Universal Journal of Renewable Energy **2 (2014), 32-44**
www.papersciences.com

Performance, Emission Characteristics of Dual Fuel (DF) & Homogeneous Charge Compression Ignition (HCCI) Engines Operated on Compressed Natural Gas (CNG) – Uppage Oil Methylester (UOME)

N.R. Banapurmath[1], B.M. Dodamani[2], S.V. Khandal[3], S.S. Hiremath[4], V.B. Math[5]
[1,2,3]Department of Mechanical Engineering,
B. V. B. College of Engineering and Technology, Hubli, India
[4,5]Basaveshwar Engineering College, Bagalkot, India
nr_banapurmath@rediffmail.com

Abstract
The greenhouse effect is a worldwide issue as more and more greenhouse gases are released into the atmosphere leading to global climate change. The effects include an increase in temperature unstable weather and an increase in ocean levels resulting in ice melting in the North and South Poles. By the present research the existing diesel engine was suitably modified to operate in dual and HCCI modes. The experimental investigations were carried out on a single cylinder four stroke compression ignition (CI) engine fuelled with diesel in single fuel mode and CNG and UOME in DF and HCCI operation modes. The CNG was inducted into the inlet manifold along with air using a suitable carburetor. From the results obtained, it is observed that DF mode of operation performed poorer compared to conventional single fuel mode of operation but lower smoke, carbon monoxide (CO), hydrocarbon (HC), NO_x emissions were resulted. The HCCI engine yielded better results in terms of higher break thermal efficiency (BTE) than DF mode of operation and lower than conventional CI mode. Further emissions such as CO, NO_x and smoke emissions were lower with higher HC emission. The NO_x and smoke emissions were decreased by about 98% and 94%respectively.

Key Word and Phrases
HCCI, UOME, CNG, ECU, Emissions.

1. Introduction

Internal Combustion engines are widely used in numerous applications such as transport vehicles, power generation, ships etc. The emissions generated from these applications have a high impact on the environment, the solution have investigated to achieve low emission levels due to strict emission regulations imposed by the regulatory bodies [1]-[3]. For more than a century, hydrocarbon fuels have played a leading role in propulsion and power generation. In recent years, declining oil reserves and increased fuel prices together with increased awareness of the environmental impacts of burning hydrocarbon fuels led to an interest in alternatives to fossil fuel based propulsion and power generation. One such alternative is to use CNG as an energy carrier some CNG production technologies are well mature and well-developed. Still a number of concerns over the conversion technologies need to be addressed in relation to power to weight ratio, price, reliability, storage and transportation as well.

The petroleum resources are finite and therefore search for their alternative non-petroleum fuels for internal combustion engines is continuing all over the world, has been reported in literature [4]. The use of CNG as an alternative fuel has far-reaching environmental and economic implications. It can be used either as a sole fuel in spark ignition engine or can be dual fuelled with liquid fuels in CI engines. DF engines have drawn a considerable research attention in the area of alternate fuels. The two main advantages of this concept are as follows: i) no major modifications are required in the existing engine and ii) there is a flexibility of engine operation to switch back to the diesel mode of operation as and when need arise. DF combustion system utilizing combination of diesel and NG fuels has been investigated in recent years [5]. From the literature survey, follows that no significant study has been done with CNG–biodiesel DF engines. Different methods of CNG utilization in diesel engines have been reported in the literature of Heywood [6]. The high NO_x emission in the conventional and DF engines has prompted to search for new combustion technologies such as HCCI and reactivity controlled compression ignition (RCCI) Engines. HCCI combustion incorporates the advantage of both spark ignition (SI) engines and CI engines. The lean homogeneous fuel /air mixture is essentially inducted into the cylinder without throttling losses and then compressed to auto ignition which occurs simultaneously throughout the cylinder charge without discernable flame propagation. These features lead to very low NO_x and smoke emissions while maintaining high thermal efficiency. HCCI engine technology has not matured sufficiently to commercialize compared with conventional engines. It can use SI or 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. HCCI, combines characteristics of both SI and CI engines and recognized as the most promising way of achieving high thermal efficiency and low NO_x emission [7]-[13]. After successful achieving HCCI combustion in gasoline engines, research were directed towards attaining diesel HCCI in the year 1990s. Early fuel injection and late fuel injection strategies were attempted for obtaining diesel HCCI however these techniques resulted in poor mixture quality inferior combustion. Some basic problems related to design and operational parameters related to diesel HCCI were evaluated by Suyin *et.al.*,[14]. They used in-cylinder mixture preparation technique and performed various experiments with varying operational conditions such as different injection strategies, injection pressure, injection timing, intake air temperature, etc. along with varying design parameters such as piston geometries, compression ratio, swirl etc. It was concluded that the possibility of attaining diesel HCCI combustion exists with various limitations but the main challenge was low volatility of diesel.

