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Brake Specific Energy Consumption (BSEC) and Emission Characteristics of the Direct Injection Spark Ignition Engine Fuelled by Hydrogen Enriched Compressed Natural Gas at Various Air- Fuel Ratios

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Abstract

Research on improving fuel consumption and emission characteristics of the internal combustion engine (ICE) become necessary as a result of increases conventional fuel energy prices couple with environmental protection and depletion. Hydrogen enriched compressed natural gas (CNG-H_2) is the best alternative fuel to be utilized in ICE. In view of the aforementioned problem caused by conventional fuel, hydrogen enriched compressed natural gas (CNG-H_2) might have the potential to achieve good fuel consumption and low engine emission. Thus, the primary aim of this research is to experimentally study the brake specific energy consumption (BSEC) and exhaust emission characteristics of the direct injection spark ignition engine fuelled by a mixture of hydrogen gas and compressed natural gas. The experiment was carried out part-throttle, constant engine speed of 2000 rpm, various hydrogen gas (0, 20, 28, 38 and 46% by volume) and various air-fuel ratios (λ = 0.9, 1.0 and 1.2 which represent rich, stoichiometric, and lean mixtures respectively). The results showed that increasing the relative percentage hydrogen gas increases the BSEC. More so, BSEC of about 42% increment at lean mixture (λ = 1.2) was observed in comparison with stoichiometric mixture (λ = 1.0). While the emission concentrations of BSCO and BSUHC, decreased with increasing percentage of hydrogen gas. Their emission shows a reduction of approximately 94% and 26% when comparing between rich and stoichiometric mixture respectively. In addition, BSNOx emission concentrations increases as the percentage hydrogen gas increases due to the fact that hydrogen fraction increase the turbulence within the engine cylinder. Thus, it can be concluded that CNG-H_2 is a very good alternative fuel technique to achieve significant reduction in basic pollutant emissions associated with DI-HCNG engine such as BSCO and BSUHC emissions.

Keywords: Hydrogen Enriched Compressed Natural Gas, Brake Specific Energy Consumption (BSEC), Air-Fuel Ratios, Emission Characteristics.

NOTE WELL: The concept of Brake Specific Energy Consumption (BSEC) was utilized in this research instead of Brake Specific Fuel Consumption (BSFC) because this research deals with two fuels (CNG-H_2) which has different energy density. BSFC is only used when we are dealing with one fuel.

INTRODUCTION

Vehicle are a major source of air pollutants such as nitric oxides, carbon monoxide, and hydrocarbons as well as the greenhouse gas carbon dioxide and thus there is a growing shift in the transportation industry from the traditional petroleum-based fuels such as gasoline and diesel fuels to the cleaner burning alternative fuels friendlier to the environment such as natural gas, alcohols (ethanol and Methanol), liquefied petroleum gas (LPG) and hydrogen [1-6]. Of all the alternative fuel investigated, natural gas is regarded as one the most promising alternatives fuels and probably one of the cleanest fuel in combustion. The use of natural gas has been realized in both spark ignition and compression ignition engine [6-7]. Natural gas comprises of mixture of different gases where methane is its major component. The combustion of natural gas produces lesser emission when compared to that of gasoline and diesel engine due to its simple chemical structure and absence of fuel evaporation. The engine possess high anti-knocking capability due to its high octane number and this allows it to operate at even high compression ratio; leading to further improvement of both power output and thermal efficiency [7-8]. However, it is also to be noted that, CNG fuel has few disadvantages which are slow burning velocity and poor lean burning capability [8]. CNG leads to the incomplete combustion, misfire, and large cycle to cycle variations which imposed a penalty on brake specific fuel consumption and power output of the engine [7-8]. To solve these problems of slow burning and poor lean burn capability, CNG is needed to be mixed or combined with fuel that possess faster burning and better lean combustion characteristics. Hydrogen is the best alternative fuel to combine with CNG in this regard. This fuel blend is called HCNG or Hythane. Hydrogen possess the faster-burning velocity and better lean combustion capability. In addition, hydrogen has a cleaner burning characteristics and better performance drives [8-9] . There are a lot researches on CNG-H_2 as an alternative fuel in the ICE, and this aspect plays the major role in this research work as it presents recent studies done on the CNG-H_2 as vehicular fuel**.** Wang J et al conducted an experimental study on the cycle-by-cycle variations of spark ignition engine fuelled by natural gas-hydrogen blends [7]. Bauer and Forest conducted an experimental study on natural gas-hydrogen combustion in a CFR engine [8]. Wong and Kareem analytically examined the effects of hydrogen enrichment and hydrogen addition on cyclic variations in homogeneously charged compression ignition engines [9].The results showed that the addition of hydrogen can reduce cyclic variations while extending the operating region of the engine. In addition, it also revealed that exhaust emission such as Unburnt Hydrocarbon (UHC), Carbon monoxide (CO) and Carbon dioxide (CO_2) could be reduced while Nitric oxide emission increases (NO) [10-13]. However, till date, there is still a communication gap on the impact of hydrogen and CNG as a dual fuel in DI-CNG engine at a various air-fuel ratios. Therefore, this study will investigate the impact of CNG-H_2 in DI-CNG engine and quantitatively analysed BSEC and emission characteristics of the engine and the clarified the engine behavior under the influence of CNG-Hydrogen gas.

