

Experimental Investigation and Energy Analysis of Natural Gas and Diesel Dual Fuel HCCI Combustion in a CI Engine

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Abstract

In conventional diesel engines the Nitrogen oxides and particulate emissions are high and there exists a trade-off between them. By using Homogeneous Charge Compression Ignition (HCCI) concept both nitrogen oxides and particulates can be reduced simultaneously. Natural Gas has been considered as the best alternative for diesel engines because of major content is methane, cleaner fuel and HOR makes it suitable for high compression ratio engines. In the present work has been done on single cylinder constant speed of 1500 rpm at varying loads where the CNG is fumigated in the intake manifold at 110mm from the intake valve along with air at injection pressure of 3 bar through CNG injector and diesel is pilot injected at 23 degree bTDC for Start of Combustion (SOC) the investigations and comparison with exergy analysis for the different equivalence ratios of the diesel and CNG is carried. From the exergy analysis for the CNG at various equivalence ratios the Combustion irreversibilities are significantly lower than diesel combustion. Homogeneous charge combustion increases work exergy whereas it decreases heat loss exergy and irreversibilities. CNG is qualitatively efficient than diesel. The second law efficiency for CNG at equivalence ratio of 0.5 is 42% which is far more than the diesel efficiency which is having 32% alone. The results of analytical and conventional diesel are took further the experimental investigation of CNG at various equivalence ratio are going to be carried out

HCCI – Homogeneous Charge Compression Ignition;
CNG – Compressed Natural Gas; bTDC – before Top Dead Centre; HC – Hydro Carbon; NOx – Oxides of Nitrogen; CO – Carbon monoxide; ECU – Electronic Control Unit;

1. Introduction

Over the past decades the environment has been severely affected by the pollution causes harmful effects and global warming. In the recent years a lot of attention has been focused on air pollution caused by automotive engines. Since the environmental protection regulations and the need to reduce fuel consumption are getting more and more stringent, among them diesel engines have been particularly targeted for their production of oxides of nitrogen (NOx), Particulate Matter (PM) and smoke emissions. There exists a trade of between NOx and PM which are not can be simultaneously reduced by the conventional combustion concepts, so there exists Homogeneous Charge Compression Ignition (HCCI) as a promising alternative combustion technology with high efficiency and lower NOx and PM emissions, has been widely investigated over the recent years.

HCCI combustion incorporates the advantage of both Spark ignition (SI) engines and compression ignition engines (CI). The homogeneous charge is inducted into the cylinder and then compressed to auto ignition which occurs simultaneously throughout the volume of combustion chamber without flame propagation and diffusion combustion. These features lead to very low NOx because of the available time is very much less for the Zeldovich mechanism to occur, less traces of soot because of homogeneous charge. The benefits of HCCI are higher compression ratio and efficiency than Otto engines with lower NOx and particulate emissions than Diesel engines which are commonly associated with its nature being a spontaneous multi-site combustion of a very lean and premixed fuel-air mixture which has high heat release rate (HRR) and no significant evidence of flame propagation (depending on the mixture homogeneity amongst others) [4]. An drawback of HCCI compared to the Spark Ignition (SI) engine and the diesel engine is higher

Emissions of unburned hydrocarbons [5]

The controlling of ignition timing and burning rate are to be solved before the HCCI engines can be practically applied to commercial use. The challenges in the HCCI engines are difficult to overcome mainly in the ignition control mechanism like the spark and direct injection timing control and also HCCI combustion is dominated by the chemical kinetics based on the fuel properties therefore the occurrences of misfiring at low load and knocking at high load are usually noted which result is a limited operation range of HCCI engine.

