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Parameters in Operating Rotary Engine with Hydrogen for Efficiency Improvement

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Alternative fuels must emit less amount of pollutants while maintaining the appropriate engine performance than the traditional fuel used. Hydrogen has been studied to be used for fuel cells or hydrogen internal combustion engines (HICEs). HICEs are known to emit nitrogen oxides (NOx) depending on operational conditions. Thus, we experimented with a rotary engine to determine how its thermal efficiency and power change with hydrogen fuels of various air–hydrogen ratios, water contents, and hydrogen storage temperatures. We measured the air–hydrogen ratio, exhaust gas temperature, and thermal efficiency and power of the rotary engine. The higher storage temperature and water content in air in the fuel mixture increased the thermal efficiency, power, and exhaust gas temperature of the rotary engine at a speed higher than that of the piston engine. This result indicates that hydrogen can be used for existing internal combustion engines with optimized operational parameters. This result also provides a reference to improve the performance of HICEs.

1. Introduction

Hydrogen is an economical fuel for the internal combustion engines (ICEs) of automobiles owing to its rapid ignition for high-speed operation. Hydrogen ICEs (HICEs) outperform conventional ICEs as HICEs show a higher thermal efficiency. However, the amount of nitrogen oxide (NOx) emitted when an HICE is operated at a high load is many times higher than that of an ICE.(1) Rakopoulos *et al.* studied the combustion efficiency, heat transfer and loss on cylinder walls, and nitric oxide emissions of HICEs.(2) They found that changes in load and the ratio and temperature of the air–hydrogen mixture affected the combustion efficiency of HICEs.

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Air–hydrogen mixture pressurization and exhaust gas recirculation increase the output power of HICEs.[3] At a low air–hydrogen ratio, the temperature in the cylinder does not increase, which forms and emits NOx. Ceper investigated the performance and emissions of HICEs at different fuel supply volumes.[4] Wakayamaa *et al.* combined hydrogen and gasoline to improve the performance of HICEs in lean oil combustion.[5] At low engine speeds and high engine loads and with a three-way catalyst, exhausted gas recirculation allowed for higher torque and more reduced NOx in HICEs than in ICEs.[5] For hydrogen-fueled diesel engines, using timed port injection technology increased fuel consumption but reduced NOx emissions owing to the decreased exhaust gas temperature. Other than such fuel adjustments, a spark plug gap turned out to significantly affect the engine performance.[6]

The rotary engine can be operated with various fuels.[7] With hydrogen as a fuel, the rotary engine shows higher performance than a reciprocating piston engine and emits less amount of pollutants.[8] On the basis of this, Ohkubo *et al.* developed a new rotary engine that showed improved engine performance and fuel economy but reduced emissions.[9] However, using hydrogen gas caused much NOx emission due to the thermal Nox effect in a high-temperature approaching situation, which necessitates finding the optimal parameters for operating the rotary engine to reduce NOx production while maintaining or improving performance.

Therefore, we investigated the effects of the air–hydrogen ratio and water content in the mixture on the thermal efficiency, power, and NOx emission of the rotary engine. The obtained results help to confirm the possibility of using hydrogen for the rotary engine and to determine its optimal parameters. Parameters such as air–hydrogen ratio, humidity in the air of the mixture, and temperature were measured using corresponding sensors. Thus, the results also provide the basis for developing an appropriate sensor technology to monitor the performance of the rotary engine using hydrogen as a fuel.

2. Methods

We measured the thermal efficiency, power, and exhaust gas temperature of a rotary engine using hydrogen at different air–hydrogen volume ratios in the mixture. The dry and humidified air–hydrogen mixture was utilized to compare the effects of water vapor on the performance of the engine. A 49-PI TYPE II rotary engine manufactured by O.S. Engine Manufacturing Co., Ltd. (Japan) was used in the experiment (Fig. 1). The rotary engine has a displacement of 4.97 cc (0.196 in^3) and weighs 450 g with a silencer and mounting bracket. Its output power is 1.1 hp at 17000 revolutions per minute (RPM).

We used a torsion gauge, an infrared tachometer, and a temperature sensor to measure the power, speed, and exhaust gas temperature, whereas a gas and airflow meter and an advanced ceramic metal-oxide moisture sensor were used to measure the air–hydrogen ratio in the mixture and relative humidity, respectively (Table 1). A thermostatic water tank was used to store hydrogen at 25 or 35 ℃, and a throttle valve was employed to supply a consistent volume of hydrogen and air into the engine. The pressure of hydrogen and airflow into the engine was maintained at 14 psi.

