Performance, Emission and Combustion Characteristics of Hydrogen, CNG operated HCCI Engines with HnOME Biodiesel

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Abstract:-**Ever increasing demand for fossil fuels and their depleting nature associated with increased exhaust emission due to their increased use has led to search for new alternative and renewable fuels which can fully or partially replace diesel. Diesel engines are highly efficient engines but are found to emit more NO_x and smoke or particulate emission. Dual fuel (DF) approach is well established technique to make use of different types of fuels in diesel engines. In the present work, experimental investigations were carried out on a single cylinder four stroke compression ignition (CI) engine fuelled with diesel and HnOME in a single fuel mode and HnOME-Hydrogen and HnOME-CNG in Homogeneous charge compression ignition mode (HCCI)mode and results were compared in terms of efficiency and emission. Hydrogen and CNG were inducted using a suitable carburetor. Diesel fuel was injected at 205 bar into the engine cylinder where as the Hydrogen and CNG were inducted at best injection timing using a Electronic Control injection (ECU) facilities. From the result obtained, it is observed that, HCCI mode of operation of HnOME and Hydrogen is higher than HnOME and CNG operation in terms of Break Thermal efficiency and also considerable reduction in NO_X and smoke were found in HCCI mode of operation and it is 98% and 94% respectively.**

Keywords: HCCI, Diesel Engine, HOME, HnOME, CNG, ECU, Emissions

I. INTRODUCTION

The automobile industry is undergoing a rapid revolution. There has been an increasing focus on the utilization of cleaner fuel because of the stringent emission norms. The energy crisis, due to rapidly dwindling resources of gasoline and diesel, has necessitated the need to develop rapidly, alternative sources of energy to power the automobiles. The serious problems faced by automobiles which regard to limit on reserve, recycling and pollutive emission are well known (Das.L M.2002). Moreover, the combustion of such fuels results in emission of noxious pollutants which threatens the very survival of life in this planet. The main pollutants from the conventional hydrocarbon fuels are unburned/partially burned hydrocarbons (UBHC), carbon monoxide (CO), Oxides of nitrogen (NO_X), Smoke and particular matter. Thus, it is very important to find suitable renewable, alternative fuel with clean burning characteristics, to ensure the safe survival of internal combustion engines (Das L M, 2002). However it is not possible to have a common alternative fuel for universal application in the existing engines that have been designed to operate on petroleum based fuels. Efforts to operate these engines on any non-petroleum based fuels are likely to give rise to problem characteristics of any "converted system". A lot of research is being carried out throughout the world to evaluate the performance, exhaust emission and combustion characteristics of the existing engines using several alternative fuels such as Hydrogen, Compressed Natural Gas (CNG), Alcohols (Methanol and Ethanol), LPG, Biogas, Producer gas, bio-diesel developed from vegetable oils and a host of others.

In recent years, there has been significant increase in the research into the use of bio-fuels as a substitute for mineral fuels. Dual fuel approach is a well-established technique to make use of different fuel in diesel engines. Dual fuel technology takes advantage of the inherent efficiencies of the compression stroke engines but with dramatically reduced consumption of diesel fuel (Banapurmath N R, 2009). This results in the engine that is more powerful than spark-ignited engines and with substantially better emission than diesel engines.

As the fuel of the future, the expert studies indicate the utilization of hydrogen for internal combustion engines. Hydrogen may become an important energy carries for sustained power consumption with reduced impact on the environment. It can be used in combustion devices or fuel cells without any carbon emissions and minimal emissions of other pollutant gases. When hydrogen is burned its combustion does not produce toxic products such as hydrocarbons, carbon monoxide, oxides of sulfur, organic acids or carbon dioxide, instead its main product is water. Like electricity, hydrogen is an energy carrier and must be produced from another substance. Hydrogen is not widely used today but it has a great potential as an energy carrier in the future.