COMBUSTION EQUATION

The combustion equation representing CNG-H_2 from which the various air-fuel ratios utilized for this experiment was calculated is given below:

$$aCH_4 + bH_2 + c\,(O_2 + 3.76N_2) \rightleftarrows x\,CO_2 + y\,H_2O + z\,N_2 \qquad (1)$$

Where:

a: represents the percentage by volume of Natural gas

b: represents the percentage by volume of Hydrogen gas.

c: represents mole number of Air (O_2 + 3.76 N_2)

x, y and z represent mole number of CO_2, H_2O and N_2. respectively.

EXPERIMENTAL PROCEDURES

This research was based on the experimental study that was conducted at the Centre for Automotive Research (CAR), Universiti Teknologi PETRONAS (UTP). The test conducted follows the SAE standard on engine performance and emission testing. The schematic diagram of the experimental setup is shown in Figure 1 below. The specifications of the engine are given in Table 1-1.

Table 1-1: Test Engine Specifications.

Engine Specification	Value / Description
Constant Engine Speed	2000 rpm
Hydrogen Fraction by volume	0%,20%,28%,38%,46%
Injection Timing	300^0 CA (Early Injection Timing)
Intake Manifold Absolute Pressure	Part throttle
No. of Cylinder, Strokes	Single Cylinder, 4-stroke
Ignition source	Spark Plug
CNG Injection pressure	18 bars
Bore	102 mm
Stroke	115 mm
Fuel	Compressed Natural Gas, Hydrogen Gas

