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Research on the Implementation of Hydrogen in Small Spark Ignition Engines

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Abstract

One of the main issues in using hydrogen as an alternative fuel for gasoline engines is the need to optimize the fuel supply system and adjust the air-fuel ratio to ensure a stable and efficient combustion process. This process should ensure complete combustion and avoid backfire or explosions in hydrogen engines, while also addressing the engine's efficiency when using pure hydrogen fuel. Single-cylinder, small-capacity gasoline engines are widely used in Vietnam. Using hydrogen fuel as a substitute for gasoline in these engines is still in the research phase and has not been widely implemented. This paper introduces a test model and experimental research results on the characteristics of a Honda Wave 100cc engine, which was modified to use hydrogen fuel. At an injection pressure of 2.5 bar, the torque and power varied according to different throttle levels of 50%, 75%, and 100%. The maximum torque of the hydrogen engine reached 7.3Nm at an engine speed of 5500rpm, and the maximum power reached 4.6kW at an engine speed of 6200rpm, with a minimum specific fuel consumption of about 110 g kWh^{-1}. The experimental results showed that the maximum power of the hydrogen engine was about 70%, and the maximum torque was about 84% of that of gasoline engines. These initial research results provide a foundation for the simple conversion of traditional vehicles in Vietnam to hydrogen fuel, without requiring significant structural changes to the engine.

Keywords

Alternative fuel, engine characteristic curve, internal combustion engine, hydrogen, hydrogen engine

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Introduction

Fossil fuels are gradually being depleted, and emission issues and environmental requirements for engines using petroleum-based fuels are increasing. Environmental considerations have led engineers and scientists to predict the need for the development of a clean, renewable, and sustainable energy system. The energy crisis has driven research and evaluation of hydrogen as an alternative fuel in internal combustion engines. Hydrogen can be used as the sole fuel in spark ignition engines or as a fuel enhancement in both gasoline and diesel engines (Verhelst & Wallner, 2009). This research provides a comprehensive overview of an H_2-ICE (hydrogen internal combustion engine). Chitrager *et al.* (2021) studied the performance characteristics, combustion process, and emissions of a four-stroke, four-cylinder hydrogen-fueled spark ignition engine. Alternative fuels like ethanol, methanol, biodiesel, propane, natural gas, and hydrogen can reduce engine emissions. Among these alternative fuels, hydrogen is the only one that, when reacting with air, produces clean products without emitting hydrocarbons, carbon monoxide, or carbon dioxide.

Hosseini & Butler (2020) conducted an overview study on the development and challenges of hydrogen-powered vehicles, finding that hydrogen has a combustion rate in an engine's combustion chamber six times higher than gasoline, contributing to increased engine efficiency. The main characteristics of hydrogen compared to other fuels used in internal combustion engines (ICE) are presented in **Table 1** (Hong *et al.*, 2003; Verhelst *et al.*, 2006; Ono *et al.*, 2007; Verhelst *et al.*, 2009; Aleiferis & Rosati, 2012; Ciniviz & Köse, 2012; Mazloomi

Table 1. Hydrogen properties compared to gasoline, diesel, and methane

Property	Hydrogen	Methane	Gasoline	Diesel
Carbon content (mass%)	0	75	84	86
Lower heating value (MJ kg^{-1})	119.9	45.8	43.9	42.5
Density (at 1 bar & 273K; kg m^{-3})	0.089	0.72	730-780	830
Volumetric energy content (at 1 bar & 273K; MJ m^{-3})	10.7	33.0	$33x10^3$	$35x10^3$
Molecular weight	2.016	16.043	~110	~170
Boiling point (K)	20	111	298~488	453~633
Auto-ignition temperature (K)	853	813	~623	~523
Minimum ignition energy in the air (at 1 bar & at stoichiometry; mJ)	0.02	0.29	0.24	0.24
Stoichiometry air/fuel mass ratio	34.4	17.2	14.7	14.5
Quenching distance (at 1 bar & 298K at stoichiometry; mm)	0.64	2.1	~2	-
Laminar flame speed in air (at 1 bar & 298K at stoichiometry; m s^{-1})	1.85	0.38	0.37~0.43	0.37~0.43
Diffusion coefficient in air (at 1 bar & 273K; m^2 s^{-1})	$8.5x10^{-6}$	$1.9x10^{-6}$	-	-
Flammability limits in air (vol%)	4-76	5.3-15	1-7.6	0.6-5.5
Adiabatic flame temperature (at 1 bar & 298K at stoichiometry; K)	2480	2214	2580	~2300
Octane number (R+M)/2	130+	120+	86-94	-
Cetane number			13-17	40-55

