DFC engine operation at 80% load are shown in Figure. 13. Due to the presence of ethanol smoke emissions were reduced during the operation of engine using biodiesel as injected fuel. From the figure it is clear that DFC perform better compared to SFC. In SF biodiesel-ethanol blend results in increased smoke opacity compared to diesel-ethanol blend. HOME-ethanol blends result into decreased smoke opacity compared to JOME-ethanol blends. The smoke opacity reduces considerably in dual fuel operation. CNG induction leads to lower smoke opacity compared to SF mode for all fuel combinations. It is considered that the biodiesel pilot fuel is mainly associated with higher smoke emissions because CNG combustion involves methane and does not produce particulate emissions

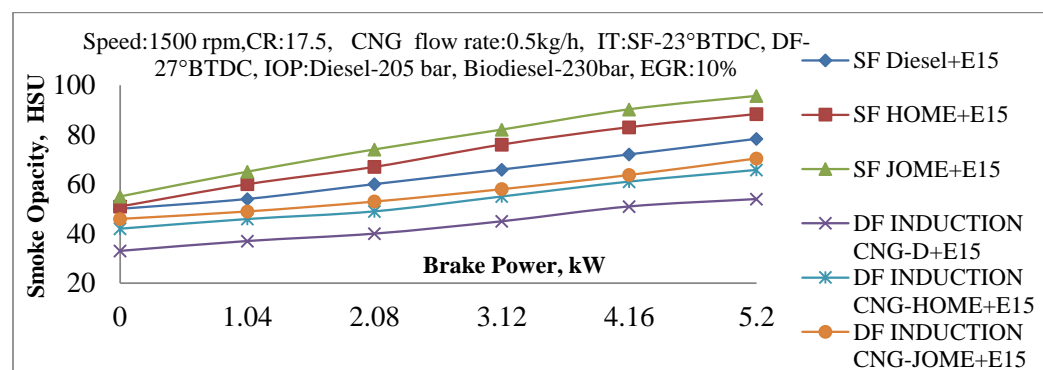


Figure 13. Smoke Variation with BP

3.3.3 HC Emissions

From the figure 14 it is clear that HC emissions in SFC are lower compared to DFC. At light loads, UBHC emissions are always higher CI engines. In SFC, biodiesel-ethanol blend results in higher HC emissions compared to diesel-ethanol blends. This could be due to high viscosity and less volatile biodiesel. Low-temperature lean combustion in DFC causes higher HC emissions levels. During dual fuel operation, the filling up of unburned CNG-air charge in crevice volume during compression and combustion is an important tends to the formation of more HC emissions in the exhaust. HC emissions of JOME-CNG operation are found to be higher than HOME-CNG and diesel-CNG dual fuel operation.

