Optimization of Air-Fuel Ratio and Compression Ratio to Increase the Performance of Hydrogen Port Fuel Injection Engines

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Abstract Climate changes and increased demands for energy, tends researchers in searching for environmental friendly resources of energy that can be used in internal combustion engines (ICEs). Hydrogen fuel is one of alternative fuels that produces zero emission. It has been extensively studied by various researchers in internal combustion engines. However, optimum performance could not be achieved due to some limitations on the configurations of air fuel ratio (AFR) and compression ratio. In this study, hydrogen fuelled engine performance and the effect of different air fuel ratios and compression ratios were analyzed. The engine performance characteristics are investigated based on the brake torque, brake power, brake mean effective pressure (BMEP), and peak pressure. Modenas Kriss 110 cc petrol engine was selected for experimentation and engine modelling. A three-dimensional engine model was created using CATIA V5R21 and the engine performance simulation was performed using GT-Suite v7.4.3. The optimum configuration was

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obtained using a design of experiments (DOE) software. From the analysis, it was found that the performance of the hydrogen fueled engine was improved by changing to a leaner AFR and higher compression ratio. The improvement was found around 7.6, 9.3, 8.0, 25.9, 30.6% for brake torque, brake power, BMEP, peak pressure and brake specific fuel consumption, respectively.

Keywords Hydrogen · Engine performance · GT-suite

1   Introduction

The unstable market price for crude oil and electricity are pushing the government and non-government bodies to find an alternative or renewable green energies to fulfill the users need. Although there are many options of renewable and alternative energies, it is not much help in preserving the quality of environment and some of them contribute to higher pollutions. Many studies have been conducted by researchers on various types of alternative fuel to power an engine and it turned up that hydrogen is one of the non-carbonaceous fuels that exists on earth [1]. It can be used as a fuel source for powering an engine. There were many experimental studies conducted using hydrogen as a fuel in an engine [2–4]. Results show that there are some limitations in configuring the air-fuel ratio, injection timing and also the compression ratio that can affect the engine performances [4, 6]. The air-fuel ratio has a significant effect on the performance of hydrogen fueled engines, where the brake mean effective pressure (BMEP) and brake thermal efficiency was found decreasing with the increment of the air fuel ratio while the brake specific fuel consumption (BSFC) increased with increases of the air-fuel ratio [4].

Studies on hydrogen addition in internal combustion engines also had found that hydrogen fueled engines suffer from power output degradation due to its low heating value (volume basis) which results in lean mixture operation [5]. In a natural-gas direct injection spark ignition engine, the compression ratio has a significant influence on the combustion duration at lean combustion. The exhaust hydrocarbon (HC) and carbon monoxide emissions decreased with an increase in the compression ratio, while the exhaust nitrogen oxide emission increased with an increase in the compression ratio [6]. Hydrogen compressed natural gas engines, on the other hand, show that the performance and emissions characteristics can be improved respectively with a hydrogen content of 30% by volume. At higher compression ratio, the specified torque value could be achieved with spark timing retard; an excess air ratio of 1.8 was found to be preferable, and the nitrogen oxide emissions are also satisfying the standard of Euro VI [7]. In the performance of hydrogen fueled engines, it was found that the peak power output was reduced up to 20% [8].

The air fuel ratio and compression ratio play a significant role on the performance of hydrogen fueled engines. This research will analyze these effects and optimize the air-fuel ratio and compression ratio in a simulated hydrogen port fuel

injection engine. The air to fuel ratios are studied from rich to lean mixture, as well as increasing the compression ratios from low to high. The optimum configurations achieved from the analysis is studied and the reasons behind will be explained in detail for future improvements.

2 Methodology

The initial preparation taken to achieve the objectives of this study is by collecting the overall engine performance results from the experimental setup. The engine performance testing was conducted using a dynamometer along with a gas analyzer coupled to the Modenas Kriss 110 cc engine, in the Engine Performance Lab located at UniKL MSI. The Wide Open Throttle (WOT) method was used during the petrol fueled engine performance test. Furthermore, different engine speeds were tested from 2000 to 8000 rpm and the results obtained from it were used for the purpose of validation and comparisons of the graphically developed engine model.

