Journal of Engineering Science and Technology
Vol. 10, No. 4 (2015) 404 - 419

COMBUSTION AND PERFORMANCE CHARACTERISTICS OF A SMALL SPARK IGNITION ENGINE FUELLED WITH HCNG

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Abstract

Due to environmental concerns and fossil fuel depletion, large scale researches were carried out involving the use of natural gas in internal combustion engines. Natural gas is a clean burning fuel that is available from large domestic natural reserve. When it is used as a fuel in SI engines, it reduces emissions to meet EURO-III norms with carburettors and EURO-IV norms with manifold injection. Countries like India with fewer natural fossil fuel reserves depend heavily on oil imported from Middle East Asian countries and on the other hand combustion of fossil fuel has negative impact on air quality in urban areas. Use of CNG as a fuel in internal combustion engines can reduce the intensiveness of these pervasive problems. The performance of CNG can further be improved by addition of small percentages of hydrogen to it to overcome the drawbacks like lower energy density of the fuel, drop in engine power and engine out exhaust emissions. When hydrogen is added to CNG it is called as Hythane or Hydrogen enriched Compressed Natural Gas (HCNG). This can be considered as a first step towards promotion of hydrogen in automobiles. In this study, the effects of mixing hydrogen with CNG on a small air cooled four stroke SI engine's performance, emissions and heat release rate was analyzed. A comparison of performance and emission by running engine separately on gasoline, hydrogen, CNG and HCNG was done. The results show a significant decrease in HC, CO and NOx emissions and marginal increase in specific energy consumption when fuelled with HCNG.

Keywords: SI Engine, HCNG, Hydrogen, CNG, Combustion.

Nomenclatures

Abbreviations

BMEP	Brake Mean Effective Pressure
BSEC	Brake Specific Energy Consumption
BTDC	Before Top Dead Centre
BTE	Brake Thermal Efficiency
CNG	Compressed Natural Gas
COV	Coefficient of Variance
DI	Direct Injection
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
HCNG	Hydrogen enriched Compressed Natural Gas
LPG	Liquefied Petroleum Gas
MBT	Maximum Brake Torque
MFB	Mass Fraction Burned
WOT	Wide Open Throttle

1. Introduction

In today's growing and competitive automotive sector, it has become a necessity to optimize the engine functioning and produce efficient and economical engines. Since the conception of IC engines, the conventional fuels have primarily been gasoline and diesel. Currently with the depletion of petroleum and on account of high pollutant emissions levels, it has become indispensable to attain an eco-friendly world. With emission norms getting tougher, it has now become paramount to improve and optimize the fuels used. Hence the search for alternative fuels has become vital. Numerous studies which have been performed in the area have lead to the use of alternative fuels or their blends with the conventional fuels, thereby reducing the emissions without any compromises on engine performance. The most viable, ultra clean fuels generally used along with the conventional fuels are CNG and hydrogen. The implementation of these alternatives can help cater to the high demand of environment friendly vehicles [1]. These fuels when blended with gasoline/diesel are expected to bring tremendous benefits and cause a reduction in emissions along-with reduction of the petroleum fuel consumption.

Hydrogen as a fuel has some unique and highly desirable properties. It is the only fuel that can be produced entirely from the plentiful renewable source, water at the expenditure of relatively much energy. Its combustion in oxygen produces uniquely only water but in air it also produces some oxides of nitrogen. These features make hydrogen an excellent fuel to potentially meet the ever increasingly stringent environmental controls of exhaust emissions from combustion devices, including the reduction of green house gas emissions [2]. Hydrogen has the highest energy content per unit weight and its calorific value is also very high. It has a high range of flammability and it burns in air at a concentration of 4-75% by volume. Hence a hydrogen engine can be operated on very lean mixtures and combusted over a wide range of fuel air mixtures [3]. The ignition energy required for hydrogen is ten times less than that of gasoline and fifteen times less than that of methane; as a result it can be ignited with a relatively weak spark. It has a very high flame speed resulting in high rate of pressure rise and instantaneous combustion. It gives almost zero CO, CO_2 and HC emissions but slightly higher amounts of NOx emissions [4].

CNG is a promising alternative fuel due to clean burning characteristics and lower exhaust emission levels. It is a fossil fuel by-product, comprising mainly of methane. It is stored in containers at 200-250 bar pressure. CNG is a safer fuel as compared to LPG (Liquefied Petroleum Gas). Its specific gravity is 0.587, i.e., it is lighter than air, if there is a leakage it would just rise up and dissipate into the atmosphere [5]. Its auto-ignition temperature is 540°C as compared to 227-500°C for petrol and 257°C for diesel. It has a narrow flammability limit and it burns in air at a concentration of 5-17% by volume, due to higher self ignition temperature. It has a high resistance to knock and causes lower greenhouse gas emissions. CNG increases engine life and the lubricating oil life is extended because CNG does not contaminate and dilute the crankcase oil [6]. CNG comprises mainly of methane and small quantities of ethane, propane and butane. The composition of CNG used in India is given in Table 1.

