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Performance Analysis of a Natural Gas Engine System Fueled with Ammonia/Hydrogen

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***Abstract*— This study evaluates a natural gas spark-ignition engine performance and efficiency fueled with ammonia/ hydrogen (NH_3/H_2). NH_3 and H_2 from NH_3 decomposition as fuels of a gas engine system has been proposed in this research. The effects of the direct injection of gaseous NH_3 together with H_2 from NH_3 decomposition on the engine performance and efficiency have been experimentally investigated. The results show that a maximum of 60 % NH_3 addition (LHV basis) can be reached when the gas engine fueled by NH_3 and CH_4 with a fixed rotation speed of 1950 rpm. The gas engine operates stably at a maximum high addition ratio of 92.5% NH_3+H_2 (LHV basis) addition to total fuel under fixed rotation speed with tiny vibration of 1.0%, showing a feasible replacement of NH_3+H_2 as major fuel of the gas engine fueled by CH_4. The cylinder pressure of gas engine decreases with the addition of NH_3, while increases with the addition of H_2. A lower energy density of NH_3 and H_2 leads a lower power generation efficiency of the gas engine when fueled by $NH_3/H_2/CH_4$ compared with CH_4.**

Keywords*— *ammonia; hydrogen; gas engine; cylinder pressure; engine efficiency

I. INTRODUCTION

With the increasing strictness of governmental regulation of greenhouse gas emissions, together with other pollutant emissions such as carbon monoxide (CO), unburned hydrocarbons (HCs), nitrogen oxides (NO_x), and particulate matter (PM). The search for carbon-free alternatives fuels is one important concern of our society. Many studies have evaluated H_2 as one of the most favorable candidates because no CO, CO_2 or soot is formed and only water is formed in the utilization of H_2 in internal combustion engines and fuel cells [1,2]. However, many challenges still exist in using H_2 as a fuel, such as production, storage, and handling issues of H_2. On the other hand, ammonia (NH_3) is another carbon-free alternative fuel, which has received much less attention. NH_3 is also a typical H_2 storage material with a highest energy density of 17.8 among other H_2 storage materials. Furthermore, NH_3 is widely used as heat medium of refrigerator, fertilizer, and de-NO_x material, the production, storage, handling, and distribution facilities of NH_3 are commercially available worldwide. NH_3 can be potentially synthesized by renewable energy sources such as wind, solar, and biomass. NH_3 can be stored in the liquid state at 20 °C and 8.0 atm, which is much easier than the storage of H_2 [3]. But NH_3 exhibits a low heating value (LHV, 18.8 MJ/kg), a high latent heat of vaporization (1370 kJ/kg), and a high ignition temperature (651°C). Because of these three factors with a slow burning velocity (5-13 cm/s), both compression-ignition and spark-ignition engines fueled by NH_3 are still challenging [4-7].

In order to eliminate the unfavorable combustion properties of NH_3, many studies on spark-ignition and compression-ignition engines fueled NH_3 together with gasoline or H_2 have been performed [5,8-15]. The addition of gasoline or H_2 can help NH_3 ignition in the combustion chamber because of high ignition energy of NH_3. No sufficient ignition energy will lead misfire and cause air pollution and hazard to health because of unburned NH_3. Furthermore, the addition of gasoline or H_2 can improve the flame propagation and burning velocity of NH_3 combustion in the chamber. Since H_2 is more reactive and has a higher burning velocity (280-300 cm/s) [3], the addition of H_2 is more reactive than gasoline for improving NH_3 combustion [16-20].

In this study, the analysis of a gas engine system fueled by $NH_3/H_2/CH_4$ was investigated. Methane and H_2 was used as the second fuel to improve NH_3 combustion. The ration

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numbers of the gas engine and cylinder pressure at different fuel composition of $NH_3/H_2/CH_4$ are presented. The power generation efficiency at different fuel composition of $NH_3/H_2/CH_4$ is also measured.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The full schematic diagram of the gas engine system fueled by $NH_3/H_2/CH_4$ is shown in Fig. 1. The system consists of a fuel supply system, a fuel mix chamber, a gas engine, a heat recovery system to provide hot water. Engine ration number, cylinder pressure, and engine power are measured. The mass flow of NH_3, H_2, and CH_4 were controlled by commercial mass flow controllers (Azbil, CMS0050) with an accuracy ±1.0% of the full scale delivered. The supply pressure of NH_3, H_2, and CH_4 are 0.1 Mpa, 0.1 Mpa, and 0.2 Mpa, respectively. The cylinder pressure was measured using a Kistler 6118BFD16 piezo-electric pressure transducer together with a Kistler 5010 charge amplifier. The engine power was measured by a digital multi-meter (Graphtec, CM-211).