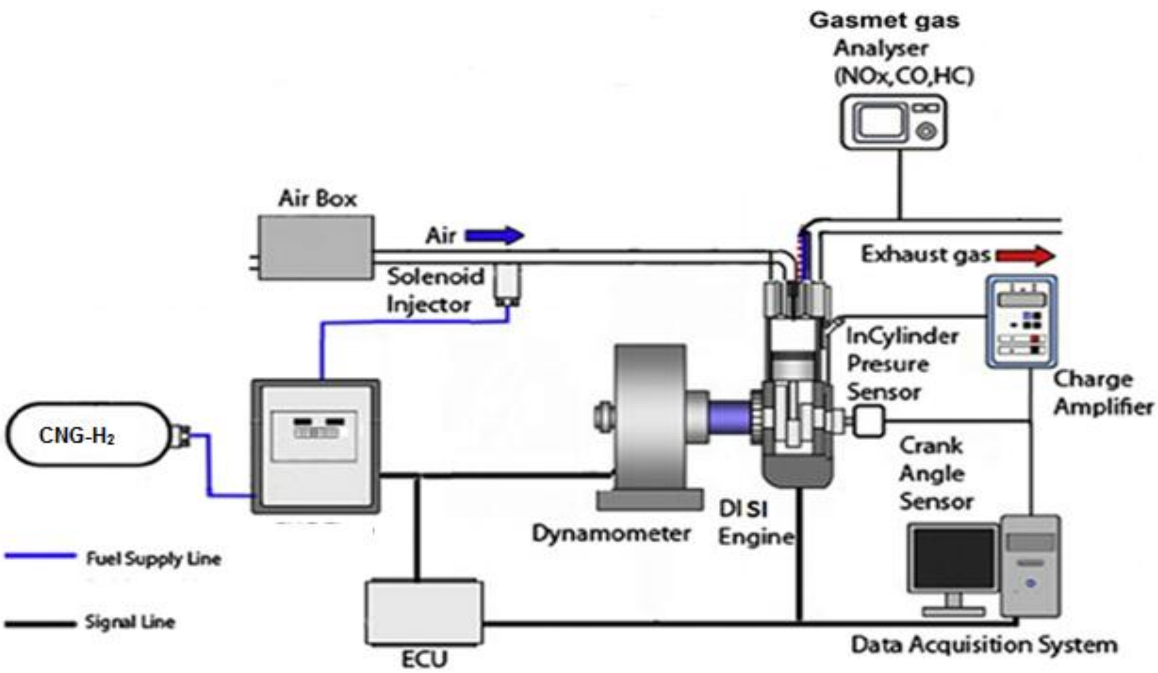

Figure 1: Schematic Diagram of the Experimental Setup.

The supply system of the experiment setup consists of fuel (CNG-H_2), pressure gauge, flow meters. The experiment was conducted after running engine until it become stable with oil and coolant temperature at 60^0C and 70^0C respectively. The experimental work was started by injecting CNG and H_2 into the engine cylinder. The mixing of CNG-H_2 was adjusted with the aid of regulating flow meter valve into the engine. Electronic control unit (E.C.U) was used to control the entire engine operating parameter such as part-throttle, various air-fuel ratios, and the constant engine speed of 2000 rpm. Eddy current dynamometer was utilized to collect the performance characteristics data such as brake torque, brake power from which brake specific energy consumption can calculated. While gasment gas analyzers was utilizes to take the data of exhaust emission such as NOx, UHC, and CO.

RESULTS AND DISCUSSION

Introduction

The results from the experiments performed on the direct-injection single cylinder four-strokes engine for maximum load operating condition are shown below. The several of the air-fuel ratios used in this experimental are $\lambda = 0.9$ (Rich Combustion), $\lambda = 1.0$ (Stoichiometric Combustion) and $\lambda = 1.2$ (Lean- Combustion). The injection timing utilized for this experimental is set at 300^0 CA (Early Injection Timing). Finally, results were analyzed and discussed for the brake specific energy consumption (BSEC) and various emission concentrations such as brake specific carbon monoxide emission (BSCO), brake specific nitric oxides emission (BSNOx) and brake specific unburned hydrocarbon emission (BSUHC) against various hydrogen gas fractions at constant engine speed of 2000 rpm.

Performance Characteristics

Brake Specific Energy Consumption (BSEC)