Table 1. Composition of CNG in India.

Component	Symbol	Mole (%)
Methane	CH_4	84.5
Ethane	C_2H_6	7.70
Propane	C_3H_8	2.40
Butane	C_4H_{10}	0.58
Pentane	C_5H_{12}	0.37

However, due to the usage of CNG, there is a difficulty in the operation of spark ignition engines. Properties of hydrogen, CNG and gasoline are given in Table 2. The lean mixture of CNG and air has a very low flame propagation velocity, which may result in poor engine power output [7]. Some improvement in the burning rate can be obtained using optimum spark timing [8], improved chamber design and increase turbulence. The level of increase in turbulence is limited, since excessive turbulence may cause excessive heat transfer and higher peak temperatures resulting in higher NOx emissions [9] and it also reduced volumetric efficiency. Hence, the need arises to enhance the combustion process without bringing about some of these disadvantages. Addition of small amounts of hydrogen to CNG results in a fuel having a much cleaner and faster rate of burning than CNG. The contribution of hydrogen addition to increased preignition reaction remains relatively small [10]. The infrastructure for CNG storage and distribution is developing rapidly in India. Natural gas is distributed to the metro cities using pipe lines. At the filling stations the gas coming from the pipe is compressed and filled into the tank of automobiles. Steel tanks are used to store the high pressure CNG. HCNG with small percentages of hydrogen (less than 5 %) can also use the same infrastructure as CNG without any changes thus reducing extra costs in setting up the facility.

Unich et al. [11] compared CNG and HCNG blends in terms of exhaust emission. The hydrogen content in the blend was 12% by volume. Same ignition timing was used for both the fuels. The vehicle was equipped with a 3 way catalytic convertor. The authors observed that CO emissions reduced by 19%, CO_2 decreased by 3% while NOx increased by 70% with HCNG fuel. HC was found to be constant for both the fuels. Fuel consumption of HCNG blend showed negligible variation with CNG on energy basis. In order to find the effect of lean limit on hythane, Kaiadi et al. [12] experimented on a heavy duty 6-cylinder CNG engine, which had an exhaust gas recirculation (EGR) system along with a turbocharger. Hythane had 10% of hydrogen by volume. At stoichiometric condition, i.e., at λ=1, no significant difference was seen between the two fuels on grounds of efficiency and emissions. By increasing the EGR ratio, combustion duration was found to be less for HCNG than CNG since it is easier to ignite hythane. It was found that as the engine operates leaner with CNG fuel, CO and NOx decrease while HC emissions increase. With Hythane in lean mode, HC decreased while NOx increased. Lean and dilution limits were extended by using Hythane.

Table 2. Property of hydrogen, methane and gasoline (Bauer [19]).

	Hydrogen (H_2)	**Methane (CH_4)**	**Gasoline (C_8H_{18})**
Equivalence ratio ignition lower limit in NTP air	0.10	0.53	0.70
Mass lower heating value (kJ/kg)	119,930	50,020	44,500
Density of gas at NTP (kg/m^3)	0.083764	0.65119	4.4
Volumetric lower heating value at NTP (kJ/m^3)	10,046	32,573	195,800
Stoichiometric air-to-fuel ratio (kg/kg)	34.20	17.19	15.08
Volumetric lower heating value in air, ϕ= 1 at NTP (kJ/m^3)	2913	3088	3446
Burning speed in NTP air (cm/s)	265-325	37-45	37-43
% thermal energy radiated from flame to surroundings	17-25	23-33	30-42
Molar carbon to hydrogen ratio	0	0.25	0.44
Quenching distance in NTP air (cm)	0.064	0.203	0.2
Flame temperature in air (K)	2318	2148	2470

Subramanian [13] tested an SI engine using CNG and 18% HCNG blend for 3-wheeler application. An oxidation catalytic convertor and EGR system was used. The engine was tested using Indian driving cycle. The fuel consumption of CNG increased with 18% HCNG fuel without adjusting the ignition timing. It slightly decreased with the addition of EGR and showed improvements with HCNG and catalytic converter. CH_4 and HC emissions were slightly reduced with HCNG and were further reduced with engine modifications (maximum with EGR and catalytic converter). NOx emissions were found to decrease with EGR. It was also noticed that CNG emits large amounts of formaldehydes which were reduced on enrichment with hydrogen.

