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Performance Improvement for a Diesel Engine Combined with a Methanol and Aqueous Urea Reformer Through Exhaust Gas Recirculation

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Keywords: performance improvement, diesel engine, methanol blended with aqueous urea reformer, waste heat recovery, exhaust gas recirculation integration

ABSTRACT

This study establishes an exhaust gas recirculation device in a diesel engine and integrate a reformation system of methanol blended with aqueous urea. Modifying the diesel engine's intake inducts hydrogen-rich gas into the exhaust gas recirculation (EGR) for testing and investigating how inducting hydrogen-rich gas influences the engine's exhaust emissions. The results are as follows. The engine exhaust outlet and intake have integrated the EGR system with the methanol and aqueous urea reformation system. When employing engine exhaust gases as auxiliary heating during methanol-urea aqueous steam reforming, the waste heat recovery rates range from 10.01% to 12.68%. The cylinder pressure increases significantly under the condition of adding hydrogen-rich gas. For 40% EGR, adding hydrogen-rich gas reduces smoke and CO emissions by about 19.29% and 40% but increases NO_X and HC emissions. However, inducting hydrogen-rich gas and 40% EGR can reduce NO_X by 18.62% compared to diesel with no EGR addition.

INTRODUCTION

The impacts of air pollution and greenhouse gasses on human health and climate change have intensified more attention. Non-homogeneous combustion is a feature of diesel engines. Since the cylinder's rich mixture center lacks sufficient oxygen for burning, part of the fuel may even directly pyrolyze to produce many black smoke emissions. In contrast, the surrounding spray is a thin mixture of gas area (Heywood, 2018). To reduce the carbon emissions of diesel engines, improve their efficiency, and reduce nitrogen oxide emissions, the introduction of hydrogen as an auxiliary fuel has attracted extensive research and discussion (Wu et al., 2018). Hydrogen's superior energy density and low carbon emissions make it a promising fuel option. Hydrogen added to a diesel engine's intake system lowers harmful emissions while increasing combustion efficiency (Wu and Wu, 2018). Hydrogen is an important energy carrier because it is a sustainable and clean energy source. It is recognized to be a very promising substitute fuel for engine applications (Kim, 2023). Also, hydrogen has a higher flame speed and a broader flammability limit, extending the operational limits (Alrazen et al., 2016) and enabling the engine to work over a greater extent of relative air-fuel ratios.

There have been reforming processes utilized to create hydrogen (Lamy et al., 2020), including the examinations of methanol steam reforming (Huang et al., 2013, Perng et al., 2019), ethanol steam reforming (Sheu et al., 2022), and methane reforming systems (Chang et al., 2019, Chao et al., 2011). Mohamed et al. (2024) explored the hydrogen directly injected into the cylinder at two direct injection locations. The two injection locations achieved stable engine operations over larger air/fuel ratios. The central location injection got greater thermal efficiencies than the side location injection. NOx emissions from the side location injection were more than those from the central location injection. Perng et al. (2017) numerically studied the influence of surface temperature, diffuser length, and angle in a cylinder-shaped methanol steam reformer on highest hydrogen generation and the evaluated fuel cell net power. Contrasted with a usual reformer, a reformer

