Hydrogen-Rich Gas for Clean Combustion in a Dual-Fuel Compression Ignition Engine

Horng-Wen Wu, Tzu-Ting Hsu, and Rong-Fang Horng

***Abstract*—Since burning of hydrogen emits fewer pollutants, it has been using as a clean alternative or auxiliary fuel of engines. This study is to develop a diesel/ hydrogen-rich gas dual fuel engine with methanol steam reforming method and design of EGR (Exhaust Gas Recirculation) system to investigate engine performance and exhausting pollutants. The measured items are composed of the gas pressure of cylinder, crank angle, diesel consumption rate, hydrogen consumption rate, air flow rate, and emissions (HC, CO_2, NO_x, and Smoke), and the contents of hydrogen-rich gas. The authors analyze how the hydrogen-rich gas addition with EGR influences the combustion performance and emissions. The heat recovery reforming system can solve the storage and producing problem of hydrogen. Furthermore, the authors little altered the engine structure, and it is easy to put the energy saving and pollutants decrease into effect.**

***Index Terms*—Clean combustion, diesel/hydrogen-rich gas engine, emission reduction, exhaust heat recovery, exhaust gas recirculation, methanol steam reforming.**

I. Introduction

There are many applications of diesel engines in the worldwide such as automobile vehicle, power generation, power source of marine, and so on [1]. The global trend of environmental protection and energy has been depleting, which also represents energy costs will be higher than ever. In view of this, how to use energy more efficiently and to seek alternative fuels for fossil fuels will allow for no delay [2].

Hydrogen is regarded as one of promising alternative clean fuels for fossil fuels [3] and also to fill the need for sustainable energy development and environment protection [4]. There are three methods of hydrogen-rich gas: steam oxidation (POX), and auto-thermal reforming (ATR). This study uses methanol steam reforming reaction to produce hydrogen-rich gas. After methanol is mixed with water, it reacts with the reforming catalyst directly and produces hydrogen, carbon monoxide and carbon dioxide. This method is the most efficient and the most widely used by producing hydrogen; and the method is also the most productive for all recombination reaction [5], [6].

Compared with common fuels, hydrogen has the characteristics of a long term renewable, recyclable and non-polluting fuel because it contains no carbon [7]-[9]. Furthermore, it had the characteristics of higher flame speed and larger diffusion speed benefit the energy efficiency and reduces emissions. The more rapid flame propagation and wider flammable range of hydrogen might lead to extended lean operating limits [10], and the engine could operate with a wide range of air/fuel ratio. The lower heating value of hydrogen is much higher (120 MJ/kg) than that of diesel fuel (42 MJ/kg). The auto-ignition temperature of hydrogen (858 K) is also higher than diesel (453 K) [11], so hydrogen cannot be used in CI engine without spark plug. It makes hydrogen only fit for pilot complementary fuel for diesel engines.

Emonts *et al*. [12] set up a methanol reformer employing the catalytic burner to heat the reformer. They found that at low hydrogen yields, the methanol conversion efficiency could be up to 100 %. As the operating temperature increased from 260 ℃ to 280 ℃, the efficiency could be significantly improved. On the other hand, they found that the higher the temperature was, the higher the concentration of CO became. Lindström *et al*. [13] employed steam reforming combined with partial oxidation to establish a methanol reformer which reached reaction time from cold start up only about 300 seconds. When the reaction temperature reached 260 ℃, methanol conversion efficiency was about 90%. Hohlein *et al*. [14] developed a methanol steam reformer system which was combined with catalytic burner and gas handling equipment at 240 ℃, 260 ℃, and 280 ℃ of operating conditions. They found that the CO concentration of reformer outputs was related to the heating mode and the changed reformer temperature curve closely. Sun *et al*. [15] mixed ethanol into water and introduced new Ni-Y_2O_3 catalyst to reform. Their experimental results showed that hydrogen concentration of output was up to 67.6% and the fuel conversion efficiency was greater than 98 % when temperature was at 350 ℃.

Moreover, Rakopoulos *et al*. [16] indicated that one of significant advantages that hydrogen might have as a fuel was its potential for increasing second law efficiency, due to fundamental differences in the mechanism of entropy generation during combustion with respect to the usual hydrocarbon-based fuels. Because of good combustion characteristics of hydrogen, Mohammadi *et al*. [17] tried to make hydrogen directly inject into cylinder of a single-cylinder test engine using a high-pressure gas injector. Their results indicated that direct injection of hydrogen prevented backfire, increased thermal efficiency and output power. Saravanan *et al*. [18] inducted hydrogen into a single-cylinder direct injection diesel engine at the intake port.

