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Development of HCNG Blended Fuel Engine with Control of NOx Emissions

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Abstract

With increasing concern about energy shortage and environmental protection, research on reducing exhaust emissions, reducing fuel consumption, reducing engine noise and increasing specific outputs has become the major researching aspect in combustion and engine development. Alternative fuels such as CNG, HCNG, LPG, LNG, Bio-Diesel, Biogas, Hydrogen, Ethanol, Methanol, Di-Methyl Ether, Producer gas, P-series have been tried worldwide. Hydrogen as a future fuel for IC engines is also being considered. But several obstacles have to overcome before commercialization of Hydrogen as an IC engine fuel for automotive sector. Hydrogen and CNG blends (HCNG) may be considered as an automotive fuel without any major modification in the existing CNG engine and infrastructure.

A strategy has been worked out for converting the optimised CNG engine to run on HCNG. The testing is carried out for the neat CNG and 5% blends of Hydrogen by volume with CNG. It is observed in the experimental work that the HCNG engines are more superior to CNG engines from fuel economy, power output and emission compliance point of view. The power improvement of 3 to 4%, torque improvement of 3% and fuel consumption reduction of 4% is observed in HCNG engine than the neat CNG engine.

The HCNG engine increases the H/C ratio of the fuel, which drastically reduces the carbon based emissions such as CO, CO_2 and HC. To increase the flame speed of HCNG engines, the ignition timing needs to be retarded; this results in reduction of NOx emissions. The HCNG reduced CO emissions by 40 to 50%, NMHC emissions by 45% and NOx emissions by 20 to 30% than the neat CNG operation. It shows that the blended HCNG fuel is more environmental friendly.

It is important to note that 5% blends of hydrogen by volume with CNG the phenomenon of hydrogen embrittlement does not occur with respect to engine components, hence no major change is anticipated in fuel system and engine components.

This research work is undertaken to demonstrate the viability of HCNG as an automotive fuel at Powertrain Engineering laboratory ARAI, Pune, India. This paper explains how CNG is the best route to ensure an early entry of hydrogen fuel into our energy infrastructure.

Key words. Natural gas engine, HCNG, CO, NMHC, NOx Emissions.

1. Introduction

Due to limited reserves of crude oil and environmental protection, development of alternative fuel engines has become more attractive in the engine development. Most of the initial interest in alternative fuels started after the oil crisis in the 1970s.The fuels such as CNG, HCNG, LPG, Bio-Diesel and Biogas are the most promising alternative fuels for India. Natural gas is a fossil fuel, clean burning, cheap and abundant in many parts of the world.

1.1. Gaseous Fuels

Gaseous fuels are best suited for IC engines. The present trend of alternative fuel utilization shows that gaseous fuels have a promising future. The specific features of gaseous fuels leads to its application potential in IC engines.

- Gaseous fuels mix uniformly with air to produce a mixture, which burns more completely than the liquid fuels.
- Physical delay is almost nil.
- Gaseous fuels generally build up minimum carbon deposition.
- Quantity of contaminating residues is very small.

1.2. Previous work and evidence for most suitable HCNG blend

Munshi, et al. [8] evaluated various blends of HCNG engines for heavy duty applications. The test results indicate that 25% hydrogen by volume in HCNG has the highest average NOx reduction. Shioji M, et al. [5] have reported that in a condition of a higher hydrogen ratio and a higher equivalence ratio, a higher compression ratio suffers the rapid combustion and the increase in heat loss into the chamber wall, from which the improvement of thermal efficiency could not expected.

Huang Z, et al [1] stated that the ignition timing has significant influence on engine performance, combustion and emissions of HCNG engine. For specific ignition timing, both mean effective pressure and effective thermal efficiency increases with the increase of hydrogen fraction in natural gas. With advancing the ignition timing, the exhaust HC concentration decreases and exhaust NO_x concentration increases while the exhaust CO gives little variation under various ignition timings.