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(diffuser length, 75 mm, and angle, 6^o) acquired the rising rate in hydrogen generation by 44.62 % and the highest raising rate in evaluated fuel cell net power (24.59 %). Kim et al. (2021) set up a reduced kinetic approach for the diesel auto thermal reforming process to hydrogen-rich gas-supplying fuel cells. They raised the accuracy when increasing the reaction numbers. Lin and Wu (2019) performed a thermodynamic investigation on fatty acid methyl esters (FAME) together with hydrotreated vegetable oil (HVO), undergoing partial oxidation reformation. The O_2 over FAME ratio of 10 could produce 45.50% hydrogen-rich gas at 800 °C, with a 21.96% concentration of H_2. The syngas production was 45.14%, and the H_2 concentration was 23.01% through an O_2 over HVO ratio (10). Ouyang et al. (2017) utilized the neural network method with radial basis function to find the optimum combined parameters in a methanol steam reformer. Their findings revealed that the optimum combined parameters were an S/C ratio (1.1), a flow rate (40 cm^3/min) for carrier gas, and reaction temperature (267 °C), resulting in declined averaged quality loss than further approaches of the principal component analysis and the Taguchi method. Urea is increasingly used as a hydrogen transporter (Rollinson et al., 2011). The blended aqueous urea added during the reforming process produces more hydrogen with the same amount of water. Wu and Lin (2019) conducted a thermodynamic investigation to examine the features of steaming and auto-thermal ethanol reformation using aqueous urea or no. Perng et al. (2021) estimated how divergent fuel channels affected the reforming performance in a plate-shaped reactor. Compared to a plain reactor, the reactor in the divergent channel with H_{out}/H_{in} = 4.0 gained the most hydrogen production (24.03 %). Furthermore, this reactor achieved the maximum rise (6.39 %) in the fuel cell net power output.

Various researchers have explored combustion engine performance employing hydrogen or hydrogen- rich gas in the cylinder. Dabir et al. (2017) studied how biogas mixed with reformate gas, compared to raw biogas, affects engine energy efficiency and NOx emissions. They discovered a decline in NOx pollutants and achieved stable combustion. Martin et al. (2018) proposed that onboard fuel reforming is feasible. They found that combustion with reformate-enhanced exhaust gas recirculation within a direct-injected gasoline engine improved combustion performance and reduced pollutants. Wu et al. (2017) utilized the Taguchi methodology to determine the optimum combined methanol-water solution flow rate, exhaust gas recirculation rate, and supplementary oil temperature. For higher exhaust temperatures, the hydrogen-fueled diesel engine without EGR increased brake thermal efficiency (BTE) by 12.9% compared to the EGR conditions. When EGR was applied, CO, HC, smoke, and CO_2 emissions increased slightly with hydrogen compared to the non-EGR condition but still showed significant reductions compared to the diesel-only condition. The NOx concentration decreased due to the EGR effect. Fernández et al. (2020) reviewed various H_2 storing systems and the burning ways of driving engines to illustrate the active feasibility aboard LNG ships. The blend of 30% H_2 and 70% CH_4 was the most appropriate since the injection system did not need any changes. Building an onboard reforming device and H_2 storage system produced enough H_2 for nearly three days of autonomy with a mixture of 30% H_2 and 70% CH_4. Prasad et al. (2021) used 5% to 20% hydrogen-rich gas, in increments of 2.5%, within a spark ignition engine operating via full throttle at varied speeds. The rise in hydrogen-rich gas improved BTE and brake power as the specific brake energy consumption decreased. Wu et al. (2018) inspected the pollutants and performance in a four-cylinder turbocharged diesel engine, adding hydrogen at an intake port with an EGR device. The turbocharged engine inducting hydrogen could raise the BTE with much lower emissions than a turbocharged diesel engine.

An exhaust heat recovery system recovers waste thermal energy from exhaust gases to provide additional work or to aid engine warm-up, and so on; otherwise, it is to the environment as waste. There is increasing interest in this technology as manufacturers of heavy-duty vehicles and automakers aim to reduce emissions, save fuel, and improve efficiency (Zhu et al., 2020). Ragupathi et al. (2020) concentrated on employing the waste thermal energy through a diesel engine's exhaust gases to produce electricity using an Al_2O_3 thermoelectric generator. In addition to improving overall efficiency, the thermoelectric generator's power significantly decreased thermal pollution caused by exhaust emissions at high temperatures. Daniel et al. (2020) integrated a heat recovery thermal apparatus with an internal combustion engine through latent heat materials. The thermal energy storage system could store around 15% of fuel power. According to Gohar et al. (2022), heat recovery from exhaust gases released by internal combustion engines was possible in several systems, including vapor absorption refrigeration units. The highest temperature decline via exhaust, reaching 104.8 ºC, occurred at an intake speed (0.3 m/s) with an outlet speed (2 m/s) employing graphene oxide nanofluids. Through exhaust gas, the 96.34 ºC with a LiBr solution refrigerant achieves the temperature decrease via 102 oC with water at a similar outlet velocity (2 m/s).