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They found that the brake thermal efficiency increased from 22.78 % to 27.9 % with 30 % hydrogen enrichment when smoke and NO_x (only under lean burn condition) emissions decreased; conducting too much hydrogen at the intake port would cause engine knock.

Little research has been done on combustion characteristics and emissions of the combination of diesel engine with the heat recovery type of steam reforming system. Therefore, this study developed such a combination to produce hydrogen-rich gas with the EGR system for low NO_x emission. The authors expected that the port addition of hydrogen in direct injection diesel engine has good combustion performance and low emissions. Moreover, the contents of hydrogen-rich gas, in-cylinder pressure, cyclic variations of indicated mean effective pressure (IMEP), heat release rate, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and CO_2, NO_x, and smoke emissions are analyzed at different added hydrogen flow rates and EGR ratios.

II. Experimental Apparatus

The experiments were conducted under various flow rates of hydrogen-rich gas and percentages of EGR for a fixed engine load and rotation speed. Fig. 1 shows a block diagram of the experimental apparatus used in this study, and Fig. 2 displays photographic view of the test setup. The engine used was a 624 cm^3 single cylinder, water cooled, and four stroke diesel engine (Kubota RK-125). The main specifications of the engine are listed in Table I. The test setup includes hydrogen injection system, hydrogen cylinder, anti-explosion device, EGR system, and emissions (CO, HC, CO_2, NO_x, and smoke) measuring equipment. Hydrogen-rich gas is supplied by a methanol reformer.

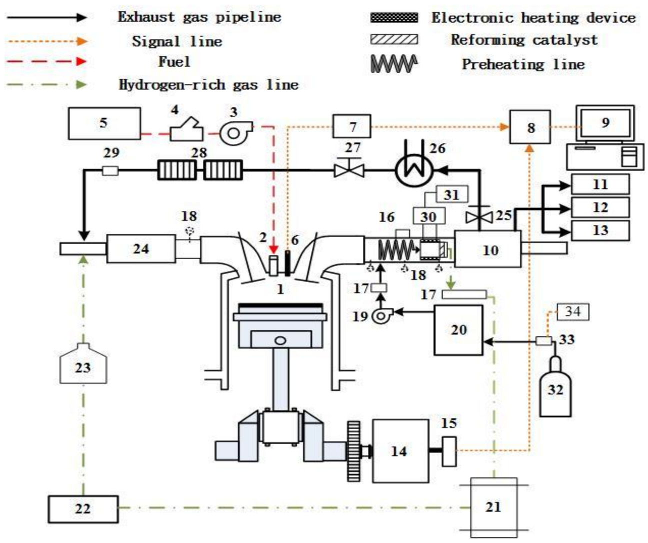

Fig. 1. Experimental apparatus.

Description: 1: diesel engine; 2: Fuel injector; 3: Fuel pump; 4: Fuel filter; 5: Fuel tank; 6: Pressure sensor; 7: Signal amplifier; 9. Analog /digital signal converter; 10: Exhaust tank; 11: NO_x analyzer; 12: CO/HC/CO_2 analyzer; 13: Smoke analyzer; 14: Dynometer; 15: Crank angle detector; 16: Methanol steam reformer; 17: Flow meter; 18: Temperature sensor; 19: Fuel pump; 20: Methanol/water tank; 21: Seperator; 22: Hydrogen- rich gas control valve; 23: Flame trap; 24:Surge tank; 25: EGR valve; 26: Exhaust gas cooler; 27: EGR valve; 28: Carbon absorber; 29: EGR flow meter; 30: Power supply device; 31: PID temperature controller; 32: Carrier gas cylinder; 33.Carrier gas flow control valve; 34: Carrier gas flow monitor.