2.1 Experimental Setup

Figure 1 shows the experimental engine setup. The apparatus involved during the experimentation are the engine dynamometer (Focus Applied-Model G7.5LC), dynamometer controller, controller software, gas analyzer (SPTC 085241), PCB Piezotronics Pressure Transducer (Model 112A05) and Dewetron Data Acquisition (DAQ) (Model DEWE-30-8). The Modenas Kriss 110 cc engine is fitted alongside with the engine dynamometer to obtain engine performance results. Wide Open Throttle (WOT) mode [8] was performed to gather the overall engine performances. The pre-process of engine parameters set via dynamometer controller which controls the dynamometer and the post-process are shown in the controller software.

A gas analyzer has been used to measure the value of various air fuel ratios during the performance test. Besides that, the peak pressure in the cylinder is measured by the pressure transducer fitted on the cylinder head. The output signal from the sensor transferred to the Dewetron Data Acquisition and the values of in-cylinder pressure were acquired through it. Performance parameters involved in this study are the brake torque, brake power, brake mean effective pressure (Bmep) and peak pressure. Equation (1) shows the formula to calculate the engine torque:

$$T = F \cdot R \tag{1}$$

where T is the torque in (N m), F is the load applied in Newton (N) and R is the distance of load cell from dynamometer in meter (m).

Fig. 1 Experimental apparatus involved

$$\text{Brake torque} = \frac{\text{WOT Torque (N m)}}{\text{Engine Ratio}} \tag{2}$$

The brake torque can be calculated using Eq. (2). Where the WOT Torque in (N m) achieved from the computer software and the engine ratio is set to be 3.31.

$$\text{b.p} = \frac{2\pi NT}{60} \tag{3}$$

where, b.p is the brake power in (kW), N is the engine speed in (rpm) and T is the torque in (N m). Finally, the brake mean effective pressure (Bmep) can be calculated using Eq. (4):

$$\text{Bmep} = \frac{2 \, \text{b.p}}{\text{ALNn}} \tag{4}$$

where A is the area of bore in square meter (m^2), L is the stroke in meter (m) and n is the number of cylinders.

2.2 Experimental Procedure

The experiments were carried out at engine speeds of 2000–8000 rpm in increment of 1000 rpm. The engine started while the dynamometer was set to speed control mode. Then, the gear shifted to top gear and the throttle was slowly opened until it

reached the maximum position. The engine and dynamometer were allowed to stabilize for a few seconds before collecting data and move on to the next engine speed. For every run the air-fuel ratio was collected from the exhaust gas analyzer. Other data such as torque, brake power and fuel consumption also was collected from the engine dynamometer setup.

2.3 Engine Modelling and Simulation

The engine modelling construction starts with creating a three-dimensional model of the engine parts by referring to the actual geometry of 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. Precision of parts dimensions in terms of its 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 GT-Suite v7.4.3 software. Once the parts were successfully modelled in 3D version, they were imported in GEM-3D to be discretized which transforms every part into a 1D diagram. During the discretization process in GEM-3D, the diameter of every pipe section and the wall temperature were set accordingly.

Once the discretization process was completed, every part was exported to the GT-Power module in GT-Suite v7.4.3 software. In this module, the 1D converted parts were arranged accordingly, starting from the air box until the tail pipe. Every part was connected using a string called junction as shown in Fig. 2. The arrangements of the engine are different according to the engine specification and can be found in various previous works [4, 9]. 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, detailed configurations were set for every parameter and engine components are involved. Valves diameters, wall temperatures, flow arrays, valves opening and closing durations were taken into serious consideration. The next thing was setting different air fuel ratios for different engine speeds and the separation to several cases. The simulation runs according to the cases set so that, the output performance can be compared to the actual experimental results which runs with different configurations of air fuel ratios for each and every different engine speed. The output from the successfully performed simulation were shown in GT-Post. The results were collected and tabulated to be used for the validation [10], comparison and optimization process.
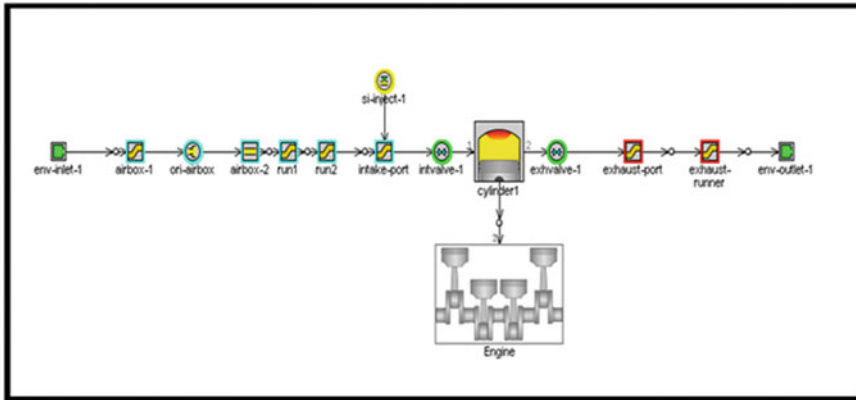
Fig. 2 1D engine model arrangements

