academicJournals

Vol. 4(6), pp. 99-112, June 2013
DOI: 10.5897/JPTAF10.002
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Journal of Petroleum Technology and Alternative Fuels

Full Length Research Paper

Improved efficiency of CNG using hydrogen in spark ignition engine

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Accepted 30 May, 2013

Experimental investigations carried out on a single-cylinder four-stroke motorcycle spark ignition engine operating on gasoline and natural gas are reported in the present paper when compressed natural gas (CNG) and hydrogen were used as fuel. The investigations were carried out by mixing a small percentage of hydrogen (5 to 30%) with CNG and supplied to the engine. Hydrogen and CNG were mixed in a developed mixer and supplied through the inlet manifold system. Performance and emission tests carried on the engine with this system showed a considerable improvement in power output and in thermal efficiency as well as reduction in brake specific energy consumption (BSEC), hydrocarbon (HC) and carbon monoxide (CO) emissions. Power loss associated with CNG utilization had improved with the addition of hydrogen fuel (20 to 30%) was observed. The combustion analysis was carried out for different rates of hydrogen addition. The rapid rate of burning of CNG-air mixture with the addition of hydrogen showed higher energy release rate, leading to higher cylinder pressures. Hydrogen blended with CNG enabled leaner operation and showed an improvement in BMEP and environmental benefit.

Key words: Hydrogen, compressed natural gas (CNG), carbon monoxide (CO) emissions, spark engine, fuel mixer.

INTRODUCTION

It is a well known fact that the conventional fuel is depleting and the emission levels of a conventional gasoline operated spark ignition engine are considerably higher than gaseous fuels. Due to new emission regulations, the gasoline-based fuel engines are getting gradually replaced by improved alternative fuelled engines. All gaseous fuels, such as compressed natural gas (CNG), liquefied petroleum gas (LPG), hydrogen (H_2) and biogas present a very promising alternative to gasoline. CNG is cheaper than the conventional petroleum based gasoline fuel. Hydrogen fuelled internal combustion engines have the carbon dioxide (CO_2) free potential with increased engine efficiency, wide flammability limits and high flame propagation speed of hydrogen. As such hydrogen mixtures allow diverse load control strategies (such as power regulation by varying the equivalence ratio, avoiding throttling loss) and the high auto ignition temperature allows an increased compression ratio. Major drawbacks with CNG are lower power output and slow acceleration. Many researchers have addressed these problems to a larger extent. Das (1996), showed utilization of hydrogen and natural gas mixtures in an internal combustion engine.

According to Karim and Klat (1966), hydrogen has been shown to be an excellent additive in relatively small concentrations, to some common fuels such as methane. Natural gas has a slow flame speed while hydrogen has a flame speed of about eight times higher; therefore, when the equivalence ratio is much higher than the stoichiometric condition, the combustion of methane is not as stable as with a blend of H_2+CNG (Nafiz et al., 2009).

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In general, it is found that HC, CO_2, and CO emissions decreases with increasing volume of H_2, but oxides of nitrogen (NO_x) emissions generally increase. If a catalytic converter is used, NO_x emission values can be decreased to extremely low levels. Consequently, equivalence zero emission vehicles (EZEV) standards may be reached. Efficiency values vary with hydrogen amount, spark timing, compression ratio and equivalence ratio. Under certain conditions, efficiency values can be increased. In terms of brake specific fuel consumption (BSFC), emissions and brake thermal efficiency (BTE), a mixture of low hydrogen percentage is suitable for use (Orhan et al., 2004). Renny and Janardan (2008) stated that a reliable performance and safe operation with enhanced fuel efficiency, better acceleration and lower exhaust emissions was achieved with hydrogen-CNG blended fueling of a CNG three wheeler. There exist an optimum percentage of hydrogen, 2 to 4 wt% (20 to 35 vol%) at which H-CNG blend shows best performance in a vehicle. Fuel efficiency of the H-CNG fueled engine is about 20 to 25% higher than that of CNG engine. Acceleration, that is, power performance of the vehicle got improved by about 15% as compared to a standard CNG fueled three wheeler. Emissions of CO, HC and NOx show a diminishing trend with increasing proportion of hydrogen in H-CNG blended mixture.

According to Sierens and Rosseel (1995), besides economical reasons, CNG is an attractive fuel for vehicles because it is a relatively clean burning fuel as compared to gasoline**.** CNG typically consists of 85-95% by volume of methane (CH_4) and is the shortest and lightest hydrocarbon molecule. The remaining 5-10% (v) comprises heavier gaseous hydrocarbons, such as ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}) as well as other gases in varying amounts. Generally, BTE increases as power increases, reaches to maximum and then decreases for higher increases of power; which is observed for all blends. This was realized by present experiments and along with this, it was found that blend continues to be the best even on rich mixture side. It was expected to obtain higher BTE with CNG+H_2 blend (Sierens and Rosseel, 2000). Difference in the BTE produced between CNG and CNG+H_2 blend fuel supply became much more significant at higher hydrogen presence (20 to 30%). The maximum BTE of a 30%H_2 + 70%CNG blend is 32%. This is about 2 times that of CNG supply. Sorensen (2005) reported that hydrogen is a useful additive for natural gas that enables leaner operation under part load conditions and improves brake mean effective pressure (BMEP) at wide open throttle near the lean limit. Moreover, NOx values are reduced, if normal hydrocarbon emissions or fuel consumption observed with natural gas are not exceeded.

In line with the foregoing, CNG as a fuel has been considered as a proven alternative to the conventional fuelled engines. It is most widely used in dual fuel applications. It has been observed from published literatures that CNG blended with fast burning gases, leads to improved performance by ways of mixing, supplying of fuel to engine and methodology of testing etc. Dedicated CNG engines have led to better performances which are not only expensive but the emissions are far from idle.

Need for the present work

In order to revive the gasoline engine industry and to take advantage of the widely used existing gasoline engines, it is necessary to find options of running these engines with alternate fuels without any significant modification. One such method that can be tried is first, using CNG in place of gasoline as it has been considered as a proven alternative from previous literature surveys. An important difficulty in the operation of spark ignition engines on lean mixture of CNG and air is the associated low flame propagation velocity.

Some improvement to the burning rate in these engines is usually obtained through measures such as the employment of optimum spark timing, improved chamber design and increased turbulence. The extent of increase in the level of turbulence in engines is usually limited and there are penalties associated with the use of excessive turbulence that include excessive heat transfer and higher peak temperatures and hence higher NOx emissions in optimum chamber geometry. Hence, there is a need to enhance the combustion process without bringing about some of the disadvantages. One approach is through the addition of a small amount of hydrogen to the CNG, a fuel having a much cleaner and faster rate of burning than CNG. It was decided to carry out a detailed experimental investigation to assess the potential of CNG and CNG-hydrogen blends as fuel for a stationary motor cycle single-cylinder spark ignition engine in dual fuel mode.

Any addition of an environmentally superior fuel such as hydrogen can still further improve the overall usage in terms of performance system and emission features. Supplying CNG blend to engine comprises various components and technologies; there is still lot of scope to enhance the performance of the engine by optimizing all the parameters of the entire component at various operating conditions.