Thipse S S, et al [2] observed in their experimental work that the CNG injection engines are more superior to CNG carbureted engines from fuel economy, power output and emission compliance point of view. The power improvement of 11% and fuel consumption reduction of 8% is observed in CNG injection than the CNG carbureted engine. It is important to note that up to 30% blends of hydrogen by volume with CNG the phenomenon of hydrogen embrittlement does not occur with respect to engine components, hence no major change is anticipated in fuel system and engine components. Moreover, it improves the engine efficiency, which lowers fuel consumption and hydrocarbon emissions. To increase the flame speed of HCNG engines, the ignition timing needs to be retarded; this results in reduction of NOx emissions.

It is observed that very low NOx can be achieved with lean HCNG mixtures [3][4][10]. Collier, et al. [7] have reported that approximately 30% hydrogen by volume, will make a significant difference in the relationship between NOx and total hydrocarbon emissions when compared to natural gas alone. It is observed that a standard CNG engine, with appropriate spark, air-fuel ratio, and engine rpm control, could be converted to operate on mixtures of natural gas and hydrogen and produce NOx emissions below any currently proposed standard. Hydrogen addition reduces intake temperatures required for natural gas HCCI engine [9].

Das L M, et al [6] have referred in their research work the HCNG system as Hydrogen Added Natural Gas (HANG) system. It is reported that 15% of hydrogen addition by energy basis to a CNG fuelled engine extends the lean misfire limit from 1.20 for neat CNG to 1.46. HANG system demonstrated significant improvement in the brake thermal efficiency and power output.

1.3. Hydrogen use in IC engines

Hydrogen is the clean burning and renewable fuel. Hydrogen is the most abundant element on the earth. The combustion and emissions characteristics of hydrogen are superior to any other competing fuel. It requires very low ignition energy and has a high heat of combustion. Hydrogen is the lightest element, being about eight times lighter than methane. Compacting it for storage or transport is expensive and energy intensive. Another rationale for making hydrogen is that it is a way to store energy. That could benefit renewable energy sources like wind and sunlight that cannot generate energy on demand. Hydrogen is regarded as the best gaseous candidate for natural gas due to its very fast burning velocity. Hydrogen may be used in IC Engines in the following forms.

- Neat Hydrogen
- Hydrogen supplementation (Petrol+ Hydrogen)
- Hydrogen + CNG (HCNG)
- Dual Fuelling (Diesel + Hydrogen)

1.4. Hydrogen blending with CNG

Traditional homogeneous spark-ignition natural gas engine has the disadvantage of low volumetric efficiency because natural gas occupies a fraction of intake charge which reduces the fresh air into the cylinder, this results in reduction of the power output compared to that of gasoline engine. Meanwhile, homogeneous charge combustion has difficulty to burn the lean mixture. Due to the slow burning velocity of the natural gas, the natural gas spark-ignition engine has the disadvantage of large cycle-by-cycle variations and poor lean-burn capability. Due to these restrictions, a natural gas engine is usually operated at the condition of stoichiometric equivalence ratio with relatively low thermal efficiency.

Traditionally, to improve the lean-burn capability and flame burning velocity of the natural gas engine under lean-burn conditions, an increase in flow intensity in cylinder is introduced, and this measure always increases the heat loss to the cylinder wall and increases the combustion temperature as well as the NO_x emission. One effective method to solve the problem of slow burning velocity of natural gas is to mix the natural gas with the fuel that possesses fast burning velocity. Hydrogen is regarded as the best gaseous candidate for natural gas due to its very fast burning velocity, and this combination is expected to improve the lean-burn characteristics and decrease engine emissions. The hydrogen blends in CNG can range from 5 to 30% by volume. Hythane is 15% blend of hydrogen in CNG by energy content, which is patented by Frank Lynch of Hydrogen Components Inc, USA [2]. A typical 20% blend of hydrogen by volume in CNG is 3% by mass or 7% by energy.

Table 1. Overall comparison of properties of hydrogen, CNG, HCNG and gasoline.