In order to study the effect of direct injection (DI) of CNG and HCNG on a single cylinder 4-stroke SI engine, Mohammed et al. [14] conducted experiments using a fuel injector and an offset spark plug in the cylinder head of the test engine. The experiment was conducted at 3%, 5% and 8% hydrogen percentages. The injection timing was varied (120°, 180° and 300° BTDC) and WOT with an air fuel ratio of 1. Advancing the fuel-injection timing would increase the available time for air fuel mixing, which would improve the quality of the air fuel mixture and shorten the ignition delay. This will lead to the increase in engine brake torque, brake power and brake mean effective pressure (BMEP). Slight decrease in engine performance was observed when the injection timing was advanced further from 200° to 300° BTDC. With respect to the emissions, NOx was highest at 180°CA while CO and THC emissions drop with advancement in the crank angles. At higher loads, the overall engine performance was enhanced at an injection timing of 300°CA rather than at 180°CA as in the case of lighter loads. Thus hydrogen addition enhanced the engine performance and reduced emissions.

Very few researchers have tried testing hydrogen methane mixture without any modifications in the engine. Akansu [15] studied the emissions and break thermal efficiency (BTE) on an SI engine using 10, 20 and 30% of hydrogen, by volume in methane. The emission analysis reported a decrease in the unburned HC, CO and CO_2 emissions and an increase in the NO values with increasing H_2 percentages in methane fuel. It was suggested that when the equivalence ratio was greater than 0.9 (rich mixtures), there was a decrease in the BTE values. When equivalence ratio was between 0.6 and 0.9, then on increasing the hydrogen fractions, BTE increased. Hence hydrogen addition led to an increase in the BTE.

This study is an attempt to explore the merits of CNG and hydrogen blends (hythane) in a small single cylinder SI engine, which is extensively used in three wheeled passenger vehicles. The experimentation was done in two phases. In the first phase part load efficiency of the engine was found at different speeds by using HCNG as a fuel. In the second phase the engine was run using gasoline, hydrogen, CNG and HCNG separately at constant speed with varying loads.

2. Experimental Setup

A single cylinder, 4 stroke naturally aspirated, air cooled spark ignition engine was used in this study. The specification of the engine is given in the Table 3. Figure 1 shows the schematic of the experimental setup. A cylinder with 42 lit standard water volume at 160 bar pressure was used to store hydrogen. Using a two stage pressure regulator, the pressure of hydrogen was reduced to 1 bar. A flash back arrester and a flame trap were installed in between the hydrogen cylinder and the engine carburettor to avoid backfire. Hydrogen was injected after the carburettor and was not throttled. A flow meter fixed next to the flame trap and just before the carburettor was used to measure the flow rate of hydrogen.

Similar to hydrogen, CNG was stored in a 40 lit standard water volume container at 180 bar pressure. A commercially available pressure regulator was used to bring down the pressure from 180 bar to 1.5 bar in two stages. A rotameter was connected to the output of the regulator, from the rotameter the CNG was injected into the inlet manifold before the carburettor.

The manifold pressure was continuously monitored, using a map sensor. Air flow rate was measured using hot film type air mass flow meter. All the plastic components were removed from the manifold assembly and were replaced with cast iron. No modifications were made in the engine. The dry exhaust gas trapped from the exhaust manifold was used to measure exhaust emissions, using a HORIBA exhaust gas analyzer. A PC based data system was used to record cylinder pressure from a piezoelectric pressure sensor mounted on the cylinder head. Pressure at every crank angle was recorded. TDC point was also traced along with pressure data using TDC sensor. The data was then analyzed and processed.

Table 3. Engine specifications.

Make	**Briggs & Stratton**
Type	Single Cylinder, 4 stroke, air cooled, OHV engine
Fuel	Hydrogen, CNG and petrol
Bore * Stroke	79.25*61.67 mm
Displacement Volume	305 cm^3
Compression Ratio	8:1
Rated Power	10 hp
Governor	Mechanical
Method of loading	Eddy Current Dynamometer

