Investigations of emission characteristics and thermal efficiency in a spark-ignition engine fuelled with natural gas–hydrogen blends

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Abstract

This paper presents the experimental results of a single cylinder Enfield engine using an electronically controlled fuel injection system which was developed to carry out exhaustive tests using neat compressed natural gas (CNG), and mixtures of hydrogen in CNG (HCNG) as 5, 10, 15 and 20% by energy. Experiments were performed at 2000, 2400 and 2800 rpm with wide open throttle and varying the equivalence ratio. Hydrogen, which has a fast burning rate, when added to CNG, enhances its flame propagation rate. The emissions of HC, CO, decreased with increasing percentage of hydrogen but NO_x was found to increase. The results indicated a marked improvement in the brake thermal efficiency with the increase in percentage of hydrogen added. The improved thermal efficiency was clearly observed to be more in lean regions when compared with rich regions.

Keywords: hydrogen supplementation; CNG; HCNG; emissions

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1 INTRODUCTION

Most of the energy requirement in the world is supplied by fossil fuels. With the increasing concerns over the environmental protection and shortage of fossil fuels, much effort has been focused on the utilization of alternative fuels in engines. The introduction of alternative fuels helps to alleviate the fuel shortage and may also be beneficial to reduce vehicle emissions. Natural gas is thought to be a good alternative to traditional vehicle fuels due to its higher octane number, low emissions, low price and plentiful reserves.

Natural gas spark-ignition (S.I.) engines either run stoichiometrically, i.e. exactly enough air for complete combustion or with an excess of air—named lean-burn engine. The lean limit is the maximum air–fuel ratio where the engine may run without experiencing misfire. A-part from low emissions of NO_x, lean operation has some other advantages. Firstly, excess air could increase the ratio of specific heats ($k = Cp/Cv$) of the burned gas and improve combustion efficiency, both of which are beneficial to the engine's thermal efficiency [1]; secondly possibilities of knock become smaller since cylinder temperature decreases, thus a higher compression ratio which is also good for thermal efficiency could be employed.

However, as the natural gas engine runs close to the so-called lean limit, problem of misfiring occurs. The reason for this is the slow burning speed of natural gas (37–45 cm/s). 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 (265–325 cm/s), much better lean-burn capability, and small quenching distance. And this combination is expected to improve the lean-burn characteristics [2, 3].

2 PRIOR RESEARCH

Varde [4] investigated the combustion characteristics of a single-cylinder S.I. engine using hydrogen-enriched gasoline. He concluded that a small amount of hydrogen addition could extend the lean limit and improve the engine's thermal efficiency as well as combustion stability.

Bysveen [5] evaluated the efficiency and emissions from an engine fuelled with compressed natural gas (CNG) and a mixture of natural gas and hydrogen. Pure CNG and 29 vol% H_2 in CNG (named HCNG) were investigated at four engine speeds under full

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load conditions, namely 1300, 1500, 1800 and 2200 rpm. For each mixture and each engine speed, four different excess air ratios (λ) were chosen, in the range of $\lambda = 1.1.-2.0$. Addition of hydrogen to CNG makes it possible to run the engine leaner, resulting in lower emissions of CO_2, CO and HC at a certain λ, and higher NO_x emissions at constant excess air ratio. When the mixtures are leaned out to $\lambda = 1.8$, the HCNG gives more power than the equivalent CNG. The efficiency for HCNG is greater than for CNG for the same λ and the difference in brake thermal efficiency (BTE) between HCNG and CNG for the same λ increases with increasing excess air ratio.

Akansu *et al*. [6] experimented on four cylinder engine with mixtures of hydrogen in methane of 0, 10, 20 and 30% by volume. Experimentation was done by varying the equivalence ratio, at 2000 rpm and constant load conditions. The result showed that NO emissions increased while HC, CO and CO_2 emission values decreased and BTE values increased with increasing hydrogen percentage.

Karim *et al*. [7] theoretically studied the effect of the addition of hydrogen on methane combustion characteristics at different spark timings. The results indicated that the addition of hydrogen could increase the flame propagation speed, thus stabilizing the combustion, especially the lean combustion process. These studies showed that the exhaust hydrocarbon (HC), CO, and CO_2 concentrations could be decreased when the engine operated on the natural gas engine. However, NO_x would increase for the natural gas–hydrogen combustion as combustion temperature increased.