& Gomes, 2012; Srinivasan & Subramanian, 2014; Gandhi, 2015; Korn, 2020).

Hydrogen has high diffusivity and a fast combustion speed, helping to quickly create a homogeneous fuel-air mixture, improving combustion efficiency. Using hydrogen during engine starting and warming will solve the problem of cold liquid fuel evaporation and uneven fuel distribution. Hydrogen's flammability limits in air is very wide (4-76%) compared to gasoline (1.4-2.3%), which allows hydrogen engines to run on lean mixtures and achieve a wide range of power levels by changing the mixture composition and allowing the engine to operate without throttling at part load, improving thermal efficiency (Heffel, 2003; Verhelst *et al.*, 2006; White *et al.*, 2006; Verhelst *et al.*, 2009; Verhelst & Wallner, 2009; Mazloomi & Gomes, 2012; Verhelst, 2014; Acar & Dincer, 2020). This helps hydrogen engines operate efficiently, reduces NOx emissions and increases brake thermal efficiency (Heffel, 2003; Schröder & Holtappels, 2005; Subash & Das, 2011; Mazloomi & Gomes, 2012; Srinivasan & Subramanian, 2014). Running an engine on a lean mixture reduces the flame temperature, reduces heat transfer to the cylinder walls, and improves fuel economy.

However, a lean fuel mixture reduces power output. At atmospheric pressure and a temperature of 273K, hydrogen has a very low density but it has the highest mass-energy ratio among chemical fuels. The mass-energy ratio of hydrogen is about three times higher than gasoline, about five times higher than alcohol, and 2.5 times higher than methane and propane. Therefore, hydrogen and hydrocarbon fuel mixtures can improve engine performance and reduce fuel consumption. The molecular weight of hydrogen is low, much lower than natural gas, as hydrogen has a very low density at atmospheric pressure and a temperature of 273K, which reduces the power output of the engine. Compressing hydrogen to 350 bar at 273K can increase its density and volumetric energy (Chong & Hochgreb, 2011; Ciniviz & Köse, 2012; Gandhi, 2015; Kumar *et al.*, 2015; Dimitriou & Tsujimura, 2017; Korn, 2020). To burn a hydrogen-air mixture with a hydrogen concentration of 22-26% requires a low energy of only 0.017mJ (Karim, 2003; Ono *et al.*, 2007; Verhelst & Wallner, 2009; Subash & Das, 2011; Gandhi, 2015). When the spark gap is 2mm and the hydrogen concentration is from 10% to 50%, the minimum ignition energy is 0.05mJ. But if the hydrogen concentration is below 10%, the risks of pre-burning and back-burning increase. Hydrogen has a very small extinguishing distance of only 0.6mm, much shorter than gasoline, making hydrogen flames more difficult to extinguish and more likely to backfire. Hydrogen burns and spreads rapidly but is short-lived. However, the small hydrogen cooling gap increases the evaporation of lubricating oil and the formation of particles in hydrogen internal combustion engines(Abdelghaffar, 2010; Faizal *et al.*, 2019) (Hong *et al.*, 2003; Aleiferis & Rosati, 2012; Ciniviz & Köse, 2012; Gandhi, 2015; Faizal *et al.*, 2019; Korn, 2020).