However, the combustion performance, HC, CO, smoke and NO_X, pollutants in a diesel engine employing a methanol-urea aqueous steam reforming reactor that recovers waste thermal energy remain unknown. This exploration used a reformer with aqueous methanol-urea to produce a hydrogen-rich gas, removing the need for a hydrogen-storing device. The high-temperature exhaust from the diesel engine is applied to waste thermal energy recovery, providing some of the energy needed for the reformer's recombination reaction. The hydrogen-rich gas is created and fed for a diesel engine. In addition, the maximum amount of EGR is feasible for testing to determine the impacts of hydrogen-rich gas on BTE and pollutant production.

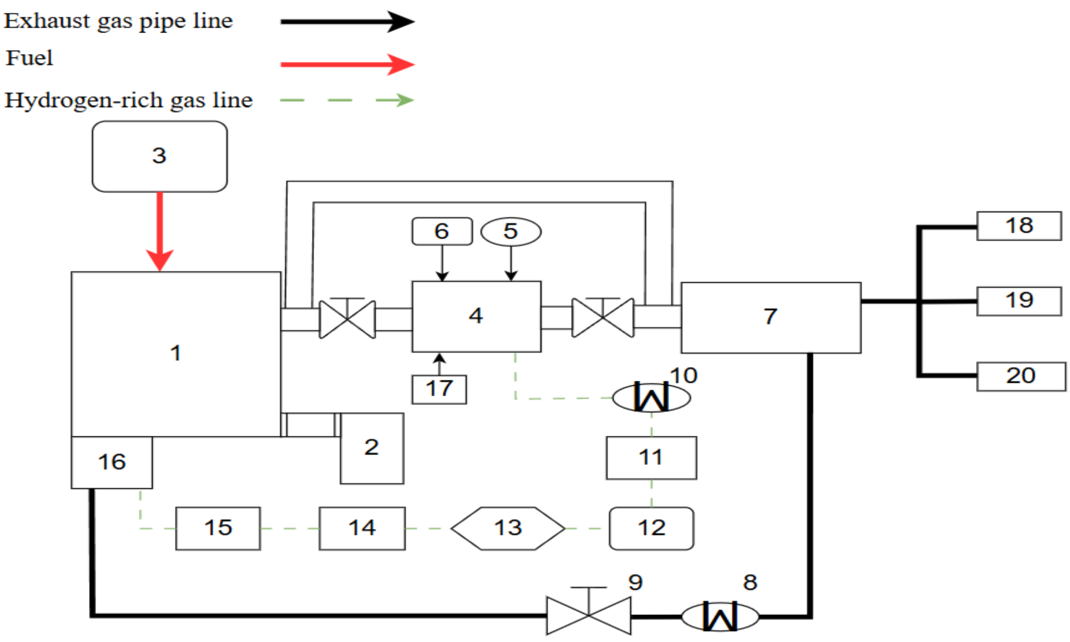
RESEARCH METHOD

In this study, to raise the heating temperature to 700°C because the theoretical reaction temperature of urea is approximately 650 to 750°C, a ceramic electric heater was used to supply the heat source for the reformer, while the auxiliary heating employed the engine's exhaust waste heat. Conduct the experiments utilizing the steam-to-carbon (S/C) ratio established to assess the waste heat recovery rate and BTE under various operating situations. The study also examined how hydrogen-rich gases affected engine exhaust pollutant emissions.