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 @ 4000 rpm
Maximum horsepower	6.6 kW @ 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 Engine parts temperature in GT-suite software

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

3 Results and Discussion

To analyze the effect of different air-fuel ratios and compression ratios on the performance of the hydrogen port fuel injection engine, three different studies have been used.

Phase 1: Comparison and validation of gasoline simulation engine model with real gasoline engine based on the percentage difference in engine performance results.

Phase 2: Conversion of gasoline fuel to hydrogen in the engine model and comparison between results with gasoline and hydrogen.

Phase 3: Optimization of the hydrogen fueled model with different altered parameters obtained from the Design of Experiments module and rerun the simulation with those parameters. Confirmation test performed to validate those results.

3.1 Model Validation

Validation is the process of confirming the results accuracy of the developed model with the results from experiments. Both engine performance results were compared to ensure that the differences are in the range of 5%. At the initial stage, the results from the model shows a quite significant amount of differences compared to the experimental results. The final outcome from the engine performance results comparison between experiment and model are shown in Fig. 3.

During the model development process, the initial parameter sets of the simulation model are rechecked and some minor alterations are 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 is set to 231° and for the exhaust to 123.9°. The angle multiplier is 0.83 and the lift array is 0.5 for both intake and exhaust valves. The flow array is configured using an excel
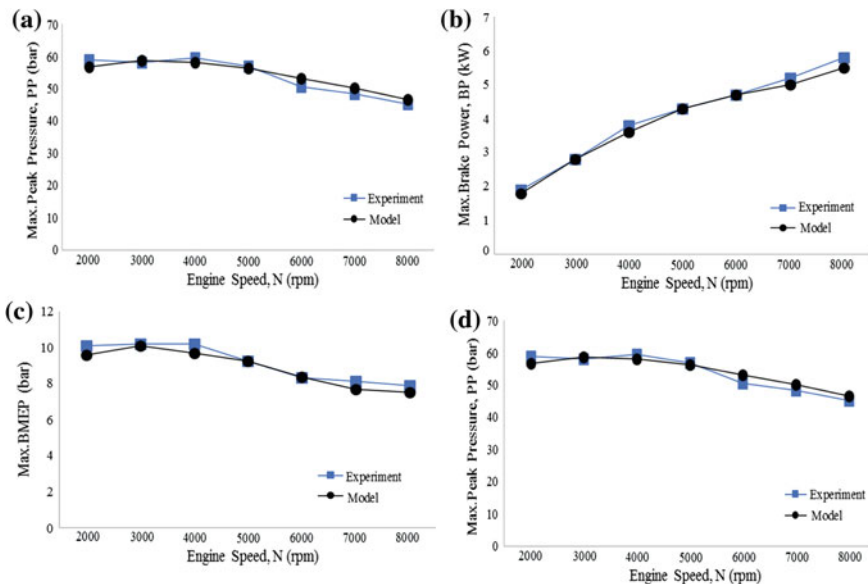

Fig. 3 **a** Max. brake torque. **b** Max. brake power. **c** Max. Bmep. **d** Max. peak pressure

self-calculating file in GT-Suite. The forward coefficient is adjusted to 0.95 to obtain the flow array values.