The theoretical air-fuel ratio (λ) of 34.29kg of air to 1kg of hydrogen for complete combustion of hydrogen in air is significantly higher than the 14.7:1 ratio required for gasoline. Hydrogen has a high burning rate at theoretical rates, and under these conditions, its burning rate is almost an order of magnitude faster than gasoline. This allows hydrogen engines to get closer to the ideal thermodynamic cycle. Another property of hydrogen is its very high diffusivity. Its ability to disperse in air is much greater than that of gasoline, which helps to create a homogeneous air-fuel mixture, and from a safety perspective, it disperses quickly in the event of a hydrogen leak (Ono *et al.*, 2007; Abdelghaffar, 2010; Srinivasan & Subramanian, 2014; Acar & Dincer, 2020). The auto-ignition temperature of hydrogen is 853K, which makes the combustion of hydrogen-air mixtures more difficult than relying solely on compression temperature. Hydrogen is more resistant to detonation than hydrocarbon fuels due to its high octane number of 130 but the upper limit of its octane number is not clearly defined.

Theoretically, the minimum ignition energy of hydrogen in air is one order of magnitude lower than that of hydrocarbon fuels, posing a risk of ignition from hot spots in the combustion chamber, leading to explosion and mechanical damage (Verhelst & Sierens, 2001; Abdelghaffar, 2010; Chong & Hochgreb, 2011; Negurescu *et al.*, 2012). According to (Verhelst & Sierens, 2001; Heffel, 2003; Abdelghaffar, 2010; Negurescu *et al.*, 2012; Acar & Dincer, 2020), using hydrogen as an auxiliary fuel helps improve efficiency and reduce emissions. Another method involves storing hydrogen in a cryogenic cylinder and pumping it through a heat exchanger to vaporize it. The cold hydrogen vapor is then injected into the engine. This method helps prevent premature ignition and reduces the formation of NOx during combustion. Finally, a mixture of hydrogen and gasoline is introduced into the combustion chamber of an internal combustion spark ignition engine. The compression ignition of this mixture is initiated by an electrical spark. This method aims to leverage the advantages of hydrogen in enhancing engine efficiency and reducing emissions. Additionally, hydrogen can also be used as an additive in compression ignition (CI) engines (Naber & Siebers, 1998; Szwaja & Grab-Rogalinski, 2009).

Similar to SI engines, nitrogen oxide (NOx) is also a significant issue in CI engines using dual-fuel hydrogen. Exhaust gas recirculation (EGR) effectively reduces NOx emissions by diluting the intake air to a lower oxygen concentration. However, increasing EGR also leads to a significant volumetric efficiency loss, approximately 15%, compared to systems not using EGR to promote dual-fuel hydrogen (Kumar *et al.*, 2015). Additionally, another issue encountered with hydrogen engines is premature ignition, which leads to inefficient engine operation and reduces maximum power output (Lee *et al.*, 1995; Kirchweger *et al.*, 2007). This also leads to another phenomenon in the engine known as engine knock. The amplitude of the pressure waves of heavy engine knock can cause engine damage due to increased mechanical and thermal stress. The issue of abnormal combustion in ICEs using hydrogen fuel has not been completely resolved. Addressing this problem requires changes in engine design, mixture strategy, load control, and several methods to mitigate premature ignition (Lucas & Morris, 1980; Maccarley, 1981; Li & Karim, 2004; Szwaja *et al.*, 2007; Liu *et al.*, 2008; Verhelst & Wallner, 2009).