Recently a lot of researches have been performed to investigate the potential control methods such as the inlet air heating [6,7], variable compression ratio (VCR) [8,9], variable valve actuation (VVA) [10,11] and EGR rates [12,13]. Moreover many studies also focused on the effects of different fuel physical and chemical properties, for instance the octane number and the cetane number, using the primary reference fuels and fuel additives [14, 15, 16, and 17]. Within

these attempts, attracting progresses have been reported, to some extent, about gaining control of the HCCI combustion process. In a HCCI engine, the fuel is injected into the (preheated) air in the intake manifold, to create a homogeneous charge. The charge is then further heated during the compression stroke to get auto-ignition, close to Top Dead Centre (TDC). The ignition timing in HCCI can only be controlled indirectly. By adjusting the operating parameters correctly, ignition will occur near TDC [18]. The auto-ignition timing in an HCCI engine is dependent on many parameters including equivalence ratio, pilot injection timing, fuel composition and properties, compression ratio, intake pressure and temperature, and external and internal EGR. The overall efficiency of the engine depends strongly on the combustion timing and duration. The homogeneous mixing of the fuel and air before the combustion, opposite to that in diesel engines, reduces the level of soot particles in the exhaust leading to cleaner combustion. HCCI provides up to a 30-percent fuel savings, while meeting current emissions standards. In regards to gasoline engines, the omission of throttle losses improves HCCI efficiency [19]. Recent research has shown that the use of two fuels with different reactivity's can help solve some of the difficulties of controlling HCCI ignition and burn rates. The operating range in HCCI mode is restricted to relatively low load due to rapid combustion which results in high pressure rise rates and thus high combustion induced noise [20]. The smaller operating range can be eliminated once the perfect closed loop system is developed for the Pilot Assisted-HCCI.

2. Dual Fuel HCCI combustion

HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels [21]. Further, on using

CNG as a fuel in HCCI engine results in even lower levels of NOx and particulate

Emissions are observed. CNG is made by compressing natural gas (which is mainly composed of methane, CH₄), to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored and distributed in hard containers at a pressure of 130 bar in cylindrical shapes. Being a gaseous fuel, CNG mixes easily and evenly in air, thus producing a homogeneous mixture essential

for working of HCCI engine along-with increasing the life of lubricating oils, as CNG does not contaminate and dilute the crankcase oil. As CNG is less likely to ignite on hot surfaces, since it has a high auto-ignition temperature around 813 K, high octane rating (120 - 130) and a narrow range (5-15%) of flammability, therefore a methodology using a small pilot quantity of diesel fuel injected during the compression stroke at 23 degree bTDC to improve the power density and operation control is implemented, thus helping the homogeneous mixture of CNG and air to combust without altering the compression ratio of the engine or installing a spark plug inside the combustion chamber.

Using CNG with HCCI along with diesel provides fuel saving up to a great extent with the minimal NOx emissions, while meeting current emission standards along with higher efficiency, lower NVH levels compared to conventional diesel within certain range of loads and reducing exhaust gas emissions by 80% as NGV is composed of methane gas.

The pilot injection will cause a relatively slow rise in the cylinder pressure and temperature and cause the homogeneous natural gas charge to auto-ignite at an appropriate timing. The pilot injection is used to lower the variation in IMEP at the lean limit, as well as prevent misfiring of the engine at marginal conditions. It can also be used to control the combustion timing in an HCCI engine and increase the efficiency of fuels like natural gas that have very high reaction rates. With HCCI, cycle-to-cycle variations of combustion are very small since combustion initiation takes place at many points at the same time. HCCI has no flame propagation; instead the whole mixture burns close to homogeneous at the same time [21]. To limit the rate of combustion, much diluted mixtures must be used. Previous studies have used extremely lean mixtures [22, 23] and/or high amounts of with Exhaust Gas Recycling (EGR) [24]. The availability and irreversibility of the CNG and diesel gives the effective use of CNG more than the diesel, heat loss, second law efficiency exergy are important to analyse

3. Aim of the experimental investigation

The aim of the present experimental investigation is to introduce CNG with intake air by injection into the manifold and ignition of charge is by means of introducing an ignition enhancer. CNG has a very low cetane number (< 2) and will not ignite within

the time available and temperature achieved in the cylinder hence to initiate the ignition diesel (self ignition temperature around 530 K) is injected at the end of compression stroke, it ignites the homogeneous charge. And the exergy of the CNG and Diesel at various equivalence ratio of the HCCI combustion are analysed to know the effective use of CNG instead of diesel.

The physical and combustion properties of diesel and NG are given in Table 1.