With the ten cycle runs of simulation, the engine performance results were plotted in GT-Post. Differentiations between average value of experiment and model are in the range of 0.6–3% for brake torque, brake power, BMEP and peak pressure for all number of engine speed. The accuracy and precision of the developed model is validated with the output results achieved and no more than 5% difference was obtained compared to the experimental engine values for all brake torque, brake power, Bmep and peak pressure.

3.2 Hydrogen Fueled Model

Before the gasoline fueled model is converted into a hydrogen fuel injected engine, the equivalence ratio for gasoline is calculated to suit with the hydrogen model. The stoichiometric air-fuel ratio for hydrogen is 34.3:1 while for gasoline is 14.7:1. To provide a fair comparison, the same equivalence ratios are used for both of the engine systems. The equivalence ratio from gasoline fuel is obtained by dividing the stoichiometric air-fuel ratio of gasoline with air-fuel ratio measured during the experiment [11]. Then, the stoichiometric air-fuel ratio of hydrogen is divided with the same equivalence ratio to obtain the value of air-fuel ratios needed for the hydrogen model as shown in Table 3.

An increase in the equivalent ratio of hydrogen fuel leads to a lower value of air-fuel ratio; this means that the engine operates at richer condition. From Fig. 4, it was found that the engine performance degrades at about 29% for the brake torque, brake power and also BMEP for hydrogen fueled engine. This can be considered as power loss. The loss in brake torque and brake power is mostly due to the low volumetric efficiency and backfiring. Buildup of a small amount of hydrogen in intake manifold when the injection duration is longer than the intake valve opening duration creates backfire by ignites the hydrogen leftover in it with hot exhaust gases released at exhaust stroke [8, 12]. Meanwhile, drops in Bmep are due to

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

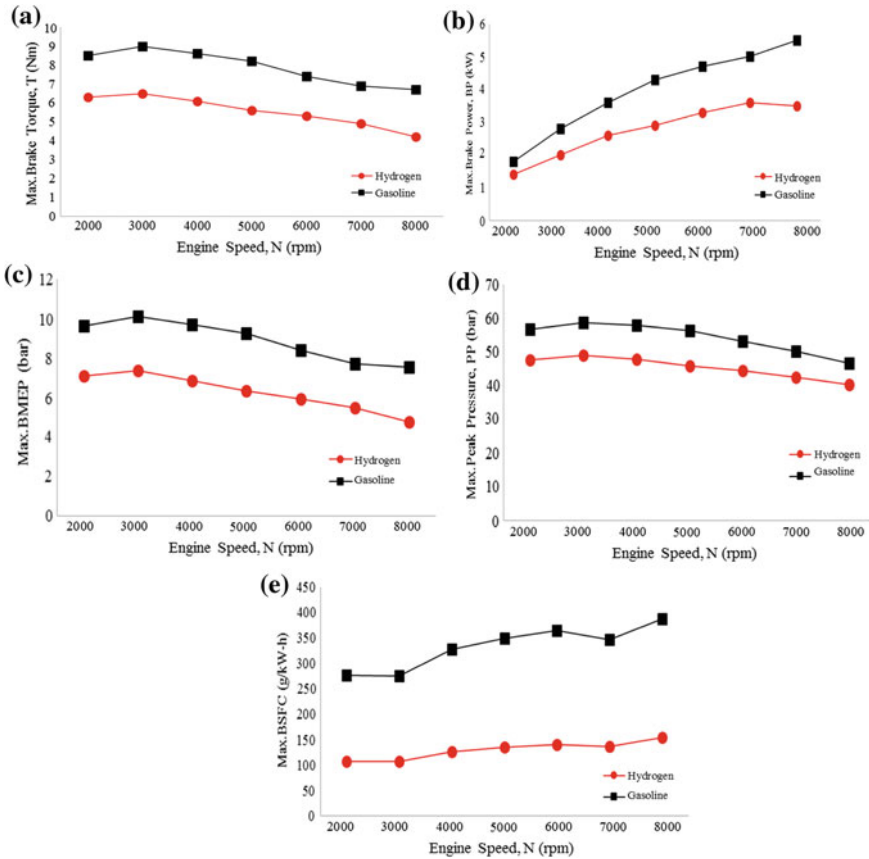| Engine speed (rpm)	AFR (Gasoline)	Equivalence ratio	AFR (Hydrogen)
2000	13.41	1.09	31.46
3000	13.05	1.12	30.62
4000	11.16	1.32	25.9
5000	10.66	1.38	24.8
6000	10.54	1.39	24.6
7000	11.34	1.29	26.5
8000	10.68	1.37	25.0