Experimental system

The study is to establish an EGR system and integrate a methanol-water-urea reforming system at the engine exhaust to investigate how hydrogen-rich gases impact engine performance. Figure 1 depicts the experimental setup and testing system. The experimental setup developed in this study includes not only the engine itself (1) but also the EGR and cooling systems (8, 9, 10, and 11), and the hydrogen-rich gas introduction system (12, 13, and 14). The 0.624 l, single-cylinder, four-stroke Kubota RK 125 diesel engine was feasible in this investigation. Using helium as a carrier gas determines the volume rate for hydrogen-rich gas. A flange connects the engine body (1) to the reformer (4). The waste heat recovery system heats the reformer through piping. At the same time, the ceramic electric heater also heats the reforming blend. A three-pass valve (16) installed in the pipelines connect the engine to the reformer and the reformer to the exhaust bucket. Exhaust gases not entering the reformer are redirected through a three-way valve to another pipeline leading directly to the exhaust bucket (7). there, the gases are sent to the EGR cooler (8) and EGR valve (9). After impurities and moisture are removed through the filter (10) and drying bottle (11), the EGR gases are recirculated into the engine intake (15).

An air pump (12) and flowmeter (13) introduce hydrogen-rich gas, which is subsequently mixed with EGR gases via a backfire prevention device (14) before entering the engine intake (15). Finally, a gas



1. Diesel Engine	2. Dynamometer	3. Diesel tank	7. Exhaust tank
4. Reformer	5. PID heater controller	6. Peristaltic pump	8. EGR cooler
9. EGR control valve	10. Filter	11. Drying barrel	11. Air pump
13. Flowmeter	14. Flame trapper	15. Intake	16. Three-pass valve
17.Carried gas	18. Smoke analyzer	19.HC/CO analyzer	20. NOx analyzer

Figure 1. Schematic experimental layout diagram

analyzer (18, 19, 20) measures the pollutants (CO, NOx, HC, and smoke) in the engine's exhaust. Table 1 summarize the evaluated measurement uncertainty (Holman, 2012).

Table 1 Measurement uncertainty

Item	Uncertainty
Pressure	± 1.6%
Smoke	± 1.9%
NO_X	± 1.1%
HC	± 1.8%
$PM_{2.5}$	± 1.5%
CO	± 2.0%
Brake horsepower	± 1.7%
BTE	± 2.1%

Exhaust Gas Recirculation (EGR)

EGR is broadly employed to lessen NOx formation for most engines. EGR involves mixing part of exhaust gas through fresh air and then reintroducing the mixture into the engine. In this study, Eq. (1) defines the EGR ratio (Khoa and Lim., 2022).

$$\mathrm{EGR}(\%) = \left(\frac{V'_{EGR}}{V_{air}' + V'_f + V'_{EGR}} \right) \times 100\% \quad (1)$$

Where V'_{EGR} represents exhaust gas's flow rate (m^3/cycle), V_{air}' is intake air's flow rate (m^3/cycle), and V' signifies fuel's flow rate (m^3/cycle).

Engine Exhaust Waste Heat Recovery (WHR)

The WHR rate refers to the proportion of waste heat energy recovered from a system or process relative to the total heat energy. A higher waste heat recovery rate indicates that more waste heat is effectively recovered and reused, thereby improving the system or process's efficiency.