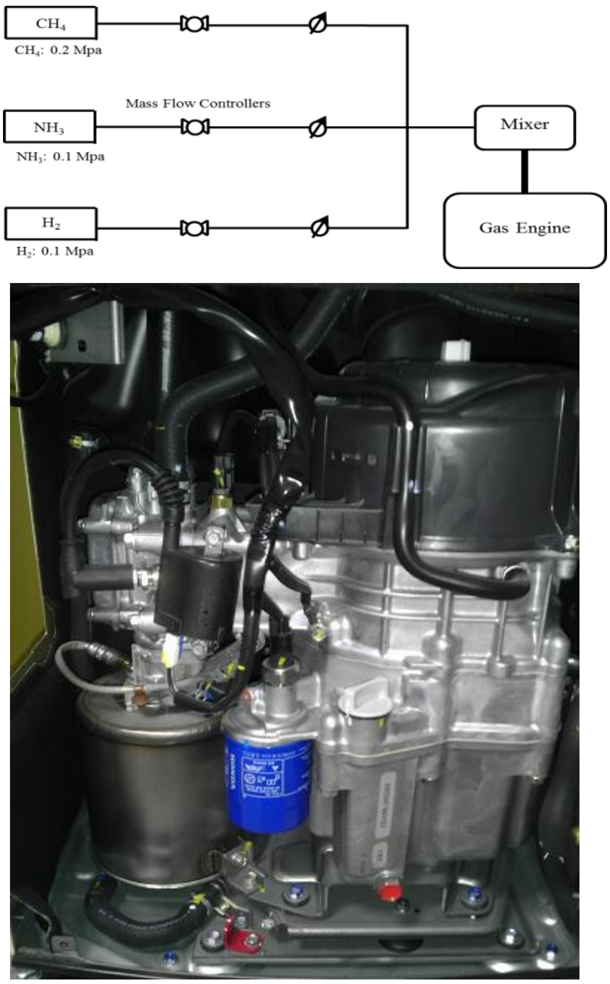

Fig. 1. Full schematic diagram of the gas engine system fueled by $NH_3/H_2/CH_4$

The experiment utilized an extended expansion linkage engine commercially produced by Honda cooperation for family power generation. Detailed specifications for the engine are shown in Table 1. The engine is a four stroke, one cylinder, spark-ignition engine with an intake stroke volume of 110 cm^3 and an exhaust stroke volume of 163 cm^3. The fixed rate speed of the engine is 1950 rpm with a fixed power generation efficiency of 26.3 % when fueled by CH_4. A heat recovery system for providing hot water is used as a set for exhaust recovery, and the exhaust heat recovery efficiency is higher as 65.7 % when fueled by CH_4, leading a high total efficiency of 92 %. Furthermore, in order to achieve the emission standard, a set of selective catalytic reduction of NO_x is included at the exit of exhaust gas. Those are beneficial when fueled by NH_3 and H_2.

Table 1: Extended expansion linkage engine specifications

Item	**Specifications**
Engine model	Honda EXlink
Engine type	Four stroke, one cylinder, spark-ignition
Intake stroke volume (cm^3)	110
Exhaust stroke volume (cm^3)	163
Rate speed (rpm)	1950
Output of electricity (Methane as fuel, kW)	1.0
Recovery of exhaust heat (Methane as fuel, kW)	2.5
Efficiency of electricity (Methane as fuel, %)	26.3
Efficiency of recovery heat (Methane as fuel, %)	65.7

III. RESULTS AND DISCUSSION

A. Ammonia addition limitation

In order investigate the possibility of NH_3 as fuel of the gas engine; we firstly use NH_3 and CH_4 as fuel of the gas engine. The limitation of NH_3 added as fuel of gas engine has been investigated as shown in Table 2. As shown in Table 2, the air to fuel ratio (A/F) of the engine decreases with the addition of NH_3 to the fuel. Furthermore, the gas engine can be operated by NH_3/CH_4 as fuel when NH_3 ration to total fuel below 60%, which shows a possibility of NH_3 replacement with CH_4 as a fuel of gas engine.

Table 2 Gas composition of gas engine fueled by NH_3/ CH_4

Run No.	CH_4 (LHV)	NH_3 (LHV)	Total (LHV)	NH_3% (LHV)	A/F
1	2.35	0.00	2.35	0.0	27.22
2	1.98	0.30	2.28	13.0	24.54
3	1.74	0.59	2.33	25.4	21.34
4	1.61	0.74	2.35	31.4	20.03
5	1.55	0.89	2.44	36.4	18.50
6	1.49	1.03	2.52	41.0	17.18
7	1.36	1.18	2.55	46.4	16.30
8	1.30	1.33	2.63	50.5	15.25
9	0.99	1.48	2.47	59.8	15.25

The effects of NH_3 ratio to total fuel (LHV basis) on rotation number of gas engine are shown in Fig. 2. It can be seen from Fig. 2, gas engine can be operated stably when NH_3 ratio to total fuel (LHV basis) below 20% without vibration of rotation number, as fixed rotation speed of 1950 rpm. While with further increase of NH_3 ratio to total fuel, the gas engine becomes unstable with a maximum rotation number change of 100 when NH_3 ratio to total fuel is increased to 60%. The unstable operation of gas engine is mainly because of the low burning velocity of NH_3 (5 to 13 cm/s), leading a low combustion rate and limits its application in the gas engine.