Engine test setup and test procedure

Figures 1 and 2 shows the schematic diagram of the experimental set-up along with the photographs of engine, load panel, fuel mixer and gas supply control developed in the laboratory. The engine was coupled to an electrical DC motor by drive chain and 12 electric heaters with 12 separate switches on a panel for loading purpose. This panel also had a voltmeter and ammeter to measure the power of the generator. The engine was equipped with a battery ignition system, which gets triggering signals from a contact breaker

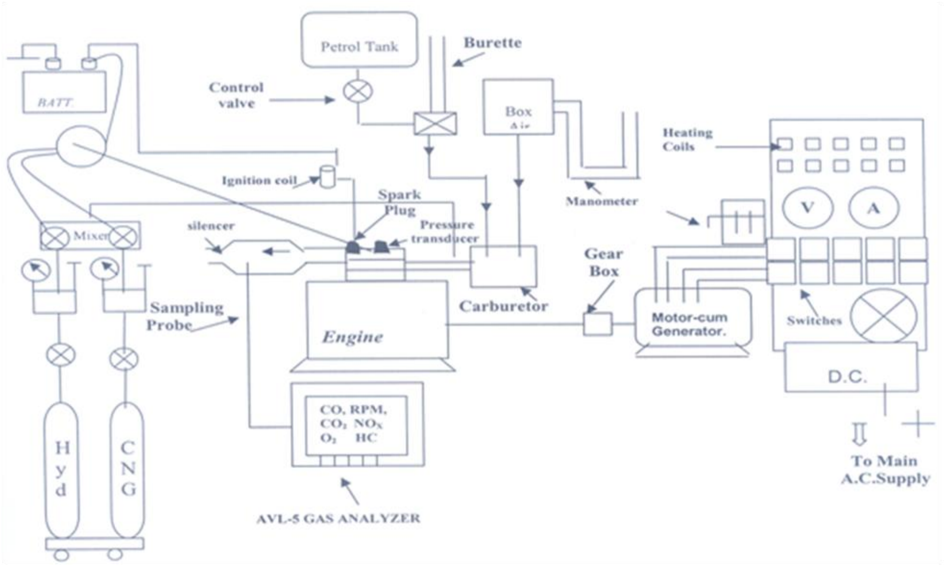

Figure 1. Schematic diagram of experiment.

Figure 2. Experimental setup at lab.

mounted on the distributor, and discharges the spark at the required crank angle position. CNG and hydrogen gas were supplied to a mixer at a pressure of 3 to 5 bar, using a pressure regulator from a pressurized cylinder maintained CNG at 200 bar and hydrogen at 150 bar for the purpose.

A volumetric measuring mass-flow meter of Flowstar make was connected in the fuel lines to measure the flow rate of CNG and hydrogen. Safety devices like pressure regulator, relief valve and flame arresters were connected in the fuel supply lines on account of the hazardous nature of hydrogen and CNG gas. Dry exhaust gas was trapped from the exhaust manifold to measure CO, CO_2, HC, O_2 and NOx with the help of gas analyzer of AVL make. Temperatures of inlet air, exhaust gas and fin were also measured using thermocouples.

Fuel induction technique developed for an SI engine with gaseous fuel

Figure 3, represents the photographs of gaseous fuel induction system and multi fuel mixture preparation; and supply system that was used to carry out the experimentation. The gas mixer was fabricated from mild steel with 3 way connectors, to facilitate fuel tubes connections. Two ways were connected with calibrated control valves mounted on separated gas cylinders of CNG and Hydrogen and the third way to the inlet manifold of the engine. The gaseous fuel supply unit was designed in such a manner that either CNG or Hydrogen or a combination of both the fuels in required proportion can be supplied to the engine and all the components of the conversion kit such as the cylinder, the pressure regulator and

Figure 3. Fuel mixer with locally designed gas supply control and view of gas injection system at manifold.

the power valve form the common fitment for every converted vehicle. However, it is the size of the mixer that differ in every converted automobile. This difference in size is mainly due to the suction pressure, the maximum speed and the size of the induction manifold bore which varies from vehicle to vehicle. An induction manifold bore should be so designed to give maximum pressure drop in the mixer venture, to give minimum resistance to air and gas flow and prevent the back flow of gas.

A pre-calculated amount of gaseous fuel on volume basis was supplied to the engine, which was inducted into the engine intake air stream continuously through a nozzle. A continuous fuel induction technique for the gaseous fuel was found to be most appropriate for the present work. The hydrogen mass share is defined below:

$$\text{Hydrogen mass share} = \frac{m_{f\,h2}}{m_{fh2} + m_{f}}$$

Where,
$m_{f\,h2}$ - is the mass flow rate of hydrogen and m_f - the mass flow rate of fuel CNG.
This mixture is inducted along with air. The calorific value (c.v) is defined below:

$$c.v = \frac{m_{f\,h2} \times c.v_{h2} + m_{f\,cng} \times c.v_{cng}}{m_{fh2} + m_{fcng}}$$

The compressed natural gas (CNG) used consisted of 99.87 vol.% methane. The hydrogen had a 99.995 vol.% purity. The mixing has been performed by the supplier prior to filling the fuels in 200 bar bottles. Table 1 summarizes the most important fuel properties.

Cylinder gas pressure measurement

In Figure 4, provision was made on the cylinder head to mount water cooled Piezo-electric pressure transducer to monitor in-cylinder gas pressure. The electrical signal produced by the transducer was connected to charge an amplifier device so that it could be recorded along with the crank angle information on a storage oscilloscope.

Before experiments, pressure transducer is calibrated using a dead weight pressure gauge tester. Pressure pickup calibration procedure was repeated three times on the testing setup for getting accuracy in the calibration. Calibration graph for piezo-electric pressure pick-up and charge amplifier were plotted and it was observed that observations obtained were almost similar and within the permissible accuracy. The calibrated pressure pickup readings obtained at different loads (bars) were used while experimentation was carried out for cylinder pressure measurement.

RESULTS AND DISCUSSION

The engine was modified at different stages to ensure smoother running on dual fuel mode using CNG-hydrogen blends. CNG-hydrogen fuel blend is inducted into the engine cylinder along with the air intake through the retrofitted arrangement to the induction manifold. The

Table 1. Summary of fuel properties.

Fuel properties	Natural gas	Hydrogen
Density at NTP (kg/m^3)	0.754	0.082
Stoichiometric fuel/air ratio (by volume)	0.106	0.420
Volumetric lower heating value (MJ/m^3)	32.97	10.22
Heating value of stoichiometric fuel-air mixtures (MJ/m^3)	3.17	3.02
Laminar burning velocity (m/s)	0.38	2.9
Minimum ignition energy (mJ)	0.28	0.02
Lean flammability limit equivalence ratio	0.5	0.1
Quenching distance (mm)	1.9	0.6