This study utilizes the waste thermal energy from the engine exhaust as an auxiliary heating source for the methanol-urea aqueous reformer. Eq. (2) defines the WHR rate as the energy consumed to the total energy of the exhaust waste heat.

$$WHR = \frac{\dot{Q}_{consumed}}{\dot{Q}_{exhaust}} \times 100\% \quad (2)$$

where, $\dot{Q}_{consumed}$ denotes the heat energy rate absorbed by the methanol-urea aqueous steam reformer, and $\dot{Q}_{exhaust}$ is the waste energy rate of the engine exhaust. The exhaust waste heat for the i^{th} exhaust gas is calculated by the following formula.

$$\dot{Q}_{\mathrm{exhaust}} = \sum \dot{n}_i \, h_{iT_{in}} \quad (3)$$

where *i = CO, CO_2, N_2, HC, H_2O, NOx (measured exhaust species)*

$$\dot{Q}_{consumed} = \sum \dot{n}_i \, h_{iT_{in}} - \sum \dot{n}_i \, h_{iT_{out}} \quad (4)$$

If the exhaust gas components behave as an ideal gas, then eq. (2) becomes the following equation.

$$\begin{aligned} WHR &= \left(1 - \frac{\sum \dot{n}_i \, h_{iT_{out}}}{\sum \dot{n}_i \, h_{iT_{in}}}\right) \times 100\% \\ &= \left(1 - \frac{T_{out}}{T_{in}}\right) \times 100\% \end{aligned} \quad (5)$$

where $\sum \dot{n}_i \, h_{iT_{out}} = \sum \dot{n}_i \, C_{pi} T_{out}$, $\sum \dot{n}_i \, h_{iT_{in}} = \sum \dot{n}_i \, C_{pi} T_{in}$, T_{in} represents inlet temperature of exhaust entering the reformer, and T_{out} denotes outlet temperature of exhaust leaving the reformer.

Cycle Variance

Eq. (3) defines the cycle variance for the indicated mean effective pressure (IMEP).

$$COV\ of\ IMEP = \frac{\sigma}{\bar{Y}} = \frac{\sqrt{\frac{\sum_{i=1}^{N} (Y_i - \bar{Y})^2}{N-1}}}{\bar{Y}} \times 100\% \quad (6)$$

Where COV detonates cycle variance, σ represents Standard deviation, $\bar{Y}$ is average IMEP of multiple cycle, Y_i signifies the IMEP of i cycle, and N is number of cycles for samples.

Brake thermal efficiency (BTE)

BTE defines the rate of the actual power output over the calorific value for the fuel consumed within an engine. Therefore, BTE represents the engine's capability of converting the heat released by the fuel into practical work, so the higher the BTE, the higher the fuel conversion efficiency. Overall, fuel consumption is the least when the BTE is highest. The following formula defines BTE follows.

$$BTE = \frac{BHP}{(LHV_D \cdot \dot{m}_D) + (LHV_{H_2} \cdot \dot{m}_{H_2}) + (LHV_{CO} \cdot \dot{m}_{CO})} \times 100\% \quad (7)$$

Where BHP is the break horsepower (kW), LHV_D denotes diesel's lower heating value, LHV_{H_2} and LHV_{CO} represent hydrogen's lower heating value and carbon monoxide's lower heating value (kJ/kg), $\dot{m}_D$, $\dot{m}_{H_2}$ and $\dot{m}_{CO}$ denote the mass rate of diesel, hydrogen and carbon monoxide (g/hr).

RESULTS AND DISCUSSION

The work involved testing the hydrogen-rich gas produced from the experimental factors and its mixture with exhaust gas recycled in the engine intake. The objective was to determine the impact of hydrogen-rich gas on engine operating performance and exhaust pollutant emissions.

Figure 2 compares the engine's cylinder pressure at 1500 rpm, 60% load, and 40% EGR for hydrogen-rich syngas or no. The cylinder pressure increases significantly under the condition of adding hydrogen-rich gas. At a 40% EGR ratio for no hydrogen-rich syngas, the peak pressure is 66.3 bar.

