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Engine Performance Characteristics Fuelled By In-Situ Mixing of Small Amount of Hydrogen and Compressed Natural Gas at Various Relative Air-Fuel Ratios

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Abstract

Spark ignition engine fuelled by in-situ mixing of small amount of hydrogen and compress natural gas ($CNG-H_2$) engine have numerous benefits compared to conventional engine like gasoline, diesel, and natural gas engine especially in emission control. Many researchers have continuously conducting experimental researches to improve $CNG-H_2$ engine and adopt a strategy aimed at realizing an improved performance. Hythane ($CNG-H_2$) is the excellent alternative fuel to be utilized in internal combustion engine (ICE). Thus, the purpose of this experimental study is to investigate the engine performance characteristics fuelled by in-situ mixing of small amount of Hydrogen gas and compressed natural gas ($CNG-H_2$). The research was conducted experimentally at wide open throttle (WOT), various hydrogen gas fractions (0, 3, 5, 7, and 10% by mass) and various air fuel ratios such as rich mixture (λ=0.9), stoichiometric mixture (λ=1.0) and lean mixture (λ=1.2) and at constant engine speed (2000 rpm). The result showed that the brake torque has a decreasing trend. This is so because of reduction in burning velocity. More so, the brake torque showed about 22.4% decrement at rich mixture (λ=0.9) under normal operating condition. While increasing the hydrogen fractions decrease the brake thermal efficiency at the lean mixture (λ=1.2). This might be due to the reduction in the degree of dissociation in the high temperature burn gases which allow more fuel chemical energy to be converted to sensible energy near TDC. In addition, BSEC increases as the percentage of hydrogen gas increase. This might be largely due to cycle by cycle combustion variations which deteriorate the combustion quality. At stoichiometric mixture and 0% and 10% of hydrogen gas fractions by mass, the BSEC showed approximately 39% reduction. Thus, it can be concluded that by adding the small amount of hydrogen gas in CNG is a not favorable technique to improve the performance characteristic of the direct injection hydrogen enriched compressed natural gas (DI-HCNG) engine. However, it might be a good technique to reduce the basic pollutants emission such as $BSNO_x$, BSCO and BSUHC in ICE but further research is still needed in future to confirm this.

Keywords: Compressed Natural Gas, Direct Injection Hydrogen Enriched Compressed Natural Gas Engine, Hydrogen gas, In-situ mixing, Performance characteristics, Relative Air-fuel ratios and Wide Open Throttle.

INTRODUCTION

Petrol and diesel engines are the two most usually used internal combustion engines. Although their operation looks similar, they have some interesting differences and each has advantages over the other [1-6]. Petrol and diesel fuels are fossil fuel that causes significant damage to the environment because nitric oxide (NO_X), unburnt hydrocarbon (UHC) and carbon dioxide (CO_2) emissions are released during combustion process, so the change from this fossil fuel to the alternative fuel is highly imperative [7-9]. A natural gas is the best alternative fuel that can be uses in internal combustion engine (ICE). The reason for this is because it is eco-friendly than petrol and diesel fuel. It is cheaper and quite renewable [10-15]. Natural gas is produced from gas wells or oil wells rich in natural gas. It is composed mainly of methane, but it also contains small amount of ethane, propane, hydrogen, helium, carbon dioxide, nitrogen, hydrogen sulfate and water vapor. On the vehicle it is stored either in gas phase at pressure of 150 to 250 atm as CNG (compressed natural gas or in the liquid phase at -162ºC as LNG (liquefied natural gas) [16]. The combustion of natural gas produces lesser emissions 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. Despite the numerous benefits that can be derived from natural gas, yet it still possess some disadvantages. The disadvantages such as slow burning velocity and poor lean burn capability of the engine [13]. One effective technique to solve these problems 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. Hydrogen is the most abundant element on the earth. The combustion and emission characteristics of hydrogen are excellent to any other competing fuel [12-13]. There are many published literatures on the utilization of $CNG-H_2$ in the internal combustion engine. Wang J et al conducted an experimental study on the cycle-by-cycle variations of spark ignition engine fuelled by natural gas-hydrogen blends [17]. Bauer and Forest conducted an experimental study on natural gas-hydrogen combustion in a cooperative fuel research (CFR) engine [18]. Wong and Kareem analytically examined the effects of hydrogen enrichment and hydrogen addition on cyclic variations in homogeneously charged compression ignition engines [19]. The results showed that the addition of hydrogen can reduce cyclic variations while extending the operating region of the engine. Most of the previous literatures on the utilization of CNG-H_2 in internal combustion engine were done using premixed (i.e. mixing of CNG and Hydrogen gas in one gas tank before the combustion) and at stoichiometric mixtures only. Up till now, information is still lacking on the implementation of in-situ mixing of CNG-H_2 (i.e. injection of CNG and Hydrogen gas separately during the combustion process) in internal combustion engine at various air-fuel ratios such as rich mixture (λ=0.9), stoichiometric mixture (λ=1.0) and lean mixture (λ=1.2). Therefore this study was focused on the performance characteristics of the in-situ mixing of CNG-H_2 in a direct injection compressed natural gas (i.e. DI-HCNG) engine. Thus, a new discovery on the implementation of the dual fuel (CNG-H_2) in a DI-CNG engine using in-situ mixing technique may be uncovered.