For resolving this issue external mixture preparation were developed, in which fuel was injected into the intake manifold and mixed with hot air to obtain premixed homogeneous charge. Ryan *et. al.,* [15] used port injection of diesel into the intake air stream to get homogeneous mixture and 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.*,[16] and they identified two key operational issues, the first issue was the requirement of high temperature for achieving diesel HCCI combustion and to avoid accumulation of diesel in the intake manifold as it has poor vaporization characteristics and the second issue was emission of very high unburnt HC (UHC).

However, they reported reduction in emission of $NO_{x.}$ Similar experiments were carried out by Maurya *et.al.,* [17] using gasoline, various primary alcohols and their blends with gasoline and external mixture preparation method was successfully implemented for a high compression ratio (16.5) engine. Nakagome *et. al.*, [18], Roy *et.al.,* [19] explored the possibility of using methods for combustible mixture formation outside of the intake manifold. Shawn *et. al.,* [20] atomized the fuel and mixed with air to prepare a homogeneous mixture in a diesel atomizer. They investigated the effect of various parameters such as exhaust gas recirculation (EGR), air fuel ratio, intake air temperature, engine speed on HCCI combustion. It was found that EGR is the most promising solution that can control the formation of NO_x and same is also reported byAgarwal*et.al.*,[21].

In contrary, HCCI combustion was achieved by controlling the temperature, pressure and composition of the lean homogeneous air fuel mixture so that it auto ignites at multiple spots and subsequently reacts homogeneously as it is compressed during upward piston movement. For neat HCCI combustion, the heat release reaction has to be distributed throughout the combustion chamber without flame propagation and local high temperature zones or rich fuel zones as reported by Lu *et. al.*,[22]. Thus it was found that uniform mixture and average low temperature limit the production of NO_x. In this combustion mode, the mixture temperature was the most important parameter, and it played a significant role in the determining combustion characteristics and emission for several reasons. First the high temperature chemical reaction or self ignition occurred only if the mixture temperature exceeded the auto-ignition threshold. Finally, the maximum temperature should be kept lower than the critical temperature of NO_x formation.

In recent years, there has been substantial increase in research using biodiesel as a substitute for diesel along with a gaseous fuel in DF engines. DF approach is well established method to make use of different types of fuels in diesel engines and it takes the advantage of intrinsic efficiencies of the compression stroke with dramatically reduced consumption of diesel fuel as reported by Banapurmath and Tewari [23]. This results in an engine which is more powerful than a dedicated spark-ignited engine and with considerably better emissions than a dedicated diesel engine. Jie Liu *et.al.*,[24] studied the CNG/diesel fuel engines with pilot fuel quantity and injection timing and reported the DF mode reduced NO_x emission by 30% in comparison to diesel mode.

The CO emission level under DF mode was considerably higher than normal diesel operation even at high load. The UHC emission under DF mode were obviously higher than that of normal diesel mode of operation, especially at low to medium loads and around 90% of total HC (THC) emissions were unburned methane, it means the flame does not propagate throughout the charge. THC emission reduced significantly with the increase of pilot diesel quantity. Shuaiying Ma *et. al.,*[25] conducted experiments on modified single cylinder diesel engine to work on gasoline/diesel DF mode to study the effect of diesel injection strategies on the combustion, emission, fuel economy and the operation range and reported that this combustion mode has the capability of achieving high efficiency with near zero NO_x.

The objective of the present work was to modify the existing diesel engine to operate in both DF and HCCI modes. It also aims to compare the performance of DF engine with HCCI engine operated on both non-renewable and alternative fuels.

2. Properties of Fuels Used

The properties of CNG, UOME were determined and summarized in Tables 1 and 2 respectively. These properties were measured in the fuel testing laboratory of the college.

Uppage Biodiesel

Amongst the many species, which can yield oil as a source of energy in the form of bio-fuel, “Garciniacambogia” (Uppage) has been found to be one of the most suitable species in India being grown; it is N_2-fixing trace. It is tolerant to water logging, saline and alkaline soils, it is grown in high rainfall region. Garcinia seeds contain 30 to 40% oil. Garciniacambogia belongs to the family species. The tree grows in forest and isa preferred species for controlling soil erosion and binding soil to roots because of its dense network of lateral roots.

These seeds largely exploited for extraction oil which is well known for its medicinal properties. So far there is no systematic organized collection of seeds. Mixture seeds consist of 95% kernel and are reported to contain about 27 to 40% oil. The yield of oil is about 35 to 40% if mechanical expellers are used for the recovery of oil from the kernels. The crude oil is brown to creamy in color, which deepens on standing. It has a bitter taste and disagreeable odour.