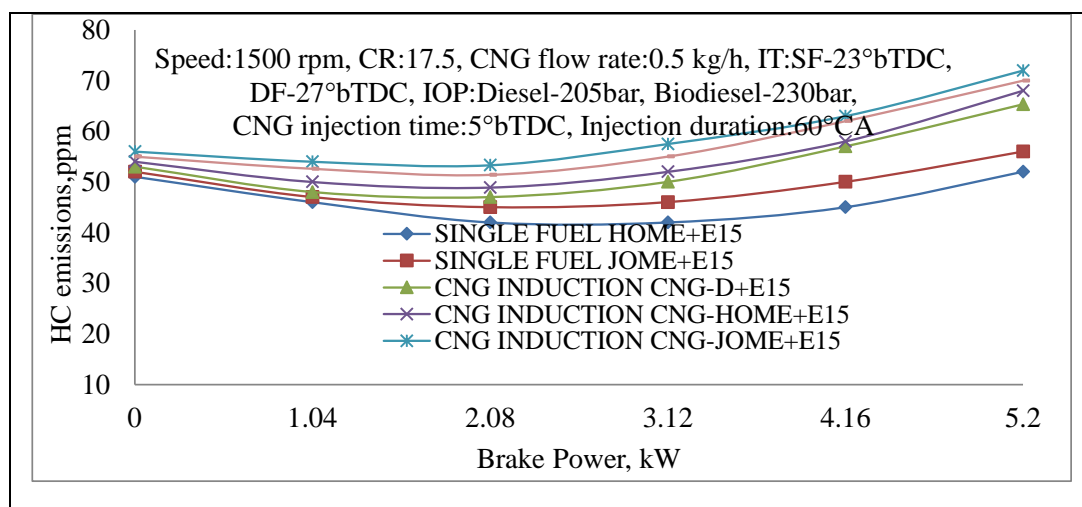


Figure 14. Variation of HC with BP

3.3.4 CO Emissions

Figure 15 shows the variation of carbon monoxide (CO) emissions with different fuel combinations in SFC and DFC engine operation. The CO emissions observed to be lower with ethanol blends of diesel, HOME and JOME. The oxygen content present in the ethanol and biodiesel causes better combustion and hence produces lower CO emissions. CO emissions in SFC are lower compared to DFC. In SFC biodiesel-ethanol blend results in higher CO compared to diesel-ethanol blend due to lower volatility and higher viscosity of biodiesel blends. HOME-ethanol blends result into lower CO compared to JOME-ethanol blends. For CNG-diesel dual fuel operations, the CO emissions were lower whereas for Biodiesel-CNG DF operations higher CO emission levels are observed.

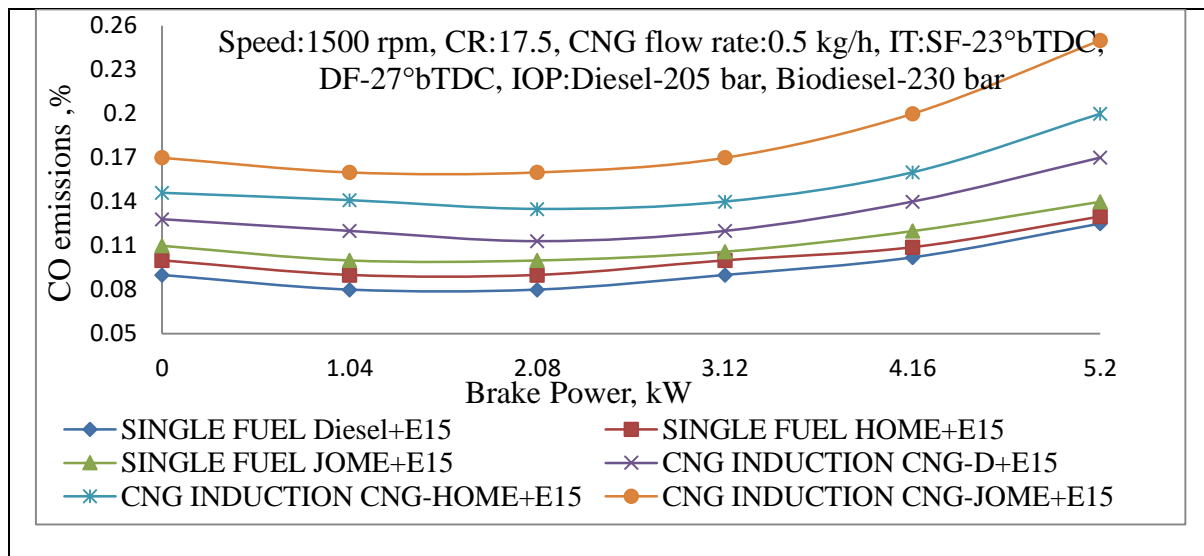


Figure 15. Variation of CO with BP

3.3.4 NO_x Emissions

Figure. 16 shows the variation of NO_x with different modes of engine operation. The NO_x emission behavior for all the fuels combinations in SFS and DFS engine operation was found to be similar at lower load with a slight increase in its magnitude at higher load. From the Fig. 16 it is clear that NO_x emissions in SFC are higher compared to. The NO_x emission behaviour for all the fuels was found to be similar at lower load with a slight increase in its magnitude at higher load. This is because at lower load, the adiabatic flame temperature of stoichiometric air/ ethanol flame is slightly lower [24]. The overall NO_x emissions levels in DFC with 10% EGR is found to be lower due to burning of fuel takes place under lean premixed conditions that results in lower temperature. Combustion was found to be smoother with optimum injection timing in manifold injection. As widely recognized, the formation of nitrogen oxides is favored by high oxygen concentration and higher charge temperature. NO_x emissions were higher for CNG–diesel dual fuel operation.