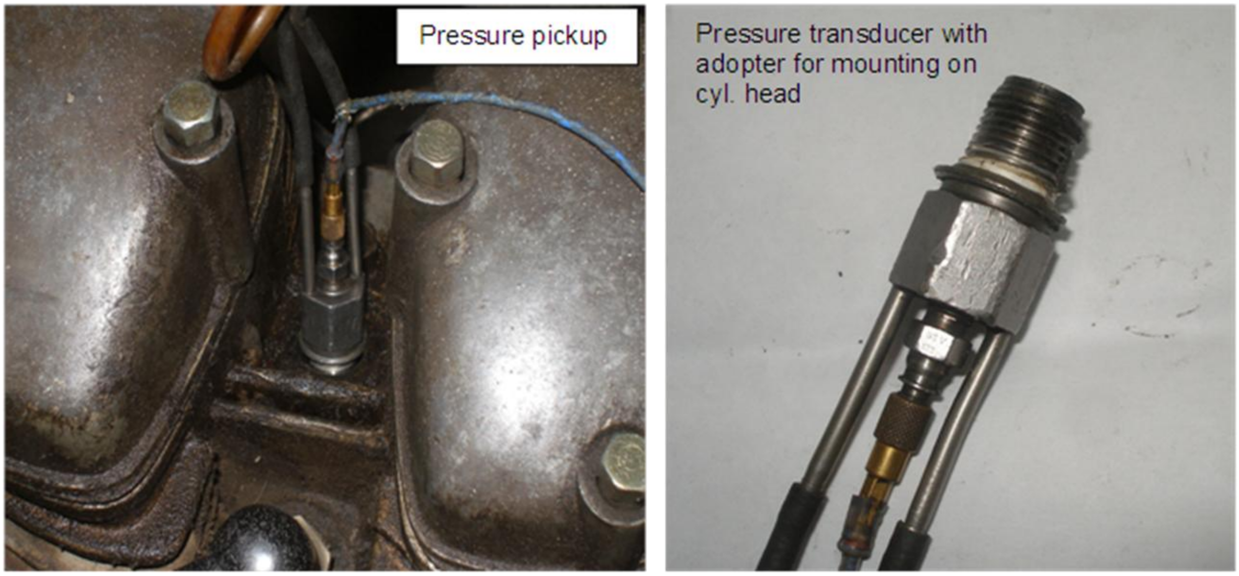

Figure 4. Pressure transducer mounted on engine head.

pre-calculated volume of gaseous fuel at different loads was supplied through a manually controlled flow regulator to study the effects on engine performance and emissions.

The present research is to further enhance the performance character of existing CNG-fuelled engines through addition of smaller levels of hydrogen, and further generate data on the addition of hydrogen-CNG blend in several proportions to engine. Six different blends such as $95CNG5H_2$, $90CNG10H_2$, $85CNG15H_2$, $80CNG20H_2$, $75CNG25H_2$ and $70CNG30H_2$ were prepared online to carry out the investigations. The operating parameters such as speed, optimum power output and compression ratio were kept constant during entire test range and the ignition timing was 23 degree before top dead center (BTDC). A typical set of results showing the effect of hydrogen on CNG operated SI engine for 37.5% throttle position and speed varying from 2000 rpm to 3000 rpm are shown in Figures 5 to 12.

Brake power

Figure 5 shows the effect of BMEP on brake power for various CNG-Hydrogen blends. Because hydrogen gas has high flame speed and clean fuel compared to other fuels, the addition of hydrogen enhanced the combustion characteristics of CNG-Hydrogen mixture, which has improved effect on the brake power of CNG fuel. It has been observed previously, that a maximum brake power with CNG as fuel was 2.2 kW at 4 bar, however, it has improved to maximum brake power of 3.21 kW at 4.2bar for 30%H_2 blends at 2400 rpm at full load condition. It is evident from Figure 5 that the addition of hydrogen to CNG and supplied in the form of blends improves the power developed nearer or more than gasoline operated vehicle as compared to CNG fuelled engine. The reason could be due to enhancement in the combustion process due to supplementation of high flame speed of hydrogen gas. Particularly 20 to 30% hydrogen blend gives the

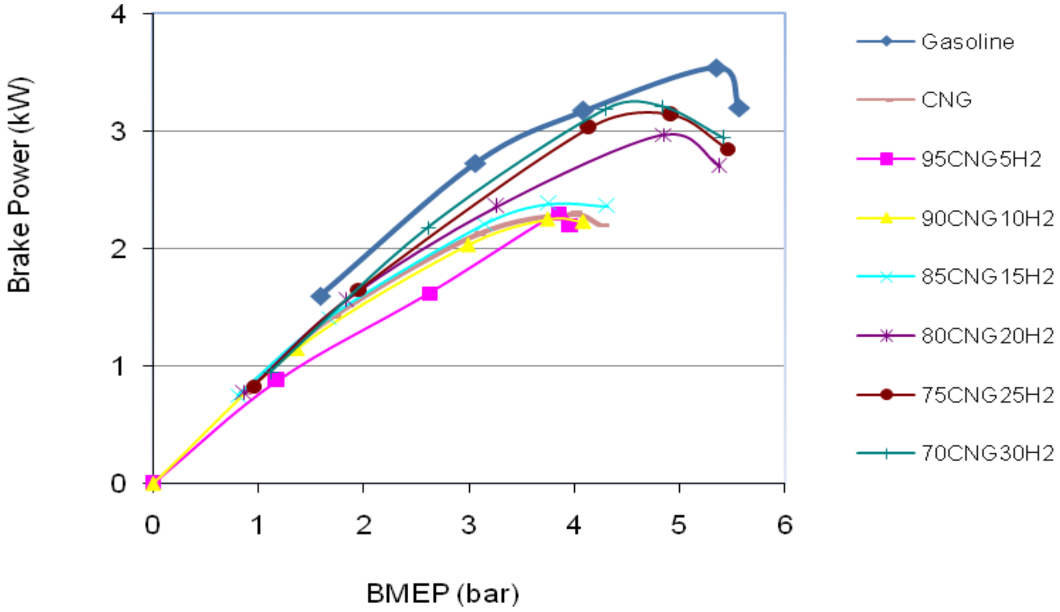

Figure 5. Brake Power vs Brake mean effective pressure for different hydrogen blends

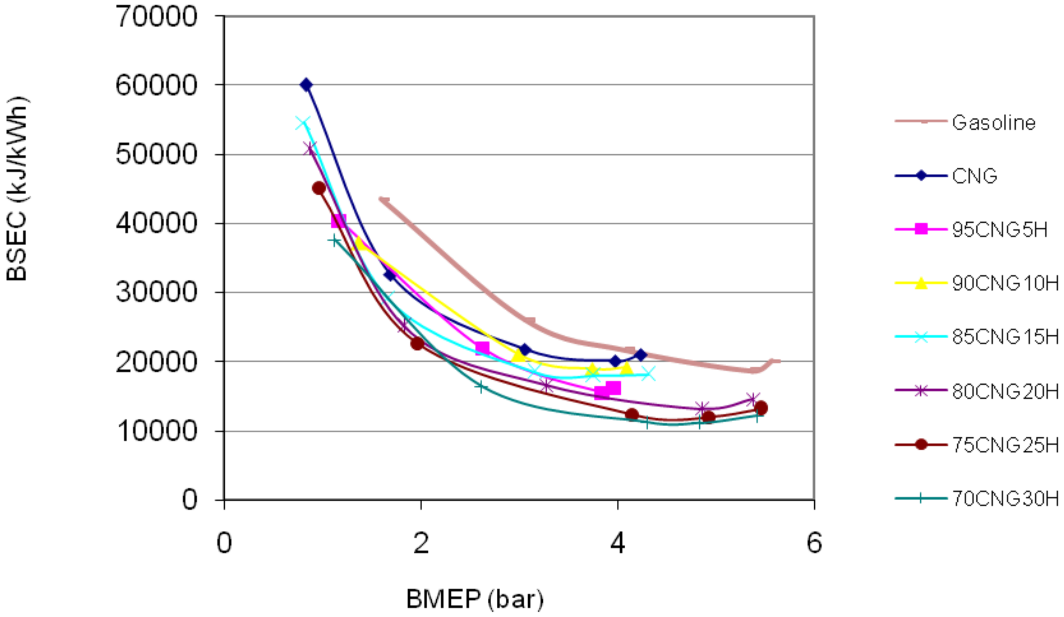

Figure 6. BSEC vs BMEP for different hydrogen blends.

maximum improvement in power up to 25 to 50%.

