Energy Conversion and Management 172 (2018) 567–578

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Reduction of smoke, $PM_{2.5}$, and NO_X of a diesel engine integrated with methanol steam reformer recovering waste heat and cooled EGR

Horng-Wen Wu*, Tzu-Ting Hsu, Chen-Ming Fan, Po-Hsien He

Department of System and Naval Mechatronic Engineering, National Cheng Kung University, Tainan, Taiwan, ROC

ARTICLE INFO

Keywords:
Combustion performance
Diesel engine
$PM_{2.5}$ reduction
Methanol steam reformer
Waste heat recovery
Exhaust gas recirculation

ABSTRACT

Over recent years, combustion engines are effectively equipped with a waste heat recovery (WHR) system to produce power or hydrogen at less additional energy input. The WHR system in this study is partially utilized to heat reforming gas in a methanol steam reformer integrated with a diesel engine and a cooled EGR (Exhaust Gas Recirculation) device to reduce smoke, $PM_{2.5}$, and NO_X emissions. The test items are such as the gas pressure of cylinder, crank angle, diesel consumption rate, hydrogen-rich gas flow rate, air flow rate, and smoke, $PM_{2.5}$, NO_X, HC and CO emissions and the molar analysis of hydrogen-rich gas. The authors analyze how the hydrogen-rich gas addition with EGR influences smoke, $PM_{2.5}$, NO_X, HC and CO emissions and combustion performance. The results show that the maximum increase rate of heat recovery efficiency with respect to reaction temperature is 17.5%. The heat recovery efficiency of the reformer rises with increasing engine load up to 24.8%. Adding hydrogen-rich gas with appropriate proportion of EGR helps reduce smoke, $PM_{2.5}$ and NO_X from a diesel engine. In addition, the engine body is rarely changed, and it is effectively to save energy and decrease pollutants.

1. Introduction

Diesel engines have been extensively employed in many kinds of power sources such as power plants, marine vessels and motor vehicles [1]. Environmental protection has attracted more attention, and energy sources have been consuming due to a wide range of engine operations. Pollutants from diesel engines contribute to the environmental pollution, such as particulate matter (PM) and NO_X emissions. UFP (ultrafine particle) and especially nanoparticles from diesel engines are penetrating cell membranes, thus intruding blood stream and accumulating in brain, liver, and lung, among others [2,3]. It has then been very imperative to look for an alternative to crude oil used in engines [4].

In general, there is about 33% of fuel energy leaving the combustion engine as a waste heat in the exhaust flow, so a WHR system can be installed in the engine to produce power or hydrogen at less additional energy input [5–11]. Singh and Pedersen [5] reviewed waste heat recovery systems in maritime applications, and concluded that the engine exhaust gas had the highest WHR efficiency due to greater quantities and higher temperature ranges. Armstead and Miers [6] pointed out that promising WHR techniques showed increases in engine thermal efficiencies ranging from 2% to 20%, relying on system design, implementation, and quality and quantity of thermal energy. Kyriakidis et al. [7] estimated the optimization performance of different configurations of steam Rankine cycles integrated with exhaust gas recirculation in a marine diesel engine by the Genetic algorithm and fmincon active-set algorithm. Their results indicated that the amount of waste heat recovery from the pressurized boiler was significantly higher than from the main boiler. They concluded that the configuration of three-pressure level steam cycle was more efficient than that of the two-pressure level cycle. Fennell et al. [8] applied thermochemical energy recovery technique to recover exhaust waste heat from a gasoline direct injection engine to reform hydrocarbon fuel to hydrogen-rich gas. The hydrogen-rich gas was recycled back to the engine to enhance the engine combustion process. Their results indicated that raising the reformer fuel flow rate increased the rate of exhaust heat recovery, and increasing dilution rate and reformed fuel fraction reduced exhaust stream exergy.

Liao and Horng [9] developed exhaust heat recovery from a 1.4-L spark-ignition engine supplying a methanol steam reformer with thermal energy to produce hydrogen. Their findings illustrated that the heat recovery rate increased with increasing engine speed. Nonetheless, as mass flow rate of exhaust gas increased, the exchange rate decreased under a higher engine speed. The case of S/C ratio of 1.2 and the methanol mass flow rate of 15.8 g/min had the methanol conversion efficiency of 93% and the hydrogen production of 75%. Suslu and Becerik [10] presented a hybrid system of a PEMFC (proton exchange

---

* Corresponding author.
E-mail address: z7708033@email.ncku.edu.tw (H.-W. Wu).

https://doi.org/10.1016/j.enconman.2018.07.050
Received 16 April 2018; Received in revised form 9 July 2018; Accepted 16 July 2018
0196-8904/

Nomenclature

BP	brake power, kW
BSFC	brake specific fuel consumption, g/kW-h
BTE	brake thermal efficiency, %
CoV(IMEP)	coefficient of variance, %
EGR ratio	exhaust gas recirculation, %
HRE	heat recovery efficiency, *%*
IMEP	indicated mean effective pressure, *bar*
$IMEP_{mean}$	average mean effective pressure, bar
k	specific heat ratio
LHV	lower heating value, kJ/g
$\dot{m}$	mass flow rate, g/h
N	number of sampling cycles
n	test number
NO_X	nitric oxides, *ppm*
p	pressure, *bar*
ppm	part per million, $mg{\cdot}L^{-1}$
Q	heat release, *J*
R	universal gas constant, $J{\cdot}mol^{-1}{\cdot}K^{-1}$
rpm	revolutions per minute
S/C ratio	molar ratio of steam to carbon
T	in-cylinder temperature, *K*
V	volume, m^3
θ	crank angle, *degrees*
σ(IMEP)	standard deviation of *IMEP*