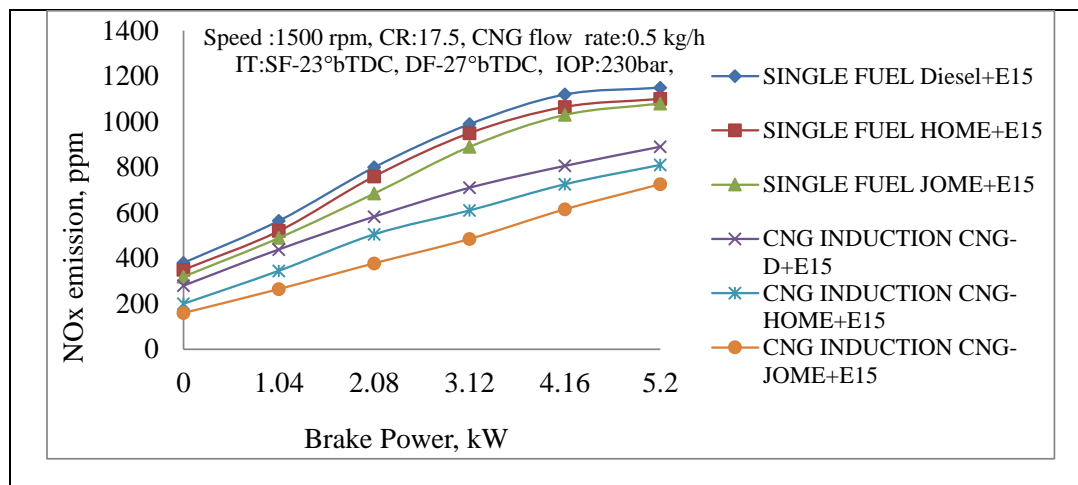


Figure 16. Variation of NO_x with BP

3.4 Combustion characteristics

The variation of in-cylinder pressure with crank angle for different fuel combination in SFC and DFC mode are shown in figure 17. The P- θ history was recorded for 100 cycles for all fuel combinations. It was observed that higher peak pressure was recorded for diesel+E15-CNG operation as compared with JOME+E15-CNG operation and HOME+E15-CNG operation lying in between. The addition of 10% EGR reduced peak pressure for all the fuel combinations tested.

Fig. 18 represents rate of heat release(HRR) during SFC with diesel/biodiesel ethanol blend as injected liquid fuels and DFC with 10% EGR. The higher HRR with ethanol blended diesel-CNG dual fuel operation was observed during premixed burning phase which resulted in higher BTE for diesel-CNG operation. The second peak is greater in diffusion-burning for ethanol blended JOME-CNG and HOME-CNG combinations compared to diesel-CNG dual fuel operation. This indicates less amount of fuel being prepared for rapid combustion with biodiesel-CNG after the ignition delay. Hence more burning occurs in the diffusion phase rather than in the premixed phase with biodiesel-CNG. This is consistent with the expected effects on the fuel spray and reduction of air entrainment and fuel air mixing rates along with slow burning CNG. Significantly higher combustion rates during the later stages with HOME and JOME-CNG leads to higher exhaust temperatures and lower thermal efficiency.