Brake specific energy consumption (BSEC)

BSEC is an important comparative performance parameter of engines that shows their ability to convert fuel into work. It is a preferred parameter over thermal efficiency as it is expressed in terms of standard and accepted physical units such as: time, power and mass. BSEC is plotted as a function of BMEP, for difference of Hydrogen substitutions at constant throttle and spark timing shown in Figure 6. As is evident from the graphs, BSEC decreases with increase in BMEP and then starts

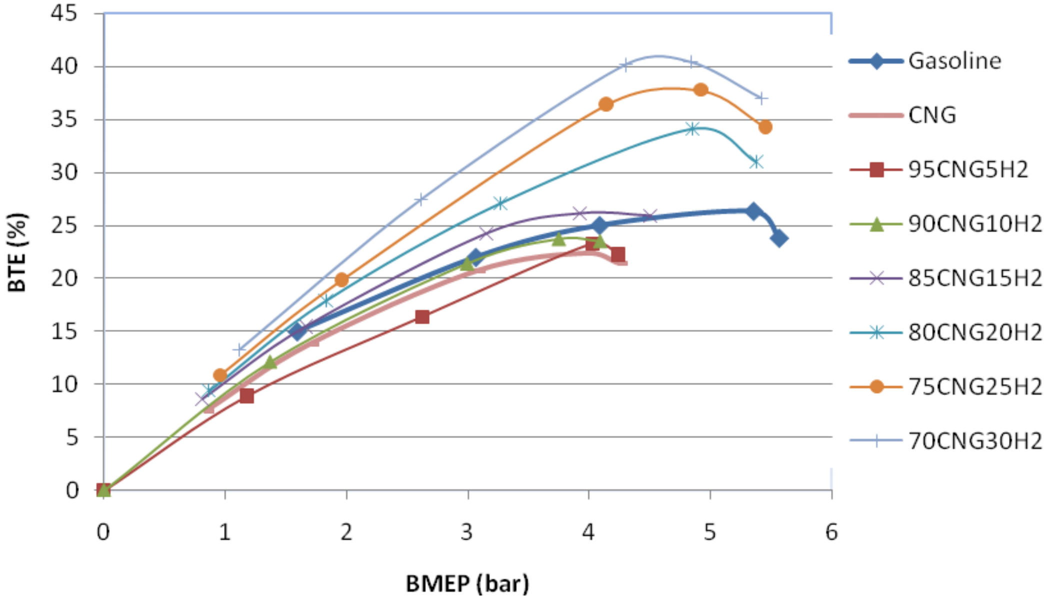

Figure 7. Brake thermal efficiency as a function of brake mean effective pressure for different hydrogen blends.

increasing after a point for entire range of hydrogen substitution to CNG. The minimum point which it attains is the best economical mixture point which occurs at a BMEP of 4.2 bar. A more readily apparent comparison is obtained by plotting BSEC, as heating values of fuel is different. In Figure 6, potential savings of 20-30% in specific energy consumption may be observed.

Brake thermal efficiency (BTE)

Brake thermal efficiency is an important parameter, which provides the readily available engine output shaft power and compares the output of the same engine with different blends of CNG and hydrogen. Figure 7 shows a comparative picture between BTE with respect to the BMEP for different hydrogen supplementations to CNG at constant throttle and spark timing.

Generally, BTE increases as power increases, reaches to a maximum and then decreases for further increase of power, which is observed for all blends. This was realized by experiments and along with this, it was found that blend continues to be the best even on rich mixture side. It was expected to obtain higher BTE with CNG+H_2 blend. Differences in the BTE produced between CNG and CNG+H_2 blend fuel supply became much more significant at higher hydrogen presence (20 to 30%). The maximum BTE of a 70CNG30H_2 blend is 32%. This is about 1.5 times that of CNG supply. Thermal efficiency is also expressed as fuel conversion efficiency and depends on specific fuel consumption of the engine. It is maximum when fuel consumption is minimum. Hence, the reason for the above trends of BTE is expressed in similar manner as that of BSEC.

Exhaust gas temperature

The temperature of the exhaust gas was measured during all the experimental conditions. Figure 8 shows the effect of exhaust gas temperature for different percentage of substitution at a constant throttle, while speed varies from (2000 to 3200 rpm) and the impact of hydrogen substitution rate on exhaust gas temperature may be observed under different load conditions at fixed ignition timing.

As shown in the above figure, exhaust gas temperature increases with increase in hydrogen substitution irrespective of load conditions. As the hydrogen substitution rate increases at a constant throttle and varying load, the preflame reaction time of fuel air mixture increases and the combustion continues into the expansion stroke. The increase in percentage hydrogen and load causes the rise of exhaust temperature by 100 to150°C.

Unburnt hydrocarbons (HC)

The mechanism of hydrocarbons formation is relatively more complicated. The main reason for the formation of hydrocarbons is a distinct combustion in which HCs are formed due to uneven mixture concentration that occurs if the mixture is very lean. These are called unburnt

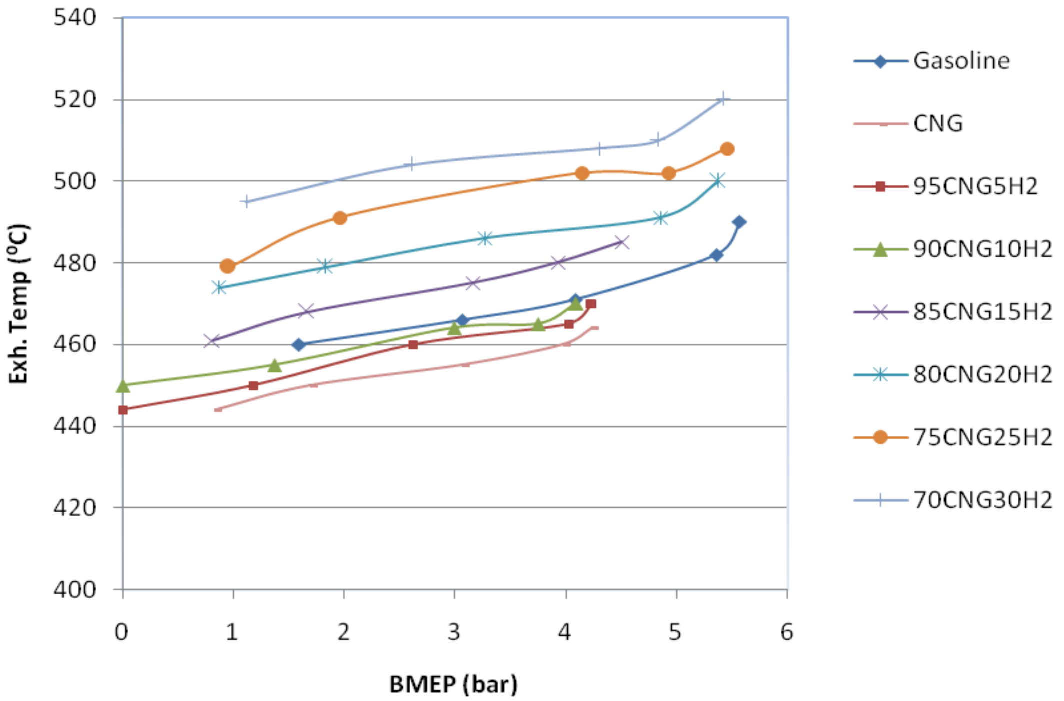

Figure 8. Exhaust gas temperature vs BMEP for different CNG-hydrogen blends.

hydrocarbons (UHCs). Hydrocarbon formation also is a function of available air. A better degree of combustion takes place up to the point where there is too little fuel. Another source is non-methane hydrocarbons which are strong functions of the natural gas composition.