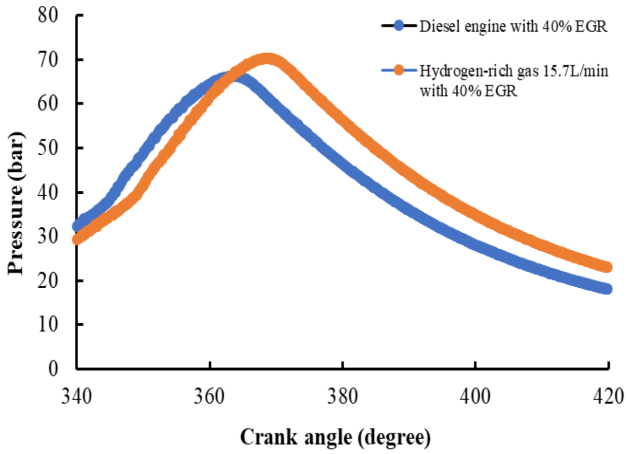


Figure 2. Pressure-crank angle diagram of the diesel engine with or without hydrogen-rich syngas

When adding 15.7 liters/minute of hydrogen-rich gas, the peak pressure rises to 70.3 bar. This increase is due to hydrogen's rapid combustion, which provides more energy and leads to higher cylinder pressure. Figure 3 shows the cycle variance of IMEP for the engine at 1500 rpm, 60% load, and 40% EGR, with and without the introduction of hydrogen-rich gas. IMEP cycle variance is an important indicator of whether the engine operates consistently and stably during the experiment. Figure 3 shows that the cycle variance of IMEP is below10% for both conditions, indicating that the

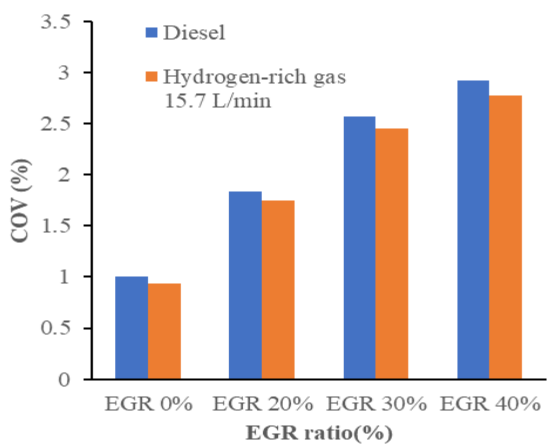


Figure 3. Cycle variance for IMEP with or without hydrogen-rich gas

engine operates with minimal variation during the combustion process and has stable performance. However, under added hydrogen-rich gas, the cycle variance of IMEP is lower since hydrogen has a quicker combustion speed and a broader combustion level than diesel fuel. It results in a more stable combustion process and reduces combustion instability and cycle variance.

Figure 4 depicts the engine's BTE at 1500 rpm, 60% load, and 40% EGR, with and without the introduction of hydrogen-rich gas. Because hydrogen-rich gas promotes the burning process of diesel fuel within the cylinder, the BTE rises when adding it. The BTE increases by 6.84% when hydrogen-rich gas (15.7

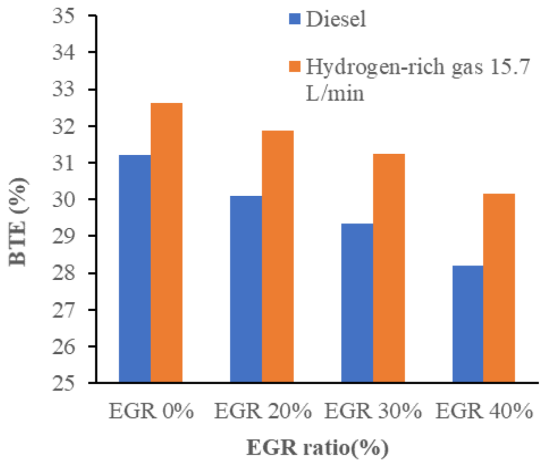


Figure 4. BTE of the Engine for hydrogen-rich syngas or no

liters/minute) is introduced compared to diesel. Figures 5 to 8 show the pollutant emission values measured at 1500 rpm, 60% load, and 40% EGR for hydrogen-rich syngas or no. Figure 5 displays that adding hydrogen-rich gas decreases smoke by 19.38% compared with