For the EGR system, the exhaust gas, which was sent into the combustion chamber, had to be cooled by using the heat exchanger. The exhaust gas temperature was maintained around 28 ℃±1 ℃ by varying the flow rate of cooling water. The gas flow was then monitored by gas flow meter while EGR valve was adjusted to obtain the desired EGR ratio. The cooling gas was separated from the moisture by a separator before the cooling gas was conducted into the surge tank. The volume flow meters with Dwyer® Series DS-300 Standard valves are rated at 13.7bar and 93.3 ℃. To measure the fuel volume flow rate, the authors used a 10 mm^3 volumetric cylinder which was a bypass pipe of the fuel pipe. When the engine was under stable condition, the fuel pipe was switched to the 10 mm^3 volumetric cylinder and the fuel consumption rate was therefore measured.

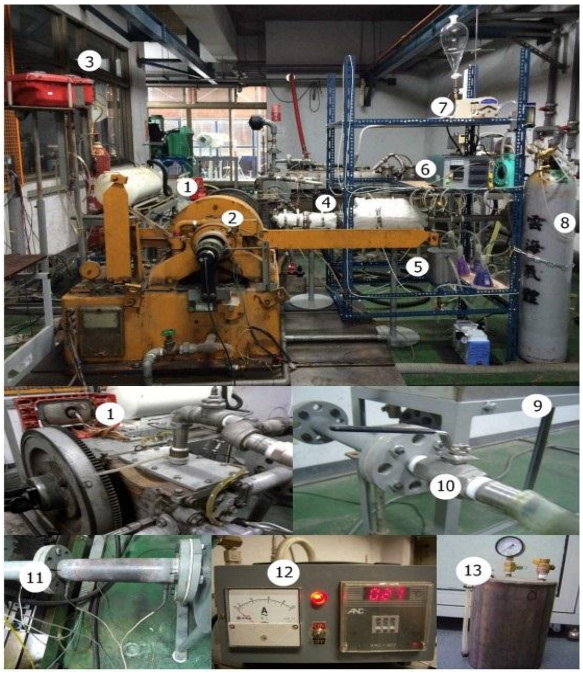

Fig. 2. Photographic view of the engine setup.

Description: 1: Diesel engine; 2: Dynamometer; 3: Fuel tank; 4: Reformer; 5: Cooler; 6: PID temperature controller; 7: Peristaltic pump; 8: Carrier gas cylinder; 9: Exhaust gas cooler; 10: EGR control valve; 11: Inlet heater; 12: Inlet heater temperature controller; 13: Flame trap.

A Kistler 6001 pressure transducer was used in conjunction with a charge amplifier, and Kistler 5011B to a data acquisition card was used to record the cylinder pressure. The crank degree signals required were obtained from a shaft encoder providing a resolution of 1o crank and an accuracy of ±0.05o crank. Analog /digital signal converter NI PCI-6259 was connected with a computer quickly acquired and the cylinder gas pressure and the crank degree signals processed. Hydrogen flow was measured by using a thermal mass flow controller, GFC-37A-VAD. Its precision was ±1.5% of full scale. The brake power arose about 1.5% when the hydrogen was injected into the chamber. BOSCH EAM3.011 was used to measure smoke emission, and HORIBA MEXA 584 was used to measure $CO/HC/CO_2$ emissions. ACHO Physics CLD-60 was for measuring NO_x emission.

As indicated in Fig. 3, the reforming system includes methanol reformer, fuel supply system, heating and temperature control system, cooling system, gas sampling and analysis system, exhaust gas analysis system, and so on. The methanol reformer is made of shell tube in concentric cylinders composed of waste heat recovery zone and methanol steam reforming zone. The shell of reformer is covered with the electric heater which provides main heat source of a reforming reaction, and the electric heater is covered with asbestos for preventing heat loss. Through the inside of the reformer, a waste heat recovery tube with exhaust gas from a diesel engine passing through provides a secondary heat source of the reforming reaction heating the reformer to reach the required reforming reaction temperature.