Nagalingam *et al*. [8] noted that the power of HCNG compared with CNG was reduced due to the lower heating value of H_2 compared with methane. However, since the flame speed of hydrogen is so much higher than that of CNG, less spark advance is required to produce maximum brake torque.

Baur and Forest [9] studied the effect of hydrogen addition in methane fuelled vehicles. Their study presented the results of a single-cylinder CFR engine test with mixtures of hydrogen in methane of 0, 20, 40 and 60% by volume. Each fuel was tested at speeds of 700 and 900 rpm, full and part loads and equivalence ratios from stoichiometric to the partial burn limit. When compared with pure methane, hydrogen addition up to 60 vol% was shown to lower the partial burn limit from an equivalence ratio of 0.58–0.34. There was a corresponding decrease in brake power up to 8% ($Ø = 1$) and a decrease in Brake-Specific Fuel Consumption (BSFC) up to 14% (from $Ø = 0.58-1.00$) For pollutant production, hydrogen addition up to 60 vol% results in a decrease in $BSCO_2$ up to 26% (from $Ø = 0.58-1.00$), a decrease in BSCO up to 40% (for $Ø > 0.95$), a decrease in BSHC up to 60% (from $Ø = 0.58-Ø = 1.00$) and an increase in peak BSNO at $Ø = 0.83$ of $\sim$30% (for 40 vol%)

Kahraman *et al*. [10] conducted the experimental study on the performance and exhaust emissions of a S.I. engine fuelled with methane–hydrogen mixtures (100% CH_4, 10% H_2 + 90% CH_4, 20% $H_2 + CH_4$, 30% $H_2 + CH_4$) at different engine speeds and different excessive air ratios. Experiments were performed at 1500, 2000, 2500 and 3000 rpm and at wide open throttle (WOT). HC, CO_2 and CO emission values decreased with increasing hydrogen fraction in methane—hydrogen mixtures. Brake thermal efficiencies were found to increase with the increase of H_2 fraction and engine speed.

Ma *et al*. [11] conducted experimental research on a S.I. natural gas engine using variable composition hydrogen/CNG mixtures. They analyzed COV in IMEP %, combustion duration/degree crank angle, NO_x, HC, CO, indicated thermal efficiency by varying excess air ratio. The results showed that lean-burn limit could be extended by hydrogen addition. Ten, 30 and 50% hydrogen addition extended lean limit to 1.82, 2.09 and 2.4, respectively, compared with 1.71 for natural gas. Hydrogen addition resulted in higher NO_x emission if spark timing was not optimized. Unburned hydrocarbon emission always decreased with the increase of amount of hydrogen added no matter whether spark timing was changed or not.

Research work by other researchers [12–16] also concentrated on the method of using lean combustion and retarding ignition timing.

Hydrogen-enriched CNG engine has attracted the attention of many researchers. There are many published papers regarding the experimental researches of the performance and emission characteristics hydrogen-enriched natural gas engines. Results of these studies generally show that hydrogen addition can decrease engine's unburned hydrocarbon and NO_x emissions (by lean burn) and speed up the combustion process. More comprehensive experimental study needs to be conducted under a wide range of hydrogen fraction and on commercially available engine so that the research can go from lab to land. For this research, instead of a research engine, a commercially available engine was selected and ECU was developed and was tested to evaluate the effect of hydrogen addition on the natural gas engine's emission and performance characteristics at constant speed.

3 EXPERIMENTAL SETUP TEST PROCEDURE

The experiments were conducted on a modified single-cylinder Enfield engine with a bore x stroke of 69.874 × 90 mm and a

Table 1. *Engine specifications*

Parameter	Specifications
Engine make	Bullet (Royal Enfield India Ltd.)
Type	Vertical Single-Cylinder, Air Cooled, 4-Stroke with overhead Valve Gear
Bore (mm)	69.874
Stroke (mm)	90
Swept volume	346 c.c.
Compression ratio	7.25:1
Intake valve opening	30°BTDC
Intake valve closing	50°ABDC
Exhaust valve opening	65°BBDC
Exhaust valve closing	15°ATDC
Valve lift	7.94 mm