Table 1

Physical and combustion properties

Properties	Natural gas	Petrol
Formula	CH ₄	C ₈ to C ₂₀
Density (kg/m ³)	0.7 – 0.9	833
Auto-ignition Temperature (K)	813	530
Stoichiometric air fuel mass ratio	17.16	14.5
Lower Calorific value (kJ/kg)	44818	42500
Octane Rating	120 – 130	15 – 25
Cetane number	< 2	40 – 55

The schematic layout of the test setup used for experimental study is shown in Fig.1. A single cylinder, water cooled naturally aspirated DI diesel engine having rated output of 3.7 kW at 1500 rpm is used for the experiments. The key specifications of the test engine are given in Table 2.

And the Natural Gas compositions are given in Table 3.

Table 2. Technical Specification of Test Engine

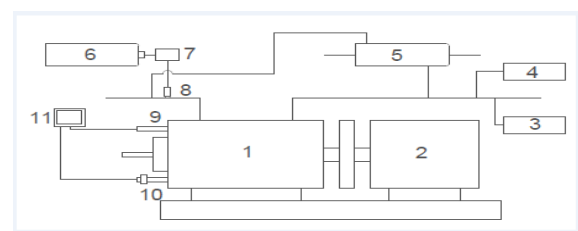
No. Of cylinders	1
Bore * Stroke	80 mm * 110 mm
Compression Ratio	16.5 : 1
Rated Output	3.7 kW, 5 hp
Rated Speed	1500 rpm
Specific Fuel Capacity (SFC)	0.241 kg/kW h
Rotation while looking at the flywheel	Clockwise
Power Take – off	Flywheel end
Starting	Crank Hand start
Fuel Injection pressure	200 Bar
Fuel injection Type	Mechanical
No. of Orifices	3

In dual-fuel HCCI combustion the NG is inducted in the intake manifold at 110mm from the intake valve using Ngi2 injector at varying pressure of 2 to 6 bar controlled by ECU. The pilot fuel is injected shortly 23 degree bTDC and retarding the timing of injection (23 to 29 degrees) because of the mechanical pump retarding is only possible, the diesel injection is act as a strong ignition source for the CNG air mixture. CNG cylinder is at the pressure of 130 Bar. The energy ratio of pilot diesel to CNG injected is kept around 0.37 (full load 3.7 kW). The loading is done by using eddy current dynamometer where the voltage is input for it and loading mass in kg is measured using the load cell.

Table 3. Composition of Natural Gas used in present investigation

Component	MASS (%)
Methane	91
Ethane	3
Propane	1.4
n-Butane	1.2
iso-Butane	0.8
Hexane	0.18
Nitrogen	0.4
Carbon dioxide	1.7
n-Pentane	0.2
iso-Pentane	0.3

Fig: 1 EXPERIMENTAL LAYOUT OF DUAL FUEL HCCI ENGINE



The test engine was equipped with

- Di-Gas Analyser
- Smoke Meter
- ECU
- Pressure Transducer
- Crank Angle Encoder
- Thermocouple

The Primary measurements for this study include the cylinder pressure, crank angle, fuel consumption measuring unit via a burette, exhaust temperature is

measured with the help of thermocouple installed in the exhaust system.

The Exhaust Emissions (NO_x, HC, CO₂, and Smoke Opacity) using AVL Di-gas Analyzer, its specification are given in Table 4 below

Table 4. Specification of Di – Gas analyzer

S.No	Parameters	Range	Resolution	Technique
1	CO	0-10% Vol	0.01% Volume	NDIR
2	CO ₂	0-20% Vol	0.1% Volume	NDIR
3	HC	0-20000 ppm Vol	<= 2000:1 ppm Volume >2000:10 ppm Volume	FID
4	NO _x	0-5000 ppm Vol	1 ppm Volume	CLP Electro Chemical Sensor

4. RESULTS

Emission test for the conventional Diesel has been done for 23 degree bTDC using the Di-Gas Analyser and Smoke meter.