Subscripts

air	air
co	carbon monoxide
diesel	diesel oil
EGR	exhaust gas recirculation
f	fuel
hydrogen	hydrogen

membrane fuel cell) and an internal combustion engine with a membrane methanol reformer and determined the efficiency of the hybrid system. The membrane methanol reformer recovered the waste heat of the internal combustion engine. They concluded that the hybrid system efficiency was less load-dependent compared to the efficiency of each of fuel cell and internal combustion engine. Orbaiz et al. [11] presented a thermodynamic study of two systems involving SI engine and hybrid system using the waste heat of the engine and the combustion of biomass to power a steam-methane reformer, and analyzed how the reformer's temperature and the steam-methane ratio affected the system performance. Their results displayed that applying biomass, larger internal combustion engine power plants could result in CO_2 emission as much as 10–20% lower than the natural gas combined cycle power stations.

Burning hydrogen emits low pollutants, so hydrogen has been applying as a highly potential alternative fuel used in engines [12]. In addition, it possesses a high flame speed and wide limits of flammability extending the lean operating limit [13], and making the engine work a wide range of equivalence ratios. Hydrogen is commonly produced by reforming methanol as a fuel of a small reformer. Methanol is very suitable because it has simple operation environments due to low temperature operation, and it is easy to store and transport due to being soluble in water and reduces the catalyst damage of the reformer due to low Sulphur content [14,15].

Among all reforming processes through methanol to produce hydrogen-rich gas, methanol steam reforming process can generate the best H_2/CO ratio at the lowest reaction temperature. The methanol steam reforming process is completed by the heated aqueous methanol reacting via a catalyst directly to produce hydrogen-rich gas mainly composed of hydrogen, carbon monoxide, and carbon dioxide [16–22]. Horng [16] investigated transient characteristics of a small methanol reformer for a fuel cell during cold start, and found that the best response for cold start was acquired by heating power of 960 W, heating temperature of 80 °C, methanol supply rate of 14 mL/min, and air supply rates of 70 L/min among the operation parameters. Ouyang et al. [17] employed various methods to determine the optimal operating parameters of reacting temperature, S/C ratio, and the volume flow rate for nitrogen carrier gas of methanol steam reformer. Their results showed that the optimal operating parameters appeared at reacting temperature of 267 °C, S/C ratio of 1.1, and volume flow rate for nitrogen carrier gas of 40 cm^3/min with radial basis function neural network method which gains less averaged quality loss than other methods such as PCA approach and Taguchi Method. Sari and Sabziani [18] numerically studied how the steam to methanol ratio, preheating temperature, geometry and size of channels, and external heat flux affected the hydrogen concentration of a mini methanol steam reformer. They observed that the prediction result of the Maxwell-Stefan model was better agreeable with experimental results than that of the mixture-averaged prediction, in particular, at the lower supply rates. Herdem et al. [19] numerically explored how the steam to carbon ratio, reforming temperature of the reformer, current density, cell temperature, stoichiometric ratio of cathode, and power production rate of high temperature polymer electrolyte membrane fuel cell influenced the reformed gas composition of the reformer and the cell performance. Their results indicated that the CO molar ratio in the reforming gas increased with a decrease in steam-to-carbon ratio and an increase in reformer temperature. Nevertheless, the impact of CO molar ratio on the fuel cell performance decreased with an increase in fuel cell temperatures. Perng et al. [20] applied three-dimensional computational fluid dynamics to study how the angle and length of the diffuser, and wall temperature of a cylindrical methanol steam reformer affected methanol conversion, hydrogen production and estimated net power of fuel cell. Their results displayed that compared with a traditional reformer, a reformer with a diffuser angle of 6° and length of 75 mm gained the maximum increase rate of methanol conversion, 22.96%, the maximum increase rate of hydrogen production, 44.62%, and the maximum increase rate of estimated net power of fuel cell, 24.59%. Ribeirinha et al. [21] integrated a methanol steam reforming cell with a high temperature polymer electrolyte membrane fuel cell in a combined stack arrangement to investigate the integration performance. Their results showed a degradation of the membrane electrode assembly and an overall increase of electrochemical impedance. Chen et al. [22] experimentally investigated how the catalyst types including high-temperature catalyst (HTC) and low-temperature catalyst (LTC), residence time of reactants, reaction temperature and CO/steam ratio affected the characteristics of CO conversion and hydrogen production. Their results revealed that the water gas shift reaction with the HTC was governed by chemical kinetics, and it with the LTC was governed by thermodynamic equilibrium. The CO conversion was enhanced if the CO/steam ratio decreased. However, the performance of the water gas shift reaction was insensitive to the variation of the CO/steam ratio for the CO/steam ratio smaller than 1/4.

Several scholars have reported on hydrogen-rich gas from reforming processes [23–33] or hydrogen introduced in the cylinder as an assisting fuel in combustion engines. Horng et al. [23] investigated the impact of hydrogen-rich gas produced by a plasma converter on exhaust emissions from a four stroke motorcycle engine during the cold start. Their results indicated that during the cold start, the motorcycle engine with the hydrogen rich gas could emit low exhaust pollutants. Tartakovsky and Sheintuch [24] reviewed technical papers on fuel reforming