To adapt a conventional internal combustion engine to run on hydrogen, significant hardware changes to multiple systems and components are required. This includes modifying the combustion chamber structure, ignition system, and the fuel injection system, as well as the structure of the engine control software and exhaust after-treatment system. Specific modifications involve altering components such as cylinder heads, spark plugs, pistons and piston rings, the compression ratio, valves, valve seats, and valve guide materials, as well as the engine control and ignition systems, ECU (engine control unit), ventilation system, and engine lubrication system. Additionally, adjustments are needed for the boosting system, such as turbocharging, and the fuel injection system, including hydrogen injectors, rails, and related pipelines, as well as the air pressure regulation system. The ignition system also needs to be modified to accommodate hydrogen fuel, including spark plugs and ignition coils (Tang *et al.*, 2002; Pauer *et al.*, 2020; Rezaei *et al.*, 2020; Rezaei *et al.*, 2021).

In Vietnam, research on the use of hydrogen fuel for internal combustion engines is still quite new, as hydrogen is mainly used as a supplementary fuel in the form of HHO or in research on the use of hydrogen in simulation models. In the study of Hoang Dinh Long & Nguyen The Luong (2009) a small amount of hydrogen was mixed into the air-gasoline mixture to reduce toxic components in engine exhaust (Hoang Dinh Long & Nguyen The Luong, 2009). At the same time, the number of motorbikes in Vietnam is still very large, leading to research on the use of hydrogen fuel for motorbike engines being considered a practical solution. As presented above, having hydrogen fuel injected directly into the combustion chamber brings many benefits such as backfire and increased engine power, however, changing the engine structure is complicated. Therefore, the group of authors did not change the engine structure but only replaced the fuel injection system with a hydrogen gas injection system into the intake pipe. At the same time, keeping the working mode of the original electronic control system, this study aimed to evaluate the economic and technical efficiency of an engine when it uses hydrogen instead of gasoline through the construction of the local characteristic curves of the hydrogen engine and the gasoline engine. The results of the test are the basis and premise for improving and manufacturing the conversion of gasoline-powered internal combustion engines in vehicles to use hydrogen fuel.

Materials and Methods

Test engine

The experimental equipment included the main system, which was the engine, and the engine power measurement system (**Figure 1**). The engine used in this experiment was a commercial Honda Wave 110cc, with the technical specifications presented in **Table 2**.

Experimental setup

The sequence of connections started from the speed sensor and the force sensor, followed by the flow rate of the hydrogen gas fuel. The installation positions are shown in **Figure 1**.

The rotational speed sensor was installed at the end of the crankshaft and positioned close to the metal tabs attached to the shaft. Each time a metal tab passed by, the sensor detected it and sent a signal to the data acquisition unit, recording the engine's rotational speed. The force sensor was installed at the midpoint of the brake disc support bracket. This position was chosen because, when using the brake force to decelerate the engine, the force will concentrate at the midpoint of the support where there is a single contact point with the force sensor, ensuring the most accurate measurement. The hydrogen flow meter was placed at the outlet of the tank, following the fuel pressure gauge. All sensors and the flow meter were installed and connected to the Gantner data acquisition system (Lee *et al.*, 1995; Kirchweger *et al.*, 2007; Pawar & Shete, 2017) according to the schematic and input sources. The data acquisition system was directly connected to a computer via an RJ45 Ethernet port, and all experimental data were displayed on the