TABLE I: THE SPECIFICATIONS OF THE ENGINE

Bore × stroke	94×90 mm
Displacement Volume	624 cm^3
Compression Ratio	18
Rated output	9.2 kW
Rated speed	2400 rpm
Injection pressure of diesel fuel injector	21.57~22.56 MPa
Start of injection	21.5~23.5 °BTDC

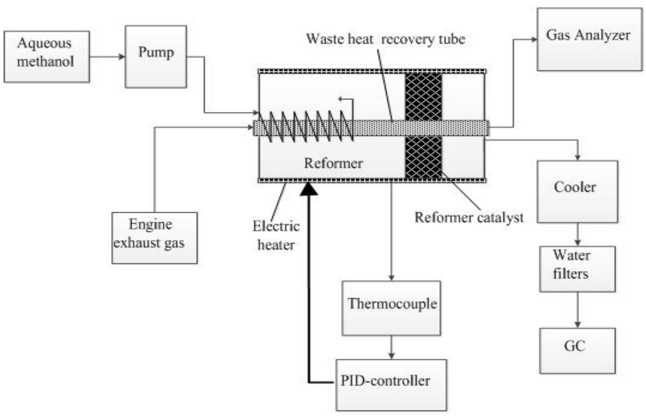

Fig. 3. Schematic of the methanol steam reforming system.

The required feeding rate of aqueous methanol is controlled by a peristaltic pump and a flow-meter. Fuel supply system includes fuel tank, peristaltic pump, flow meter, and feed preheat tube. The peristaltic pump is LongerPump C9ES-DG100M at 1-150 rpm with peristaltic pump head YZ1515X at 0.07-2200 ml/min. The flow meter is AALBORG 022-13-ST within 0.550-5.78 ml/min. The PID controller provided a resolution of 1% crank and an accuracy of 2% crank. The electronic air flow meter is AALBORG CFC-17 within 0-10 l/min.

The cooling system includes a cooler body, submerged pumps, cryogenic tank, and anti-corrosion vacuum pump. The cooler is a parallel heat exchanger of 65 mm diameter and 200 mm length with internal copper pipes inside it. The gas sampling and analysis system includes airtight sampling bag and gas chromatography. After the gas mixture goes through the dry bottle, the gas is collected by gas sampling bag for gas composition analysis using gas chromatography. The gas chromatography is Agilent 6850 using thermal conductivity detector with error within 0.5% to measure the concentration of sampling gas, such as H_2, N_2, CO, and CO_2.

III. RESEARCH METHOD

EGR is a NO_x reduction technique used in most gasoline and diesel engines. EGR works by re-circulating a portion of an engine's exhaust gas back to the engine cylinders. With higher specific heat, EGR can reduce the burning temperature in the cylinder for reducing NO_x emission. The definition of EGR ratio [11] in this study is given as

$$\mathrm{EGR}(\%)=V_{\mathrm{EGR}}/(V_{\mathrm{air}}+V_f+V_{\mathrm{EGR}}) \tag{1}$$

where V_{EGR} is the volume of engine's exhaust gas, V_{air} the volume of the intake air, and V_f the volume of fuel.

BSFC is the ratio of fuel mass flow rate to output power of an engine given by the following equation.

$$\mathrm{BSFC}(\mathrm{g/kW}\times\mathrm{h})=\frac{\dot{m}_f(\mathrm{g/h})}{BP(\mathrm{kW})} \tag{2}$$

where BP is the brake power and $\dot{m}_f$ is the mass flow rate of fuel (g/h); the fuel includes diesel, hydrogen, and carbon monoxide.

BTE is the ratio of work done by engine to the energy supplied to an engine given by the following equation.

$$\mathrm{BTE}(\%)=\frac{\mathrm{BP}}{\mathrm{IER}}\times 100\% \tag{3}$$

where BP is the brake power measured by dynamometer and IER is input energy rate which means total energy rate inputted to the engine from combustion of fuel.

In this study, the IER means is determined as follows.

$$\mathrm{IER}=\dot{m}_d\times h_d+\dot{m}_{H_2}\times h_{H_2}+\dot{m}_{CO}\times h_{CO} \tag{4}$$

where h_d is the lower heating value of diesel fuel (42.5 MJ/kg), h_{H_2} is the corresponding lower heating value of hydrogen (120 MJ/kg), and h_{CO} is the corresponding lower heating value of carbon monoxide (1.18 MJ/kg).

Heat release rate reveals the combustion event and stages, but the actual formation is complicated. The heat release rate model [12] is used here by

$$\frac{dQ}{d\theta}=\frac{1}{k-1}\left(kp\frac{dV}{d\theta}+V\frac{dp}{d\theta}\right)-\frac{pV}{(k-1)^2}\frac{dk}{d\theta}(J/CA) \tag{5}$$

where $dQ/d\theta$ is the net heat-release-rate (J/CA), θ is the crank angle in degrees, and V is the volume of the cylinder (m^3). k is the specific heat ratio calculated from the composition and temperature of in-cylinder gas, treated as a variable, and $dk/d\theta$ is thus obtained.