SI engines are most suitable for hydrogen use but in recent time CI engines are also in the process of modifications to run with hydrogen (P K Bose and Majji D, 2009). Combustion triggering devices such as installation of glow plugs in the combustion chamber and preliminary addition of fuel to the combustion chamber through either pilot injection or a small leak are few solutions to the problem. After exhaustive tests on a research engine with various fuel induction techniques, (Das L M, 2002) concluded that timed manifold injection is the most pragmatic mode of hydrogen fueling. He reported decrease NO_X emission by five and half times, while other emissions increased by 1.4 times as compared with diesel fuel. Bose et.al, 2009 used timed manifold induction, which is electronically operated to induct hydrogen into the intake manifold. For the entire investigation the hydrogen flow rate had been kept at 0.15 kg/hr. NO_X emissions were seen to be high as diesel was substituted with hydrogen and attainment of high temperature. In order to reduce NO_X emission EGR (Exhaust Gas Recirculation) technique was used and lower particulate emissions as well as NO_X emissions were reported. Saravanan et.al, used hydrogen enriched air as a intake charge in a diesel engine adopting EGR technique with hydrogen flow rate maintained at 20 l/min. Usage of hydrogen in the dual fuel mode with EGR technique resulted in lower smoke level, particulate and NO_X emissions. The use of EGR is believed to be most effective in improving exhaust emission in hydrogen fuelled engines. Sarvanan et.al, injected hydrogen in the intake manifold and injected diesel fuel inside the engine cylinder in the conventional manner. Exhaust gas recirculation technique adopted to reduce the oxides of nitrogen emissions. From the result it was observed that for hydrogen diesel dual fuel (DF) engine, the optimal operating parameters of hydrogen injection were start of injection at a gas exchange top dead center with injection duration of 301 crank angle and hydrogen flow rate of 7.5 liters per minute. With EGR the optimized condition was found to be 20 % for the entire load. The break thermal efficiency with 20 % EGR increased by 16 % at 75% load a compared with diesel, while at a full load it reduced. Gaseous fuels can also be burned in compression ignition engines with gaseous fuel supplemented into intake air as dual fuel combustion mode (Sahoo B B et.al, 2009). When supplied into the intake air of diesel engines, a homogeneous gaseous fuel-air mixture is formed during the intake and early compression stroke. At the end of the compression stroke, a pilot of diesel fuel is injected into the hot gaseous fuel-air-diluents mixture and serves as an ignition source. Prior to the injection of pilot diesel fuel, gaseous fuels have been mixed well with air and heated through compression to high temperature, but not high enough to initiate the auto ignition process of the gaseous fuels. After being injected into the hot bulk mixture, the pilot diesel fuel is first atomized and then vaporized, mixed with the hot gases fuel-air mixture, ignited and burned through compression ignition. The energy released by diesel fuel combustion serves as an ignition source of the gaseous fuel. Several works focusing on the addition of hydrogen to CNG has been reported in the literature of (Banapurmath et.al, 2012). The reason for mixing natural gas with hydrogen is that natural gas has an advantage of producing hydrogen from reforming because of its high H/C ratio, and the utilization of its infrastructure (including charging dispenser) is easy. Hydrogen can extend the flammability limit of natural gas because it burns quickly and has a short quenching distance. Gatts et.al, 2012 performed experiments on a heavy duty diesel engine supplementary by hydrogen and natural gas and concluded that engine load was the dominant factor in determining the amount of gaseous fuels to be admitted in intake manifold. It was also concluded that when NG and hydrogen was added in large quantities combustion efficiencies were comparable but CH_4 of the NG dual fuel engine reported lower combustion efficiency due to CO emission which were accounted as the incomplete combustion products of CH_4. In some regards, HCCI combustion incorporates the advantage of both spark ignition (SI) engines and compression ignition (CI) engines. The lean homogeneous fuel /air mixture is essentially inducted into the cylinder without throttling losses and then compressed to autoignition which occur simultaneously through the cylinder without discernable flame propagation. These features lead to very low NO_x and smoke emissions while maintaining high thermal efficiency. Homogeneous charge compression ignition (HCCI) engine technology is relatively new and has not matured sufficiently to be commercialized compared with conventional engines. It can use spark ignition (SI) or compression ignition (CI) engine configurations, capitalizing on the advantages of both: high engine efficiency with low emissions levels. The HCCI engines can use a wide range of fuels with low emissions levels. Due to these advantages, the HCCI engines are suitable to be used in a hybrid engine configuration, where it can reduce the fuel consumption even further. However, the HCCI engines have some disadvantages such as knocking and low to medium operating load range, which need to be resolved before the engine can be commercialized. Therefore, a comprehensive study has to be performed to understand the behavior of HCCI engines. Homogeneous charge compression ignition (HCCI), combines characteristics of both spark ignition (SI) and compression ignition (CI) engines and recognized as the most promising way of achieving high thermal efficiency and low nitric oxides (NO_x) emissions [4].Ryan et. al., applied homogeneous mixture preparation technique and used port injection of diesel into the intake air stream. An intake air heater was installed upstream of fuel injector to preheat the air. This concept of external mixture preparation was further developed by Gray et.al. And they identified two key operational issues with this technique. The first issue was the requirement of high temperature for successful achieving diesel HCCI combustion and to avoid accumulation of diesel in the intake manifold because of poor vaporization characteristics. The second issue was emission of very high unburnt HC. However, they reported reduction in emission of NO_x.