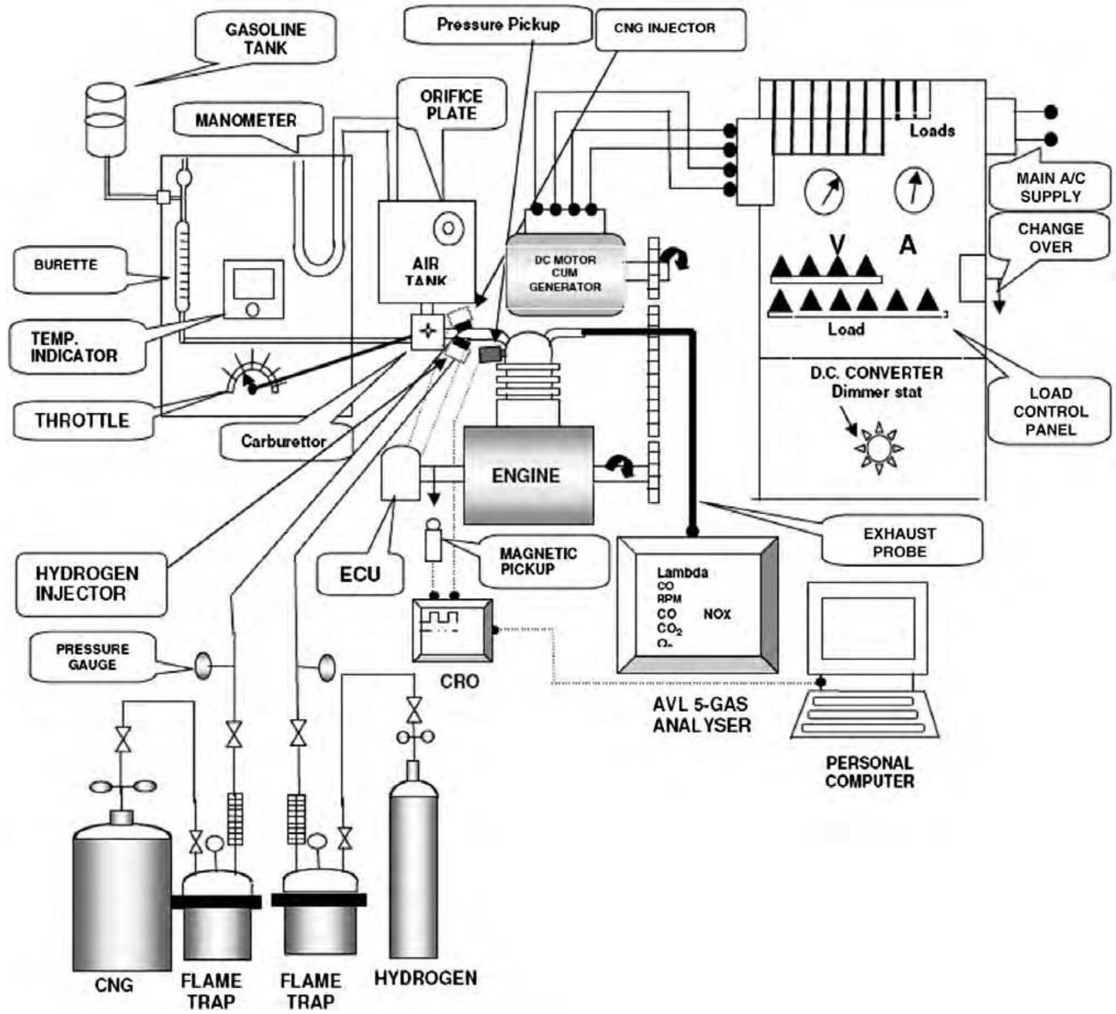

Figure 1. *Schematic of experimental setup.*

Table 2. *Composition of natural gas*

Item	CH_4	C_2H_6	C_3H_8	I-C_4H_{10}	N-C_4H_{10}	I-C_5H_{12}	N_2	CO_2	Hexanes
Volumetric fraction (%)	96.1	2.571	0.359	0.05	0.09	0.01	0.598	0.14	0.06

compression ratio of 7.25:1. The engine details are given in Table 1. This engine has been commercially used in motor bikes in UK and India for a couple of decades. Figure 1 is a schematic of the experimental setup.