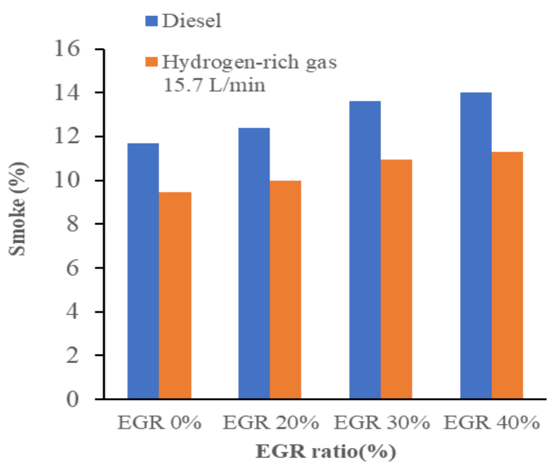


Figure 5. Smoke emission from the engine for hydrogen-rich syngas or no

diesel fuel because it can make the combustion processin the engine more complete, which leads to the reduction of the generation of smoke. Figure 6 indicates inducting hydrogen-rich gas tends to increase HC contrasted with diesel fuel because the oxygen concentration in the intake decreases, and the hydrogen

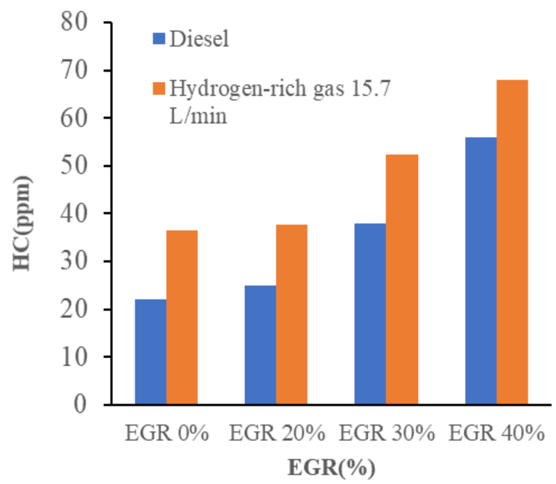


Figure 6. HC emission from the engine for hydrogen-rich syngas or no

in the fuel increases. Figure 7 illustrates inducting hydrogen-rich gas tends to reduce CO by 40% compared to diesel fuel. The inducted hydrogen-rich gas makes the burning process more complete within the engine, which leads to the reduction of the generation of

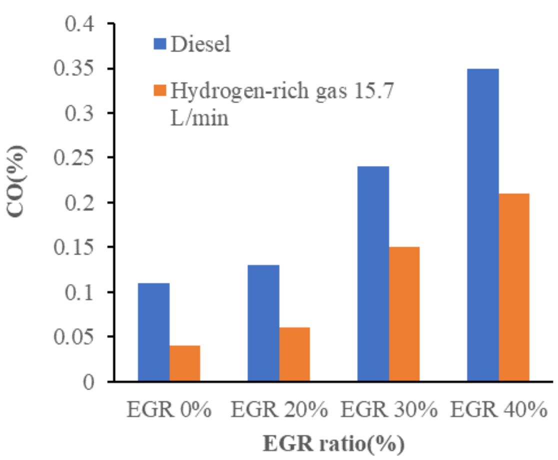


Figure 7. CO emission from the engine for hydrogen-rich syngas or no

CO. Figure 8 depicts that introducing EGR reduces the oxygen concentration at the inlet and lowers the burned gas temperature, inhibiting NOx formation. Adding hydrogen-rich gas makes combustion relatively complete, and the average temperature inside the cylinder increases, resulting in the formation of NOx, so for 40% EGR addition, the increase rate reaches 19.93%. However, inducting hydrogen-rich gas and 40% EGR can reduce NO_X by 18.62% compared to diesel with no EGR addition.