II. PROPERTIES OF FUELS USED

The properties of CNG, Hydrogen, and HnOME were determined and summarized in Tables. These properties were measured in the fuel testing laboratory.

Transesterification of Honne oil (HnOME)

There are three stages are involved in transesterification of Honne oil. The acid esterfication and alkali esterfication stages are required for production of HnOME. Following steps explain an optimized method of production of HnOME.

1) First Stage: 2000 ml of raw Honne oil is heated up to 105°C in a round bottom flask in order to remove moisture content. Then the oil sample is titrated against NaOH solutions to calculate Free Fatty Acid (FFA). The FFA content was found to be 8 %.

2) Second Stage: Next, 1000 ml of moisture-free Honne oil is heated up to 60 °C. Then, 150 ml of methanol and 1.5 ml sulphuric acid are added to the oil. The resulting solution is stirred vigorously with magnetic stirrer at 450 rpm for one hour. The resulting solution is allowed to settle for eight hours. Then, the top layer of acid content is removed. Residue oil is tested for FFA. It is found to be 5.6%. Since it contains high FFA, the above procedure was repeated. Finally, the residue oil content showed 2.8% FFA.

3) Third Stage: Now, the residue oil is heated to 60 °C. A mixture of 100 ml methanol and 7.6 grams of NaOH are added to the residue oil. The resulting mixture is maintained at that temperature and stirred at 450 rpm. After 90 minutes, the mixture is transferred to separating funnel for settling under gravity as shown in Figure 1. After eight hours, heavier part of glycerin is separated out to obtain methyl ester of Honne Oil which is further washed with water for 3 or 4 times as shown in Figure 1.with a solution containing 10ml of acetic acid and hot water to remove moisture and other sediments to obtain clean Honne Oil Methyl Ester (HnOME). The biodiesel yield per 1000 ml oil was found to be 890 ml or 89%.The properties of HnOME were determined using Bureau of Indian Standards (BIS) in the college laboratory and are summarized in Table 3.

Fig. 1 Biodiesel Preparation

The properties of gaseous fuels CNG and Hydrogen are shown in Table 1 and 2 respectively.

Table1.Properties of Compressed Natural Gas

Properties	Natural Gas
Boiling range (K @101325Pa)	147
Density (kg/m³) at 1 atm. & 15^0 C	0.77
Flash Point (K)	124
Octane Number	130
Flammability Limits Range Rich Lean	 0.5873 1.9695
Flame Speed (cm/s)	33.80
Net Energy Content (MJ/kg)	49.5
Auto Ignition Temperature (K)	923 (650^{0}C)
Combustion Energy (KJ/m³)	24.6
Vaporization energy (MJ/m³)	215 – 276
Stoichiometric A/F (kg of air/kg of fuel)	17

Table2. Properties of Hydrogen

Properties	Hydrogen
Density at 1 atm and 300 K (kg/m^3)	0.082
Stoichiometric composition of air (% by Volume)	29.53
Stoichiometric fuel air mass ratio	0.029
No. of moles after combustion to before	0.85
Higher heating value (MJ/kg)	141.4
Lower heating value (MJ/kg)	1119.7
Higher heating value (MJ/m^3)	12.10
Lower heating value (MJ/m^3)	10.22
Combustion energy per kg of Stoichiometric mixture (MJ)	3.37
Kinematic viscosity at 300K (mm^2/sec)	110
Thermal conductivity at 300K (mW/ mK)	182
Diffusion coefficient in to air at NTP (cm^2 /sec)	0.61
Flammability limits (%by Volume)	4-75
Minimum Ignition energy (mJ)	0.02
Laminar Flame Speed at NTP (m/s)	1.90
Adiabatic Flame Temperature (K)	2318