Fig. 4 **a** Max. brake torque. **b** Max. brake power. **c** Max. Bmep. **d** Max. peak pressure. **e** Max. BSFC

improper combustion. This is due to increasing of the hydrogen fraction in the overall fuel intake which reduces the air intake [6].

For the peak pressure, an average value of 16% difference is achieved from the comparisons. A lower peak pressure is produced due to improper combustion mostly due to lower amount of oxygen induced during the intake process. However, the Bsfc for hydrogen is better than the gasoline. The fuel consumptions of hydrogen fueled model are better at an average value of 61% compared to the gasoline fueled engine. Although the overall engine performance of hydrogen is low compared to gasoline, the Bsfc for hydrogen fueled is better, probably due to the lower mass flow rate of hydrogen compared to gasoline. Therefore, optimization of air-fuel ratio and compression ratio could lead to an improvement in engine performances.

3.3   Hydrogen Model Optimizations

Table 4 shows the design configurations for optimization from the Design of Experiments (DoE) module. The DoE module has been used to obtain various setup values for the air-fuel ratio and compression ratio to study their effects on the performance of the engine. Thirty set of tests were performed using different configurations for hydrogen engine with the engine speed of 3000, 4000, 5000 and 6000 rpm. The inlet valve open timing also was advanced to 40 degree and retarded to $0°$ before TDC (standard timing is $40°$ BTDC). While for exhaust valve open timing, it was advanced to $75°$ and retarded to $35°$ before BDC. Outputs from the model (brake torque, brake power, Bmep, peak pressure and BSFC) are used as the respond in the software, for optimization process. Table 5 shows the selected optimum configurations which resulted from the Design Expert software.

Figure 5 shows the analysis of engine performance based on the suggested configuration by the Design Expert software. It was found that all of the engine performances had improved due to the optimization of the air-fuel ratio, intake/exhaust valve opening timing and compression ratio. The brake torque increased by an average value of 7.6% compared to before optimization. For the brake power, it had achieved 9.3% improvement with the optimized configuration. The Bmep also had achieved some improvement although still lower compared to gasoline. The peak pressure had achieved the major improvement for the hydrogen fueled engine, and even exceeded the gasoline engine. The improvement on the overall engine performance is due to the increased compression ratio. When the compression ratio is increased, it increases the in-cylinder pressure and temperature, thus increases the in-cylinder pressure during the compression stroke [13]. The higher temperature during the compression stroke resulted in a better fuel conversion efficiency. The air-fuel ratio also plays a significant factor as the combustion is suggested to occur at slightly rich condition. Moreover intake valve open timings are suggested to be advanced to provide longer duration for air and fuel mixing process. Advancing the IVO will ensure a better preparation of fuel and air mixture thus produces a complete and fast combustion process [14].

The brake specific fuel consumption also had shown improvements with higher compression ratios. The reason behind this is the enhancement of fuel conversion efficiency at high engine pressure and temperature. Moreover, the increasing of Bsfc is due to the improvement of power output compared to low amount (mass) of fuel used for combustion process.

Table 4 Optimization values from design expert and respond

No	Air-fuel ratio	Compression ratio	IVO (BTDC)	EVO (BBDC)	Respond
1	29.5	15	20	55	1. Brake torque
2	29.5	11	0	55	2. Brake power
3	24	7	40	35	3. BMEP
4	35	11	20	55	4. Peak pressure
5	24	11	20	55	5. BSFC
6	29.5	11	20	55	
7	29.5	11	40	55	
8	29.5	11	20	55	
9	24	7	0	35	
10	29.5	11	20	55	
11	29.5	11	20	35	
12	35	7	40	35	
13	29.5	11	20	75	
14	29.5	11	20	55	
15	35	15	40	75	
16	35	7	0	35	
17	24	15	0	75	
18	35	7	40	75	
19	35	15	0	35	
20	24	15	0	35	
21	29.5	7	20	55	
22	24	15	40	75	
23	35	15	40	35	
24	29.5	11	20	55	
25	35	7	0	75	
26	35	15	0	75	
27	24	7	40	75	
28	24	15	40	35	
29	29.5	11	20	55	
30	24	7	0	75	