During the flame quenching, HCs tend to form near the vicinity of metallic surfaces of cylinder walls or cylinder heads which are relatively cooler. At these locations the flame front is quenched and the fuel does not burn. A typical variation of hydrocarbon emission as a function of brake mean effective pressure is shown in Figure 9. From the graph it is observed that there is a reduction in hydrocarbons with increase in brake mean effective pressure due to improvement in combustion. As blend of CNG and hydrogen is in a gaseous state, the mixing of percentage hydrogen and natural gas with the air is much better and a condition leading to distinct combustion does not usually take place resulting in the reduction of HC emissions. Also, with increase in temperature of cylinder, the engine runs hotter thereby facilitating improved combustion. The concentration of HCs decreases with an increase in BMEP up to a certain value and then it starts increasing. The minimum value with $70CNG30H_2$ is observed to be 0.1 g/kWh.

Nitrogen oxides (NO_x)

NOx formation in an engine is primarily a function of reaction temperature and duration and availability of oxygen in the combustion chamber. The combustion temperatures and the availability of oxygen govern NOx formation. Running an engine on either very lean or very rich mixtures reduces NOx formation. In the former case, the temperature is lowered, and thus thermal environment is not adequate of NOx formation. In an environment of increased oxygen supply, the burning temperature is higher and subsequently, NOx formation increases.

Figure 10 represents the variation of NO_x concentration with load and hydrogen substitution percentage. It is observed that as substitutions increases, the level for NO_x increases at all loads up to 30 percent hydrogen substitution and exhibits an increasing trend later on with higher substitution. This is so because increase in smaller amount of hydrogen gas substitution ensures higher BMEP.

Further, it has been observed form the trend that for a fixed load and also for a fixed amount of hydrogen substitution, the NO_x emission rate increases. NOx formation in blend of natural gas and air is dependent on factors such as reaction temperature, oxygen availability and residence time for its kinetic process to occur. Because of the influence of combustion temperature, increasing combustion temperature tends to bring about increasing NOx concentration. Thus any method which increases the peak temperature in the engine cycle, would also increase the NOx emissions. The maximum value of NOx is observed at 22 g/kWh for 30%Hydrogen between 16:1 to 22:1 air fuel ratio.

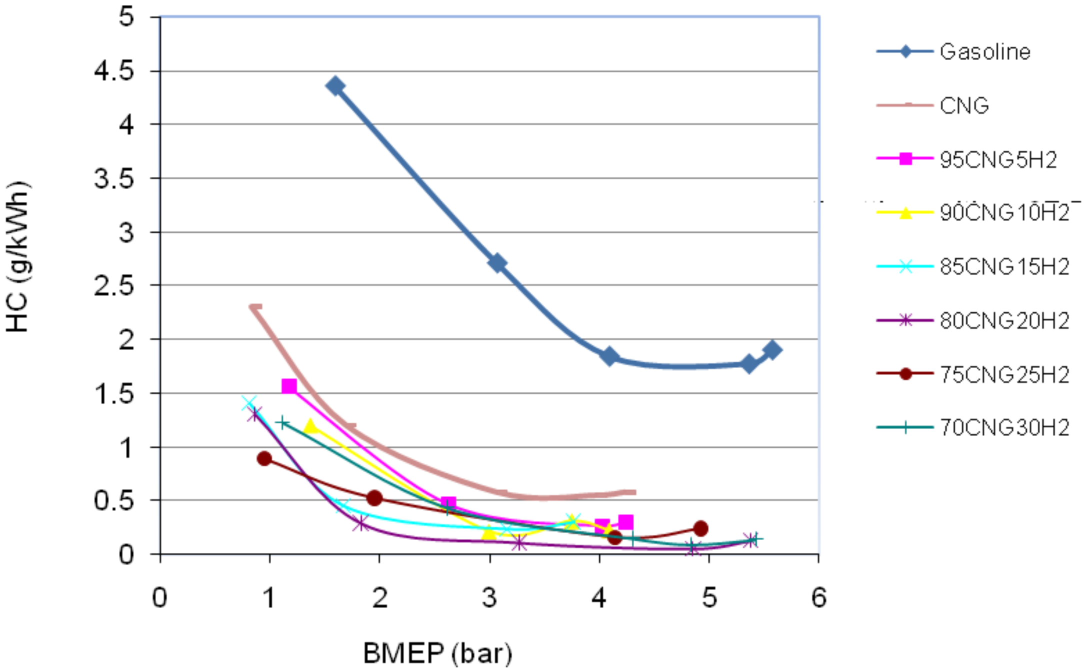

Figure 9. Hydro carbon emissions vs brake mean effective pressure for different hydrogen blends

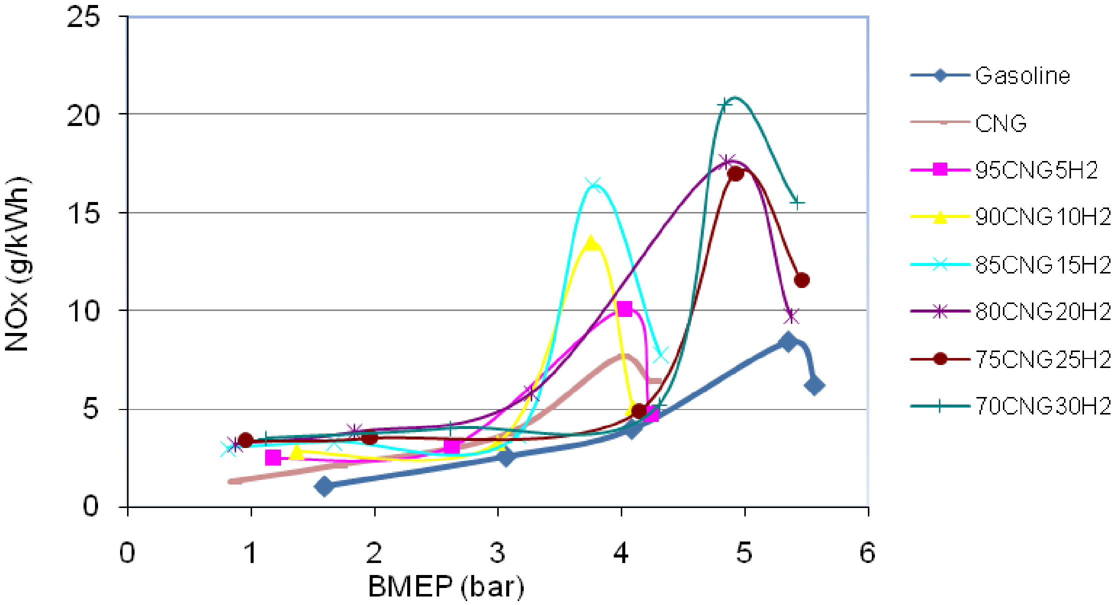

Figure 10. Nitrogen Oxide Emissions vs Brake Mean Effective Pressure for different Hydrogen blends.