(a)Uppage Tree	(b)Uppage Fruits	(c) Uppage seeds

Fig.1 Uppage biomass

Transesterification of Uppage Oil

Fig. 2 shows the transesterification process in which the upper layer forms the ester and lower layer forms the glycerol as reported in literature [26]. The parameter such as temperature, molar ratio and catalyst concentration that affect the transesterification of UO were optimized initially. The transesterification set up is of 2 liter Capacity, round bottom flask provided with three necks that was placed in a water container for heating the oil. A heater with a temperature regulator was placed in the round bottom flask. A high speed motor with a magnetic stirrer was used for vigorous mixing of the oil. In the transesterification process triglycerides of UO reacts with methyl alcohol in the presence of catalyst (NAOH/KOH) to produce a fatty acid ester and glycerol. In this process 1000 grams UO, 230 grams methanol (MERC brand) and 8 grams sodium hydroxide pellets were placed in the round bottom flask. Then the mixture was heated to 70^{o}C and stirred vigorously for one hour to promote ester formation.

The mixture was next transferred to a separating funnel and allowed to settle under gravity overnight. The upper layer in the separating funnel consists of ester whist the lower layer is glycerol which was removed. The separated ester was mixed with 250 gram of hot water and allowed to settle under gravity for 24 hours. The water washing separates residual fatty acids and catalyst and these were removed using a separating funnel. Finally the moisture from the ester was removed by adding silica gel crystals. The properties of UO and UOME blends were determined using Bureau of Indian Standards (BIS) in the college laboratory and are summarized in Table 2.

(a) 3-Neck conical glass bottle for transesterification | (b) Separation of Glycerin | (c) Washing with hot water

Fig. 2 Biodiesel preparation

Table 1 Properties of CNG

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 (650^0C)
Combustion Energy (KJ/m³)	24.6
Vaporization energy (MJ/m³)	215 – 276
Stoichiometric A/F (kg of air/kg of fuel)	17

Table 2 Properties of Diesel, UO and UOME

Sl. No.	Properties	Diesel	Uppage oil	UOME
1	Viscosity @40^{o}C (cst)	4.59	44850	5.6
2	Flash point ^{o}C	56	270	163
3	Calorific value in kJ/kg	45000	35800	36010
4	Density kg/m^3	830	915	890

1. Experimental Engine Setup

A four stroke single cylinder direct injection water cooled CI engine whose specification is given in Table 3 was modified to operate in both DF and HCCI modes of operation. The engine was operated using different fuel combinations of UOME and CNG in DF and HCCI modes using an appropriate carburetor. In DF mode UOME was injected at 27^0bTDC. The intake charge temperature of 50^0C was maintained by means of air preheat controller. The schematic representation of experimental set up is shown in Figs.3 and 4.

The engine was operated at 60%, 80% and 100% loads. For DF combination the engine 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. Exhaust gas analyzer and Bosch smoke meter were used to measure HC, CO, NO_x and smoke emissions. Stoichiometric air to gas (CNG) ratio of 17:1 was maintained which can be varied from 15:1 to 18:1.

Fig.3 Overall view of engine test rig with dual fuel arrangement

Fig. 4: Overall view of engine test rig with HCCI arrangement

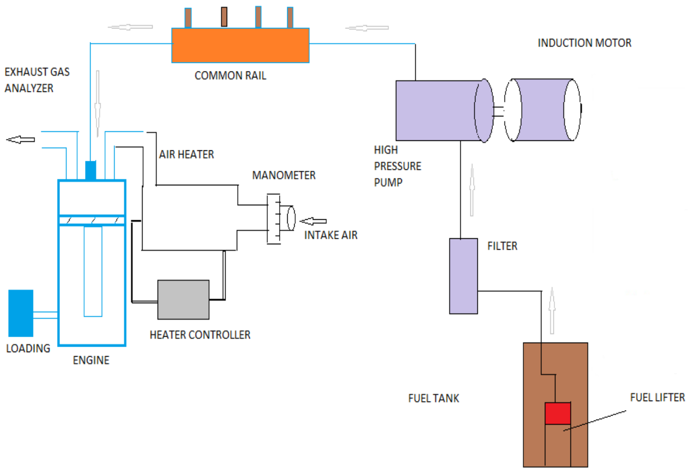

Fig.5 Schematic representation of the experimental set up used to collect HCCI data

Table 3 Specification of Engine

Make and Model	Kirloskar, TV1
Number of Cylinders	One
Orientation	Vertical
Cycle	4 stroke
Ignition system	Compression ignition
Bore x 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

The HCCI mode uses high pressure common rail direct injection system (HPCRDIS)to inject the fuel at high pressure and the maximum injection pressure was limited to 1000 bar due to hardware constraints of the engine. The specification of HPCRDIS is given in Table 4.

Table 4 Specification of HPCRDIS

Number of holes	1
Diameter of the nozzle	0.201 mm
Angle of injector hole	Parallel to head
Injection pressure	1000 bar

4. Results and Discussion

This section discusses the results of the experiments carried out on modified CI engine in DF and HCCI modes using UOME and CNG fuels. For a given load three readings were taken and averaged values are presented in the graph.