All the research work was conducted in the Engines and Unconventional Fuels Laboratory in the Centre for Energy Studies at the Indian Institute of Technology Delhi. The tests were conducted by varying the equivalence ratio at a constant speed of 2000, 2400 and 2800 rpm and constant spark timing of 25° Before Top Dead centre (BTDC). The CNG-H_2 supplying system of the engine consisted of CNG and hydrogen tank, pressure regulators, flame traps, Electronic Control Unit (ECU) and two different injectors for injecting CNG and hydrogen. ECU was used to inject the fuel timely and vary the duration of injection and thus vary the equivalence ratio. The flow rate was metered by Proline Promass 80 A04 micro-motion flow meters which use the Coriolis effect for a direct measure of mass flow The hydrogen used in this study has a purity of 99.99%, while the constitution of natural gas is listed in Table 2. Table 3 gives the fuel properties of natural gas and hydrogen. It can be seen that the laminar burning velocity of hydrogen is seven times that of natural gas. Thus, adding hydrogen into natural gas is expected to increase the flame propagation speed and stabilize the combustion process.

In this study, four fractions of natural gas–hydrogen blends were studied. The fractions of hydrogen in the natural gas–hydrogen blends are 0, 5, 10, 15 and 20% by energy, respectively.

Table 3. *Fuel properties of hydrogen and natural gas*

Property	Hydrogen	Natural gas
Density at 1 atm and 300° K (kg/m^3)	0.082	0.754
Mass lower heating value (MJ/kg)	119.930	43.726
Stoich. air/fuel mass ratio (kg/kg)	34.20	17.19
Volumetric lower heating value at 300° K and 1 atm (MJ/m^3)	9.82	32.97
Equivalence ratio of lean-burn limit at 293° K and 1 atm	0.1	0.53
Volumetric fraction of fuel at stoichiometric A/F ratio (%)	29.0	9.5
Molar carbon to hydrogen	0	0.25
Quenching gap at NTP (mm)	0.64	2.03
Laminar flame speed (m/s)	2.90	0.38
Adiabatic flame temp (°K)	2318	2148
Minimum ignition energy (mJ)	0.02	0.29
Flammability limits (% by volume)	4–75	5.3–15.0
Conductivity at 300° K and 1 atm (mW/m^{2}k)	182	34
Octane number	130+	127

Table 4. *Accuracies in measurements*

Measurements	Accuracy
Speed	5 rpm
Time	±2%
NO_x	±20 ppm
CO	±1 ppm
HC	0.05%.

Table 5. *Uncertainties in results*

Calculated results	Uncertainty (%)
Power	±2
Thermal efficiency	±3
Mass flow of air	±1.9
Mass flow of CNG	±2.3
Mass flow of hydrogen	±2.1

The accuracies of the measurements and the uncertainties in the calculated results are shown in Tables 4 and 5.

4 RESULTS AND DISCUSSIONS

4.1 Carbon monoxide emissions

Figure 2 shows the brake-specific carbon monoxide as a function of equivalence ratio with the engine speeds of 2000, 2400 and 2800 rpm. CO emission is mainly due to incomplete combustion. It is seen that CO emissions are very low in the lean region up to an equivalence ratio of 0.65. As the mixture is further leaned out, the flame propagation becomes so slow that incomplete combustion takes place and hence CO