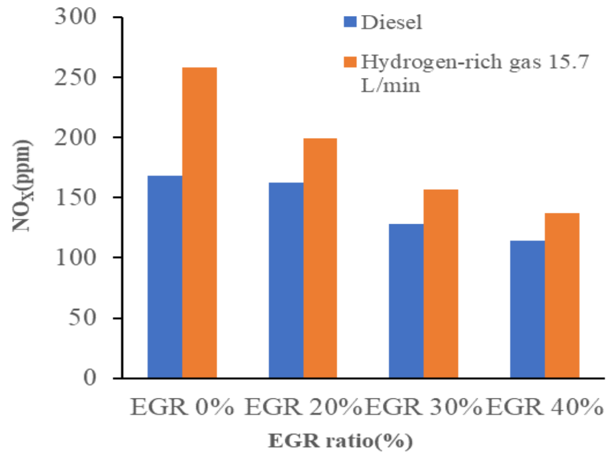


Figure 8. NOx emission from the engine for hydrogen-rich syngas or no

Table 2 provides the components concentrations of the hydrogen-rich gas (H_2, N_2, CO_2, CO, and He) obtained by chromatography analysis during methanol-urea aqueous steam reforming at 700 ºC and S/C of 0.8 for varied volume rates of methanol and aqueous urea. The concentrations of H_2 and CO are significantly higher than those of N_2 and CO_2 leaving the reformer. As the volume rate of methanol with aqueous urea rises, the hydrogen and carbon monoxide mole fractions increase due to more reacted methanol and aqueous urea. The concentrations of hydrogen with carbon monoxide that can aid combustion reach up to 77.1%.

Table 2. Composition concentration of hydrogen-rich gas

methanol and aqueous urea	H_2 (%)	N_2 (%)	CO_2 (%)	CO (%)	He (%)
6.5 g/min	61.82	5.37	10.43	15.3	0.55
10g/min	62.76	5.62	9.63	14.5	0.35
13.5g/min	63.66	5.72	8.21	14.44	0.26

Table 3 shows the waste heat recovery rate when using engine exhaust gases as auxiliary heating during methanol-urea aqueous steam reforming from steam reforming experiments using a methanol-urea aqueous with S/C (0.8) and methanol and aqueous urea of 13.5 g/min with helium as the carrier gas at a 30 c.c./min flow rate for varied engine loads. More exhaust energy occurs because of more injected fuel per cycle as the engine works at high loads. Thus, the heat recovery rate rises as engine load ascends. Overall, the experiment findings indicate that the waste heat recovery rate can reach a maximum of 12.68% and a minimum of 10.01%.

Table 3. Waste heat recovery rate of engine exhaust at 700 ºC, S/C of 0.8 and methanol and aqueous urea of 13.5 g/min

Engine Speed (rpm)	Load (%)	T_in (k)	T_out (k)	WHR (%)
1500	40	520	467	10.01
1500	60	646	573	11.3
1500	80	620	540	12.68

CONCLUSION

The original diesel engine has been successfully modified to integrate a reformer at the exhaust end. The engine's exhaust waste heat is used as auxiliary heating for aqueous methanol-urea steam reforming. After completing the EGR and hydrogen-rich gas introduction systems, the study conducted tests with and without inducting hydrogen-rich gas. Throughout the research process, the entire system has operated continuously and reliably.

Finally, the findings indicate that inducting hydrogen- rich gas in the engine intake positively affects engine combustion performance and exhaust pollutant emissions. When employing engine exhaust gases as auxiliary heating during methanol-urea aqueous steam reforming, the waste heat recovery rates range from 10.01% to 12.68%. BTE increases by 8.6% when adding hydrogen-rich gas compared to diesel fuel. Introducing hydrogen-rich gas at the intake end of the engine can improve the engine's performance and decrease smoke and CO by about 19.29% and 40%.

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