Carbon monoxide (CO)

Carbon monoxide occurs only in engine exhaust. It is a product of incomplete combustion due to insufficient amount of air in the air fuel mixture or insufficient time in the cycle for completion of combustion. By better mixing of fuel with air and by providing more air, complete combustion can be achieved. As far as gasoline engine is concerned it also depends upon the degree of the fuel either vaporized (carbonized or gasified) and thoroughly mixed. Due to this, gasoline engines produce a large portion of CO during the cold start, when the fuel is

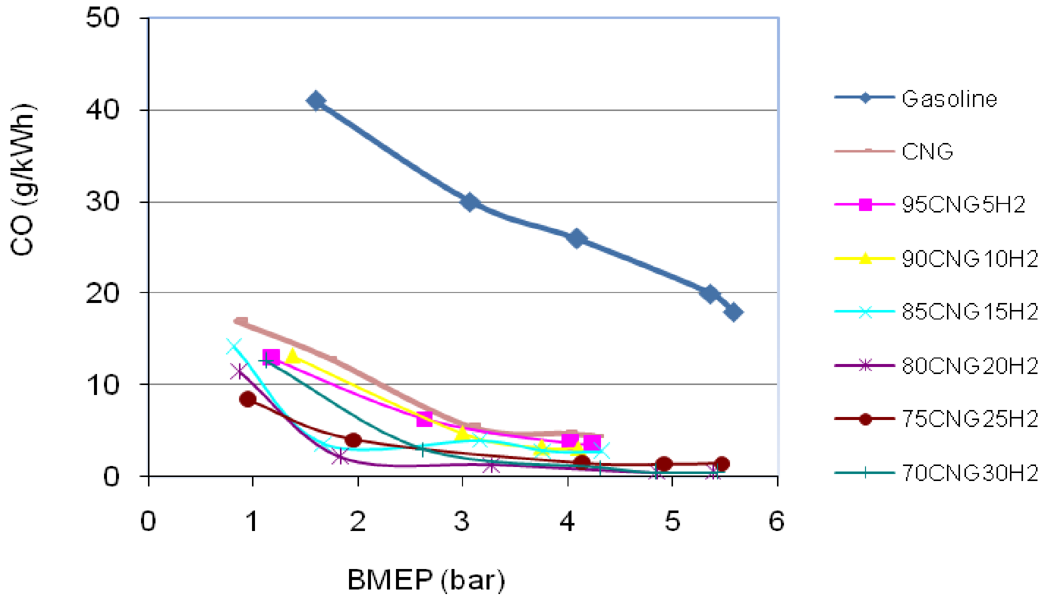

Figure 11. Carbon monoxide emissions vs brake mean effective pressure for different hydrogen blends.

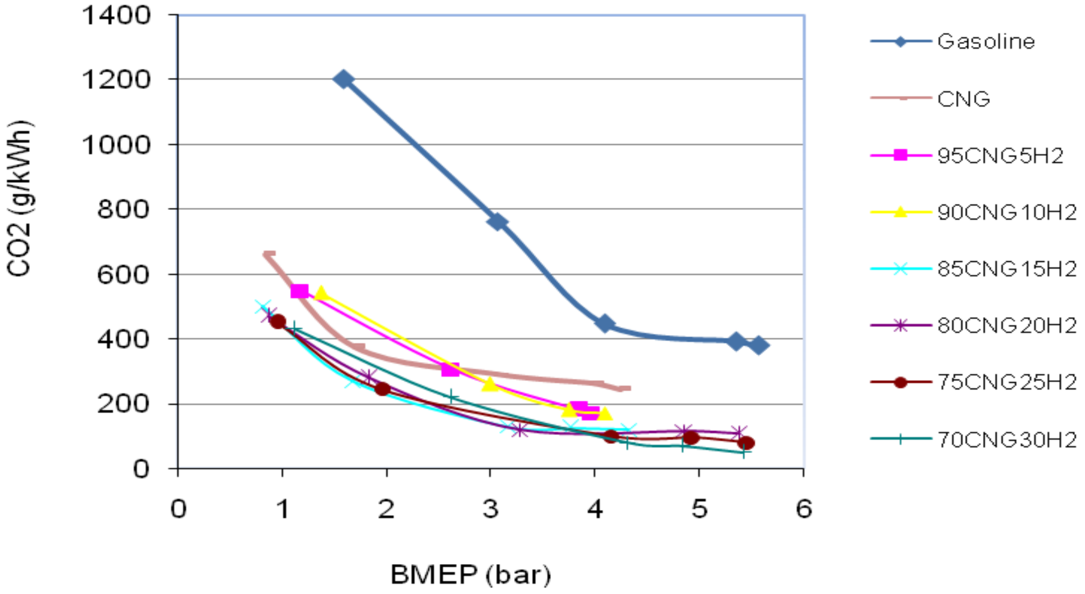

Figure 12. Carbon dioxide emissions as a function of brake mean effective pressure at constant throttle for various hydrogen blends.

incompletely vaporized and poorly mixed, where the mixture is poor in quantity or air. A blend of percentage hydrogen with CNG carbonization and mixing with air is an easy task because of the diffusivity of high-pressure gaseous fuel. So the CNG runs leaner than gasoline and gives lower level of CO.

The variations of CO exhaust emissions as a function of BMEP for various blends are shown in Figure 11. It is observed from this, that the CO emissions reduces with an increase in BMEP up to a certain point and then starts increasing. The CO level is reduced because more complete combustion takes place with CNG and hydrogen blend. The approximate value with 30% hydrogen addition is 0.5 g/kWh.