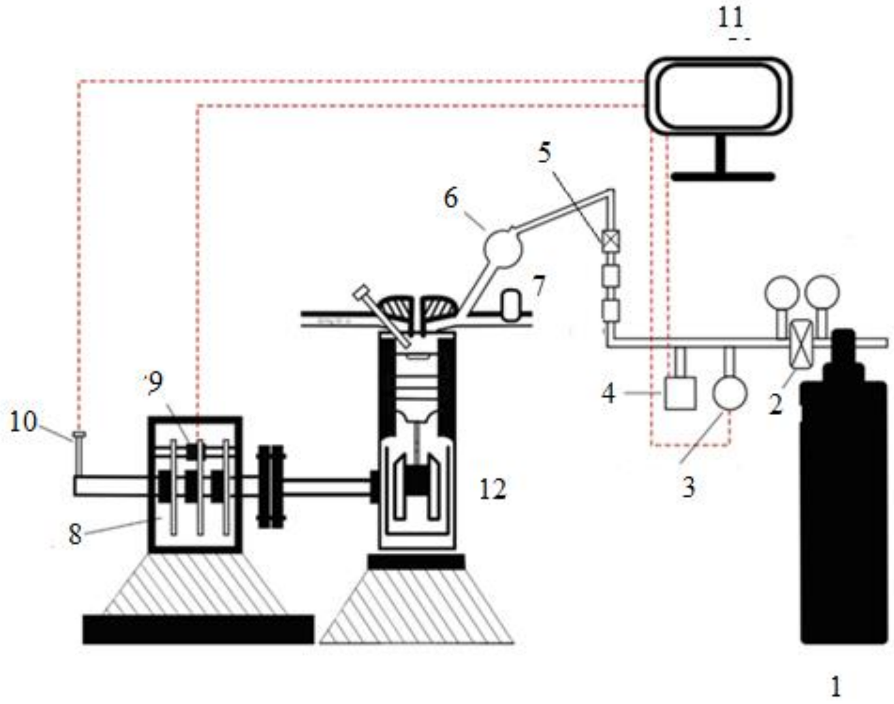


Figure 1. Schematic diagram of the hydrogen-powered engine

Where 1 - Hydrogen tank; 2 - Pressure regulator; 3 - Pressure gauge; 4 - Mass flowmeter; 5 - Safe valve; 6 - Fuel injection; 7 - Air filter; 8 - Load generator; 9 - Force sensor; 10 - Speed sensor; 11 - Computer; 12 - Engine

Table 2. Technical specifications of the engine

Wave RSX-FI engine	Specifications
Engine type	4-stroke
Number of cylinders	Single cylinder
Fuel system	PGM-Fi
Cylinder capacity	109.1 cc
Compression ratio	9.3:1
Bore x stroke	50.0 x 55.6mm
Cooling system	Air-cooled
Maximum power	6.56kW/7,500rpm
Maximum torque	8.77Nm/6,000rpm
Fuel consumption	360 g kWh^{-1}
Maximum speed	7500rpm
Gearbox	Mechanical, 4-speed round

computer screen through the GI.bench application. Raw data were recorded and then processed in the next step using MATLAB software.

To use hydrogen by the injection method in the Wave RSX-Fi engine, the following components were required. First, the hydrogen injection system for the 110cc-Fi engine fuel injection and electronic ignition system incorporated several key components to ensure optimal performance and accurate data collection during experiments. Second, the ECU-gas control unit played a crucial role by taking the injection control signal from the original gasoline injection ECU and the absolute pressure signal from the intake manifold of the engine. It then adjusted the amplification factor k to maintain an air-fuel ratio of $\lambda \approx 1$ for the hydrogen engine. Aiming at a practical transfer from traditional fuel to hydrogen fuel engines, the ECU-gas control unit worked identically to the original Wave RSX-Fi ECU. The amount of hydrogen supplied to the engine was determined theoretically by a scale factor k, which was defined based on the energy density ratio between hydrogen and gasoline. The implementation was then experimentally set up by compromising between the supply hydrogen pressure and the injection characteristics of the hydrogen injector. In this study, the experimental settings were set at 2.5 bar of hydrogen pressure and 0.37mm of the featuring nozzle diameter of the injector. Together, these components worked seamlessly to ensure the hydrogen injection system was correctly set up and operated efficiently.

Experimental procedure

The experiment with a hydrogen-powered engine was conducted at three throttle positions, 50%, 75%, and 100%, with the injection pressure maintained at a constant under stable engine operating conditions. A corresponding experiment was also conducted with a gasoline-powered engine using 100% gasoline at equivalent throttle levels, serving as the basis for evaluation and comparison. The load was applied using a hydraulic-driven mechanical brake mechanism, which produced the torque at the engine output shaft using the monitored braking force. Force sensors, gas flow measurement devices, and speed sensors recorded the measurement signals, which were then transferred to a computer for further processing. The measured data were stored and visually displayed on the computer screen.