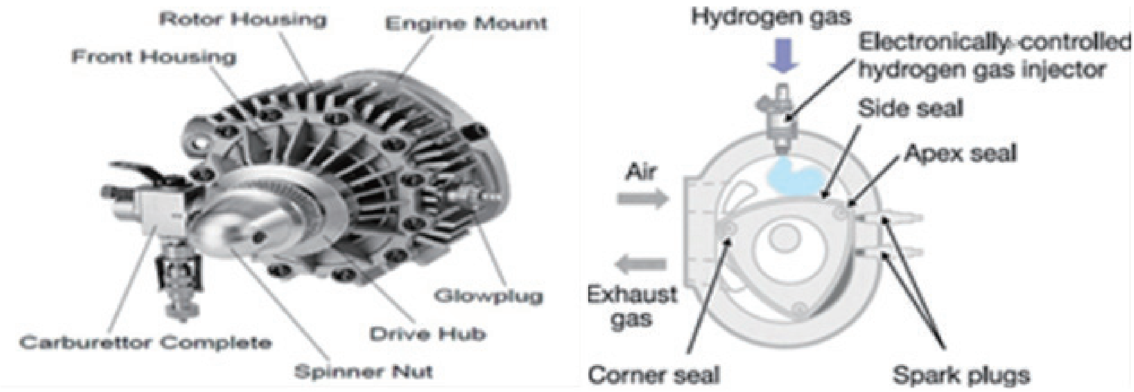

Fig. 1. (Color online) Cross-sectional view and architecture of rotary engine.

Table 1
Sensors used to measure various parameters in this research.

Sensor	Model	Manufacturer	Detection range
Torsion gauge	SGK-SDH3B-K350U-PC11-E	Omega Engineering, Inc.	Resistance: 1000 Ω Maximum voltage: root-mean-square voltage of 11
Infrared tachometer	IC-DT-207LR	ELECTROMATIC Equipment Co., Inc.	Measurement range: (Noncontact) 6–99999 RPM (Contact): 0.8–25000 RPM Accuracy: 1 RPM Resolution: (Noncontact) 1 RPM (Contact) 0.1 RPM
Temperature sensor	S80 Thermocouple Temperature Probe	Ashcroft	−40–750 °C (±2.2 °C)
Gas flow meter	Thermal mass gas flow meter	IPSH SDN BHD	0–50 L/min (± 2.0%)
Air flow meter	GFM mass flow meter	Aalborg Instruments & Controls, Inc.	Measurement range: 0–20 L/min, measurement accuracy: ± 1% of F.S.
Ceramic metal-oxide moisture sensor	Easidew Pro XP	Envent	Measurement ranges: −110 up to +20 °Cdp (−166 to 68 °Fdp) Accuracy: ±1 °Cdp (±1.8 °Fdp)

In general, two types of cooling system are used for the rotary engine. The first is a double-bladed propeller installed on the leading edge of the engine, which rotates synchronously with the engine to generate forced convection from front to rear to dissipate heat from the engine body. The engine body is equipped with heat dissipation fins to increase the area for heat dissipation and reduce the temperature. The second is a peristaltic pump to inject engine oil into the engine body to lubricate the moving parts and dissipate heat. Excess engine oil is discharged from the exhaust end of the engine, which also lowers the temperature of the engine.

3. Results

3.1 Air–hydrogen ratio

We operated the rotary engine with hydrogen gas stored at 25 and 35 ℃ to understand how the storage temperature of hydrogen affects the performance of the engine (Tables 2 and 3). When using hydrogen stored at 25 ℃, as the engine speed increased, the air–hydrogen ratio decreased, implying that the engine needed more hydrogen to increase the speed and the corresponding power. At 10000 RPM, the power of the engine reached 150.69 W. At the same speed, the thermal efficiency reached 27.55%, which was the highest in the experiment. The temperature of the exhaust gas increased with speed, and at 10000 RPM, the temperature reached 294 ℃. The result indicated that more hydrogen is demanded to obtain a higher power and speed of the engine. At 10000 RPM, the air–hydrogen ratio by mass was 31:1, which is close to the ideal ratio of 34:1.[10] When using hydrogen stored at 35 ℃, the highest power and thermal efficiency were 156.52 W and 28.33%, respectively, at 10000 RPM, which were higher than those obtained when using hydrogen stored at 25 ℃. In this case, the stoichiometric air–hydrogen ratio by mass was also 31:1.

The temperatures of the exhaust gas were 335 and 294 ℃ when using hydrogen stored at 25 and 35 ℃, respectively. In HICEs, airborne nitrogen reacts with oxygen in the exhaust gas, leading to thermal NOx formation. When exhaust gases are heated, NOx formation is suppressed.[11] Also, a high hydrogen temperature ensures a high combustion temperature for the optimal performance of HICEs.[10] In the experiment, at a high exhaust gas temperature, NOx decreased, which coincides with previous findings.[10]

Table 2
Air-fuel ratio and its effects on power and thermal efficiency when using hydrogen stored at 25 ℃.

Engine speed (RPM)	Air–hydrogen ratio (in volume)	Temperature of exhaust gas (℃)	Thermal efficiency (%)	Power (W)
6000	61.78:38.22	174	16.87	60.78
7000	49.38:50.62	199	19.68	88.85
8000	49.21:50.79	248	17.42	91.58
9000	52.48:47.52	269	22.78	124.00
10000	53.12:46.88	294	27.55	150.69

Table 3
Air-fuel ratio and its effects on power and thermal efficiency when using hydrogen stored at 35 ℃.