Carbon dioxides (CO_2)

Figure 12 illustrates CO_2 values versus BMEP for various percentage hydrogen additions. As seen in this figure,

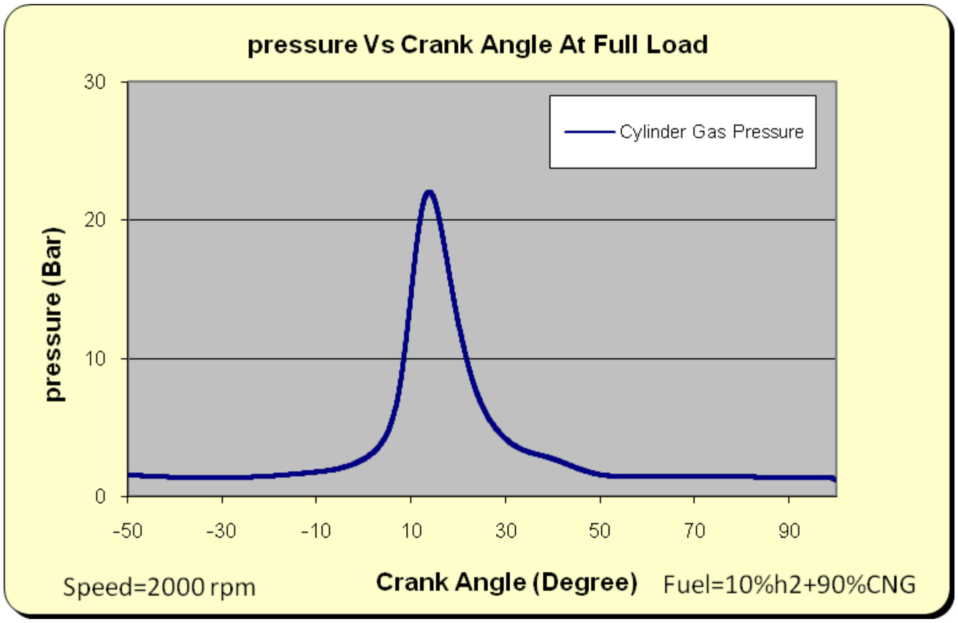

Figure 13. Peak pressure at 22 bars for CNG+10%H_2.

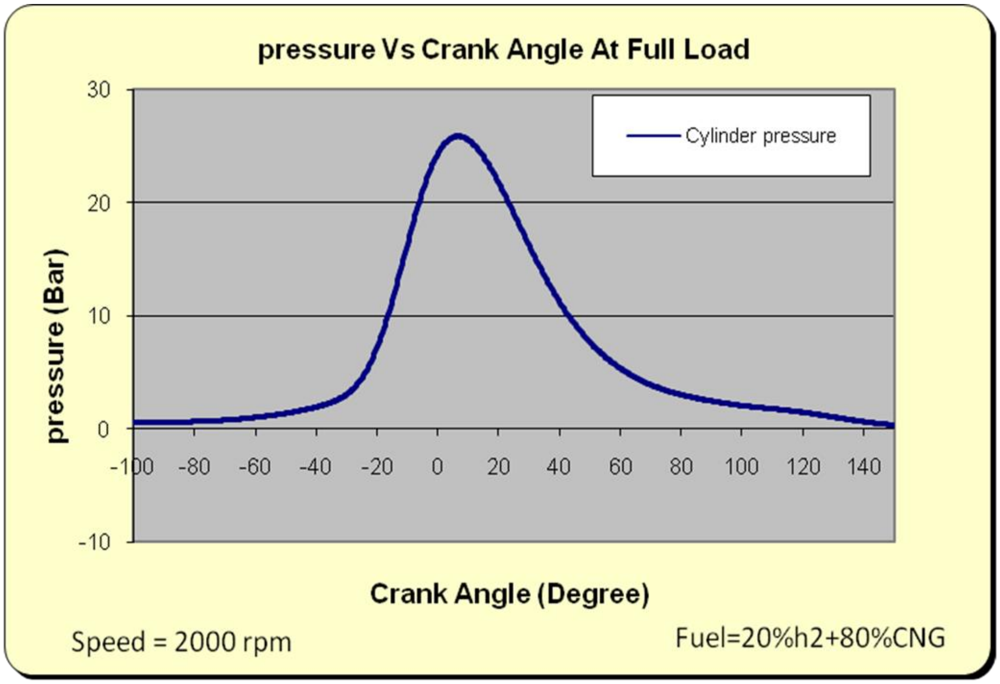

Figure 14. Increase of peak pressure at 26 bars for CNG+20%H_2.

with increasing hydrogen percentage, brake specific carbon dioxide values decreases as compared to gasoline engine. The reasons for decrease in the CO_2 emissions are due to improvement in combustion. Hydrogen addition up to 30% decreased CO_2 approximately 200 g/kWh (26%).

Combustion analysis of gasoline and CNG-hydrogen fuel blends

Figure 13 shows that the peak pressure at maximum power was about 22 bars with CNG+10%H2 at a speed of 2000 rpm and at full load. Furthermore, Figure 14 shows

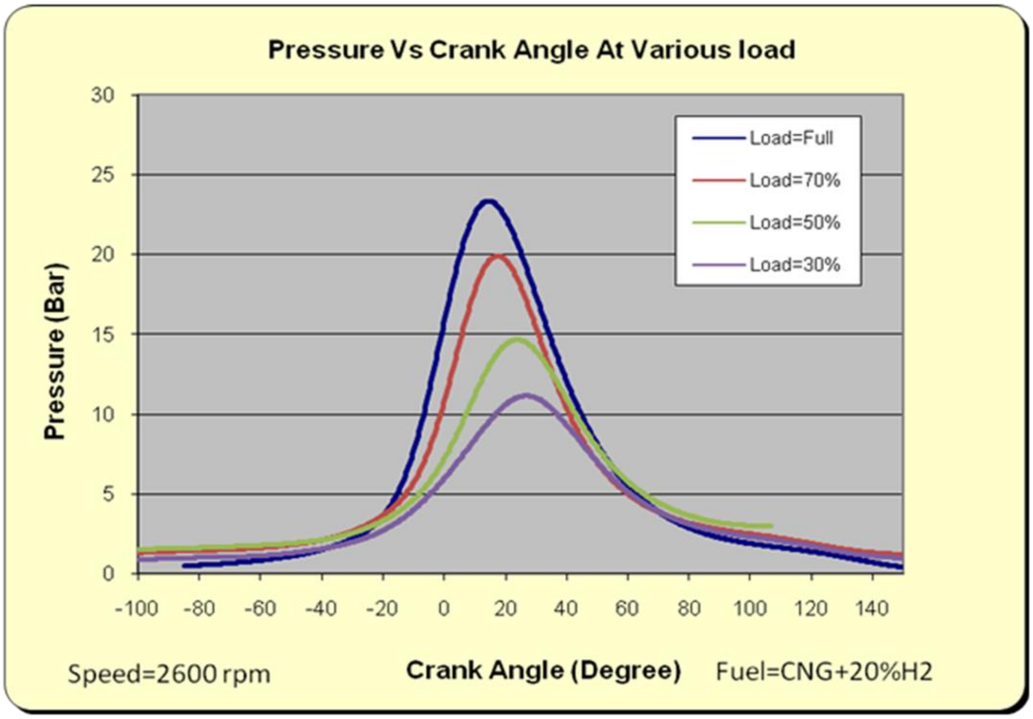

Figure 15. Peak pressure at 24 bar.

an increase of peak pressure to 26 bars for CNG+20%H_2 for the same operating condition that is, full load and same speed. It is clear from the figures that maximum cylinder gas pressure increases with increasing hydrogen contents in CNG and hydrogen blend. Peak pressure mainly depends on the combustion rate in the initial stages, which is influenced by the fuel taking part in uncontrolled heat release phase. Maximum peak pressure values are increased and found to be close to the top dead center. The engine reached its highest efficiency when maximum pressure occurred at 17.29 ATDC and 13.69 ATDC degree crank angle for CNG+10%H_2 and CNG+20%H_2 respectively.