Properties	H_2	CNG	HCNG	Gasoline
Stoichiometric composition in air, vol %	29.53	9.48	22.8	1.76
Limits of Flammability in air, vol %	4-75	5-15	5-35	1.0-7.6
Auto Ignition Temp, K	858	813	825	501-744
Flame Temp in air, K	2318	2148	2210	2470
Minimum energy for Ignition in air, mJ	0.02	0.29	0.21	0.24
Burning velocity in NTP air, cm s^{-1}	325	45	110	37-43
Quenching gap in NTP air, cm	0.064	0.203	0.152	0.2
Diffusivity in air, $cm^2 s^{-1}$	0.63	0.2	0.31	0.08
Percentage of thermal energy radiated	17-25	23-33	20-28	30-42
Normalised Flame Emissivity	1.00	1.7	1.5	1.7
Equivalence ratio	0.1-7.1	0.7-4	0.5-5.4	0.7-3.8

An overall comparison of properties of Hydrogen, CNG, 5 % HCNG blend by energy and Gasoline is given in Table 1 . It is to be noted that the properties of HCNG lie in between those of Hydrogen and CNG.

2.Experimental set-up

2.1. Baseline CNG engine

The baseline engine used for this research work at ARAI, Pune is 4 cylinder, 3 litre naturally aspirated diesel engine which is converted into a CNG engine by addition of a suitable CNG fuel-system kit, an electronic ignition system etc. The selection of suitable piston geometry was done to obtain a reduced compression ratio of 11.2:1. The specifications of the baseline Tata 4 SP NA CNG engine are given in Table 2.

Table 2. Specifications of the baseline engine

Parameter	Specification
Bore (mm) x Stroke (mm)	97x 100
No. of cylinders	4
Rated speed (rpm)	3200
Swept volume (cc)	2955
Aspiration	Naturally Aspirated
Cooling system	Water cooled
Compression ratio	11.2:1
Idle speed (rpm)	900 – 950
Valve overlap	49 ° CA

The baseline CNG engine is compliant with BS-II emission norms, as determined by conducting the 13 mode ESC cycle. The schematic diagram and the experimental set-up of the baseline engine is shown in Figure 1.

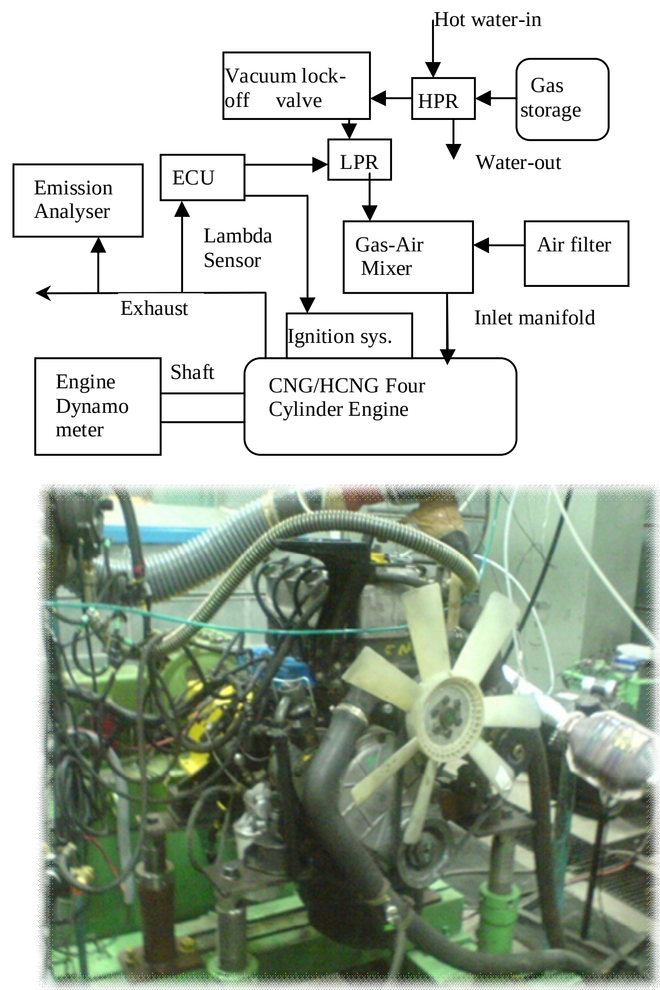

Figure 1. Schematic diagram and experimental set-up of the baseline engine

2.2. CNG/HCNG fuel feed system

The baseline CNG engine employed a CNG fuel feed system from IMPCO, consisting of an HPR, LPR, and a gas-air mixer (model CA 125). The Electronic control unit (ECU) is developed by TL.