Figure 2- illustrates the variation of BSEC against percentage hydrogen gas by volume for various air-fuel ratios. From the graph it is quite obvious that increase the percentage by volume of hydrogen gas shows an increasing trend for BSEC. The reason is due to variations in turbulence level which leads to high cycle by cycle combustion variations in the early stages of the combustion process. Also, comparing the BSEC at various air-fuel ratios; the highest BSEC occurred at stoichiometric mixture ($\lambda = 1.0$). This occurs because all the oxygen are effectively utilized for combustion process. In addition, at the stoichiometric mixture ($\lambda = 1.0$) and percentage by volume of hydrogen gas 0% and 46%, the BSEC respectively are 21.03- MJ/kW.hr and 34.48 MJ/kW.hr. This reveals that there is about 40% increment at that operating condition. While at lean mixture ($\lambda = 1.2$) with the same operating condition under consideration the BSEC respectively are 18.60 MJ/kW.hr and 32.30 MJ/kW.hr. This shows approximately 42% increment in BSEC. Thus, it is cleared from the above analysis; that more increment is occuring at lean mixture ($\lambda = 1.2$). This might be so because of inefficient combustion occur at that operating condition. Good agreement is achieved between these experimental results and [8].

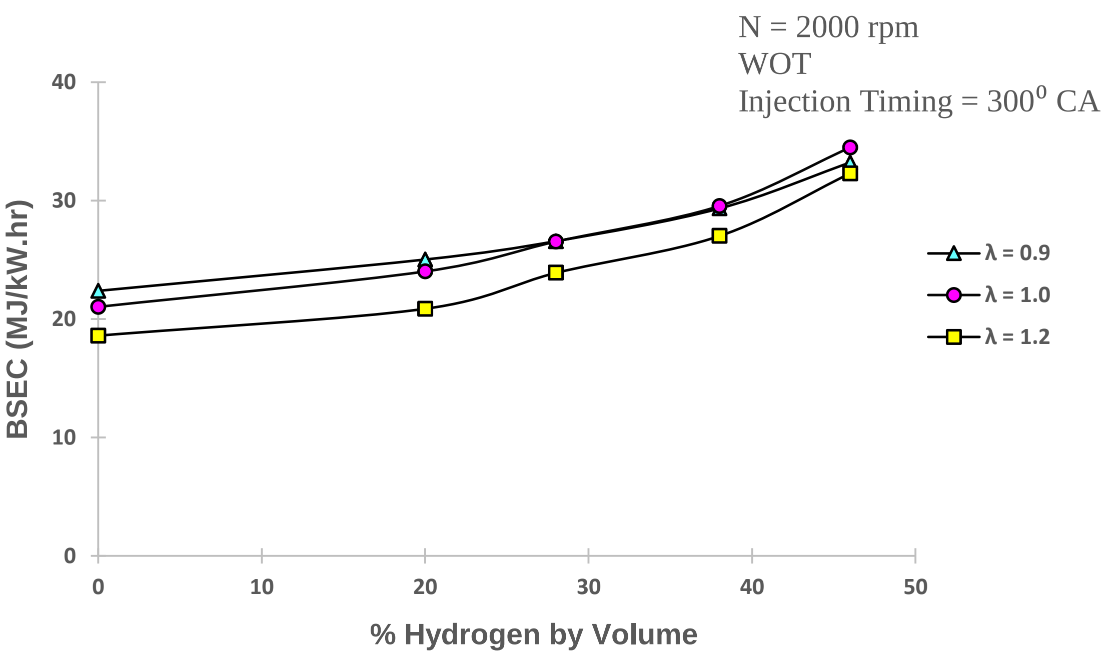

Figure 2: BSEC against % of Hydrogen Gas at Various Air-Fuel Ratios.

Emission Characteristics.

The emission characteristic in single cylinder engine was analyzed using gas analyzer. The engine was run at constant speed of 2000 rpm with different air-fuel ratios and at part-throttle. The experimental results are presented in Figure 3-5 as shown below.