Significance Statement

This study discovers the implementation of in situ-mixing of small amount of hydrogen gas with compressed natural gas in a direct injection compressed natural gas (DI-CNG) engines at a various relative air-fuel ratios that is beneficial in achieving an improved performance characteristics of the engines. This study will help the engine researchers to understand the effects of adding small amount of hydrogen gas to CNG (using In situ – mixing technique) at a various relative air-fuel ratios in a direct injection compressed natural gas (DI-CNG) engine which until now remains elusive. Thus, a new discovery on the implementation of the dual fuel (CNG-H_2) in a DI-CNG engine using in-situ mixing technique may be uncovered.

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:

$$aCH_4 + bH_2 + c\,(O_2 + 3.76N_2 \quad (1) \quad + y\,H_2O + z\,N_2$$

Where:

a: represents the percentage by mass of Natural gas

b: represents the percentage by mass 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.

EXPERIMENT PROCEDURE

The specification of the test engine is listed in Table 1 below. A four-stroke single cylinder research engine was used to investigate the performance characteristics of the direct injection compressed natural gas engine fuelled by in-situ mixing of CNG-H_2. For the purpose of this study, percentage by mass of hydrogen gas is considered. The schematic of the experimental setup is given in Figure 1. The experiment was conducted in "Center of Automotive Research and Electronic Mobilty (CAREM), University of Technology PERONAS" on the 30th April, 2017.