4.1 Brake Thermal Efficiency

Fig. 6 compares the BTE of HCCI and DF modes of engine operation with the diesel in single fuel operation at different BMEPs. In the DF mode, the BTE always dropped when CNG was added because of reduced volumetric efficiency. The BTE of HCCI as well as the DF mode was lower than that of conventional single fuel diesel operation and similar results were reported in literature (16,27) but the BTE of HCCI engine operation was slightly better than that of DF mode due to higher heat release rates.

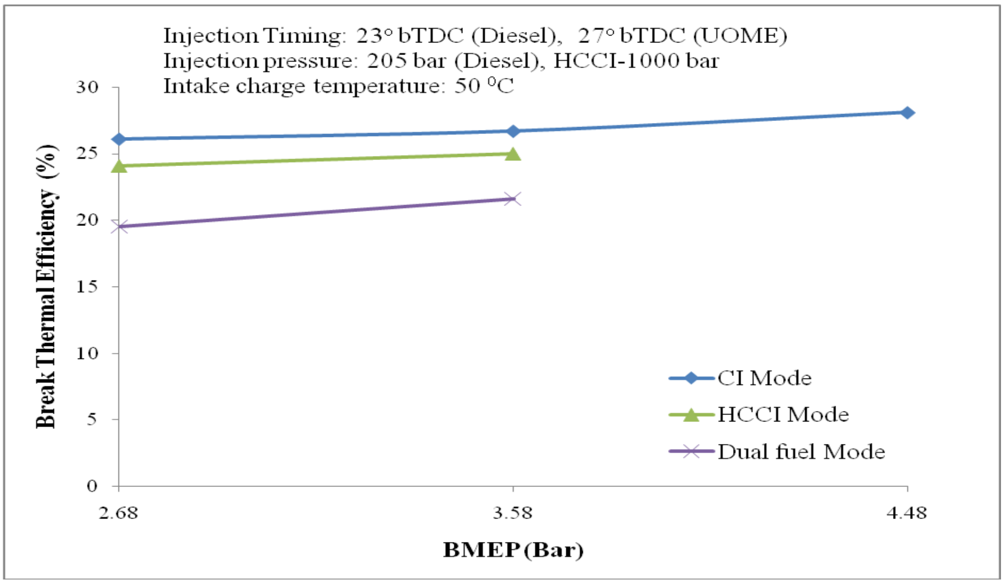

Fig.6 Variation of BTE with BMEP

4.2 Hydrocarbon Emission

HC emission in the exhaust gas is largely due to incomplete combustion of fuel. The HC emission is higher in HCCI mode due to the homogeneous mixture trapped in crevice volumes and stagnant layers close to the cylinder walls. In the HCCI mode, entire cylinder volume is of homogeneous mixture of fuel and air and the combustion temperature is lower and hence higher HC emission was observed compared to CI mode. Another reason for high HC emission could be injection of fuel early in the compression stroke when the temperature and pressure in the cylinder were low as revealed in the literature [28], [29]. Higher charge temperature could have lowered the HC level in the DF mode compared to CI mode.

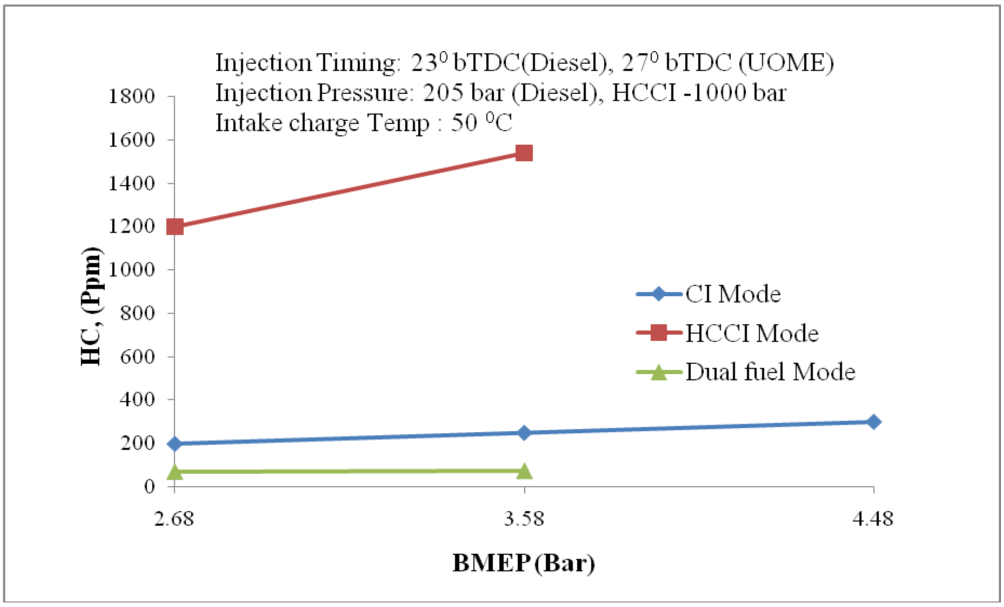

Fig.7 Variation of HC with BMEP

4.3 CO Emission

The CO emission level in the exhaust gas is higher in HCCI mode and DF mode than conventional single fuel mode of operation due to lower peak combustion temperature, combustion product CO cannot be fully oxidized in to CO_2 as shown in Fig. 8. Higher CO emission is one of the major drawbacks of HCCI combustion. Levels of CO emission increased with increase in BMEP due to relatively higher combustion temperature and higher amount of fuel injected into the cylinder.