The properties of Diesel, Honne oil are given in Table 3

Table 3.Properties of Diesel, Honne oil, Honne oil methyl ester

Sl. No.	Properties	Diesel	Honne seed oil	HnOME
1	Chemical Formula	$C_{13}H_{24}$	----	----
2	Density (kg/m^3)	840	910	880
3	Calorific value (kJ/kg)	43,000	39100	39798
4	Viscosity at 40^{o}C (cSt)	2-5	32.48	4.5
5	Flashpoint (^{o}C)	75	228	187.5
6	Cetane Number	45-55	51	
7	Carbon Residue (%)	0.1	0.01	0.01
8	Cloud point	-2	-2.5	-1

	(°C)			
9	Pour point (°C)	-5	-0.8	-8
11	Molecular weight (kg/kg mole)	181	--	--

Experimental investigations were conducted on a four-stroke single cylinder direct injection water cooled compression ignition engine operated on different fuel combinations such as Hydrogen, Natural gas and HnOME combinations. The experimental set up for CNG and Hydrogen in HCCI mode is shown in Fig.2. The specification of the engine is given in table 4.The engine was always operated on rated speed of 1500 rpm. The engine is incorporated with HPCRI (High pressure common rail injection) which is meant for achieving high injection pressures of 600, 800, 1000 bar and its specifications are given in Table 5. The gaseous fuels are inducted into the inlet manifold by means of a suitable carburetor with best injection timing and it is controlled by Electronic control unit (ECU). The injection timing for biodiesel is maintained at 19^0 before top dead center (bTDC) whereas 23^o bTDC for Diesel. To achieve HCCI mode of operation inlet air heating technique were used and heater controller which controls the inlet air heating and it is maintained at 80^o C. The flow rate for CNG and Hydrogen were kept constant at 9 and 10 LPM respectively. For dual fuel combination the engine run smoothly up to 80% of load and for full load condition the engine knocking was high and hence readings are not reported. Exhaust gas analyzer and Hartridge smoke meter were used in order to measure HC, NO_X, CO and smoke emissions. The flow rate of gaseous fuel is measured by means of a gas flow meter.

Fig. 2 Overall view of engine test rig with HCCI arrangement

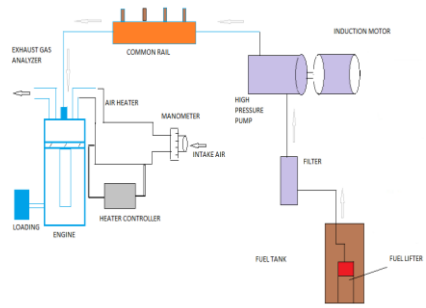

Fig. 3 Schematic representation of the experimental set up used to collect HCCI data

Table4. Specifications of the Engine test rig.

Make and Model	Kirloskar, TV1
No of Cylinders	One
Orientation	Vertical
Cycle	4 stroke
Ignition system	Compression ignition
Bore× Stroke	87.5mm×110mm
Displacement volume	660cc
Compression ratio	17.5:1
Arrangement of valves	Overhead
Combustion chamber	Open chamber(Direct ignition)
Rated power	5.2 Kw (7 HP) @ 1500rpm
Cooling medium	Water cooled

Table5. Specifications of HPCRI

No of holes	1
Diameter of the nozzle	0.201
Angle of injector hole	Parallel to head
Injection pressure	1000 bar

III. RESULTS AND DISCUSSIONS

This section discusses the results and discussions of the experiments carried out on HCCI mode using HnOME+H_2, HnOME+CNG fuel combinations. For a given load three readings were taken and only averaged values are presented in the graph.

Break Thermal Efficiency

Fig 4 depicts the comparison of BTE with different combination of fuels and mode of engine operations such as HnOME with H_2 and CNG in HCCI mode of operation and HnOME and Diesel in CI Mode of operation with different injection pressures such as 600,800 and 1000 bar. From the results we found that HnOME and H_2 HCCI mode of operation yields good results compare with HnOME and CNG HCCI operation. Break thermal efficiency of HnOME biodiesel in HCCI mode of engine operation is comparatively higher than HnOME biodiesel in CI mode of engine operation. The maximum injection pressure is limited to 1000 bar due to hardware constraints of the engine