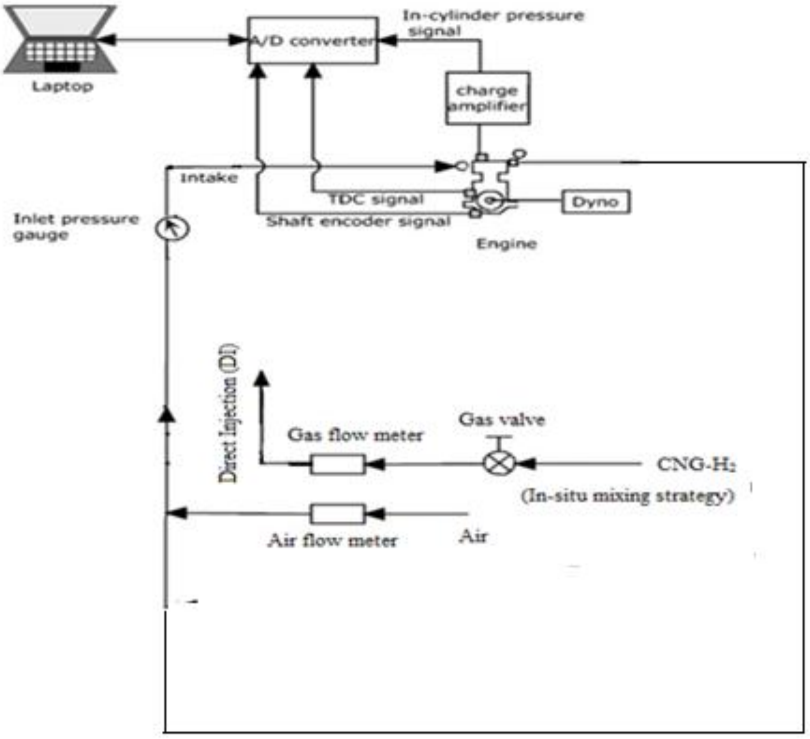

Figure 1: Schematic of the experimental set up

Table 1: Test Engine Specifications

Engine specification	Value/ description
Injecting Timing	300˚ CA (Early Injecting Timing)
Intake Manifold Absolute Pressure	Wide Open Throttle
Ignition Sources	Spark plug
No. of cylinder, Stroke	Single Cylinder, 4 Stroke
CNG Injecting Pressure	18 bar
Engine Speed	2000 rpm
Fuel	Hydrogen Gas, Compressed Natural Gas
Bore	102mm
Stroke	115mm
Percentage Hydrogen	0, 3, 5, 7, and 10% by mass

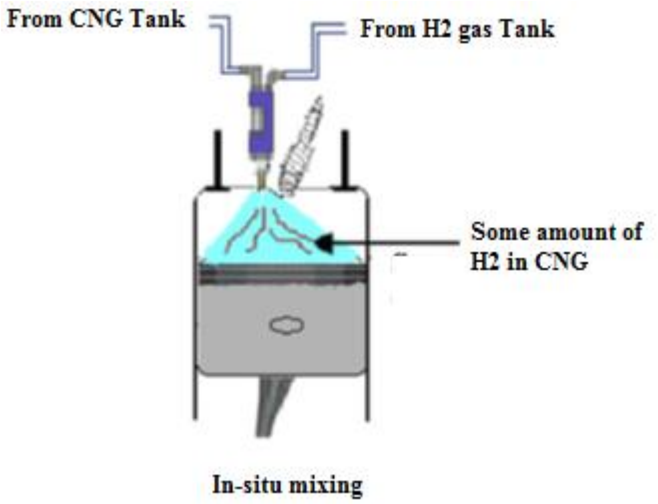

Figure 2: In-situ mixing of CNG and Hydrogen gas.

The supply system of the experiment setup consists of fuel ($CNG-H_2$), pressure gauge, flow meter. The experiment was conducted after running the engine until it becomes stable and the oil and cool temperatures is at 60˚C and 70˚C respectively. The experiment work was started by injecting CNG and H_2 into the engine cylinder. The flow of $CNG-H_2$ was adjusted with the aid of regulating flow meter valve into the engine (Fig. 2). Electronic control unit (E.C.U) was used to control all the engine operating parameters such as wide open throttle (WOT), air-fuel ratios (stoichiometric, rich, and lean mixture), and the engine speed. Eddy current dynamometer was utilized to collect the performance characteristics data such as Brake torque, Brake specific Energy Consumption (BSEC) and Brake Thermal Efficiency.

*However, 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.

RESULTS AND DISCUSSION

Performance Characteristics

This section focus on the analysis and discussion of the best results obtained from the experiment. The experiment was performed using in-situ mixing of small amount of hydrogen and CNG in a DI-CNG engine. The various air-fuel ratios use in this experiment are rich combustion (λ=0.9), stoichiometric combustion (λ=1.0) and lean combustion (λ=1.2) and the fractions of hydrogen are 0%, 3%, 5%, 7% and 10 % by mass. The experiment was conducted using early injection timing (300˚ CA) and engine speed of 2000 rpm. The performance characteristics parameters consider in this study are brake torque (BT), brake thermal efficiency (BTE) and brake specific energy consumption (BSEC) and was fully explored in this section.