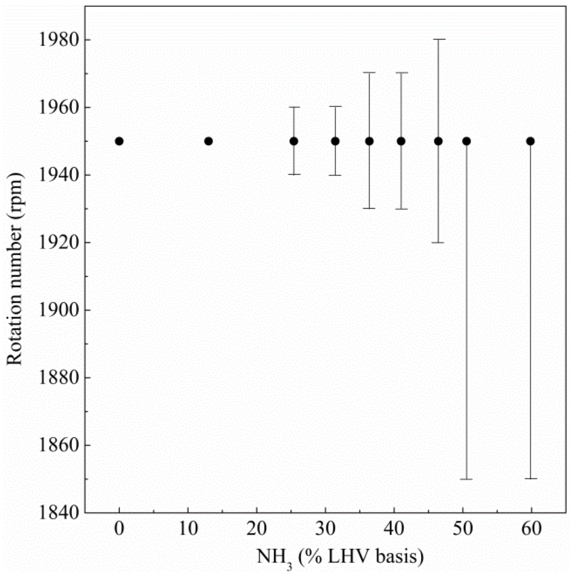

Fig. 2 Effect of NH_3 energy ratio (LHV basis) on rotation number of gas engine fueled by NH_3/CH_4

In order to improve the replacement of NH_3 to gas engine as a practical fuel, NH_3+H_2 is added as fuel of gas engine. The ratio of NH_3/H_2 (volume ratio) has decided to be 1.25:1.00 according to the burning velocity of NH_3/H_2 mixture, the burning velocity of NH_3/H_2 mixture at this condition approximately equals that of methane, which can be seen from our past research [3]. The limitation of NH_3/H_2 mixture added as fuel of gas engine has been investigated as shown in Table 3. As shown in Table 3, the gas engine can be operated only by NH_3/H_2 as fuel. Whereas, the gas engine can be stably operated about 20s, results from a misfire when fueled by NH_3/H_2 mixture only. The reason is mainly because of the higher ignition temperature of NH_3/H_2 mixture, leading a misfire when operated only by NH_3/H_2 as fuel.

Table 3 Gas composition of gas engine fueled by $NH_3/H_2/CH_4$

Run No.	CH_4 (LHV)	NH_3 (LHV)	H_2 (LHV)	Total (LHV)	NH_3+H_2% (LHV)	A/F
1	2.35	0.00	0.00	2.35	0.0	27.22
2	1.86	0.30	0.14	2.30	19.1	21.34
3	1.55	0.59	0.29	2.43	36.2	16.58
4	1.30	0.74	0.36	2.40	45.8	15.25
5	1.11	0.89	0.43	2.43	54.2	13.90
6	0.99	1.03	0.50	2.53	60.8	12.58
7	0.87	1.18	0.57	2.62	66.9	11.47
8	0.74	1.33	0.65	2.72	72.7	10.53
9	0.62	1.48	0.72	2.82	78.0	9.73
10	0.49	1.63	0.79	2.91	83.0	9.02
11	0.37	1.77	0.86	3.01	87.6	8.41
12	0.25	1.92	0.93	3.10	92.0	7.86
13	0.19	2.07	1.01	3.26	92.5	7.31
14	0.00	2.07	1.01	3.08	100.0	7.51

The effects of NH_3+H_2 ratio to total fuel (LHV basis) on rotation number of gas engine are shown in Fig. 3. It can be seen from Fig. 3, gas engine can be operated stably without vibration of rotation number, as fixed rotation speed of 1950 rpm. Even at high addition ratio of NH_3+H_2 to total fuel of 92.5%, the gas engine can be operated at fixed rotation speed with tiny vibration of 1.0%, which shows that the addition of H_2 to NH_3 fueled engine can increase the stability of the engine. Furthermore, it is necessary to point out that the gas engine has been operated 20s when use 100% of NH_3+H_2 as fuel, which shows that it is feasible to replace NH_3+H_2 as major fuel of the gas engine fueled by CH_4.