Brake Specific Carbon Monoxide (BSCO)

Figure 3 shows the BSCO emission concentrations against various hydrogen gas fractions at different air-fuel ratios. From the graph, it was found that the BSCO emission concentrations for rich mixture (λ = 0.9) and stoichiometric mixture (λ = 1.0) are significantly reduced at various fraction of hydrogen gas. This is due to higher combustion temperature of hydrogen gas which results in more complete combustion. While for lean mixtures (λ = 1.2), CO levels are approximately constant at a low level of about 0.5 percent or less. Also, comparing the BSCO emission concentrations at various air-fuel ratios; the highest BSCO emission occurred at rich mixture (λ = 0.9). This occurs because complete oxidation of the fuel carbon to CO, is not possible due to insufficient oxygen (incomplete combustion). In addition, at rich mixture (λ = 0.9) and percentage by volume of hydrogen gas 0% and 46%, the BSCO emission concentrations respectively are 8440.32 ppm/kW and 931.06 ppm/kW. This reveals that there is about 90 % reduction in BSCO emissions concentrations at that operating condition. While at stoichiometric mixture (λ = 1.0) with the same operating condition under consideration; the BSCO emission concentrations respectively are 7751.01 ppm/kW and 477.80-ppm/kW. This show a reduction of almost 94% in BSCO emission concentrations. Thus, it is clear from the foregoing that the drastic reduction of BSCO emission is occuring at stoichiometric mixture (λ = 1.0). This could be due to efficient combustion occuring at that operating condition. The result obtained here is coherent with [1, 9 and 11].

Brake Specific Nitric of Oxide (BSNO)

Figure 4 gives the brake specific NO concentration versus hydrogen gas fractions at different air-fuel ratios. The figure clearly showed that BSNO emission concentrations has an increase trend with the increase of hydrogen fractions and this phenomenon is more obvious for rich mixtures (λ = 0.9) and stoichiometric mixture (λ = 1.0). The increasing trend might be due to the fact that the introduction of hydrogen gas into the combustion chamber enhance the turbulence within the combustion chamber and this leads to increase in combustion temperature; consequent upon this, the concentration of BSNO emissions increase. This will be so because the formation of NO emission depends on combustion temperature. While for lean mixture (λ = 1.2) and at percentage hydrogen gas above 20%, the BSNO emission concentrations shows a decreasing trend. This might be largely due reduction in combustion temperature and burning velocity at that operating condition. The highest BSNO emission concentrations occurs at rich mixture (λ = 0.9) when compared to other mixtures. This might be due insufficient oxygen gas to ensure a complete reaction with the fuel. In furtherance, at rich mixture (λ = 0.9) and percentage hydrogen gas by volume of 0% and 46% the BSNO- emission concentrations respectively are 214.59 ppm/kw and 519.25 ppm/kW. From this, an increment of about 59% on BSNO emission concentrations is observed. While at stoichiometric mixture (λ = 1.0) with the same operating condition the BSNO emission concentrations are 146.34 ppm/kW and 421.34 ppm/kW respectively.