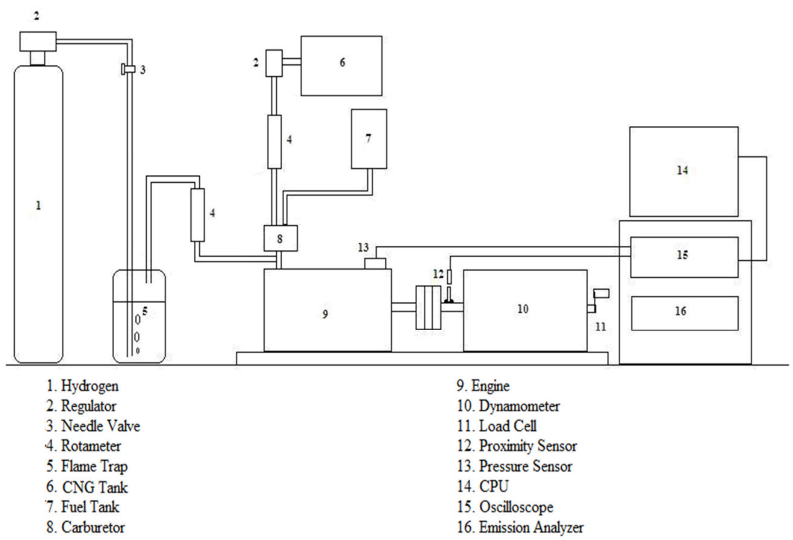

Fig. 1. Schematic of experimental setup.

For testing with hydrogen as a fuel, the CNG valve was closed and hydrogen alone was injected after the carburettor. For testing CNG as a fuel, hydrogen valve was closed and CNG alone was injected before the carburettor. For testing with HCNG as a fuel, both hydrogen and CNG were injected simultaneously. The flow rate of hydrogen was fixed at 3% and rest of the 97% CNG at different speed and fixed load. The testing of HCNG mixtures was done in two phases. In the first phase the engine brake torque was kept constant at 5.8 Nm and 7.35 Nm and the speed of the engine was varied from 2000 rpm to 4000 rpm. In the second phase the load on the engine was varied and the speed was maintained at 3000 rpm.

The ignition timing was fixed for maximum braking torque (MBT) of gasoline and it was not modified at any time. The use of fixed ignition timing implies that the performance of the engine is affected just for the blend used as fuel [16]. In India, when retro fit kits are used for converting gasoline engines to CNG engines, the ignition timing is not changed, the authors through this study wanted to analyze the effect of HCNG on such an engine without making any modifications in the engine.

3. Results

The first phase of testing targets the engine's performance at part load (around 40% of maximum load), where the engine will run for most of its lifetime. Figures 2 and 3 show the cylinder pressure, and rate of change of cylinder pressure with respect to crank angle, for HCNG having 3% flow rate of hydrogen, torque of 7.35 Nm and at different engine speeds. The maximum cylinder pressure values recorded for 2000, 2500, 3000, 3500 and 4000 rpm were 18.83, 21.3, 20.23, 22.29 and 22.3 bar respectively. It can be seen that the maximum peak pressure occurred at 4000. The lowest maximum cylinder pressure occurred at 2000 rpm, since the combustion was so slow that it led to decrease in engine performance. It can be said that at lower engine speed, the heat transfer to the combustion chamber walls increased and this caused the peak temperature, pressure and thermal efficiency of the engine to decrease [17]. Higher pressure gradient was observed for 3500 rpm engine speed.

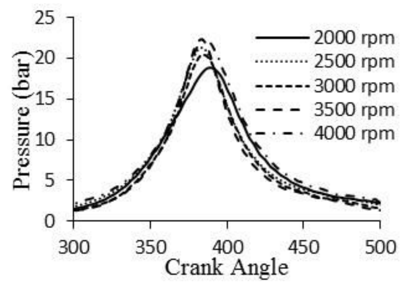

Fig. 2. In cylinder-pressure rise at 7.35 Nm.

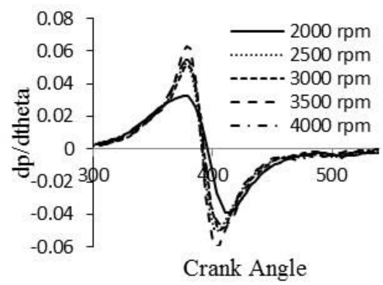

Fig. 3. Rate of change of pressure at 7.35 Nm.

Figure 4 shows the maximum heat release rate at different engine speed for two torque values. With the increase in engine speed an increase in maximum heat release rate was observed, also for higher load the maximum heat release rate was higher. On the other hand, the combustion duration from Fig. 5, showed a decreasing trend with the increase in engine speed and also it was lower for higher load. Combustion duration is defined as the interval of crank angle from 10% of mass fraction burned (MFB) to that 90% MFB. At higher engine speed, the turbulence intensity is so high that rapid combustion takes place and the combustion duration is reduced. High volumetric efficiency, high amount of fuel and higher reaction rate also lead to reduction in combustion duration at high speeds. However, at higher speeds, the difference in combustion duration was insignificant for both the loads.