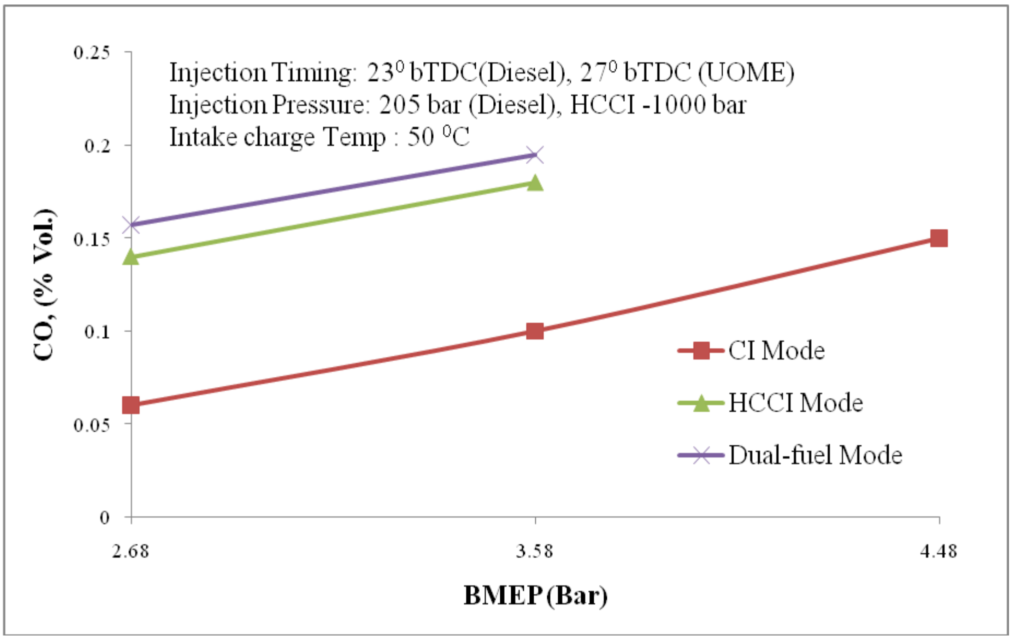

Fig.8 Variation of CO with BMEP

4.4 NO_X Emission

Fig. 9 shows NO_x emission variation in different modes of engine operation. High combustion temperature and nitrogen present in the atmospheric air are the two favorable conditions, which leads to NO_X formation. In CI mode, the NO_x was formed in very hot zones closer to stoichiometric conditions and soot was formed in the fuel rich regions as reported in literature [30]. Since HCCI mode ensures homogeneous mixing of fuel and air before combustion and the in-cylinder temperature achieved was low as compared to CI mode and hence NO_x emission was significantly reduced and similar results were reported by [31].

Even at elevated temperatures, the NO_x emission was too low in the HCCI mode. In the DF mode, it was high even at a lower charge temperature due to the non-uniform distribution of biodiesel and further increased with increase in load compared to HCCI mode but these values were very less compared to CI mode which was also revealed by [4],[33].The HCCI operation resulted in less than 30 ppm of NO_x emission always.

