Simulation Analysis on the Performance of a Hydrogen Port Fuel Injection Engine

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Abstract Over the past few years, many researchers have conducted experimental and simulation studies using alternative fuels for internal combustion engines. Selected fuels should contain less or no carbon products from combustion process and eventually decrease the primary energy usage. Hydrogen has been taken into consideration. Previous researchers found that hydrogen can be used in spark ignition internal combustion engines. However, the optimum performance of an engine could not be achieved due to some limitations in regards the configurations of the air fuel ratio and compression ratio. In this work hydrogen fuel was tested in a single cylinder port fuel injection engine as the preliminary study in optimizing the engine performance. The engine performance study was based on the brake torque, brake power, brake mean effective pressure (Bmep) and peak pressure. The engine model was developed based on the Modenas Kriss 110 cc 4-stroke single cylinder gasoline engine. The CATIA software was used in developing the 3D engine model and followed by utilization of GT-Suite software in analyzing the engine performance. From the analysis, it was found that the performance of the hydrogen fueled engine is lower compared to the gasoline engine.

Keywords Engine · GT-Suite · Hydrogen · Air-fuel ratio · Compression ratio

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1 Introduction

The needs in finding renewable energy resources are keep growing to fulfill the energy demand that keeps increasing years after years. Fluctuating of oil price and environmental issues have increased the activities in finding alternatives fuel resources that will provide a sustainable energy and achieve greener environment. There are many researches were done by various researchers using various types of fuel and hydrogen is one of non-carbonaceous fuels that exists on the earth [1]. It can be used in internal combustion engines. Experimentation and studies were performed by previous researchers using hydrogen as a fuel in internal combustion engines [2, 3], ended up with the results showing there are some limitations in configuring the air-fuel ratio and compression ratio. Changing both parameters will give optimum performance of the hydrogen engine.

The studies of hydrogen addition in internal combustion engines have found that hydrogen fueled engines suffer from output power reductions due to the very low heating value on volume basis which results in lean mixture operation [4]. High stoichiometry of hydrogen to air ratio also causes the mass of the intake air being reduced for any engine sizes. Increasing the compression ratio increases the maximum cylinder gas pressure and the maximum gas mean temperature [5]. A desirable Bmep can be achieved at lean mixture at low engine speed but is unacceptable for higher engine speed [1].

Performance improvements can be achieved by retarding the spark timing and together with a change in compression ratio [6, 7]. This project attempts to analyze the engine performance characteristics of a hydrogen port fuel injection engine and its potential as an alternative fuel for internal combustion engines.

2 Methodology

The model development starts with collecting the overall engine performance results from the experimental setup. The first step taken is determining the performance of a gasoline engine by using an experimental setup. An engine dynamometer was used simultaneously with a gas analyzer to determine the gasoline engine performance and air-fuel ratio. The engine performance test is performed at wide open throttle (WOT) condition. The experimental results are used for validation of the developed engine model.

The engine modelling starts by creating a 3D model of engine parts by referring to the actual geometry from the Modenas Kriss 110 cc engine. The CATIA V5R21 CAD software was used to model the air box, intake runner 1 and 2, intake port, exhaust port and exhaust runner. The precise dimensions of parts in terms of their volume, diameters of runner's throat, radius of bending on intake and exhaust port and also the length of parts were taken into consideration during modeling. Every part was created separately in order to be exported in GEM-3D which is a module in the GT-Suite v7.4.3 software. Once the parts were successfully modelled in a 3D version, they were imported in GEM-3D to be discretized which transforms every part to 1D diagrams. During the discretization of every part in GEM-3D, the diameter of every pipe section and the wall temperature were set according to the factory settings of the engine.

After the discretization process completed, every part was dragged to the GT-Power module in the GT-Suite v7.4.3 software. Here the 1D converted part diagrams were arranged according to the original arrangements from the actual engine starting from the air box until the tail pipe and connected with a string called junction [8]. Then, using the engine technical specifications as shown in Table 1 and temperature for engine parts in GT-Suite v7.4.3 software as shown in Table 2, the detailed configurations were set for every parameters and engine components involved. Manuals and tutorials from the GT-Suite software were used during the modeling process. Valves diameters, wall temperatures, flow arrays, valves opening and closing durations were taken into serious priority to achieve the same output performance as the actual engine. The next step was the setting of different air fuel ratios for different engine speeds and separated to several cases. Based on the simulation runs of the different sets, the output performance can be compared to the actual experimentation results which run with different configurations of air fuel ratios for each different engine speed. The output from the successfully performed simulations was shown in GT-Post. The results were collected and tabulated to be used for the validation [8] and comparison.