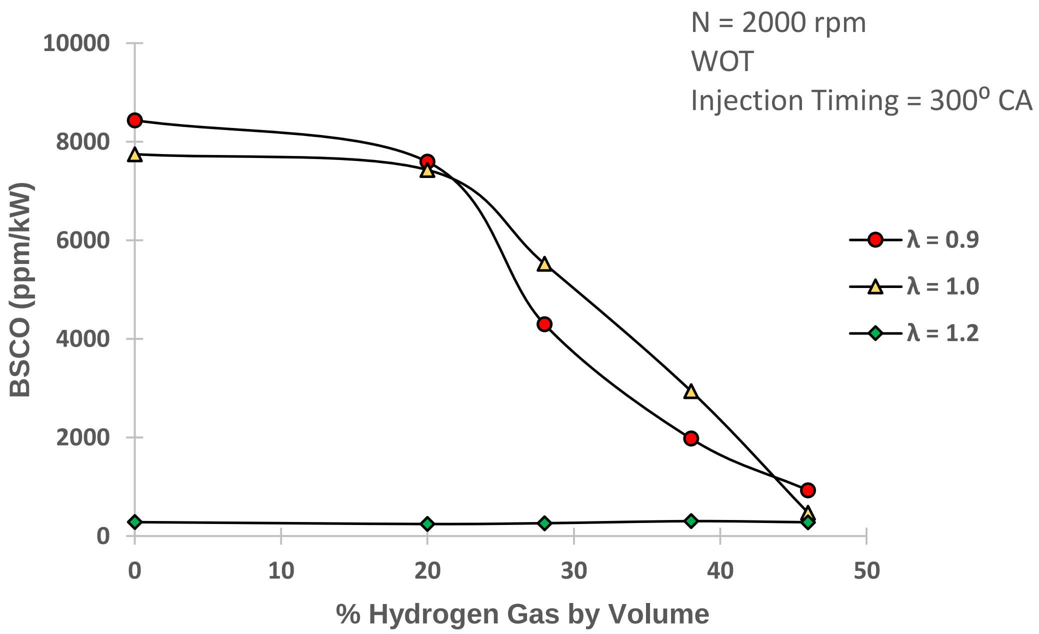

Figure 3: BSCO against % of Hydrogen Gas at Various Air-Fuel Ratios.

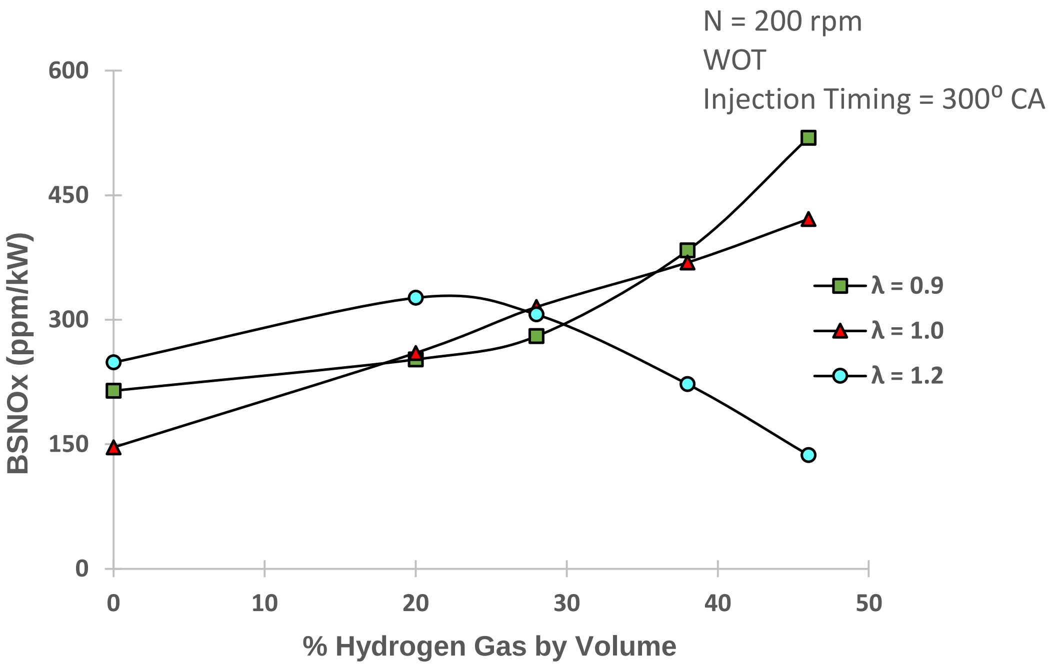

Figure 4: BSNOx against % Hydrogen Gas at Various Air Fuel Ratios.