Engine speed (RPM)	Air–hydrogen ratio (in volume)	Temperature of exhaust gas (℃)	Thermal efficiency (%)	Power (W)
6000	66.25:33.75	198	17.37	63.24
7000	53.26:46.74	227	20.27	92.44
8000	52.69:47.31	282	17.94	95.28
9000	56.49:43.51	306	23.46	129.01
10000	56.89:43.11	335	28.33	156.52

Table 4
Results of humidification at relative humidity of 30% and water mass in air–hydrogen mixture at different volume ratios when using hydrogen stored at 25 °C.

Engine speed (RPM)	Air–hydrogen ratio (in volume)	Water content (g/m^3)	Thermal efficiency (%)	Difference* (%)	Power (W)	Difference* (%)
6000	66.25:33.75	11.63	10.68	−58.0	33.57	−81.1
7000	53.26:46.74	15.99	18.41	−6.9	74.6	−19.1
8000	52.69:47.31	16.18	20.84	16.4	99.96	8.4
9000	56.49:43.51	14.95	23.81	4.3	118.61	−4.5
10000	56.89:43.11	14.83	36.05	23.6	180.53	16.5

(Difference from the results of Table 2 without humidification)

3.2 Water content

Hydrogen has a higher diffusivity than gasoline, which leads to the formation of a uniform air–hydrogen mixture. However, hydrogen leak causes the dispersion of hydrogen.[12] We calculated the diffusion coefficient of hydrogen stored at 25 °C in the air–hydrogen mixture to estimate the water content. The diffusion coefficient of hydrogen in air at 25 and 35 °C was 0.756 cm^2/s. Thus, when hydrogen was directly injected into the combustion chamber, it was mixed completely with air. Different from gasoline engines, HICEs do not demand lubrication. However, dry hydrogen can wear engine components. Thus, hydrogen is humidified for lubrication, flame stability, reduced oxidation, and the cooling and prevention of detonation.[13] We introduced water vapor at the intake of air to understand the effect of the water content of the air–hydrogen mixture on the performance of the rotary engine. We controlled the relative humidity at 30% as the relative humidity of 0–90% does not affect the minimum ignition energy (MIE).[14]

With the measured water content (Table 4), the thermal efficiency of the humidified air–hydrogen (stored at 25 °C) mixture was significantly lower at lower speeds but higher at higher speeds of the engine. The power of the rotary engine increased at speeds of 8000 and 10000 RPM but considerably decreased at 6000, 7000, and 9000 RPM. The humidified air–hydrogen mixture enhanced the thermal efficiency of the rotary engine at high speeds, but the improved thermal efficiency was not directly related to the increase in power. The power increased at a speed higher than 10000 RPM with the humidified air–hydrogen mixture, which needs further research at speeds higher than 10000 RPM. When the mixture was humidified, the combustion heat at a speed lower than 10000 RPM decreased as it was absorbed by air and water vapor. This caused insufficient volume expansion to generate the power of the engine. However, as the speed increased, a sufficient amount of combustion heat was generated for water vapor in the combustion chamber to absorb heat, which produced more power.

4. Conclusions

Hydrogen is used for fuel cells or ICEs of vehicles as it does not emit pollutants. There has been research on the use of hydrogen for HICEs to save costs and protect the environment. However, HICEs may emit NOx depending on operational parameters. At different air–hydrogen ratios and water contents in the air–hydrogen mixture, the thermal efficiency and power of a rotary engine were measured. Hydrogen stored at 25 and 35 ℃ was used to determine the optimal parameters for using hydrogen for HICEs. The air–hydrogen ratio, exhaust gas temperature, thermal efficiency, and power of the rotary engine were determined at different engine speeds. The storage temperature of hydrogen affected the performance of the engine significantly. When using hydrogen stored at 35 ℃, the thermal efficiency and power increased by 3.0 and 4.0%, respectively, in the speed range of 6000–10000 RPM. The temperature of exhaust gas also increased by 14%. The air–hydrogen ratio by mass was 31:1, which was close to the ideal ratio of 34:1. We controlled the water content in the mixture at 30% and measured the thermal efficiency and power. The mixture with humidified air increased the thermal efficiency and power at a speed higher 10000 RPM. However, additional research is necessary to validate the effect of humidification at speeds higher than 10000 RPM of the rotary engine. When using hydrogen as a fuel for the rotary engine, it is important to increase the exhaust gas temperature to reduce the NOx emission. The result of this research showed that the exhaust gas temperature is higher when the air–hydrogen ratio is closer to 34:1. Such results help us understand how to use hydrogen for existing ICEs. The results also indicate that an appropriate sensor technology needs to be developed to monitor the performance of the rotary engine with hydrogen as a fuel to maintain the optimal operational parameters of HICEs.

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