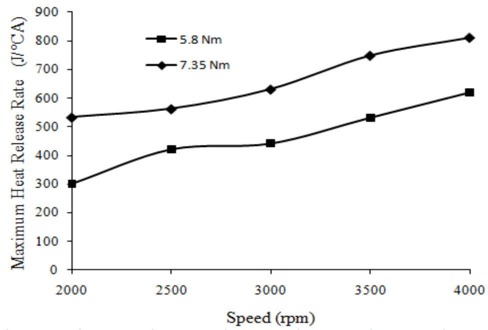

Fig. 4. Maximum heat release rate with variation in speed.

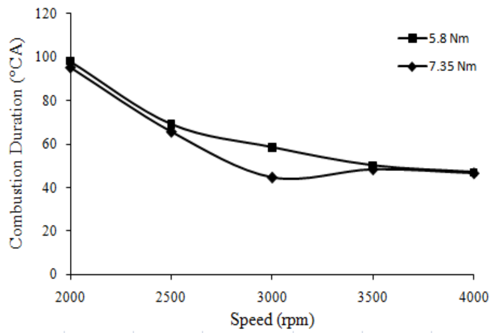

Fig. 5. Combustion duration with variation in speed.

Figure 6 shows coefficient of variation for maximum pressure (COV_{pmax}) at different engine speed for two torque values. The cycle by cycle variation of maximum pressure increases up to 3000 rpm and then decreases, also at lower loads the variation is less. At 4000 rpm the COV_{pmax} was found to be the lowest because hydrogen combustion causes engine combustion process closer to ideal constant volume cycle, thus improving combustion stability and cyclic variations in engine cylinders.

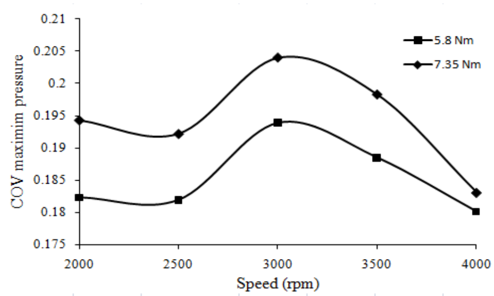

Fig. 6. COV_{pmax} with variation in speed.

Experiments were performed for HCNG by varying the speed and keeping the torque constant. Readings were taken at two engine torque values viz. 5.8 Nm and 7.35 Nm. Flow rate of hydrogen was fixed at 3% in the HCNG mixture for this test. Figure 7 shows the variation of HC emissions against engine speeds for different torque values. It is observed that HC emissions decreased for both the cases with the increase in engine speed. Also with the increase in engine load, the HC emissions decreased, this can be attributed to complete combustion of the charge at higher loads. Presence of hydrogen in the mixture is the main reason for complete combustion since it has shorter burning time. Due to the presence of hydrogen in the mixture the amount of CNG is also reduced and hence HC emission is reduced

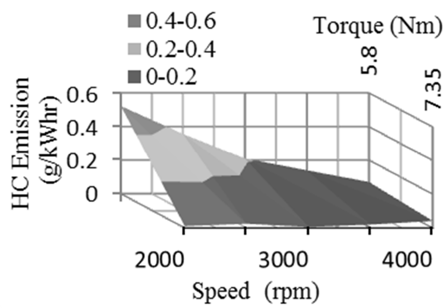

Fig. 7. Variation of HC emission with change in speed.

CO emissions, shown in Fig. 8, was found to increase first and it reached a maximum at 2500 rpm, later it was found to decrease, almost linearly, with the increase in engine speed. The in homogeneity of the in-cylinder charge, that hydrogen is burned in some oxygen rich area, the fast burning properties and high stoichiometric air – fuel ratio of hydrogen make it consume more adjacent oxygen, which stimulates CO formation [18]. CO_2 emissions, shown in Fig. 9, follow the same trend as CO emission. It can be seen that due to complete combustion of the charge, unburned hydrocarbon and carbon monoxide is oxidized to CO_2, thus reducing the regulated emissions. The complete combustion of the mixture took place due to higher temperature and higher availability of the oxygen as the engine ran on lean mixture. Figure 10 shows the NOx emission against engine speed for different torque values. For higher load the NOx emission was found to be higher and it decreased with the increase in engine speed.

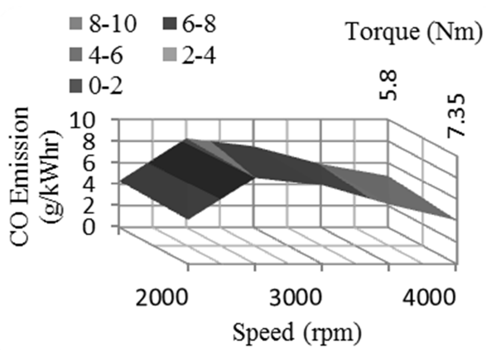

Fig. 8. Variation of CO emission with change in speed.