Data collection and processing

The measurement and data processing diagram is shown in **Figure 2**. The measured data of speed (in pulse form) and force were processed to calculate the torque and speed. These calculations were then used to construct the characteristic curve of the hydrogen engine.

The raw data were smoothed using MATLAB, resulting in smoothed torque and speed characteristic graphs. The characteristics of the hydrogen-powered engine were built based on the measured dataset at throttle positions of 100%, 75%, and 50%, with the hydrogen injection pressure set at 2.5 bar.

Results and Discussion

The torque characteristic curve of an engine is an essential technical parameter to evaluate its performance. For the engine using 100% hydrogen at an injection pressure of 2.5 bar, the torque characteristic curve was compared with that of the engine running on 100% gasoline at the three different throttle positions, 50%, 75%, and 100%, as shown in **Figure 3**. The results indicated that the gasoline-powered engine had a higher maximum torque compared to the hydrogen-powered engine. Specifically, at 50% throttle, the maximum torque of the hydrogen engine and gasoline engine differed by about 4Nm at 4000RPM, while the gasoline engine reached approximately 4.5Nm at 4200rpm. At 75% throttle, the maximum torque of the hydrogen engine was 5.8Nm at 4800rpm, whereas the gasoline engine achieved 7Nm at 5000rpm. At 100% throttle, the maximum torque of the hydrogen engine was 7.3Nm at 5500rpm, while the gasoline engine achieved 8.7Nm at 5700rpm.

In addition to torque, other important parameters to evaluate the engine's efficiency were the power characteristic curve and specific fuel consumption. In **Figure 4**, at the same throttle position, the power of the hydrogen engine was lower compared to the gasoline engine. Specifically, at 50% throttle, the maximum power of the hydrogen engine was 1.75kW at 4200rpm, whereas the gasoline engine achieved 2.2kW at 5500rpm. At 75% throttle, the maximum power of the hydrogen engine was 3kW at 5500rpm, while the gasoline engine reached 4kW at 5700rpm. At 100% throttle, the maximum power of the hydrogen engine was 4.6kW at 6200rpm. Correspondingly, the specific fuel consumption of the hydrogen engine reached its minimum value of approximately 110 g/kWh as shown in **Figure 5**. In contrast, the gasoline engine achieved 6kW at 7200rpm, and this was compared with the manufacturer's published specific fuel consumption of gasoline, which is 360 g kWh^{-1}.