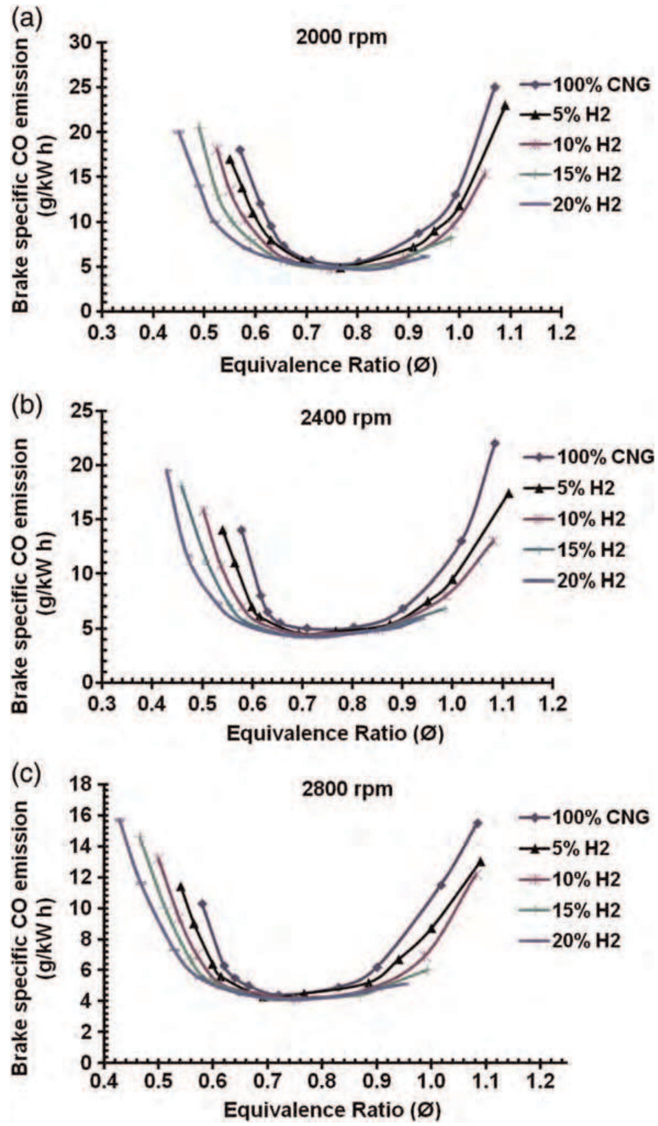

Figure 2. *(a–c) Variation of brake-specific CO emissions versus equivalence ratio for various hydrogen blends at 2000, 2400 and 2800 rpm.*

emission increases sharply. When the equivalence ratio was increased above 0.65, the CO emission reached the minimum and then increased rapidly when the mixture was made further rich. The low emissions of CO occurred in fuel air equivalence range of 0.7–0.82. In this range, complete combustion ensured maximum conversion of carbon atoms to CO_2. CO values are highly concentrated when equivalence ratio is increased above 0.86, i.e. in fuel-rich mixtures, due to incomplete combustion. As the percentage of hydrogen is increased, CO emissions decrease. This is due to higher combustion temperature of hydrogen which results in more complete combustion. The CO emissions decrease with the increase in the engine speed. The probable reason for this is the increase in cylinder temperature as at high engine speed, less time is available for the heat to conduct from cylinder to cylinder walls. The results are consistent with Ref. [9].

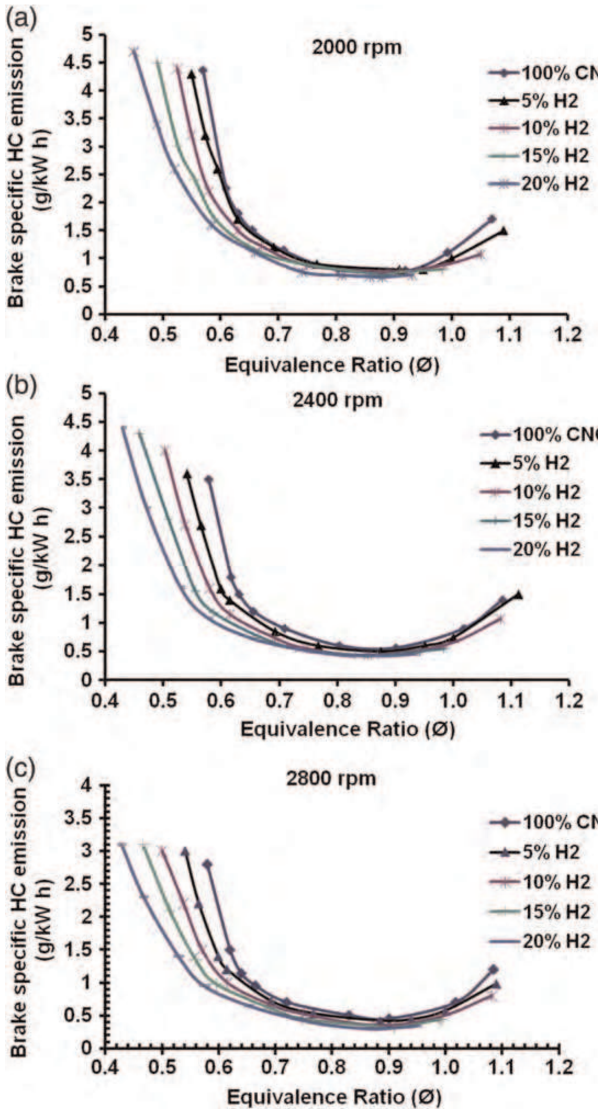

Figure 3. *(a–c) Variation of brake-specific HC emissions versus equivalence ratio for various hydrogen blends at constant speed of 2000, 2400 and 2800 rpm.*