Table 3. Key components of the CNG/HCNG Fuel system

Component	Function	Input	Output
High Pressure Regulator (HPR)	Initial reduction of CNG/HCNG pressure from storage pressure.	200 bar	11 bar
Low Pressure Regulator (LPR)	Reduction of gas pressure in two stages to supply gas to Gas-Air mixer. This is also part of the closed-loop control system used to closely control the air-fuel ratio of the charge.	11 bar	0.01 bar
Solenoid operated Gas shut-off valve	This valve is used to isolate the gas from the engine when the engine is not operating as a safety feature and is also used for governing of the engine speed.		
Vacuum Lock-off Valve	This is vacuum operated gas shut-off valve used as a safety feature and also contains the replaceable element for filtering the gas.		
Gas-Air Mixer	Controlled mixing of gas and air to achieve stoichiometric air-fuel ratio at all engine operating conditions.		
Electronic Control Unit (ECU)	The ECU maintains the air-fuel ratio by monitoring the signal received from the Oxygen sensor in the exhaust manifold. It controls the duty-cycle of the fuel metering solenoid valve, thereby regulating the supply of CNG from the LPR to the Gas-Air Mixer.		

The flow rate of gas and the instantaneous pressure depend upon the engine developed vacuum applied to one side of the diaphragm of the LPR. The engine vacuum is proportional to the load on the engine.

3.Engine testing

3.1.Initial CNG engine test

The initial test is carried out on the baseline CNG engine by conducting the 13-mode Engine Steady-State Cycle (ESC) for the compliant of BS-II emission norms. With a view to minimizing development and manufacturing costs, along with development time, it was decided to retain the principal parts of the baseline CNG engine, including the cylinder head, piston, the combustion chamber, and the valve-train. In order to achieve the desired objectives of reduction in emissions and improvement in performance, the development work therefore focused only on optimization of the fuel-system, the ignition-system, and after treatment. The idea was to achieve the required stringent control over the air-fuel ratio by improving the combustion process inside the combustion chamber, and to have effective treatment of the engine out pollutants.The initial CNG test results compliant with BS-II emission norms are shown in Table 4.

Table 4. Initial CNG test results compliant with BS-II norms

Pollutant	BS-II Norms	Initial CNG test results
CO (g/kWh)	4.0	2.95
HC (g/kWh)	3.66	0.05
NMHC (g/kWh)	1.1	0.017
NOx	7.0	1.52

4.Engine optimisation

Several optimisation steps were undertaken to upgrade the existing baseline four cylinder BS-II CNG engine to obtain improvements in the performance and fuel economy of the engine and achieve compliance with BS-III emission norms to finalise the CNG engine configuration.

4.1.Exhaust system

The diameter of the exhaust pipe is increased, which helped to reduce the vehicle’s pass-by noise to ensure compliance with the current noise norms. Also the increase in the diameter of the exhaust piping resulted in a reduction in the exhaust back pressure from 160 mbar to 105 mbar. This boosted the full-throttle torque output of the engine and helped to improve the specific fuel consumption.

4.2.Selection of suitable spark plug

The non-resistive type spark plug is used in the baseline BS-II CNG engine. During the vehicle- level Electromagnetic Interference (EMI) tests, unacceptably high levels of EMI are recorded, which are attributed to the use of the non-resistive type spark plug. To reduce the EMI levels to acceptable values, resistive type spark plugs are selected for the present development, which successfully reduced the EMI to acceptable levels of BS-III norms.

4.3.Optimisation of spark energy

The changeover to a resistive type spark plug introduces an additional resistance in the ignition circuit, causing a decrease in the spark energy, tending to increase in the mass emissions of HC and CO compared to the values obtained with the non-resistive spark plugs. In order to maintain the emissions at the target levels, the spark energy was therefore boosted by suitably increasing the " coil-on-time" (dwell time) setting in the Igniter ECU, thereby increasing the output of the H.T. coils and ensuring complete combustion of the CNG fuel.

4.4.Optimisation of ignition timing

Ignition timing curve of the baseline engine was 15° btdc to 21° btdc from idling speed to rated speed (950 rpm to 3200 rpm). To achieve the power and torque performance and to meet 13 mode ESC mass emission test of CNG engine, ignition timing was optimised for each speed and load. The optimised ignition timing is 7° BTDC to 35° BTDC which has resulted into a flat torque curve at FTP.