Because of many factors affecting combustion characteristics, even if engine operates under steady conditions, they are not same completely from cycle to cycle. If combustion variation is larger from cycle to cycle, then engine will operate unstably and produce burning incompletely to affect combustion characteristics of engine. The formula of cyclic variation written by its coefficient of variations (COV) [12] is as follows:

$$\mathrm{COV} = \frac{\sigma}{\overline{Y}} = \frac{\sqrt{(N-1)\cdot\sum_{i=1}^{N}\left(Y_i-\overline{Y}\right)^2}}{\overline{Y}} \quad (6)$$

where COV is the coefficient of variation, σ is standard deviation, is the mean value, and N is cycle numbers of sample; N is equal to 100 in this study.

This study uses waste heat recovered from the exhaust gas to methanol reformer as its secondary heating source. Engine exhaust waste heat recovery ratio is defined as the ratio of consumption energy rate to total energy rate of engine exhaust gas. If the content of exhaust gas does not change after entering the reformer, the heat recovery ratio can be calculated by the difference between inlet and outlet temperature of reformer. The formula is defined as follows.

$$\mathrm{WHR}(\%) = \frac{\dot{Q}_{\mathrm{consumed}}}{\dot{Q}_{\mathrm{exhaust}}}\times 100 = \left(1-\frac{T_{\mathrm{out}}}{T_{\mathrm{in}}}\right)\times 100 \quad (7)$$

where $\dot{Q}_{\mathrm{exhaust}}$ is the total energy rate of engine exhaust gas, and $\dot{Q}_{\mathrm{consumed}}$ is the heat energy rate absorbed by methanol steam reforming.

IV. Results and Discussion

The operating parameter of steam reforming was input changed by flow rate of methanol aqueous solution. Changing the flow rate of methanol aqueous solution can control the production rate of hydrogen-rich gas. Other parameters of steam reformer was fixed at S/C ratio 1.3, reacting temperature 300 ℃, and the flow rate of carrier gas is 40 c.c./min. Under the setting experimental condition, the contents of hydrogen- rich gas were listed in Table II. Hydrogen and carbon monoxide account for most of the contents up to more than 73.9%, and they can assist engine combustion. Engine experiment was carried out by adjusting continuous hydrogen-rich gas with supplied flow rate of 7.6 l/min, 11.6 l/min, and 15.7 l/min and 20 to 40% EGR ratio. The test engine is fixed at 60% load for various engine speeds. The results for 1800 rpm and 45% load are discussed from Fig. 4 to Fig. 12.

The authors used exhaust gas introduction of reformer gas inlet temperature (T_{in}) and exhaustion of reformer gas outlet temperature (T_{out}) to get the waste heat recovery ratio (WHR) of engine exhaust gas, and the results are shown in Table III. The waste heat recovery ratio will be enhanced as the amount of the feed methanol aqueous solution is increased. Generally, the waste heat from exhaust gas accounts for some of the fuel input energy. If the waste heat cannot be used with an appropriate method, it will be discharged to the atmosphere directly. From the experimental results, the different ratios of methanol and water and reforming reaction temperatures will influence waste heat recovery ratio of reformer. For the overall experimental results, the highest rate of waste heat recovery can be up to 11.29 %, and the lowest rate of waste heat recovery is 10.4 %.

The hydrogen-rich gas conducted into the engine causes higher peak pressure. Fig. 4 shows the variations of in-cylinder pressure with hydrogen-rich gas flow rate for an EGR of 40%, and the load at 60%. The peak pressure with 7.6 l/min hydrogen-rich gas is 56.6 bar, with 11.6 l/min hydrogen is 57.7 bar, and with 15.7 l/min hydrogen is 62.4 bar. The fast flame speed causes the advance in peak pressure for higher hydrogen flow rate compared with the lower one. Hydrogen-rich gas addition generates an increase in the peak heat release rate. This is because of the longer ignition delay, and a greater amount of diesel fuel is thus burned during the premixed combustion phase. Similar to the in-cylinder pressure, the higher hydrogen-rich gas flow rate causes higher peak heat release rate as displayed in Fig. 5. In this study, the coefficient of variation (COV) of indicated mean effective pressure (IMEP) with hydrogen flow rate and the EGR ratio can determine the stability of engine combustion. Problems often occur when COV of IMEP exceeds about 10%. Fig. 6 demonstrated that higher EGR ratio would cause the more variation of COV. Fortunately, the COV of IMEP values for all conditions are lower than 10 % (from 1.2 % to 2.8 %), and these are small cyclic variations. From Fig. 6, COV of IMEP with EGR is obviously higher; this is because EGR causes poor combustion to increase the post-combustion, and thus leads to more unstable engine operation. However, these are still small cyclic variations. As a result, the addition of hydrogen-rich gas and EGR would not generate the unstable combustion.