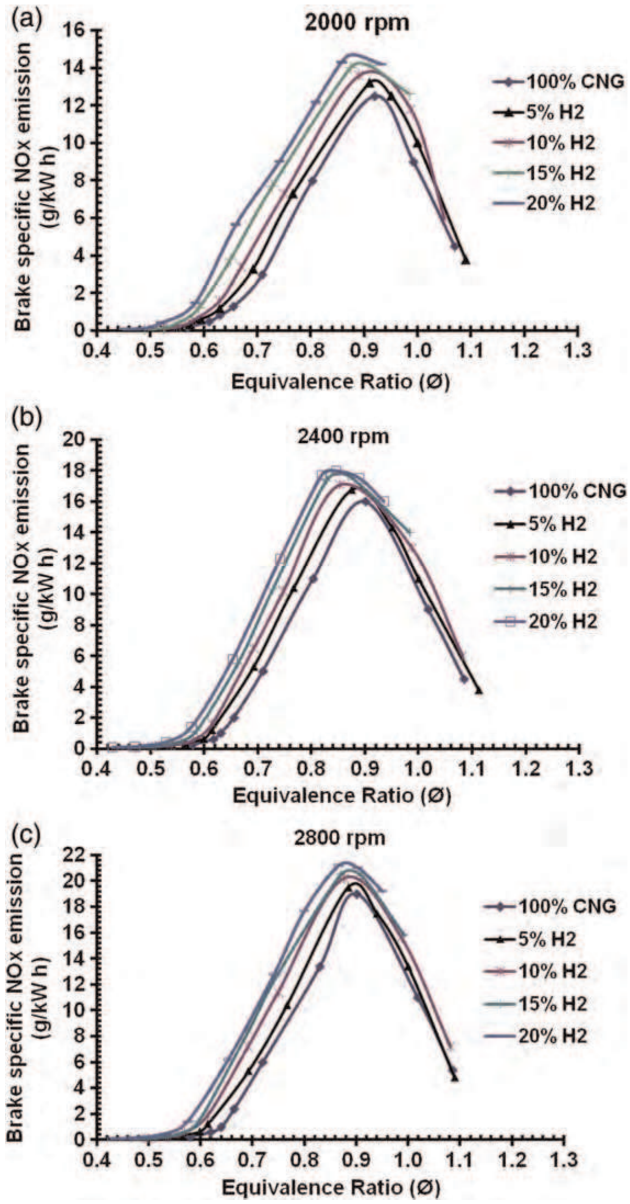

Figure 4. *(a–c) Variation of brake-specific NO_x emissions as a function of equivalence ratio for various hydrogen blends at constant speed of 2000, 2400 and 2800 rpm.*

4.2 Unburned hydrocarbon emissions

Figure 3 shows the brake-specific unburned hydrocarbon (HC) versus equivalence ratio. HC emissions are maximum at the leaner mixture, decrease with equivalence ratio and once again increase with rich mixture. HC emissions are reduced by excess air (lean mixture) until reduced flammability of the mixtures causes a net increase in HC emissions. The HC emissions are minimum between equivalence ratios of 0.8–0.9. This is because at this point, firstly there was extra air to ensure combustion completeness and secondly the fuel–air mixture was not too lean, so the exhaust temperature could keep at a high level, which was beneficial to the further oxidation of HC formed through crevice and flame quenching. The emissions increase at high equivalence ratio due to incomplete combustion. With increasing percentage of hydrogen, HC emissions reduced, which could be explained by the fact that hydrogen could speed up flame propagation and reduce quenching distance, thus depressing the possibilities of incomplete combustion [17]. Moreover, with the increase in hydrogen percentage, carbon concentration of the fuel blends decreased which resulted in reduced HC emissions.

4.3 NO_x emissions

Figure 4 shows brake-specific NO_x versus equivalence ratio. NO_x emissions increase with higher temperature, longer high-