4.5.Optimisation of fuel flow

Prototype diaphragms with various shims, specially designed for BS-III applications by M/s Minda Impco were tried. Combination of shims with prototype diaphragm and position of power screw is optimised in such a way that Lambda remains in a tolerance band close to unity at full throttle as well as part throttle application.

4.6.Optimisation of ECU control map

The ECU minutely controls the instantaneous output pressure of the CNG from the low pressure regulator and thus the instantaneous air-fuel ratio of the gas–air mixture supplied to the engine. This ECU is selected from the point of view of calibration access to individual load and speed. ECU is calibrated in such a way as to achieve the targeted performance of power and mass emission.

4.7. Diaphragm and power screw of air-gas valve

Gas flow to engine was optimized by varying shims & position of power screw. ESC BS-III 13 mode test results show that maximum power and torque with minimum emission is in case of power screw position at 80% & prototype diaphragm having 3 shims.

4.8.Lambda Variation

After carrying extensive trials, it is observed that route cause of problem for non meeting stringent emission norms is variation in lambda is due to improper mixing. Variation in lambda in closed loop system was found to be minimal in elbow mixing tube resulting in sufficient margins (more than 50%) than any other configuration tested.

4.9.Optimisation of low pressure regulator

The output pressure of the CNG from the Low Pressure Regulator can be adjusted by varying the spring preload of the secondary diaphragm. Based on the recommendations from the fuel system manufacturer, the setting is selected to obtain a pressure 120 to 140 mm of water-column at engine idling conditions.

5.Test results and discussion

For ESC 13-mode cycle, conditioned air at pressure of 100 kPa with relative humidity of 50% is fed to engine. Several engine tests are conducted on engine dynamometer. CNG flow of the engine has been optimised for maximum power and idle operation of the engine. It was decided to run the engine from 1200 rpm to 3200 rpm, at the interval of 200 rpm, for full throttle condition. Engine parameters were also recorded at the basic performance related data such as power, SFC, various temp. and pressures. Fuel flow is adjusted such that to achieve the max power and to operate the lambda in narrow band. Apart from the full throttle performance, fuel flow is optimised for 13 mode ESC cycle to achieve the targeted emission performance.

A strategy has been worked out for converting the developed CNG engine to run on HCNG. The testing is carried out for the neat CNG and 5% blends of Hydrogen by volume with CNG. The test results of optimized CNG engine and HCNG engine are given in Table 5.

Table 5. Test results of CNG and HCNG engine

Parameters	CNG Engine Performance	5% HCNG Engine Performance
Corr. Rated Power (kW) @3200 rpm	51.14	53.04
Corr. Max. Torque (Nm) (@1800 rpm)	198.53	199.28
Obs. BSFC @ 3200 rpm at max. Power (g /kW–hr)	278.4	268.19
Obs. BSFC at @ 1800 rpm at full load (g /kW–hr)	229.35	232.46
BMEP (bar) @ 3200 rpm at max. Power	6.49	6.73
BMEP (bar) at @ 1800 rpm at full load	8.24	8.49
BTE (%) @ 3200 rpm at max. Power	26.35	25.55
BTE (%) @ 1800 rpm at full load	31.99	29.51
Air inlet temp (Approx.)	27° C	27° C
Exhaust Temp (max)	722° C	731° C
Water out Temp (max)	84° C	83.2° C
Oil Temp (Sump - max)	101.1° C	104.16° C

6. Performance characteristics

6.1. Brake power and torque

Engine performance is verified by comparing the torque curve. The torque curve demonstrates the capability of the engine to maintain full load under HCNG fuelling. Results are shown in Figure 10.1 and 10.2 comparing full torque achieved under CNG and HCNG fueling.

As seen from the test results the HCNG torque is either equal to or slightly higher than the CNG torque. The HCNG achieves the peak torque of 199.28 Nm against the 198.53 Nm of CNG engine at 1800 rpm and a rated torque of 158.17 Nm against 155.22 Nm of CNG at 3200 rpm. The corresponding results of the engine power are shown in Figure 2 and Figure 3. The HCNG engine achieves a rated power of 53.04 kW against 51.14 kW of CNG engine at 3200 rpm rated speed.