TABLE II: The Contents of Hydrogen-Rich Gas

Experimental run	H_2 (%)	N_2 (%)	CO_2 (%)	CO (%)
T300, S/C 1.3, 6.5 g/min	70	0.521	21.6	3.879
T300, S/C 1.3, 10 g/min	70.6	0.339	22.3	2.761
T300, S/C 1.3, 13.5 g/min	71.1	0.253	21.8	2.847
Experimental run	Hydrogen-rich production rate (L/min)		Methanol conversion efficiency (%)	
T300, S/C 1.3, 6.5 g/min	7.6		65.08	
T300, S/C 1.3, 10 g/min	11.6		63.95	
T300, S/C 1.3, 13.5 g/min	15.7		62.42	

TABLE III: The Waste Heat Recovery with Various Flow Rate of Methanol Aqueous Solution

Experimental run	T_in (k)	T_out (k)	WHR (%)
T300, S/C 1.3, 6.5 g/min	538	482	10.40
T300, S/C 1.3, 10 g/min	541	481	11.09
T300, S/C 1.3, 13.5 g/min	540	479	11.29

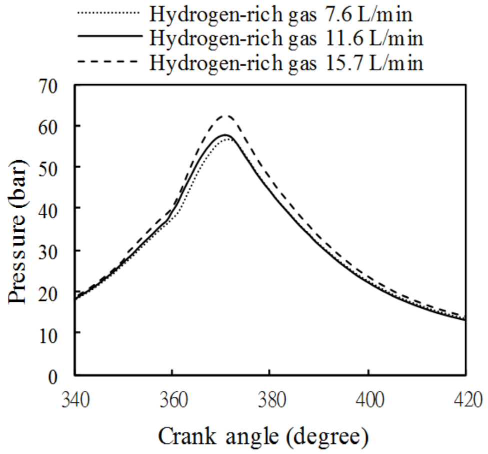

Fig. 4. Variations of in-cylinder pressure with hydrogen flow rate for the load at 60% and the EGR ratio of 40%.

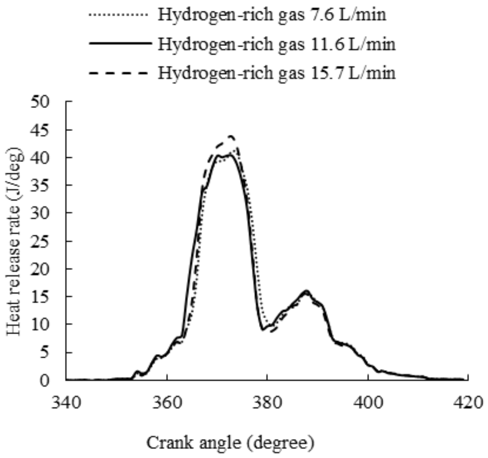

Fig. 5. Variations of heat release rate at different EGR ratios.

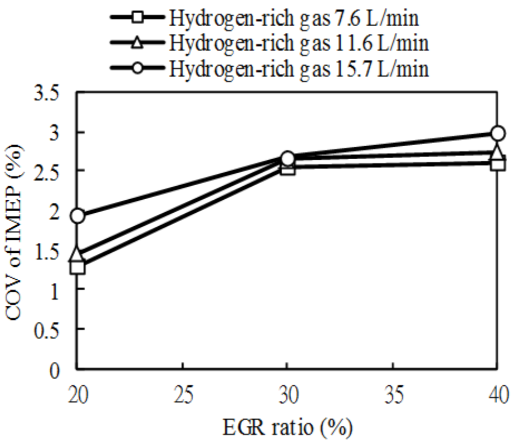

Fig. 6. Variations of COV of IMEP at different EGR ratios.