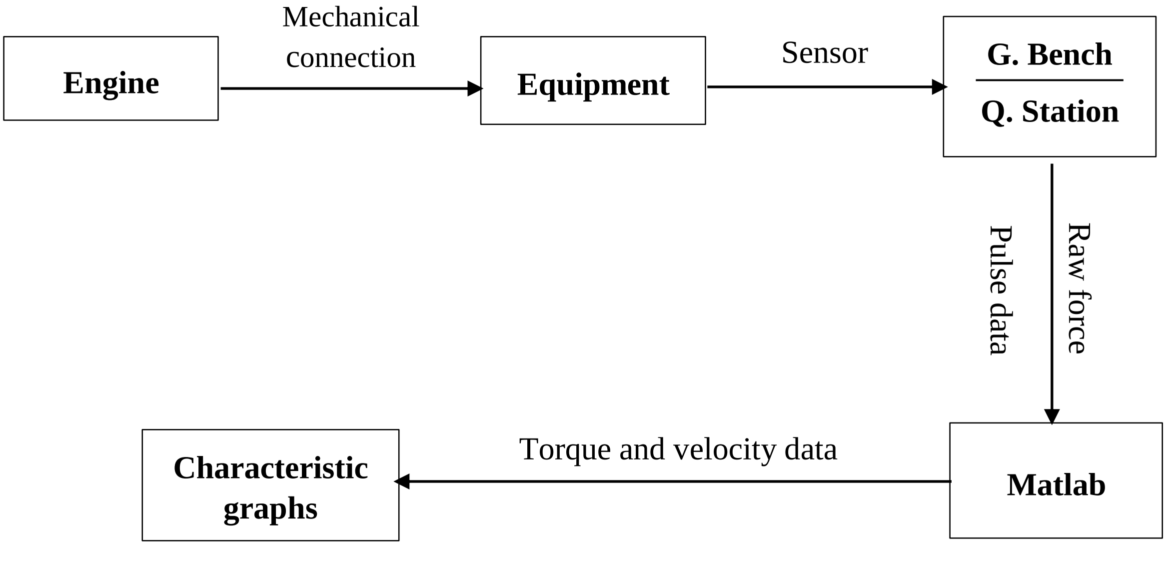
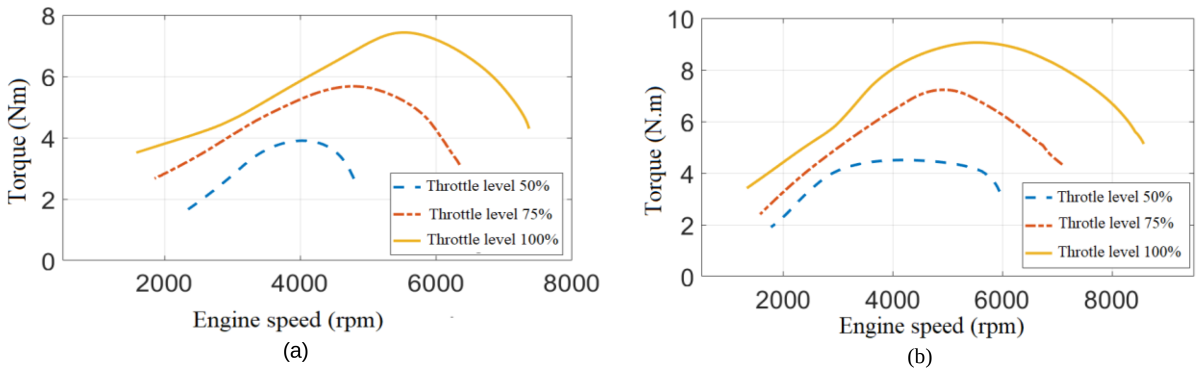
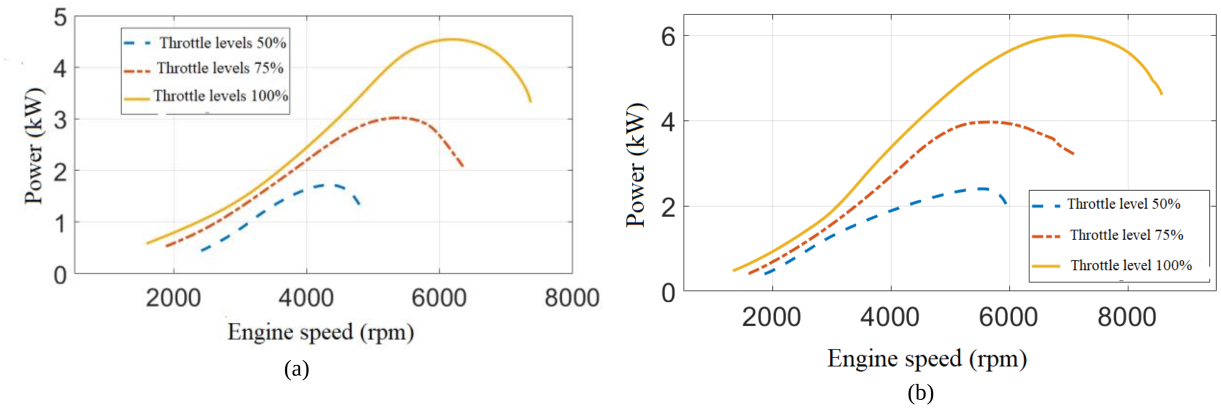