Table 1 Engine technical specifications

Engine parameter	Value
Bore × Stroke	53 mm × 50.6 mm
Total displacement	111 mL
Maximum torque	9.3 N.m at 4000 rpm
Maximum horsepower	6.6 kW at 8500 rpm
Compression ratio	9:3:1
Intake valve open (IVO)	20° BTDC
Intake valve close (IVC)	60° ABDC
Exhaust valve open (EVO)	55° BBDC
Exhaust valve close (EVC)	25° ATDC
Total duration intake/exhaust	260°

Table 2 Parts temperature in GT-Suite software

Engine parts	Temperature (K)
Cylinder head	550
Piston	590
Cylinder block wall	450

3 Results and Discussion

3.1 Model Validation

To validate the constructed model, verification to the experimental data is needed. The accuracy of the constructed model was verified by comparing the engine performance between model and experiment. Both of the results were correlated based on their trends and values. At the early stages of the verification, the simulation results show a quite significant difference when compared to experimental results. Thus, the parameter set in the simulation model was rechecked and some minor alterations were performed. There are some increments shown from the alteration of cam timing angle, angle multiplier, lift multiplier and flow array. The cam timing angle for the intake valve was set to 231° and for the exhaust to 123.9°. The angle multiplier was 0.83 and the lift array was 0.5 for both intake and exhaust valve. The flow array was configured using an excel self-calculating file in GT-Suite. The forward coefficient was adjusted to 0.95 to obtain the flow array values.

Engine performance results were plotted in GT-Post after the 10 cycle runs of the simulation. Differences between the average value of experiment and model are in the range of 0.6–3% for brake torque, brake power and Bmep. Thus, the accuracy and precision of the developed model was validated with the output results achieving no more than 5% difference compared to the experimentation engine. The outcome from engine performance results are plotted in graphs as shown in Fig. 1.

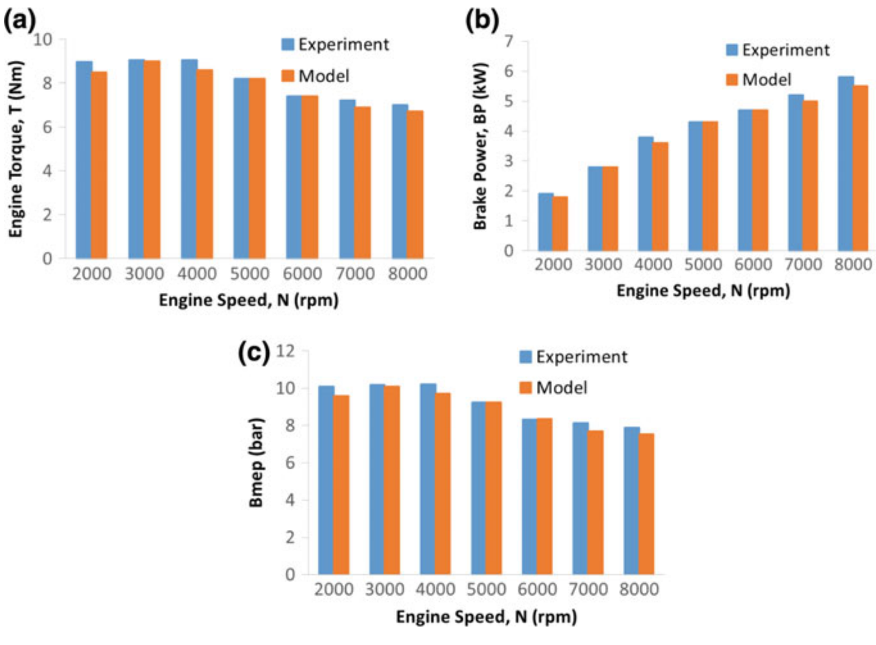

Fig. 1 Validation of gasoline model according to **a** engine torque, **b** brake power and **c** Bmep

3.2 Hydrogen Fueled Model

For hydrogen fueled engine, the air-fuel ratios from the gasoline experimentation and modeling is calculated to suit hydrogen model. The stoichiometric air-fuel ratio for hydrogen is 34.3:1 meanwhile for gasoline it is 14.7:1. If the same settings of the air-fuel ratios from gasoline were used for hydrogen, the simulation was not completed and ended with errors. To eliminate this problem, an equivalence ratio from gasoline fuel was obtained by dividing the stoichiometric of gasoline with air-fuel ratio set during the experiment [9]. Then, the stoichiometric of hydrogen was divided by the equivalence ratio to have the output value of air-fuel ratios needed for the hydrogen model as shown in Table 3.

The same procedure was followed as in the case of gasoline model, and the results from GT-Post were collected and plotted as shown in Fig. 2. A comparison between the gasoline and hydrogen graphs shows some significant differences for the overall engine performance. An increase in the equivalent ratio of hydrogen fuel lead to higher value of air-fuel ratio and this created non-consistent differences between the gasoline and hydrogen model. An average value of 30% performance difference was observed from the gasoline to hydrogen comparisons results for brake torque, brake power and also Bmep, that can be considered as performance degradation. The loss in brake torque and brake power is due to the knock and backfiring. Buildup of a small amount of hydrogen in the intake manifold when the injection duration is longer than the intake valve opening duration creates backfire by ignition of the hydrogen leftover in it with hot exhaust gases released at the exhaust stroke [7, 10]. Meanwhile, drops in Bmep are due to improper combustion as increasing of the hydrogen fraction in the overall fuel intake which reduces the air intake [5].