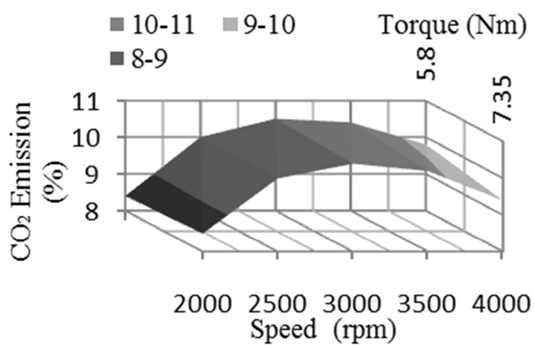

Fig. 9. Variation of CO_2 emission with change in speed.

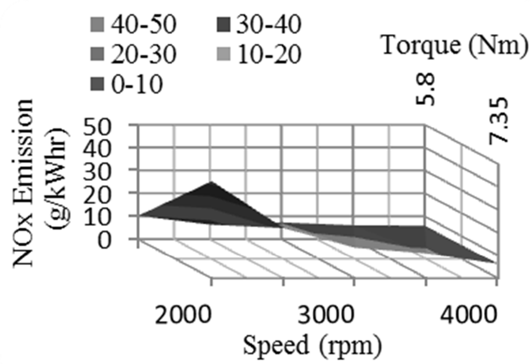

Fig. 10. Variation of NOx emission with change in speed.

The second phase of the experiment was conducted by keeping the speed constant at 3000 rpm and the load was varied. The following discussion shows the effect of the change in equivalence ratio at the constant speed. Equivalence ratio is defined as the ratio of actual air-fuel ratio to stoichiometric air-fuel ratio. Volumetric efficiency, shown in Fig. 11, was found to increase with the increase in equivalence ratio for gasoline and there was a decrease in volumetric efficiency for CNG, HCNG and hydrogen, with increasing equivalence ratio. Carburettors are designed to choke at higher speeds with wide open throttle (to put more fuel) in the engine, in this case CNG is mixed with air and throttled, hence the mixture is lean at maximum load. In a carburetted engine the volumetric efficiency of gaseous fuels is lower as compared to liquid fuels, because of displacement of air by the gaseous fuel. It will lead to lower brake thermal efficiency and brake power as shown in Figs. 12 and 13 respectively. The BTE was found to decrease with the increase in equivalence ratio, but for gasoline the trend was reversed. With the addition of hydrogen to CNG the BTE was found to increase and for neat hydrogen the BTE was further increased. The reason for this increase is better burn rate and combustion efficiency with hydrogen addition [14]. Brake power also follows the same trend as BTE. As the brake power decreases so does the BTE, as a greater proportion of the fuel energy is utilized in overcoming friction [19].

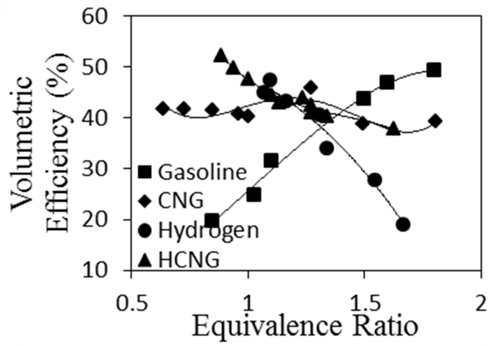

Fig. 11. Variation of volumetric effeciency with equivalence ratio.

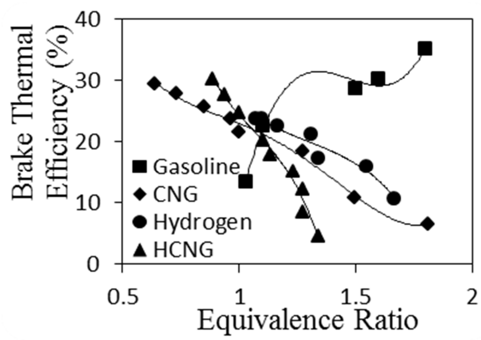

Fig. 12. Variation of brake thermal effeciency with equivalence ratio.

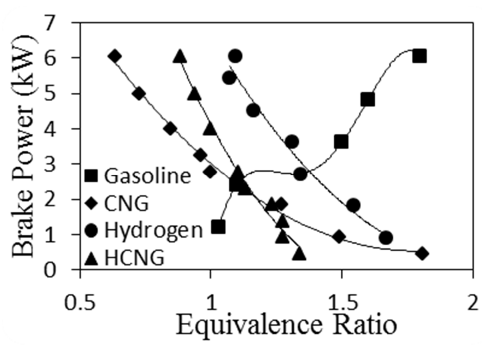

Fig. 13. Variation of brake power with equivalence ratio.