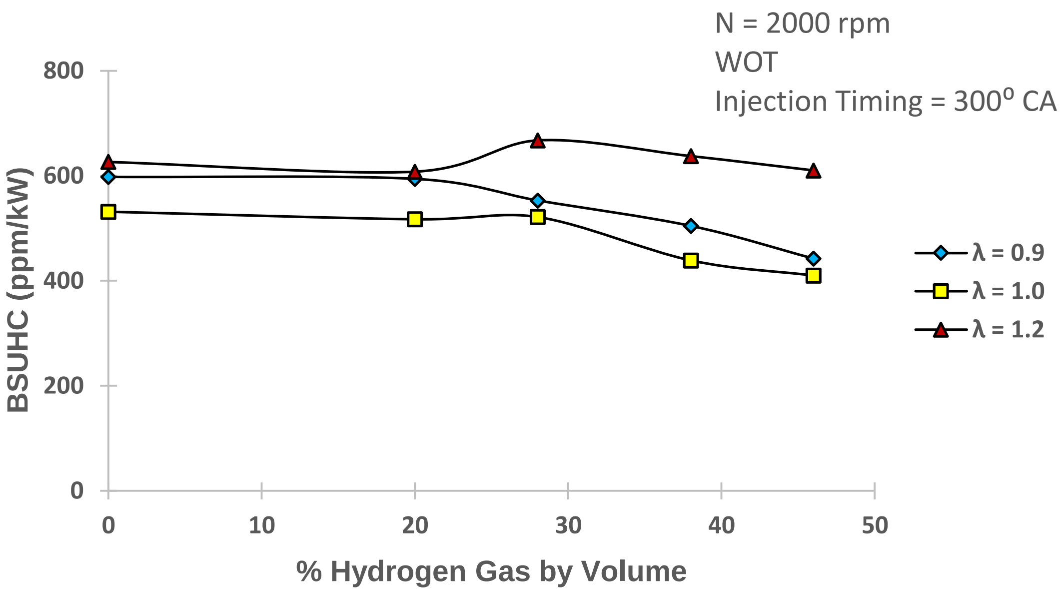

Figure 5: BSUHC against % of Hydrogen Gas at Various Air-Fuel Ratios.

This shows approximately 65% increment in BSNO emission concentrations at that operating conditions. It is noteworthy to say that the use of rich mixture (λ = 0.9) should be avoided while controlling the NO emission in a direct-injection hydrogen enriched compressed natural gas engine. Good agreement is achieved between this experimental results and [10-13].

Brake Specific Unburnt Hydrocarbon (BSUHC)

The variations of brake specific unburnt hydrocarbon (BSUHC) emission with percentage hydrogen gas are shown in Figure 5. It is clear from Figure 5 that BSUHC emission concentrations shows approximately constant trend line for hydrogen gas fraction from 0-20% for all the mixtures under consideration. While above approximately 30% hydrogen gas the BSUHC emission shows slightly decreasing trend line for all mixtures under consideration. The decreasing trend line obtained might occur because hydrogen could speed up flame propagation and reduce the quenching distance, thus reducing the possibilities of incomplete combustion. Highest level of BSUHC emission concentrations is presented at lean mixture (λ = 1.2) when compared to other mixtures. This might occur because of decreasing fuel concentration and increasing oxygen concentration essentially offset the effect of decreasing bulk gas temperatures. As the lean operating limit of the engine is approached, combustion quality deteriorates significantly and HC emissions start to rise again due to the occurrence of occasional partial-burning cycles. While the lowest BSUHC emission occur at stoichiometric mixture (λ = 1.0). This is because of the efficient combustion occuring at that operating condition. Comparing the BSUHC at rich mixture (λ = 0.9) for 0% and 46% hydrogen gas. The BSUHC emission concentrations respectively are 597.82 ppm/kW and 442.55 ppm/kW. This shows approximately 26% decrement at that operating condition. While for the stoichiometric mixture (λ = 1.0) at the same operating condition. The BSUHC emission concentrations are 531.71 ppm/kW and 410.16 ppm/kW. This reveals approximately 23% of reduction in BSUHC emission concentrations. Thus, it is cleared from the above analysis; that more decrement is occuring at rich mixture (λ = 0.9). Good agreement is achieved between these experimental results and[1, 10-13].