The trend of increase in peak pressure is due to higher energy release rate. The higher energy release is due to complete utilization of the air. Figure 15 shows the peak pressure of about 24 bar at maximum power. Peak pressure is further decreased as the load is reduced and there is a drop in peak pressure. The peak pressure values were noticed for 30%, 50% and 70% and full load at 16, 13, 12 and 12 degree crank angle ATDC respectively. The effect of speed on combustion characteristics gas pressure in the cylinder of an engine varies throughout the Otto four-stroke engine cycle. The engine speed determines the point at which the fuel/air mixture stops flowing into the cylinder. At lower revolutions per minute (rpm), the start of compression is closer to Inlet Valve Closes; at higher speeds, it is closer to bottom dead centre. The volume of the cylinder during intake increases as the piston descends, thereby drawing in the fuel mixture. There is little resistance to gas flow into the cylinder, which causes the pressure in the cylinder to remain relatively constant and equal to the inlet pressure.

Work is done on the gases by the piston during compression and the gases produce energy through the combustion process. These changes in energy combined with changes in the volume of the cylinder lead to fluctuations in gas pressure. Figure 16 shows 2000 rpm and 2600 rpm engine speed for CNG+10%, these values are obtained at 13 and 12 degree crank angle ATDC respectively.

Generally, the engine can reach its highest efficiency when maximum pressure occurs at 5-15°. The experimental results shows that, with the increase of hydrogen fraction in the mixture, the normalized mass burning rate increases while the flame development duration and the total combustion duration decrease with the increase of the hydrogen fraction in natural gas-hydrogen blends as shown in Figure 17. The maximum pressure increases with the increase of the hydrogen fraction in the mixture for lean mixture combustion.

CONCLUSION

Comprehensive experimental study using hydrogen as a substitute fuel in stationary motor cycle engine brings out

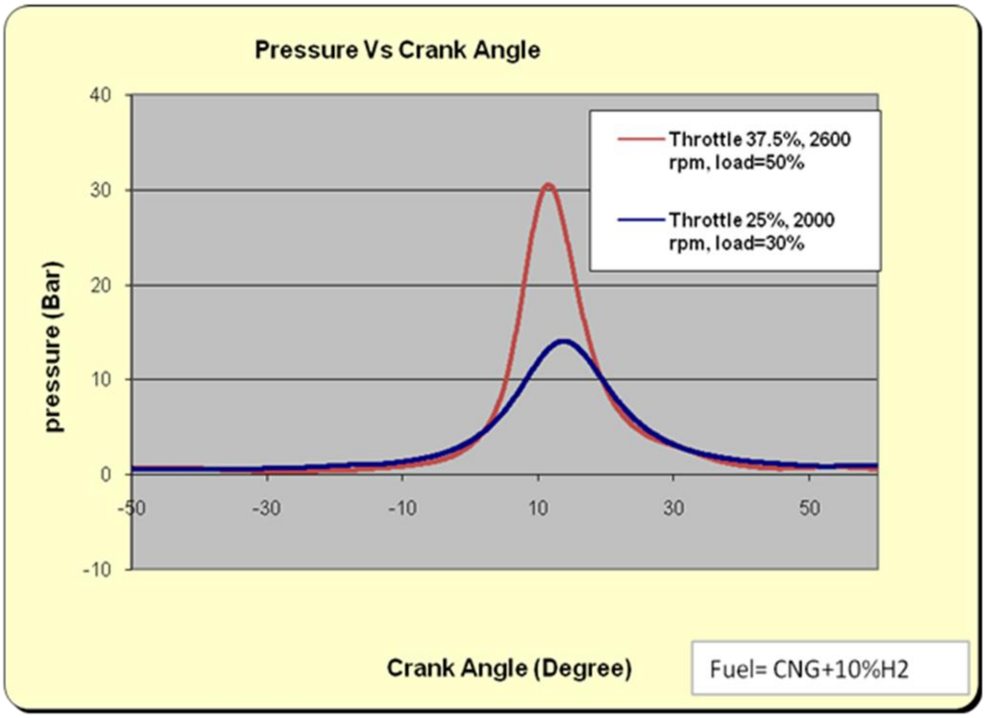

Figure 16. Shows variation in engine speed for CNG+10%.

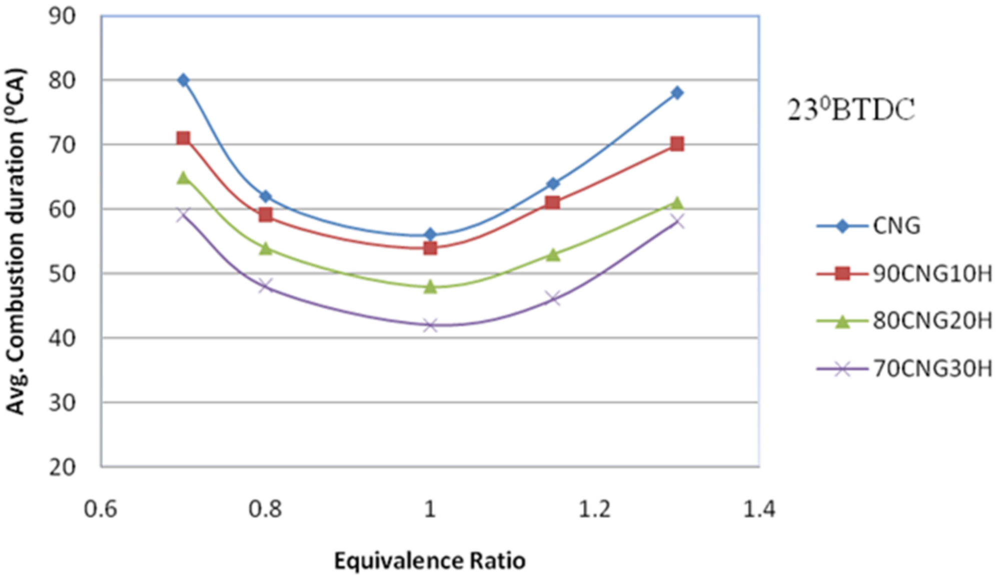

Figure 17. Maximum efficiency of hydrogen fraction in natural gas-hydrogen blends.

the following conclusions:

(1) Mixing a small percentage of hydrogen and CNG and supplying it to the engine very clearly shows that hydrogen gas could be easily substituted up to 30% in CNG in S I engine.

(2) A better or comparable performance was obtained with about 20 to 30° by volume wise substitution of hydrogen fuel under all load conditions.

(3) Brake thermal efficiency increases by 20% and brake specific energy consumption values decrease by 14% with increasing hydrogen.

(4) HC and CO emissions values decrease by 30% and 80% respectively.
(5) Marginal increase in exhaust temperature level was observed.
(6) An increase in the level of NOx emissions values by 13% takes place with addition of hydrogen to CNG.
(7) CNG replacement reduces as hydrogen substitution rate is increased.
(8) Exhaust gas temperatures are higher in the hydrogen enriched mode of operation due to faster combustion and high temperature reached in the cylinder.
(9) Hydrogen enrichment of natural gas enhances combustion characteristics of the engine.

The tests show that the optimum concentration of hydrogen in the fuel mixture for producing a power gain appears to be about 20-30% by volume over the range of conditions considered. Higher hydrogen contents undermine the knock resistance characteristics of natural gas, lower power output of the engine and increase of the fuel cost.

ACKNOWLEDGEMENT

The authors gratefully acknowledge all technical staff of IIT, Delhi associated with providing information, assistance, guidance, encouragement and support during this study.

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