Since, brake specific fuel consumption is not an effective parameter in comparing two fuels having different calorific values and density, brake specific energy (BSEC) is a better choice. Figure 14 shows the BSEC plotted against the equivalence ratio. It can be seen that the trend of the plot is inverse to that of the BTE plot. With the increase in equivalence ratio the BSEC was found to increase, for pure hydrogen it was lowest and for HCNG it was found to be a maximum.

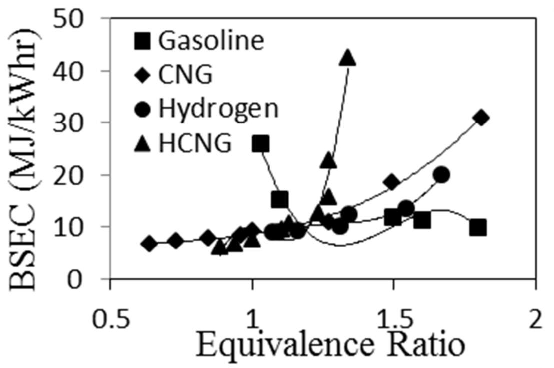

Fig. 14. Variation of brake specific energy consumption with equivalence ratio.

Figure 15 illustrates the exhaust gas temperature (EGT) for various values of equivalence ratio. The EGT was found to decrease with the increase in equivalence ratio. The addition of hydrogen to CNG led to a decrease in EGT and it was found to be minimum for pure hydrogen. Complete combustion and higher burning rates led to this trend. Gasoline on the other hand showed a reverse trend and a maximum value of 650 °C was registered for an equivalence ratio of 2.

Figure 16 shows the unburned hydrocarbon values versus equivalence ratio. When hydrogen percentage is increased, the unburned hydrocarbon value decreases which could be explained by the fact that hydrogen could speed up flame propagation and reduce the quenching distance, thus reducing the possibilities of incomplete combustion [20]. Unburned hydrocarbon emissions are reduced with lean mixtures until reduced flammability of the mixture causes a net increase in HC emission. Temperature of combustion chamber is increased with increasing hydrogen fraction resulting in decreased HC emission [7]. Another reason for reduction in unburned hydrocarbon emission is reduced fraction of CNG in the HCNG mixture. For neat hydrogen the emission analyzer did not register any value since, carbon is not present.

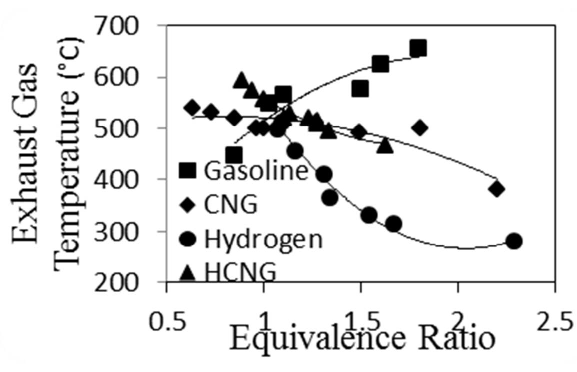

Fig. 15. Variation of exhaust gas temperature with equivalence ratio.

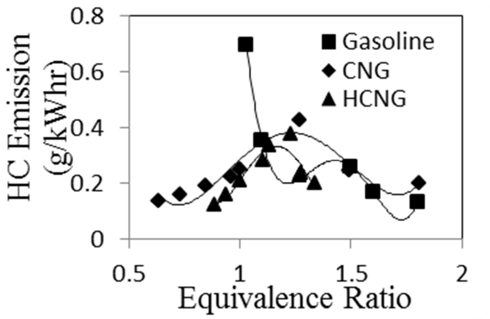

Fig. 16. Variation of HC emisssion with equivalence ratio.

The CO emissions are plotted versus equivalence ratio for gasoline, CNG and HCNG in Fig. 17. Since hydrogen cannot generate CO emission, there is no CO trend in Fig. 17. It can be seen that CO emission is very low for CNG and HCNG as compared to gasoline. This trend in emission can be seen, because by adding hydrogen, the percentage of CNG in the mixture is reduced and complete oxidation of CO into CO_2 is possible. Also, the mixture is lean as a result there is an increase in oxygen content in the mixture. At higher equivalence ratio, the increase in CO is because of unstable combustion which includes incomplete oxidation that produces CO [21]. At lower loads and higher equivalence ratio, the CO emissions were found to be maximum with gasoline as a fuel.