Brake Torque

Fig. 3 showed the graph of brake torque against percentage of hydrogen at various air fuel-ratios which are at rich (λ=0.9), stoichiometric (λ=1.0) and lean mixtures (λ=1.2). From the graph, it is obvious that the brake torque decreases when the hydrogen fractions are increased. This is so; because increase in hydrogen fractions will reduce the energy density (LHV) and the brake torque will decrease. The highest amount of brake torque occurs at rich mixture (λ=0.9) simply because of incomplete combustion which is caused by insufficient supply of oxygen (air). In addition, the lowest brake torque occurs at lean mixture (λ=1.2) due to inefficient combustion which is caused by excess supply of oxygen. Consider the brake torque at rich mixture (λ=0.9) and the engine speed of 2000rpm and at 0 and 10% Hydrogen gas. The brake torques respectively is 22.25- Nm and 17.30 Nm. This show that the brake torque at 2000 rpm engine speed and at different percentage hydrogen gas and wide open throttle (WOT) under rich mixture condition (λ=0.9) decreases by 22.4% under normal operating condition. While for lean mixture (λ=1.2) the brake torque are 18.36 Nm and 12.20 Nm respectively. This show approximately 34% decrement in the brake torque. Hence more reduction occurs at lean mixture simply because it contains less fuel than air in the engine cylinder. Good agreement was achieved between the experimental results and Bauer CG [18].

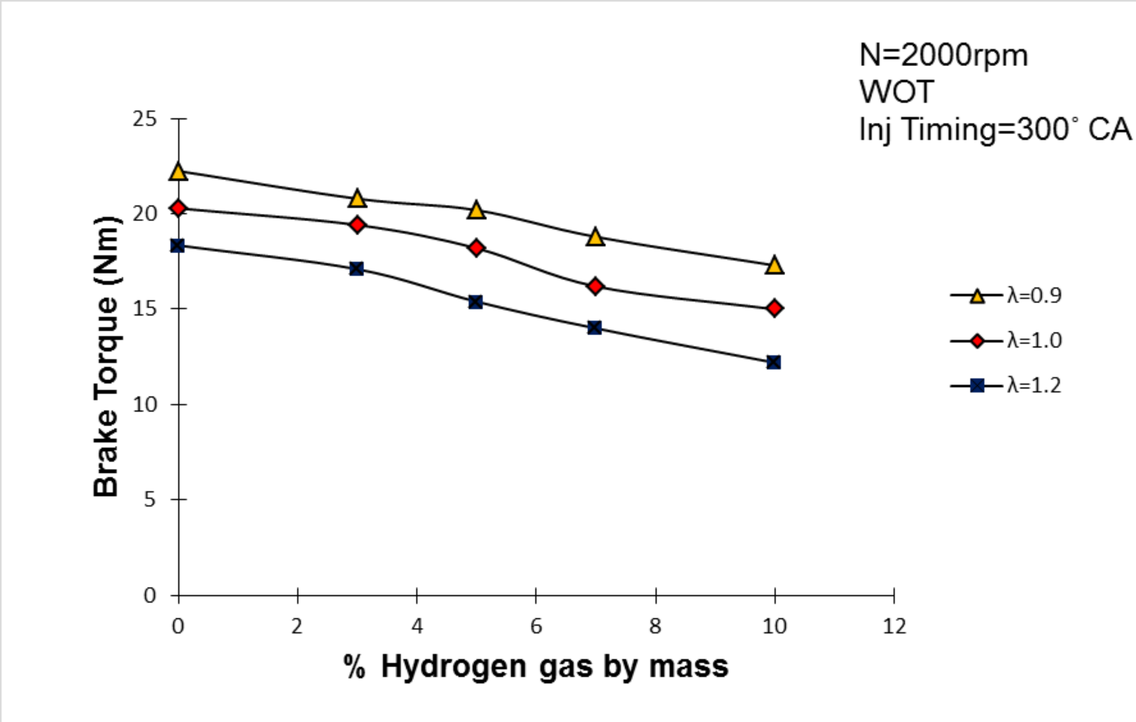

Figure 3: Brake Torque against percentage of Hydrogen gas by mass at various air-fuel ratios.