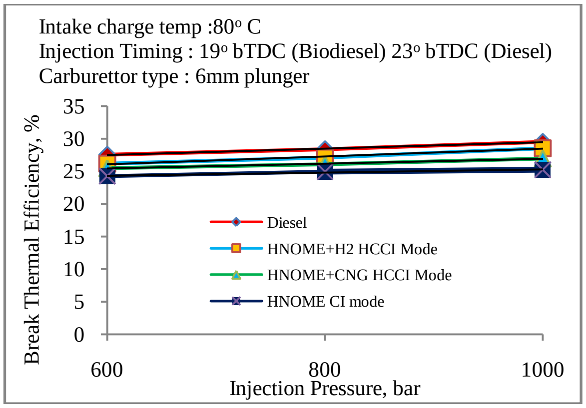

Fig. 4 Variation of BTE with Injection pressure

Hydrocarbon Emissions

Fig 5 depicts HC emissions comparison with different combination of fuels and is observed that HC emissions were higher in HCCI mode of operation compare with CI Mode of operations. HC emissions of HnOME and H_2 HCCI mode of operation are slightly higher than the HNOME and CNG HCCI mode of operation. From the results it is observed that the HC emissions of HnOME CI mode of operation are higher than the Diesel CI mode of operation.

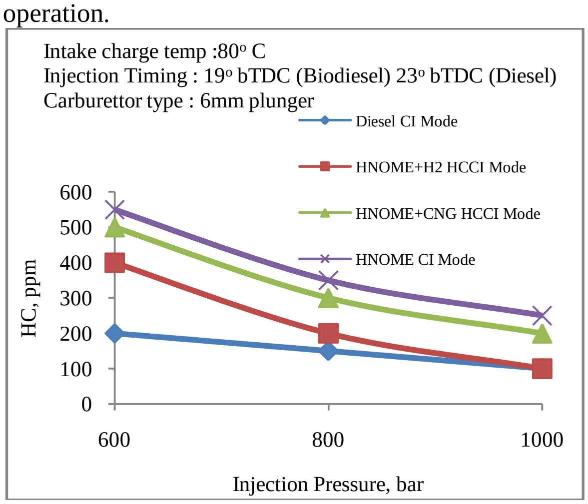

Fig. 5 Variation HC with Injection pressure

CO emissions

Fig 6 depicts CO emissions with different combination of fuels and is observed that HC emissions were higher in HCCI mode of operation compare with CI Mode of operations. CO emissions of HnOME and H_2 HCCI mode of operation is slightly lower than the HnOME and CNG HCCI mode of operation. From the results it is observed that the CO emissions of HnOME CI mode of operation are higher than the Diesel CI mode of operation.

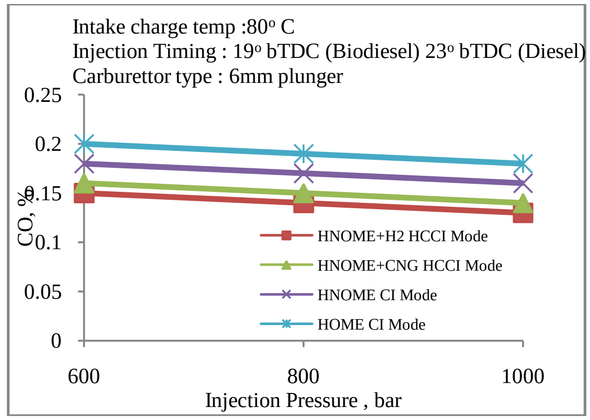

Fig. 6 Variation CO with Injection pressure

NO_X emissions

Figure 7 depicts NO_x emission variations in different modes of engine operation. In CI mode, the NO_x is formed in very hot zones closer to stoichiometric conditions and soot is formed in the fuel rich regions and hence higher NO_x emission as reported in the literature [15]. But since HCCI mode ensures homogeneous mixing of fuel and air before combustion, the in-cylinder temperature achieved is low as compared to CI mode and hence NO_x emission significantly reduces. Even at elevated temperatures, the NO_x emissions are too low in the HCCI mode. The HCCI operation results in less than 20 to 30 ppm of NO_x emissions always. This is a very significant advantage of HCCI engines.