Fig. 7 indicates that the brake thermal efficiency alters significantly at low EGR ratio, but adding hydrogen-rich gas makes BTE become insignificant as EGR ratio increases. However, the fuel consumption would decrease at higher hydrogen-rich gas flow rate as shown in Fig. 7. There are two reasons to for this phenomenon. First, the CO_2 concentration increased as the amount of re-circulated exhaust gas additive increased. A certain volume of intake air was substituted by CO_2, so it would reduce the combustion temperature and cause some poor combustion. The original output power would be affected by incomplete combustion. For the sake to get the same power, the engine must consume more fuel. Second, hydrogen helps chemical reactions of diesel in the cylinder enhance combustion. For better effect of energy saving, the amount of hydrogen-rich gas additive and EGR ratio should take a trade-off.

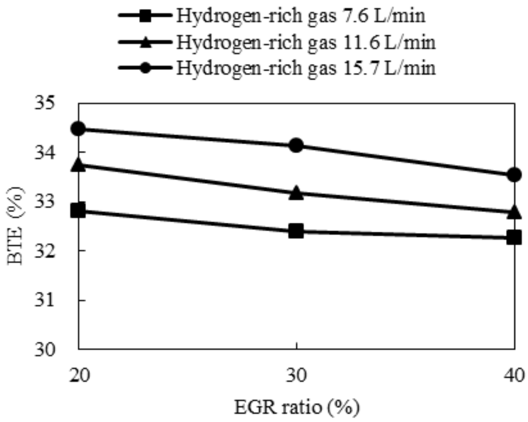

Fig. 7. Variations of BTE at different EGR ratios.

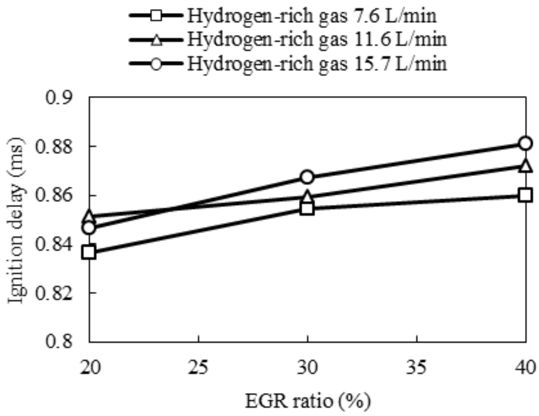

Fig. 8. Variations of ignition delay at different EGR ratios.

Fig. 8 displays the variation of ignition delay. The increase in ignition delay for EGR condition is as a result of decreasing of heating value of fuel by EGR and the increase in ignition delay for adding hydrogen-rich gas with diesel is due to adding hydrogen will decrease the cetane number of the mixing fuel and lower compression temperature caused by diluted oxygen, so the ignition delay increases. Fig. 9 shows that CO_2 concentration decreases with an increase in hydrogen-rich gas addition because of more complete combustion. When the EGR ratio increases, the CO_2 concentration becomes higher since CO_2 is present in exhaust gas with EGR. Fig. 10 indicates that HC concentration rises owing to less oxygen in air and more hydrogen in fuel when hydrogen addition increases. The more the EGR ratio is, and the higher the HC concentration becomes since oxygen concentration is lower to burn more incompletely. Fig. 11 displays that NO_X concentration increases with an increase in hydrogen-rich gas addition because of higher combustion temperature. When the EGR ratio increases, the NO_X concentration becomes lower compared with original baseline diesel engine. This is since the re-circulated exhaust gas dilutes the intake gas mixture to lower the combustion temperature. Fig. 12 shows that smoke concentration decreases owing to fewer carbons in fuel as hydrogen-rich gas addition is raised. The smoke concentration increases with an increase in the EGR ratio since oxygen concentration is lower when the re-circulated exhaust gas is added more. After being validated with previous research work [7], [8], this paper has the same trend of smoke and NO_x with their results, but the change magnitude is different due to different amounts of hydrogen.

Moreover, with EGR ratio 40% and hydrogen flow rate 15.7l/min, the CO, CO_2, NO_x, and smoke give better results; this is because when hydrogen into the cylinder is at high flow rate, the in-cylinder temperature is higher and the hydrogen burns quickly. A reduction in NO_x emissions is observed due to hydrogen addition at higher EGR ratios.