In the experimental work the Power improvement of 3 - 4 % is observed in HCNG engine than the CNG engine and the Torque is slightly improved about 2 - 3 % in HCNG engine than the CNG engine.

6.2. BSFC

Brake specific fuel consumption is very important characteristic for comparing the performance of CNG and HCNG engine. Figure 4 shows the BSFC plotted against the engine speed, for the same engine operating under the same conditions. It shows that the BSFC drops as the speed is increased in the low speed range, nearly levels off at medium speeds, and increases in the high speed range. At low speeds, the heat loss to the combustion chamber walls is proportionately greater and combustion efficiency is poorer, resulting in higher fuel consumption for the power produced. At the high speeds, the frictional power is increasing at a rapid rate, resulting in a slower increase in brake power than in fuel consumption, with a consequent increase in BSFC.

It is observed during experimentation that due to addition of hydrogen in CNG the engine is operated at leaner side than the CNG engine which reduced the fuel consumption about 4% than the CNG engine. It shows that addition of hydrogen into natural gas increases the burning velocity of the mixture which shortens the combustion duration and increases the cylinder gas temperature. It shows that by blending Hydrogen with CNG the fuel consumption reduces.

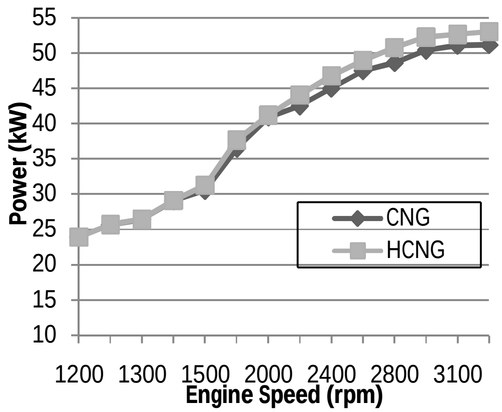

Figure 2. Power Comparison of CNG and HCNG Engine

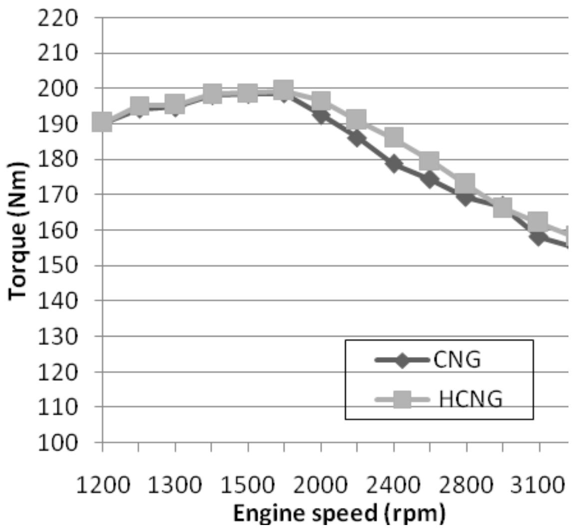

Figure 3. Torque comparison of CNG and HCNG engine

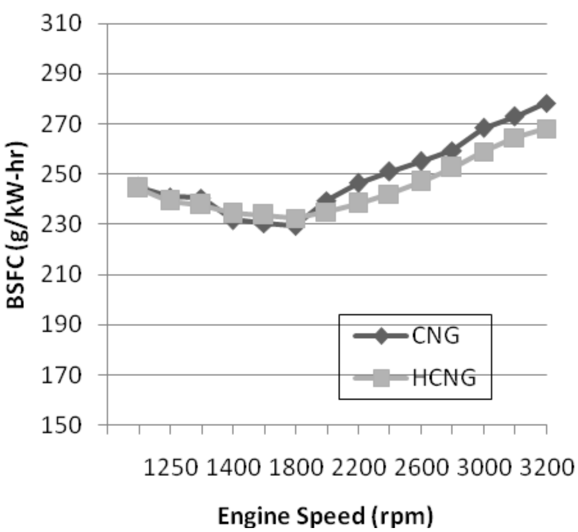

Figure 4. BSFC Comparison of CNG and HCNG engine

7. Emissions

The HCNG engine increases the H/C ratio of the fuel, which drastically reduces the carbon based emissions such as CO, CO_2 and HC. The experimental exhaust emission results of optimized CNG and 5% HCNG engine are given in Table 6.