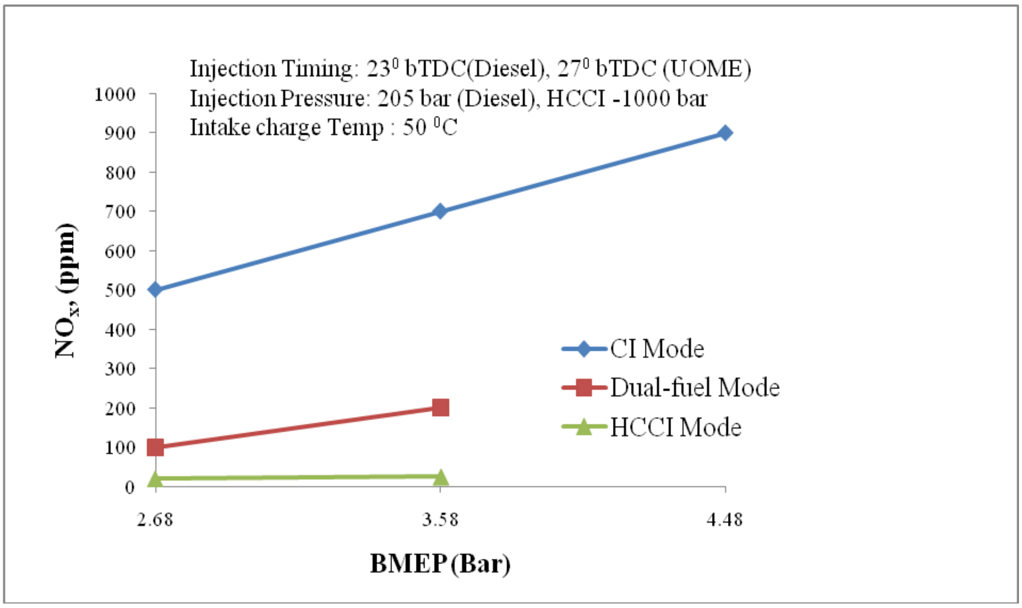

Fig.9 Variation of nitric oxide with BMEP

4.5 Smoke Opacity

Fig. 10 depicts the smoke opacity at different loads. As expected, the lower smoke levels were seen in HCCI mode due to the homogeneous nature of charge and this is contributed purely by the injected UOME. UOME being common in DF and HCCI modes of operation apart from CNG induction, the higher injection pressure in the latter process ensured uniform mixture of air and fuel injected in spite of higher viscosity of UOME (being twice diesel) and hence smoke opacity was less in HCCI mode compared to DF mode due to the absence of very high temperature zones, diffusion combustion and localized fuel rich pockets and similar outcomes were reported in literature [33].

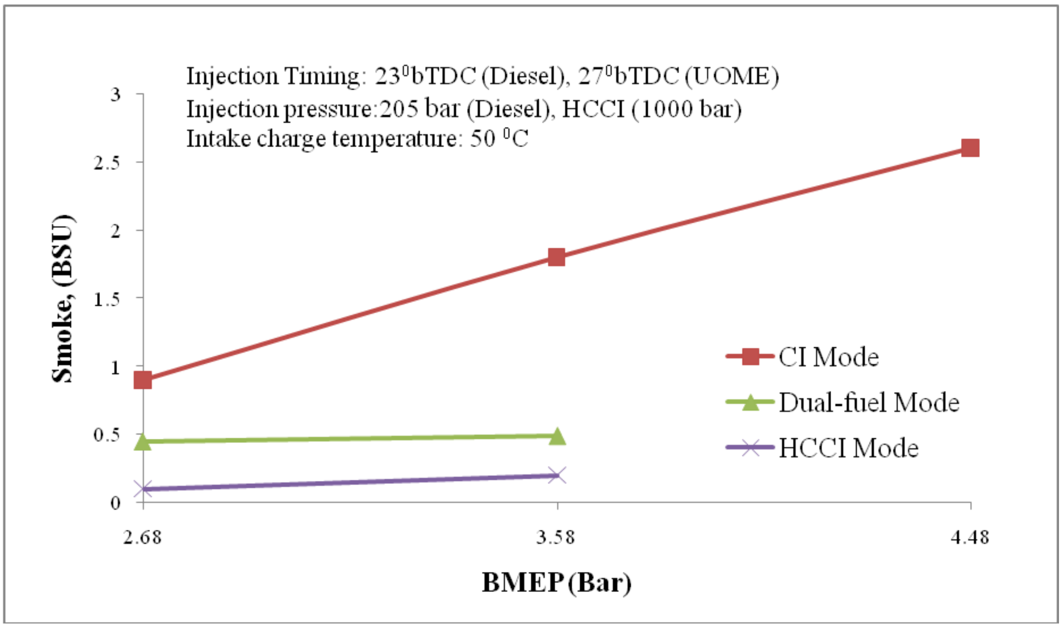

Fig.10 Variation of smoke opacity with BMEP

4.6 Cylinder Peak Pressure

The variations of heat release rate during combustion affect the in- cylinder peak pressure and temperature. Fig. 11 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 was lesser in HCCI Mode compared to other modes studied and similar results were also reported in the literature [12], [32].