Figure 2. Measurement and data processing diagram



(a) (b)

Figure 3. Engine torque characteristics of the (a) hydrogen engine and the (b) gasoline engine



(a) (b)

Figure 4. Engine power characteristics of the (a) hydrogen engine and the (b) gasoline engine

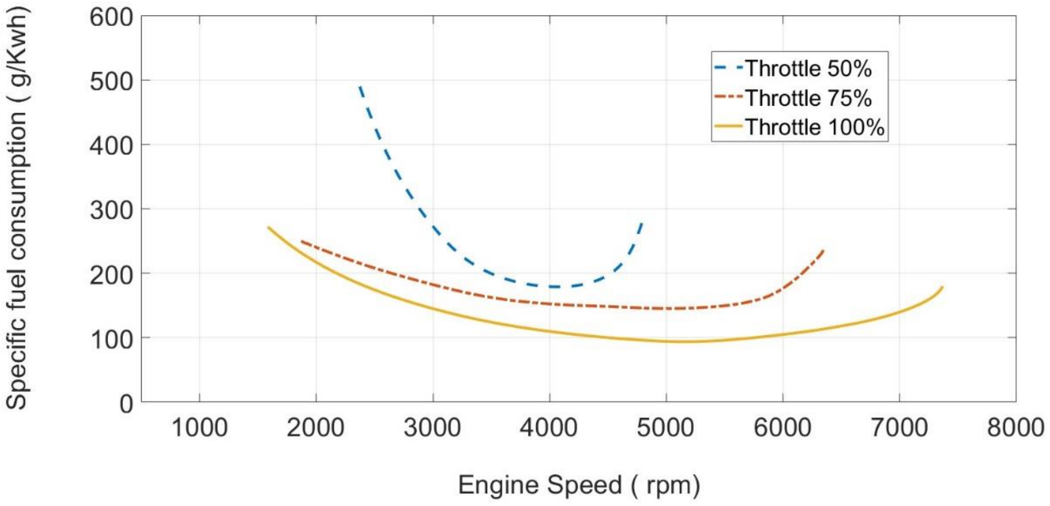


Figure 5. Hydrogen engine specific fuel consumption

The torque, power characteristics, and specific fuel consumption derived from experiments showed that the engine using hydrogen fuel exhibited reduced technical parameters (torque and power), but increased economic efficiency indicators (specific fuel consumption) compared to the original gasoline-powered engine. The characteristics obtained in this study are similar to the theoretical research results from various published works both domestically and internationally, which provide explanations for the decreased torque and power of converted engines related to the very low molar heat of hydrogen.

Conclusions

In this study, a fuel supply system was designed and constructed to replace the gasoline fuel supply system on a Honda Wave 110 engine. A test model of the engine, which ran entirely on hydrogen fuel, was developed by adapting the original gasoline engine. This model was utilized in experimental research to determine the torque, power, and specific fuel consumption characteristics of the engine running on 100% hydrogen, compared to the original engine running on 100% gasoline. The main characteristics of the Honda Wave 110 engine using the two types of fuels were successfully established. The experimental research results showed similarities to the theoretical calculations from various published studies. Therefore, the model and experimental equipment system can be used in further experimental studies to determine the parameters and verify the theoretical calculations of models for small-capacity engines. The experimental setup and initial research results provide the foundation and conditions for proposing and implementing technical solutions to improve the combustion chamber structure, enhance the fuel supply systems, and optimize fuel combustion. These efforts aim to improve the economic and technical efficiency of engines converted from gasoline to hydrogen fuel.

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