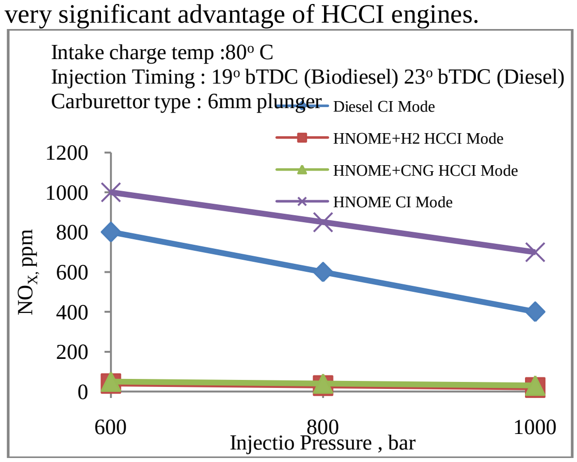

Fig. 7 Variation NO_X with Injection pressure

Smoke opacity

Fig 8 depicts variation of smoke opacity with different injection pressures. As injection pressure increases results in complete combustion in both HCCI and CI Mode of operation. As expected, the lower smoke levels are seen in HCCI mode due to the homogeneous nature of charge. HnOME being common in HCCI modes of operation apart from CNG and H_2 induction the higher injection pressure used in the latter process ensures uniform mixture of air and fuel injected in spite of higher viscosity of UOME (being twice diesel) used.

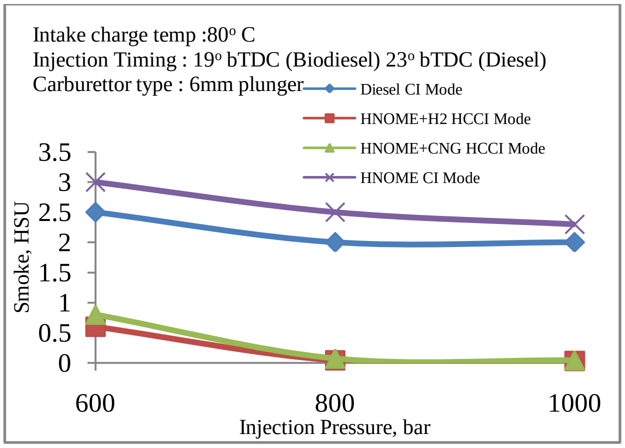

Fig. 8 Variation Smoke with Injection pressure

Cylinder pressure

Fig 9 depicts the variation of cylinder peak pressure with crank angle for different modes of engine operation at BMEP of 3.58 bar. It is observed that the cylinder peak pressure will be maximum in HCCI Mode compared to CI mode while the peak pressure will be lower in case of dual-fuel mode of operation.

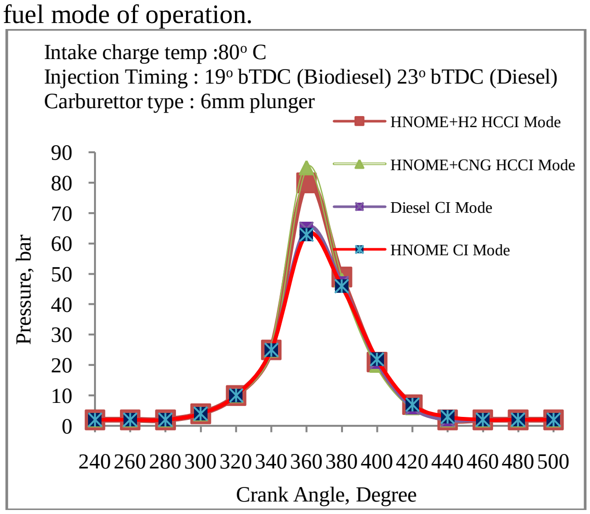

Fig. 9 Variation Cylinder peak pressure with Crank angle

CONCLUSION

Based on the comprehensive experimentation carried out on HnOME-H_2 and HnOME-CNG HCCI modes of operations with optimized engine parameters the following conclusions were made:

1. The performance of the single fuel operation in terms of higher BTE than the two fuel combination of HCCI modes of engine operations considered.
2. It is observed that the HnOME-H_2 HCCI operation in terms of higher BTE than HnOME-CNG operation.
3. Though HCCI performs inferior to single mode of operations but it can effectively reduces NO_x and smoke emissions which are a major problem with CI engines.
4. In HCCI mode of operation, the NO_x and smoke emissions decreased by about 98%, 94% respectively when compared to single fuel operation.
5. HCCI modes of operation could run smoothly up to 80 % load and for full load operation the engine knocking was high and hence reading were not reported for full load conditions.
6. The maximum injection pressure is limited to 1000 bar due to hardware constraints of the engine.

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