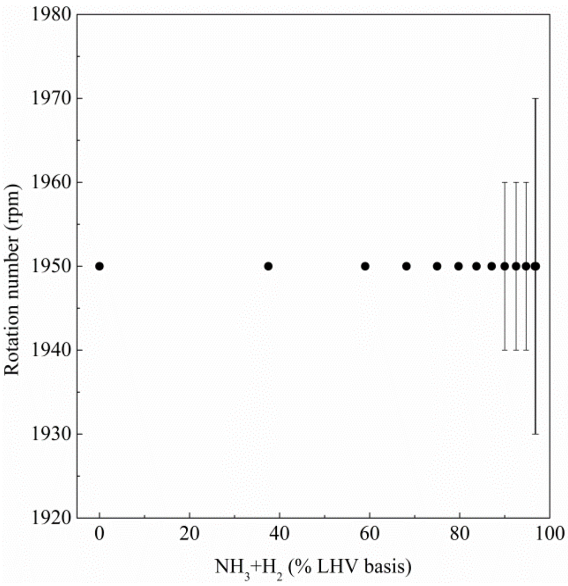

Fig.3 Effect of NH_3+H_2 energy ratio (LHV basis) on rotation number of gas engine fueled by $NH_3/H_2/CH_4$

B. Combustion performance

The in-cylinder combustion using $NH_3/H_2/CH_4$ exhibits characteristics of a conventional spark-ignition engine. Fig. 4 shows the cylinder pressure of gas engine at different fuel composition of $NH_3/H_2/CH_4$ at 1950 rpm. As shown in Fig. 4, the cylinder pressure of gas engine decrease with the addition of NH_3, while increase with the addition of H_2. The cylinder pressure of gas engine at $NH_3/H_2/CH_4$ of 5:4:1.2 (L/min, volume velocity basis) equals to that when fueled by CH_4, the energy input at this condition is approximately 1.4 times of that at CH_4 (3.2 L/min), which confirms the lesser efficacy of NH_3/H_2 with respect of CH_4.

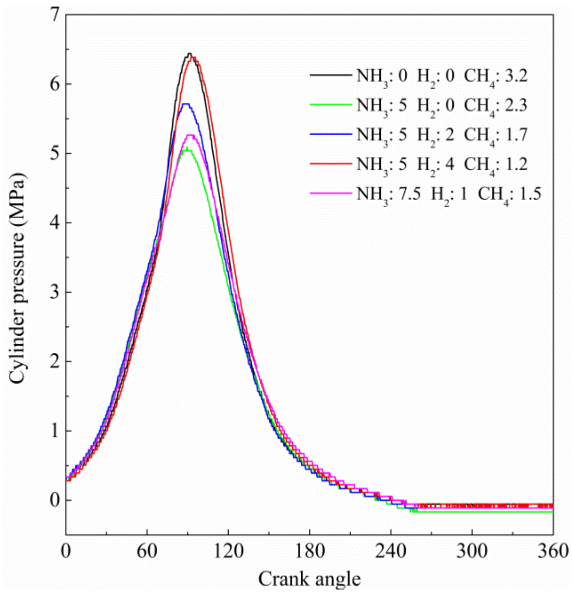

Fig. 4 Cylinder pressure of gas engine fueled by $NH_3/H_2/CH_4$

The power generation efficiency of gas engine is shown in Table 4. As shown in Table 4, the efficiency of gas engine reaches the standard efficiency of power generation as shown in Table 1, whereas, the efficiency of gas engine when fueled by $NH_3/H_2/CH_4$ at 5:4:1.2 (L/min, volume velocity basis) is only 40 % of that of when fueled by CH_4 only at 3.2 L/min. This also confirms that the addition of NH_3/H_2 has a less efficacy than that of CH_4 when use NH_3/H_2 as the alternative fuel of gas engine.

Table 4 Power generation efficiency of gas engine fueled by $NH_3/H_2/CH_4$

Run No.	CH_4 (L/min)	NH_3 (L/min)	H_2 (L/min)	Current (A)	Ranges (A)	Total (kW, LHV)	Efficiency (%)
1	3.2	0	0	4.5	4.4～4.6	1.90	26.1
2	2.3	5.0	0	2.5	2.4～2.5	2.55	10.8
3	1.3	5.0	4.0	2.5	2.4～2.5	2.62	10.5

IV. CONCLUSIONS

The performance of a spark-ignition gas engine system fueled with ammonia and hydrogen was evaluated in this study. The effects of ammonia and hydrogen as fuel on gas engine performance and efficiency were experimentally investigated. The major conclusions in this study are as follows. A maximum of 60 % NH_3 addition (LHV basis) can be reached when the gas engine fueled by NH_3 and CH_4 with a fixed rotation speed of 19500 rpm .The gas engine operates stably at a maximum high addition ratio of 92.5% NH_3+H_2 (LHV basis) addition to total fuel under fixed rotation speed with tiny vibration of 1.0%, showing a feasible replacement of NH_3+H_2 as major fuel of the gas engine fueled by CH_4.A lower energy density of NH_3 and H_2 leads a lower power generation efficiency of the gas engine when fueled by $NH_3/H_2/CH_4$ compared with CH_4.

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