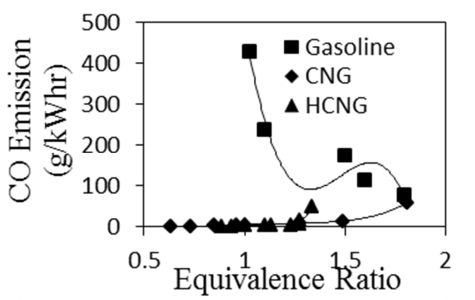

Fig. 17. Variation of CO emission with equivalence ratio.

Figure 18 shows the NOx variation with equivalence ratio for gasoline, H_2, CNG and HCNG. NOx emission decreases with an increase in equivalence ratio for all cases except CNG where an increasing trend can be seen. NOx emissions were less for HCNG in all the cases. This can be attributed to the fact that the engine had an internal EGR which led to the decrease in emissions. Pure hydrogen, on other hand, showed higher NOx emissions for λ =1 but with the increase in λ, NOx emissions reduced. Fast burning velocity and high flame temperature of hydrogen tend to simulate the formation of NOx [18]. The NOx emission for CNG was higher than gasoline, this is due to the fact that the engine was designed and calibrated for gasoline. As CNG has a lower flame speed than gasoline due to which the combustion occurs late in the power stroke and continues for a longer time in expansion stroke. Due to slow combustion, peak pressure is low and the combustion temperature is also lower. However, the combustion continues late into the cycle which increases the exhaust gas temperature [22].

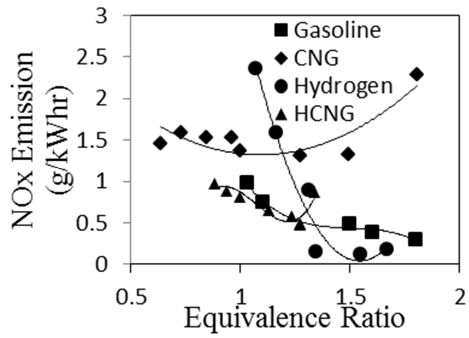

Fig. 18. Variation of NOx emission with equivalence ratio.

4. Conclusions

A study was conducted in two phases, on a naturally aspirated, air cooled, small spark ignition engine, to explore the merits of HCNG. In the first phase, the experimentation was done at two different loads by varying the engine speed. The following observations were made:

- Highest peak pressure of 22.3 bar was observed at 4000 rpm for 7.35 Nm load and lowest was observed at 2000 rpm.
- The maximum heat release rate was found to increase with the increase in speed and it was higher for 7.35 Nm torque.
- With the increase in speed the combustion duration was found to decrease but not much difference in combustion duration was observed for two loads.
- The variation in COV_{pmax} was found to first increase and then decrease for variation in speed, also the value at 4000 rpm was lesser than that at 2000 rpm, i.e., with the increase in speed the cycle by cycle variation was found to decrease.
- The HC emissions were found to decrease with the increase in speed.
- The CO emissions increased first and then decreased with the increase in speed and at higher load it was found to be higher.
- NOx emission was found to be higher at lower speed and at higher load, since at lower speed the hydrogen content is more in the mixture leading to higher NOx.

During the second phase, load on the engine was varied at a constant speed of 3000 rpm, for different fuels; gasoline, hydrogen, CNG and HCNG. The following conclusions were drawn from the experimental results of the second phase:

- The volumetric efficiency was found to decrease with increase in equivalence ratio for gaseous fuels as the gases displace air in a carburetted engine.
- The brake power was found to decrease with the increase in equivalence ratio; BTE also followed the same trend as brake power.
- The BSEC was found to increase with the increase in equivalence ratio, i.e., at higher loads the fuel consumption was found to less as compared to lower loads, also HCNG showed the highest BSEC at 42 MJ/kWhr at 1.3 equivalence ratio.

- The unburned HC emissions were found to be lesser for HCNG for all equivalence ratio values as compared to CNG and gasoline.
- The CO emissions were also found lower for HCNG than CNG and gasoline. Since hydrogen does not contain any carbon, no unburned HC and CO emissions were observed.
- NOx emission for HCNG was also found to be lower than CNG and gasoline. While running the engine on hydrogen, significant NOx emissions were observed at higher load but at lower load the emissions were found to be lower than all other fuels. Lower NOx emissions were observed for gasoline as well.

Thus, it can be seen, that the engine has good part load efficiency while running with HCNG, the emissions were lower and the cycle-by-cycle variation is also low. HCNG as compared to other fuels gave better engine performance, lower fuel consumption and lower emissions. HCNG can play a major role in reducing the environmental pollution and our dependence on fossil fuels. Optimization of ignition timing and fuel injection using an injector can be the future work of this study.

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