For the innate design of engine, too much hydrogen additive may cause cylinder temperature to become very high. The overheat exhaust would cause the cylinder broken and the temperature of cooling water to climb to boiling point.

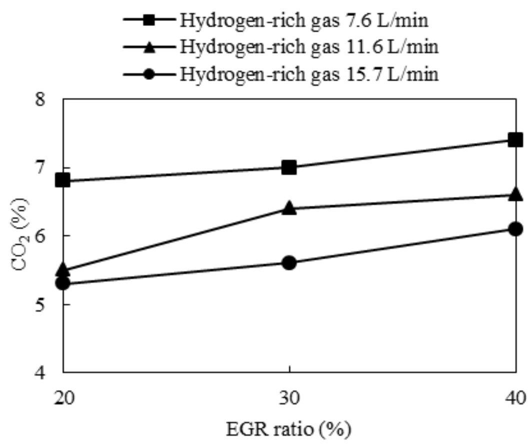

Fig. 9. Variations of CO_2 at different EGR ratios.

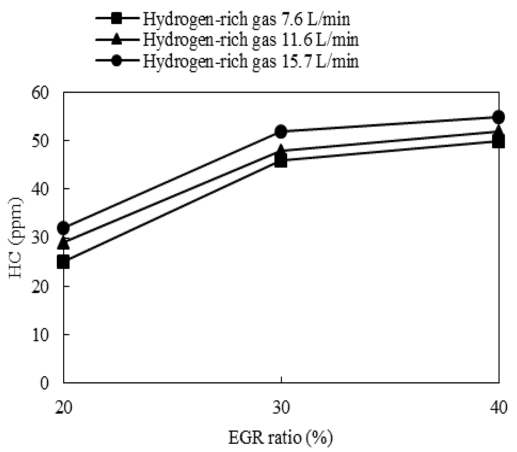

Fig. 10. Variations of HC at different EGR ratios.

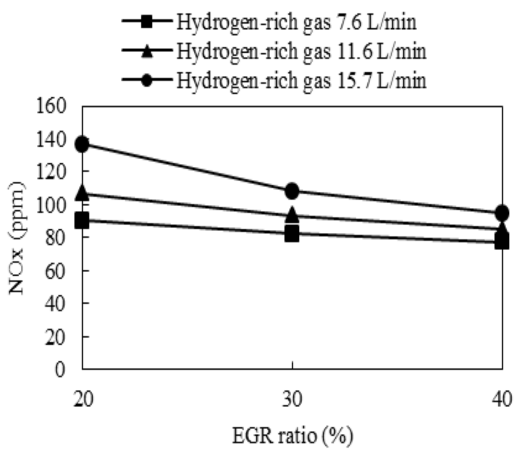

Fig. 11. Variations of NO_x at different EGR ratios.

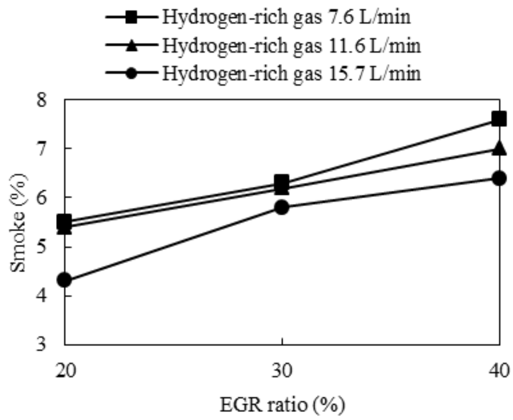

Fig. 12. Variations of smoke at different EGR ratios.

For these reasons, this study only choose hydrogen-rich gas flow rate at 15.7 l/min to add into the manifold. As a result, the condition makes good combustion, and thus reduces the emissions.

V. Conclusion

After having finished a diesel/ hydrogen-rich gas dual fuel engine with methanol steam reforming method and EGR system, this study investigated the engine combustion performance and emissions at different added hydrogen–rich gas flow rates and EGR ratios. Employing port-induced hydrogen and EGR system can increase engine efficiency with a greater reduction in emissions. The integration of methanol steam reforming system and diesel engine effectively can recover the waste heat energy from exhaust gas. The combination of reformer and engine also solves the storage problem of hydrogen. If hydrogen has much safer source, the application of hydrogen energy may be proved to commonly use.

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