Table 6. Exhaust emission results

Pollutants	BS- III Norms	Optimised CNG Test Results	5% HCNG Test Results
CO	2.1	0.99	0.56
NMHC	0.66	0.153	0.075
NOx	5.0	1.09	0.32

7.1. Carbon monoxide emission

The better mixing of fuel with air leads to complete combustion which help in reducing the CO emissions. Moreover, since the combustion temperatures are higher with HCNG fuel, the engine runs hotter thereby facilitating better combustion. It is observed in the experimental work that the CO emissions are drastically reduced with HCNG operation. There is about 40 to 50% reduction in CO emissions with HCNG operation is observed than the neat CNG operation.

7.2. NMHC emissions

The H/C ratio of the HCNG engine increases and also due to the tendency of flame quenching becomes less as cylinder walls and cylinder head runs hotter the NMHC emissions of HCNG engine are reduced about 45% than the neat CNG engine.

7.3. NOx emissions

Nitric oxide (NO) and nitrogen dioxide (NO_2) are usually grouped together as NOx emissions. NO is the predominant oxide of nitrogen produced inside the engine cylinder. Principal source of NOx is oxidation of atmospheric (molecular) nitrogen and high combustion temperature. Three different engine tests are conducted with HCNG fuel by increasing the fuel flow and retarding the ignition timing. Initially, slightly NOx emissions are increased but by retarding the ignition timing throughout the curve by 5^0 the NOx emissions are reduced due to increase in the flame speed of HCNG engine. It is oserved from the graph that NOx emissions are reduced by about 20 to 30% with HCNG operation as compared to that with neat CNG fuel.

8. Conclusion

The following conclusions may be drawn based on the present experimental research work:

- The lean-burn capability and flame burning velocity of the natural gas engine is improved by blending it with fast burning velocity fuel such as hydrogen.
- The HCNG engines are more superior to CNG engines from fuel economy, power, and torque point of view due to better combustion.
- The addition of hydrogen into natural gas increases BMEP compared with that of natural gas combustion. This is due to the increase of burning velocity of the mixture by hydrogen addition which shortens the combustion duration and increases the cylinder gas temperature.
- The HCNG engine improves Power by 3 - 4 % and the Torque about 2 - 3 % than the CNG engine. The HCNG engine operates at leaner side than the CNG engine which reduces the fuel consumption about 4% than the CNG engine.
- The HCNG reduces CO emissions by 40 to 50%, NMHC emissions by 45% and NOx emissions by 20 to 30% than the neat CNG operation. Thus the blended HCNG fuel is more environmental friendly.
- The 5% blends of hydrogen by volume with CNG the phenomenon of hydrogen embrittlement does not occur with respect to engine components, hence no major change is anticipated in fuel system and engine components.
- The ultimate goal of a hydrogen economy is to displace fossil fuels with clean burning hydrogen and CNG is the best route to ensure an early entry of hydrogen fuel into an energy sector.

Further experimental optimization is in progress at ARAI on HCNG engine and there is lot of scope for research work on various blends of HCNG with different C.R., A/f ratios, ignition timings, swirl effects etc.

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Author biographies

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S.S. Thipse has done his Masters in Thermal sciences from Bradley University, USA and his Ph.D. from New Jersey Institute of Technology in the field of Alternative Fuels Combustion. He has Research experience of over 10 years in the development of Alternative Fuel vehicles and has been working at ARAI as an Assistant Director since 2004. At ARAI, he is working on the development of CNG, LPG and HCNG engines at the Engine Development Laboratory. He serves as a core member in the expert committee on Alternative fuels of Department of Science and Technology (DST) as a nominee of Director, ARAI. He is the member of ISO TC 22 SC 25 committee on gaseous fuels and Member of BIS TED-26 & ME_16 committees. He is Treasurer and Governing board member of SAE India Western section, life member of Combustion Institute and ISTE.

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