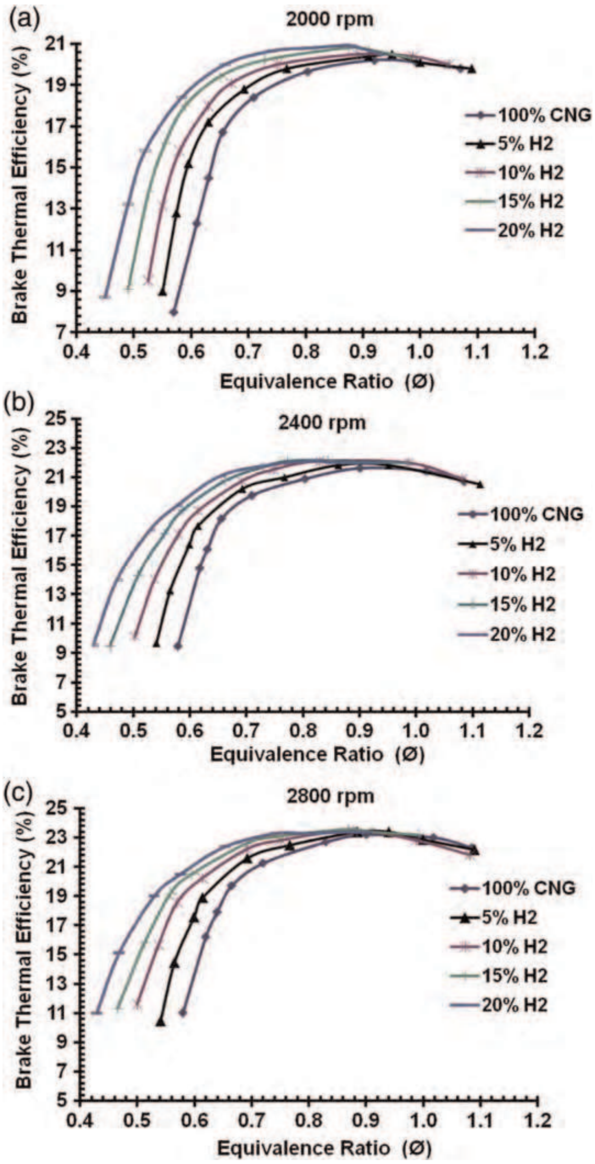

Figure 5. *(a–c) Variation of BTE as a function of Equivalence Ratio for various hydrogen blends at constant speed of 2000, 2400 and 2800 rpm.*

temperature combustion duration and greater availability of oxygen (up to a point). In the present study, brake-specific NO_x reach peak around Ø = 0.82–0.9. Higher combustion temperature and availability of sufficient oxygen seem to be the cause of NO_x levels peaking around the stoichiometric value. However, the in-homogeneity in the cylinder shifts the maximum brake-specific NO_x towards the leaner side of the stoichiometric value. For a specific equivalence ratio, brake-specific NO_x concentration increased due to increase of peak combustion temperature by hydrogen addition. It must be noted that NO_x emissions were extremely low when equivalence ratio was further reduced below 0.58. The increase in engine speed resulted in increase of brake-specific NO_x emissions. This probably occurred due to increase in cylinder temperature.

4.4 Brake thermal efficiency

Figure 5 shows the BTE versus the equivalence ratio. The brake thermal efficiencies are found to increase with hydrogen addition to CNG. In case of lean mixtures, specific heat values are found to be more reduced than the stoichiometric equivalence ratio value. In case of rich mixtures, combustion is incomplete due to insufficient oxygen. As complete combustion does not occur, there will be a decrease of a certain level of thermal efficiency when equivalence ratio is increased above stoichiomety.

The highest BTE was observed around 0.82–0.98 equivalence ratio. In the case of rich mixtures, combustion is not complete. The trend obtained is similar in character to [2].

5 CONCLUSIONS

An experimental study on the performance, combustion and emission characteristics of a natural gas fuelled engine supplemented with 0, 5, 10, 15 and 20% hydrogen supplementation was conducted. The main results are summarized as follows.

- The timed manifold injection through electronic fuel injection was very advantageous for the smooth operation of the engine.
- The BTE increase with the increasing hydrogen percentage. This increase in BTE is more pronounced in the leaner region.
- The emissions of CO and HC decreased with the increasing percentage of hydrogen.
- The increasing percentage of hydrogen resulted in the increased emissions of NO_x. NO_x level is very low at lean mixture.

CNG has slower laminar burning velocity and higher ignition energy, both of which have negative effects on the engine's lean-burn capability and thus the aim of low CO and NO_x cannot be realized. At the present stage, the use of neat hydrogen as a fuel in IC engine seems to be a long-term prospect mainly due to its undesirable properties and thus the fear attached with its usage. In the initial stage, the addition of hydrogen in small percentages can improve the reputation of hydrogen as a dangerous fuel. The blending of hydrogen in CNG can be very much beneficial for increasing the lean-burn limit and for a trade off relation between HC, CO and NO_x emission.

The authors hope that this study could give some practical guidance to the development and calibration of hydrogen supplemented CNG engines.

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