Brake Specific Energy Consumption (BSEC)

The relationship between brake specific energy consumption against percentage of hydrogen at various air fuel ratios is presented in Fig. 4. The graph trend reveals that adding the small amount of hydrogen gas increase the BSEC at all various air fuel ratios (ʎ=0.9, ʎ=1.0, and ʎ=1.2). This is due to the cycle by cycle combustion variation which deteriorates the combustion quality. The highest amount of BSEC occur at stoichiometric mixture (ʎ=1.0) simply because complete combustion caused by efficient utilization of oxygen (air) in combustion process. While the lowest BSEC occur at lean combustion (ʎ=1.2) due to the fact that lean combustion contain more air than fuel which promotes inefficient combustion at that operating condition. Consider the BSEC at stoichiometric mixture (λ=1.0) and engine speed of 2000rpm and 0% and 10% hydrogen gas by mass. The BSEC respectively are 24.81 and 15.05 MJ/kW hr. This show approximately 39% decrement at this operating condition. While for the lean combustion (ʎ=1.2) the value of BSEC are 23.25 and 13.31 MJ/kw hr respectively and this measures about 43% increasing in brake specific energy consumption. Thus, more increment occurring at lean mixture. Good agreement was achieved between these experimental results and Akansu S.O [13].

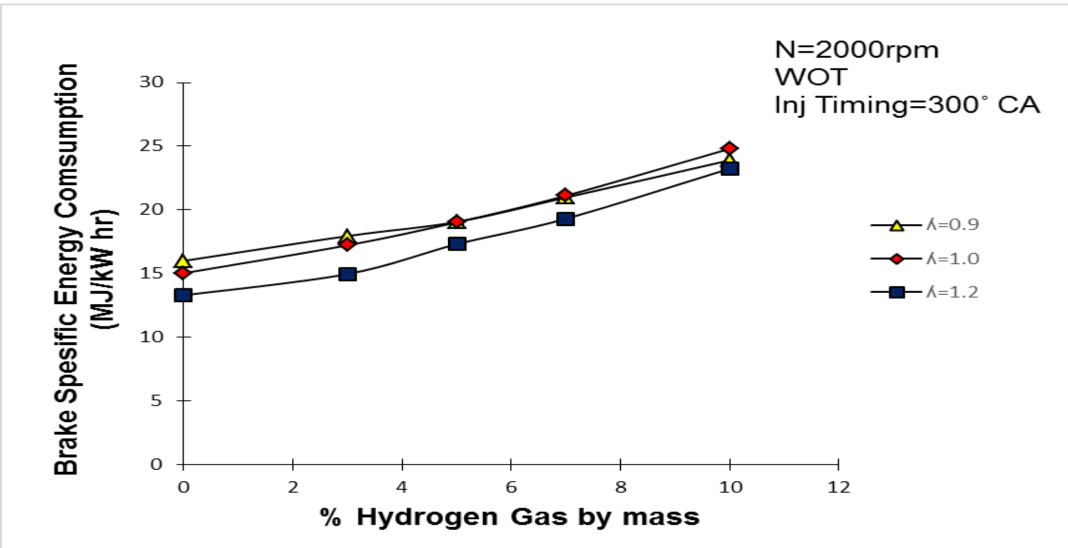

Figure 4: Brake Specific Energy Consumption against percentage of Hydrogen at various air-fuel ratios.