Test Conditions

Engine Speed	1500 rpm
Diesel Injection Timing	23 ⁰ bTDC
Intake air temperature	27 ⁰ C
EGR rate	0 %

The following Figures shows the Relationship between Regulated Emissions (CO, NO_x, HC) and Load in kg

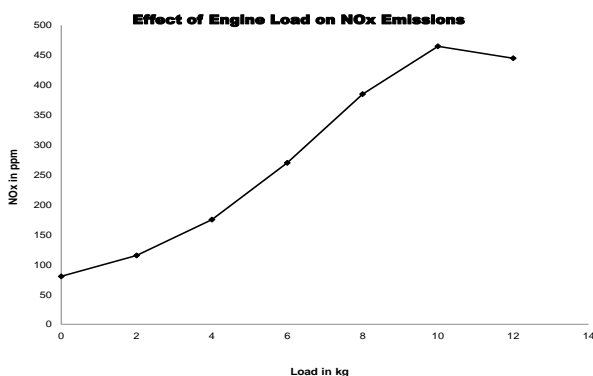


Fig. 2 Effect of engine load on CO emissions

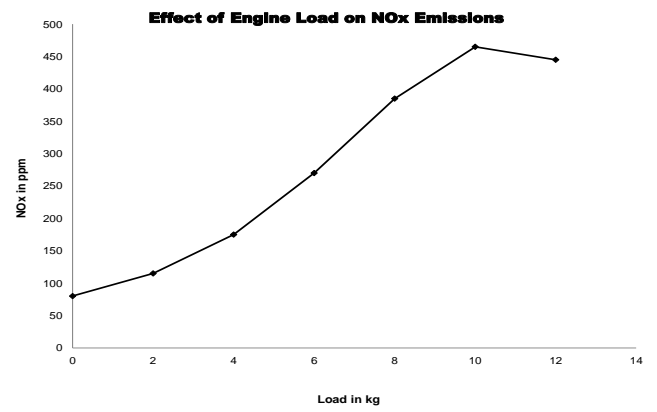


Fig. 3 Variation of NO_x (ppm) with Load (kg)

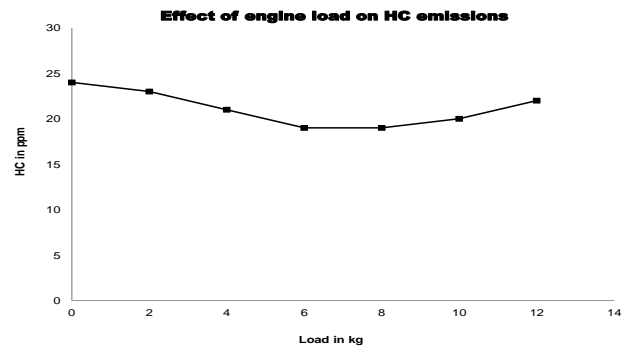


Fig. 4 Variation of HC (ppm) with Load (kg)

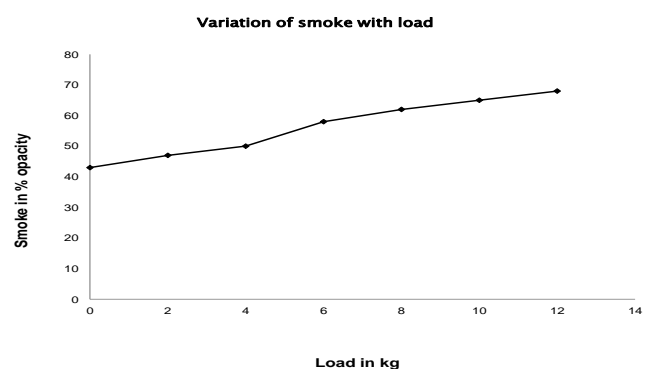


Fig.5 Variation of smoke (% opacity) with Load (kg)

4.1 Exergy Analytical Results

Exergy for the CNG Diesel at various premixed ratios or equivalence ratios the second law efficiency, irreversibilities, Heat loss, Pressure, Heat Release has been analysed using Star CD, CCM.