For the peak pressure, an average value of 15% difference was observed from the comparisons. A lower peak pressure was achieved due to the low compression ratio. Finally, the Bsfc for hydrogen gives a two times better value than the gasoline because of the rich mixture of the air-fuel ratio. The fuel consumption of the hydrogen fueled model achieved improvements at an average value of 60% difference compared to the gasoline fueled engine. Although the overall engine performance of hydrogen is low compared to gasoline except for Bsfc, an optimization could lead to increments in outputs.

Table 3 AFR configurations of gasoline and hydrogen using the same equivalence ratio

Engine speed (rpm)	AFR (Gasoline)	Equivalence ratio	AFR (Hydrogen)
2000	13.41	1.09	31.46
3000	13.05	1.12	30.62
4000	11.16	1.32	25.9
5000	10.66	1.38	24.8
6000	10.54	1.39	24.6
7000	11.34	1.29	26.5
8000	10.68	1.37	25.0

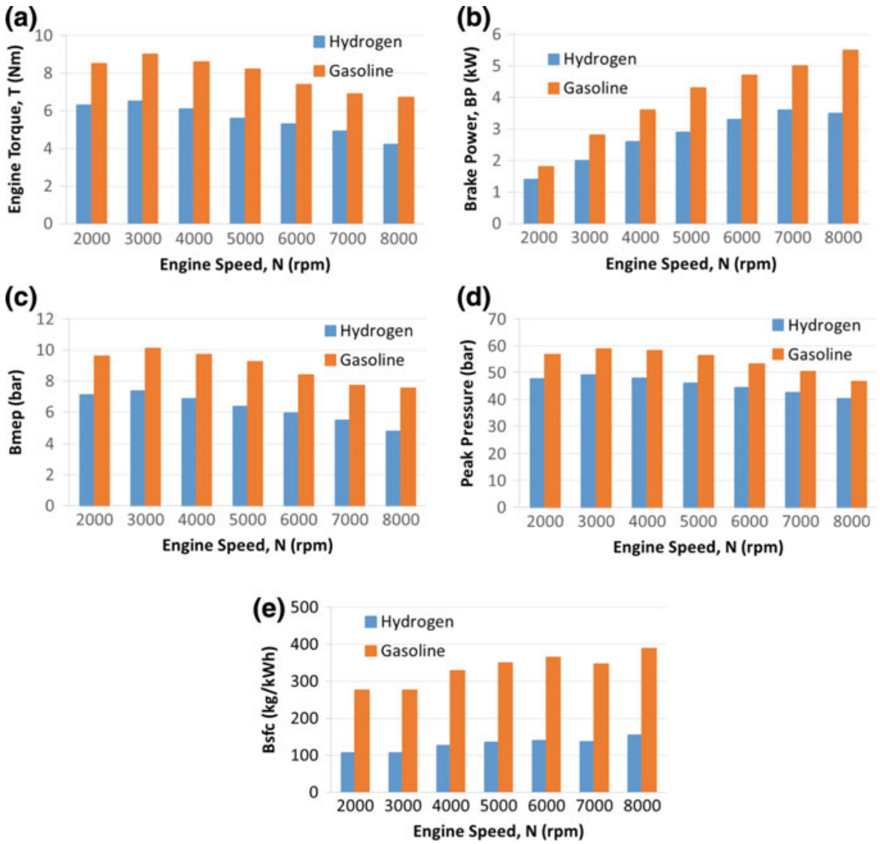

Fig. 2 Comparison of **a** brake torque, **b** brake power, **c** Bmep, **d** peak pressure and **e** Bsfc at various engine speeds

4 Conclusion

As a conclusion it was found that hydrogen fuel produced a lower engine performance with an average value of 29% performance difference compared to hydrogen comparisons results for brake torque, brake power and also Bmep. Other findings are as follows:

i. A loss in brake torque and brake power is due to the knock and backfiring. The buildup of a small amount of hydrogen in the intake manifold when the injection duration is longer than the intake valve opening duration creates backfire by ignition of the hydrogen leftover in it with hot exhaust gases released at the exhaust stroke.
ii. Drops in Bmep are also due to improper combustion as increasing of hydrogen fraction in the overall fuel intake which reduces the air intake.

iii. For the peak pressure, an average value of 15% difference was observed from the comparisons due to low energy density of hydrogen.
iv. Bsfc for hydrogen gives a two times better value than the gasoline due to its gaseous fuel form.

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