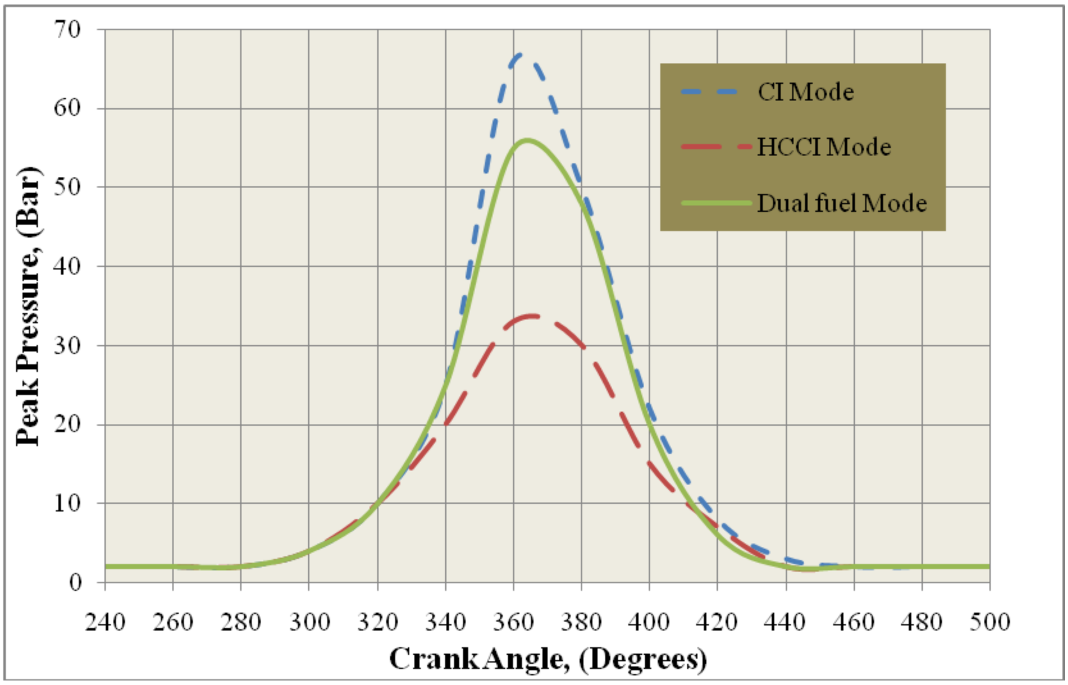

Fig.11 Variation of Cylinder peak pressure with Crank angle

5. Conclusions

Based on the comprehensive experimentation carried out on modified single cylinder water cooled four stroke CI engine fuelled with CNG-UOME in DF and HCCI modes of operation with optimized engine parameters the following conclusions were made:

a. The performance of the single fuel operation in terms of BTE was better than the two modes of engine operation considered i. e., DF and HCCI modes.
b. DF mode of operation results in inferior performance compared to single and HCCI mode of operation. However, lower smoke and NO_X were observed with DF mode of operation compare to conventional mode of operation.
c. Though HCCI performs inferior to single mode of operations but it effectively reduced NO_x and smoke emissions which are a major problem with CI engine.
d. In HCCI mode of operation, the NO_x and smoke emissions decreased by about 98%and 94% respectively when compared to single fuel operation
e. The BTE in HCCI mode decreased by about 12-14 % in comparison with single fuel operation.
f. DF and HCCI modes of operation could run smoothly up to 80 % load and for full load operation the engine knocking was high.

References

1. *EPA*, 'Control of air pollution from new motor vehicles: tier 2 motor vehicle emissions standards and gasoline sulfur control requirements', *United States: U.S. Environmental Protection Agency. 2000.*