CONCLUSIONS

An experimental study has been performed to study the brake specific energy consumption (BSEC) and exhaust emission characteristics of the direct injection hydrogen enriched compressed natural gas engine (DI-HCNG) at various air-fuel ratios. The main results are summarized below:

- The BSEC was found to increase with the increase in percentage hydrogen gas by volume at various air-fuel ratios. This is so because high cycle by cycle combustion variations in the early stages of the combustion process. Also, BSEC showed about 42% increment at lean mixture (λ = 1.2) compared to other mixtures.
- For the emission characteristics:
  i. BSCO emission shows a decreasing trend at rich mixture (λ = 0.9) and stoichiometric mixture (λ = 1.0). This is due to higher combustion temperature of hydrogen gas which results in more complete combustion. While at lean mixture (λ = 1.2) it is approximately constant. In addition, at stoichiometric mixture (λ = 1.0) about 94 % reduction in BSCO emissions concentrations was observed in comparison with rich mixture.
  ii. BSNOx emission shows an increase trend with increasing hydrogen gas fraction. This effect is more pronounced at rich mixture (λ = 0.9) and stoichiometric mixture (λ = 1.0). This is because hydrogen fraction will increase the turbulance within the engine cylinder consequence upon this, BSNOx emission will increase. While at lean mixture (λ = 1.2) BSNOx level is very low.
  iii. BSUHC emission was found to decrease with the increasing percentage of hydrogen gas above 30% for all the mixtures under consideration. The reasons might be due to the decrement in fuel concentration in the engine cylinder. While an approximately constant trend line was obtained with hydrogen gas from 0-20%, for all the mixtures under consideration.

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REFERENCES

[1] Heywood, J. B. 1998. *Internal Combustion Engine Fundamental.* United State: McGraw Hill.

[2] Brady, R. N. 2013. *Internal Combustion (Gasoline and Diesel) Engines*

[3] Yunus A.C., Michael, A., 2011. Thermodynamics: An engineering approach. United State: McGraw Hill.

[4] Guwahati, T. 2013. Internal Combustion Engines. Alternative Fuels Data Centre, Alternate Fuels Technologies Inc.

[5] Jiang Deming, Chen Changyou, Yang Jialin, et al. 2006 Advance Internal Combustion Engine Fundamentals. Xi’an: Xi’an Jiaotong University Press, 103-107.

[6] Darade, P. M. 2012. Performance and Emissions of Internal Combustion Engine Fuelled With CNG - A Review, *1*(5), 473–477.

[7] Wang J. Hao Chen, Bing Liu, Zuohua Huang. 2008. Study of cycle-by-cycle variations of spark ignition engine fuelld with natural gas-hydrogen blends. Int J Hydrogen energy; doi; 10.1016/j.ijhydene.2008.06.062.

[8] Bauer CG., Forest TW. 2001. Effect of hydrogen addition on performance of methane feulled vehicles, Part 1: Effects on SI. Engine performance. International Journal of Hydrogen Energy, 26(1): 55-70.

[9] Wong and Kareem. 2015. Effects of hydrogen enrichment and hydrogen addition on cyclic variations in homogeneously charged compression ignition engines. International Journal of Hydrogen Energy.

[10] Akansu S.O, Zafan Dulger, Nafiz kahrahman, T. Nejat Veziroglu. 2004. Internal Combustion Engine fuelled by natural gas-hydrogen mixtures. International Journal of Hydrogen Energy, , 29(14): 1527-1539.

[11] Karim G., Wierzba I and Alousi Y. 1996. Methane-Hydrogen mixtures as fuels.. International Journal of Hydrogen Energy , 21(7): 625-631.

[12] Liu Bing, Huang Z., Zeng Ke et al. 2008. Experimental study on emissions of a spark-ignition engine fueled with natural gas-hydrogen blends. Energy and fuels, 22(1): 273-277.

[13] Sierens R., Rossel E. 2000. Variable composition hydrogen/natural gas mixtures for increased engine efficiency and decrease emissions. Transactions of the ASME, Journal of Engineering for Gas Turbines and Power, 122(1); 135-140.