Table 5 Hydrogen engine performance at optimum configurations

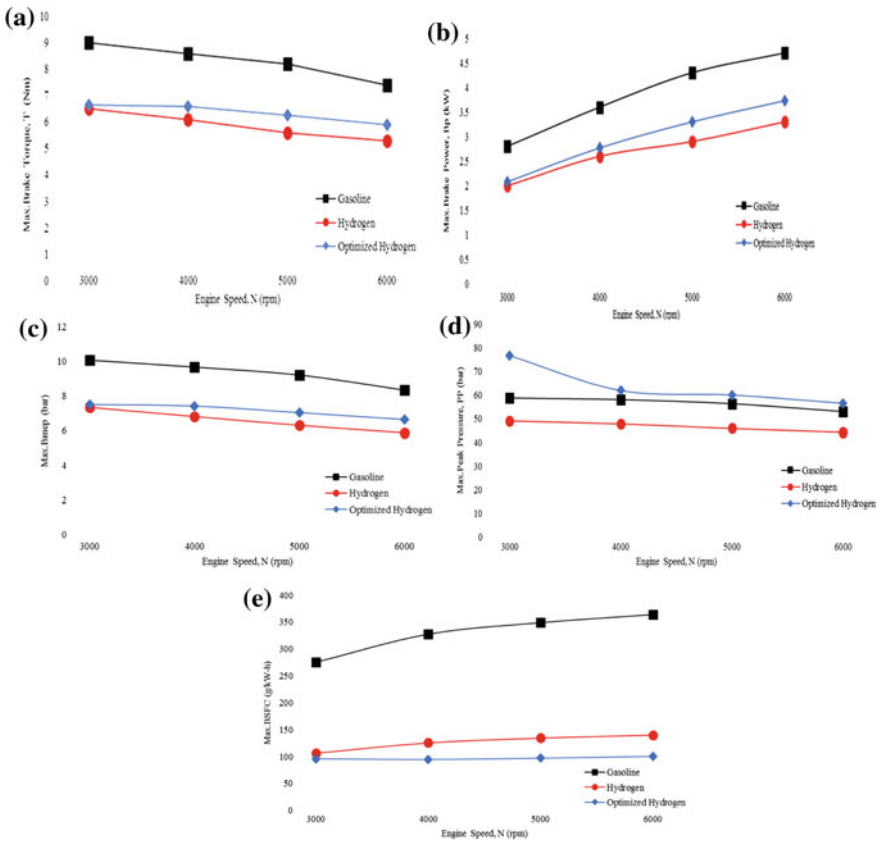| Engine speed (rpm)	Air-fuel ratio	Compression ratio	IVO	EVO
3000	35.00	14.95	39.14	49.95
4000	34.99	12.12	30.74	35.00
5000	35.00	12.07	17.43	35.71
6000	34.61	11.74	25.52	35.98

Fig. 5 **a** Max. brake torque. **b** Max. brake power. **c** Max. Bmep. **d** Max. peak pressure. **e** Max. BSFC

4   Conclusion

Based on the simulation study the findings can be summarized as follows;

(a) The analysis with different air-fuel ratios and compression ratios gives significant improvements in the overall engine performance of the hydrogen fueled engine at average values of 7–30%, respectively.

(b) With higher compression ratio; brake torque, brake mean effective pressure and brake power increases throughout every engine speed been tested. Higher compression ratios also produced high peak pressure and thus improved the brake specific fuel consumption.

(c) From the optimization, the total average value for valve opening duration shows that advance the IVO and retard the EVO would improve the overall engine performance.

As the overall conclusion, higher compression ratio and advance IVO would improve the performance of the engine. Balanced configuration in between air to fuel ratio and compression ratio should be handled with the actual hydrogen engine and simulated model in the future.

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