Brake Thermal Efficiency (BTE)

Fig. 5 shows the relationship between brake thermal efficiency (BTE) against different hydrogen fractions at constant engine speed. As expected, the characteristics of the BTE plot are the inverse of the plot of BSEC. It can be observed from the figure that the thermal efficiency value is found to decrease with addition of hydrogen. Increasing percentage of hydrogen gas resulted into decrease in BTE simply because of the reduction in the degree of dissociation in the high temperature burn gases which allow more fuel chemical energy to be converted to sensible energy near TDC. The highest brake thermal efficiency occurs at lean mixture (λ=1.2). The reason might be due to the decrease in burning velocity occasioned by insufficient fuel supply at that operating condition. In addition, the lowest brake thermal efficiency occurs at stoichiometric mixture (λ=1.0) and this could be due to complete utilization of oxygen (air) (efficient combustion) at that operating condition. Comparing the BTE at lean and stoichiometric mixtures for 0% and 10% hydrogen. The brake thermal efficiency for lean mixture (λ=1.2) at 0% and 10% hydrogen respectively are 27.04% and 15.48%. This shows 43% decrement in BTE at that operating condition. While the brake thermal efficiency at stoichiometric mixture (λ=1.0) are 23.91% and 14.51% respectively which shows there is a decrement of about 39% in brake thermal efficiency at that operating conditions. The reason why more decrement occurred at lean mixture might be due to inefficient combustion (inefficient utilization of oxygen (air). The result obtain here is coherent with Sierens R., Rossel E [20].

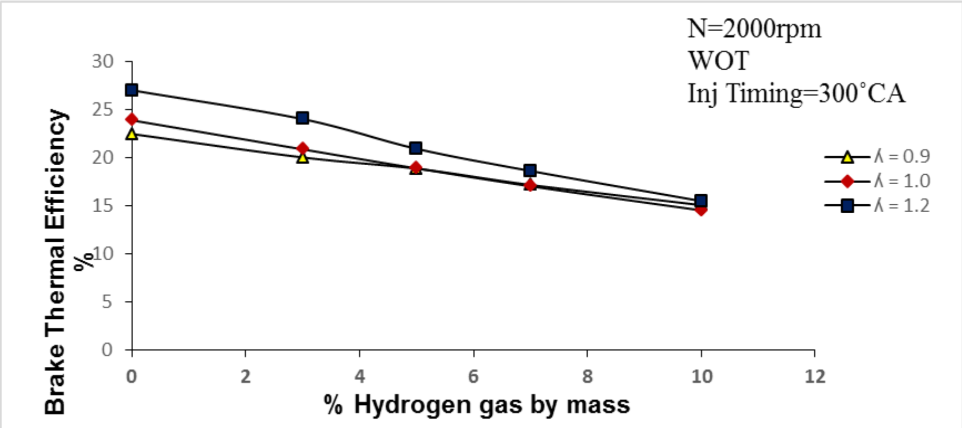

Figure 5: Brake Thermal Efficiency against percentage of Hydrogen at various air-fuel ratios.

CONCLUSION

An experiment study has been performed to study the performance characteristics of the direct injection compressed natural gas (DI-CNG) engine fuelled by in-situ mixing of the small amount the hydrogen and compressed natural gas ($CNG-H_2$) under wide open throttle position (WOT) and various air-fuel ratios which are rich mixture (λ=0.9), stoichiometric mixture (λ=1.0) and lean mixture (λ=1.2) and the main results are highlighted below:

- The brake torque decreased as the percentage hydrogen fractions is increased at various air fuel ratios. This is so, because increase in hydrogen fractions will reduce the energy density (LHV) and consequent upon this, the brake torques wills decreases.
- The brake specific energy consumption (BSEC) increase for the operating condition under consideration simply because of cycle by cycle combustion variations which deteriorate the combustion quality.
- Increase in hydrogen fractions decreased the brake thermal efficiency. The reason might be due to the reduction in the degree of dissociation in the high temperature burn gases which allow more fuel chemical energy to be converted to sensible energy near TDC.

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