The Exergy analysis is done at equivalence ratios of

CNG at 0.2, 0.3, 0.4, 0.5 and full diesel

Pressure vs. Crank angle

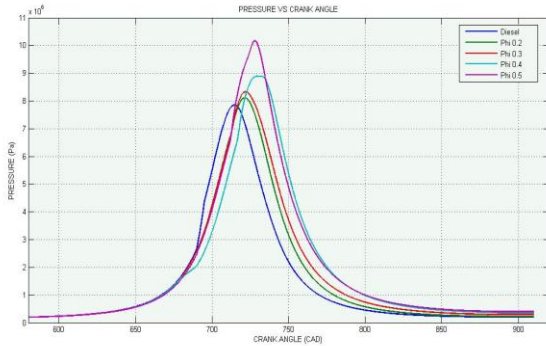


Fig 6. Variation of pressure for the crank angle at different equivalence ratios

Pressure for the high equivalence ratio of CNG is higher because the LCV is higher than the LCV of diesel

Temperature vs. Crank Angle

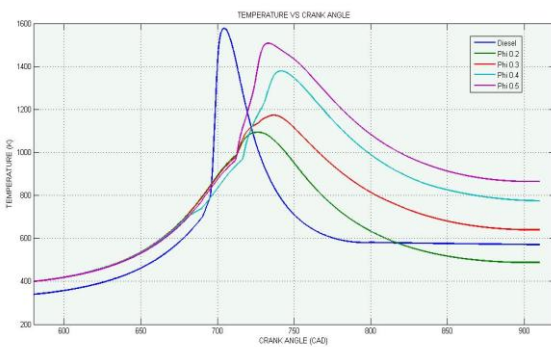


Fig 7. Variation of Temperature with crank angle for different equivalence ratio of CNG

Temperature is high for the diesel because of the combination of premixed combustion followed by the diffusion combustion and after burning

Work done exergy

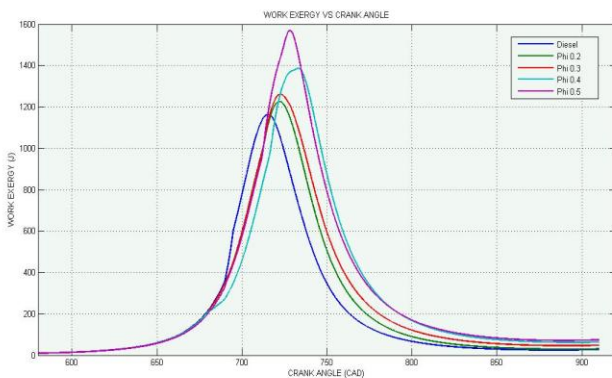


Fig 8. Work Exergy variation with crank angle

Heat loss exergy



Fig 9. For various Equivalence Ratio of CNG Heat Loss Exergy with crank angle

Irreversibilities



Fig 10. Irreversibilities for varies equivalence ratio of CNG and Diesel

From the irreversibilities analysis diesel having the highest irreversibilities among all the equivalence ratio of CNG because of this high irreversibility diesel engine having low efficiency

Burned fuel exergy

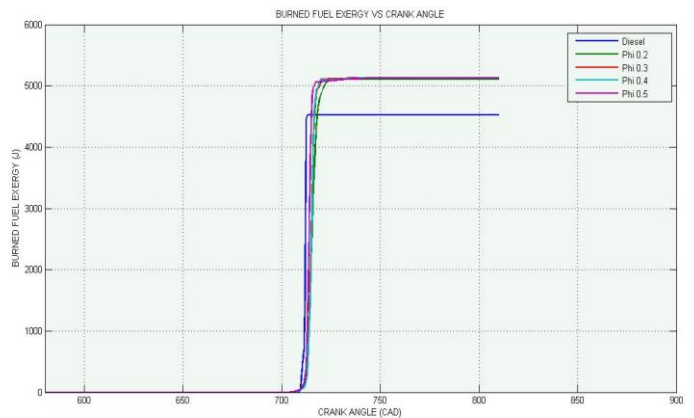


Fig 11. Burned fuel Exergy for the different equivalence ratio of CNG and Diesel

5. Conclusion

From the exergy analysis for the CNG at various equivalence ratios the Combustion irreversibilities are significantly lower than diesel combustion. Homogeneous charge combustion increases work exergy whereas it decreases heat loss exergy and irreversibilities. CNG is qualitatively efficient than diesel. The second law efficiency for CNG at euivalence ratio of 0.5 is 42% which is far more than the diesel efficiency which is having 32% alone. The results of analytical and conventional diesel are took further the experimental investigation of CNG at various equivalence ratio are going to be carried out..

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