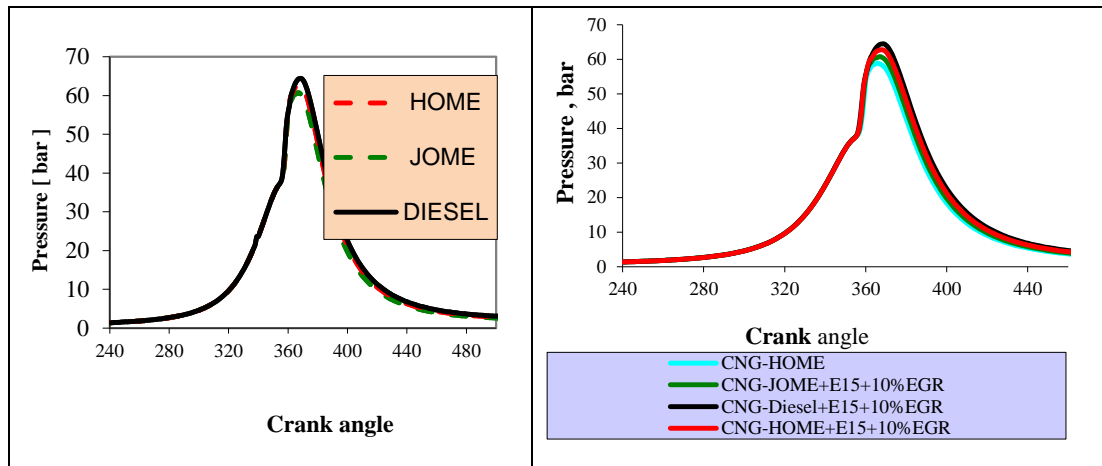


Figure 17. Variation of in-cylinder pressure with crank angle

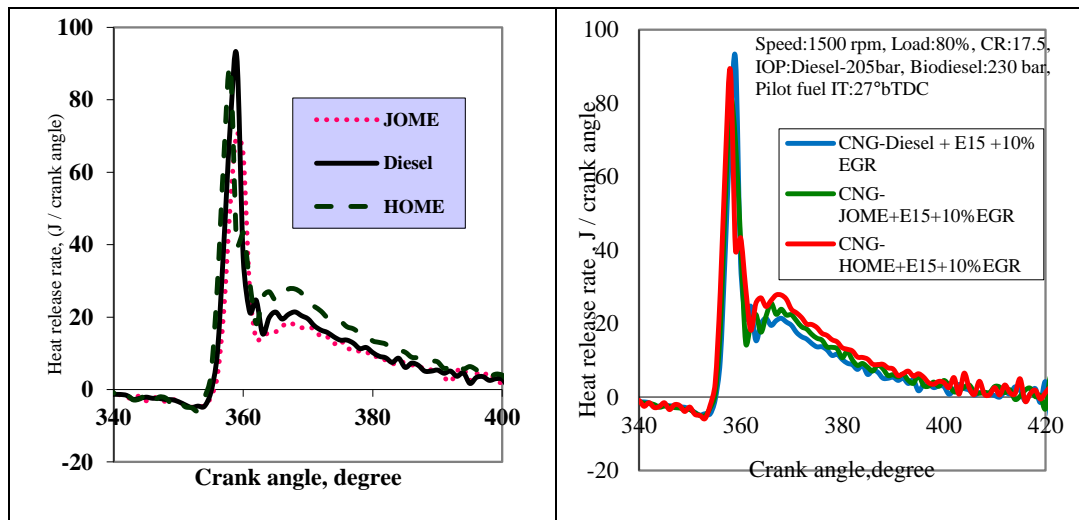


Figure 18. Variation of HRR with crank angle

4. Conclusion

It is observed that BTE was higher for the CNG supply of 0.25kg/h, however exhaust emissions over the entire load are also higher compared to 0.5 kg/h. At CNG flow rate of 1 kg/h, engine performance was very poor due to severe knock. Hence optimum flow rate of CNG is found to be 0.5 kg/h with pilot fuel combinations of diesel, HOME and JOME. In DFC mode at 27°BTDC injection timing, BTE observed to be higher compared to other injection timings tested for all the selected fuel combinations. HOME-CNG operation resulted in better performance compared to JOME-CNG operation. CNG-diesel DFC operation resulted in higher BTE than HOME and JOME operation. The advance in the injection timing resulted in reduced HC, CO and smoke opacity, whereas NO_x emissions increased considerably. It was concluded that HOME and JOME with 15% ethanol can be used as a promising alternative fuels for diesel engines either in SFC or DFC mode. Operating the engine with CNG induction dual fuel mode operation requires no major modifications in the existing diesel engine.

It is concluded that, cheaper and clean burning gaseous fuels like CNG and renewable liquid fuels like HOME and JOME and ethanol are more suitable for DFC mode besides addressing the sustained energy supply and energy security.

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