2. *Popp D,* 'International innovation and diffusion of air pollution control technologies: The effects of NO_x and SO_2 regulation in the U.S., Japan, and Germany', *Cambridge: National Bureau of Economic Research. 2004.*
3. *Wesselink LG, Buijsman E, Annema JA,* 'The impact of Euro 5: facts and figures', *The Netherlands. 2006.*
4. *Papagiannakis, R.G. and Hountalas, D.T,* 'Experimental investigation concerning the effect of natural gas percentage on performance and emissions of a DI dual fuel engine', *Journal of Applied Thermal Engineering, **23** (2003), 353–356.*
5. *Balasubramanian, V, Sridhara, K. and Ganesan, V,* 'Performance evaluation of a small agricultural engine operated on dual fuel (diesel and natural gas) system', *SAE paper no. 951777, 1995.*
6. *Heywood, J.B,* 'Internal combustion engine fundamentals', New York, McGraw Hill,. *1988.*
7. *Onishi S, Jo S, Shoda K, Jo P, Kato S,* 'Active thermo-atmosphere combustion (ATAC)-A new combustion process for internal combustion engines', *SAE paper no.79050, 1979.*
8. *Saravanan N, Nagarajan G.,* 'An experimental investigation on hydrogen fuel injection in intake port and manifold with different EGR rates', *Energy Environ, **1**(2010), 221–48.*
9. *Mack JH, Aceves SM, Dibble RW,* 'Demonstrating direct use of wet ethanol in a homogeneous charge compression ignition (HCCI) engine', *Energy, **34** (2009), 782–7.*
10. *Aceves S, Flowers D,* 'Engine shows diesel efficiency without the emissions'. *Sci Technol Rev, (2004) 17–9..*
11. *Christensen M, Johansson B, Einewall P,* 'Homogeneous charge compression ignition (HCCI) using iso-octane, ethanol and natural gas – a comparison with spark ignition operation',. *SAE Paper 971676. 1997.*
12. *Nathan SS, Mallikarjuna JM, Ramesh A,* 'An experimental study of the biogas-diesel HCCI mode of engine operation', *Energy Convers Manag, **51** (2010), 1347–53.*
13. *Mohamed Ibrahim M, Ramesh A,* 'Experimental investigations on a hydrogen diesel homogeneous charge compression ignition engine with exhaust gas recirculation', *International Journal of Hydrogen Energy, **38** (2013), 16-25.*
14. *Suyin,G, Hoon,K.N., & Kar,M.P.,* 'Homogeneous charge compression ignition (HCCI) combustion: Implementation and effects on pollutants in direct injection diesel engines', *Applied Energy, **88** (2013), 559-567.*
15. *Ryan III T. W.Callahan T.J,* 'Homogeneous charge compression ignition of diesel fuel', *SAE paper no.961160*
16. *Gray III, A. W., RyanIII, T.W,* 'Homogeneous charge compression ignition of diesel fuel', *SAE paper no.971676*
17. *Maurya. R.K, & Agarwal, A.K,* 'Experimental study of combustion and emission characteristics of ethanol fuelled port injected homogeneous charge compression ignition(HCCI) combustion engine', *Applied Energy, **88** (2013), 1169-1180*
18. *Nakagome, K., Shimazaki, N., Niimura, K., Kobayashi S.,* 'Combustion and emission characteristics of premixed lean diesel combustion engine', *International Congress & Exposition, SAE Paper no.970898:pp 24-27.*
19. *Roy, H., Hiromichi, Y,* 'HCCI combustion in a DI diesel engine', *SAE Paper no.2003-01-0745.*
20. *Shawn, M.M., Yann, G., & Giorgio, R, 'Mixed-mode diesel HCCI with external mixture formation', DEER. 2003.*
21. *Agarwal, A.K.,Sinha,S., Shukla, M.K.,&Singh, S.,* 'Effect of EGR on the exhaust gas temperature and exhaust opacity in an experimental diesel engine', *SADHANA (Indian Academy of Science proceedings in engineering sciences), 29 (Part 3),pp 275-284.*
22. *Xingacai Lu, Dong Han, Zhen Haung,* 'Fuel design and management for the control of advanced compression-ignition combustion modes', *Progress in Energy and Combustion Science, **37** (2011).*
23. *N.R.Banapurmath and P.G.Tewari,* 'Effect of biodiesel derived from Honge oil and its blends with diesel when directly injected at different injection pressures and injection timings in single cylinder water cooled compression ignition engine', *Proceedings of Institute of Mechanical Engineers, Vol.223 (1): pp 31-40, Part A: Journal of Power and Energy, Professional Engineering Publications. 2009.*
24. *Jie Liu, Fuyuan Yang, HewuWanga, MinggaoOuyang, ShougangHao,* 'Effects of pilot fuel quantity on the emissions characteristics of a CNG/diesel dual fuel engine with optimized pilot injection timing', *Applied Energy, **110** (2013), 201-206.*
25. *Shuaiying Ma, ZunqingZheng, Haifeng Liu, Quanchanga Zhang, Mingfa Yao,* 'Experimental investigation of the effect of diesel injection strategy on gasoline/diesel dual-fuel combustion', *Applied Energy, **109** (2013), 202-212.*

26. *N R Banapurmath, P.G. Tewari. R.S. Hosmath, '*Combustion and emission characteristics of a direct injection, compression-ignition engine when operated on Honge oil, HOME and blends of HOME and diesel', *International Journal of Sustainable Engineering, **1** (2008), 80-93.*
27. *D. Ganesh, G. Nagarajan, '*Homogeneous charge compression ignition (HCCI) combustion of diesel fuel with external mixture formation'*, Energy, **35** (2010), 148-157.*
28. *Zheng Ming, Kumar Raj„'*Implementation of multiple pulse injection strategies to enhance the homogeneity for simultaneous low-NOx and soot diesel combustion'. *International Journal of Thermal Science, **48** (2009), 18-29.*
29. *Akagawa H, Takeshi M, Akira H, Satoru S, Naoki S, Takeshi H, et al., '*Approaches to solve problems of the premixed lean diesel combustion'. *SAE paper. 1999-01 0183. 1999.*
30. *D.Yap, S.M.Peucheret, A. Megaritis, M.L.Wyszynski, H.Xu, '*Natural gas HCCI engine operation with exhaust gas fuel reforming', *International Journal of Hydrogen Energy, **31** (2006), 587-595.*
31. *Yusaf T.F, Buttsworth D.R, Saleh K.H, Yousif B.F, '*CNG-diesel engine perfor- mance and exhaust emission analysis with the aid of artificial neural network', *Appl Energy, **87**(2010),1661–1669.*
32. *Zheng Q.P, Zhang H.M, Zhang D.F, '*A computational study of combustion in compression ignition natural gas engine with separated chamber'. *Fuel, **84** (2005), 1515–1523.*
33. *Arjan H, Denbartt Ingemar, '*HCCI operation of a passenger car common rail DI diesel engine with early injection of conventional diesel fuel', *SAE paper 2004-01-0935. 2004.*