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Exergy analysis of the woody biomass Stirling engine and PEM-FC combined system with exhaust heat reforming

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ABSTRACT

The woody biomass Stirling engine (WB-SEG) is an external combustion engine that outputs high-temperature exhaust gases. It is necessary to improve the exergy efficiency of WB-SEG from the viewpoint of energy cascade utilization. So, a combined system that uses the exhaust heat of WB-SEG for the steam reforming of city gas and that supplies the produced reformed gas to a proton exchange membrane fuel cell (PEM-FC) is proposed. The energy flow and the exergy flow were analyzed for each WB-SEG, PEM-FC, and WB-SEG/PEM-FC combined system. Exhaust heat recovery to preheat fuel and combustion air was investigated in each system. As a result, (a) improvement of the heat exchange performance of the woody biomass combustion gas and engine is observed, (b) reduction in difference in the reaction temperature of each unit, and (c) removal of rapid temperature change of reformed gas are required in order to reduce exergy loss of the system. The exergy efficiency of the WB-SEG/PEM-FC combined system is superior to EM-FC.

1. Introduction

Utilization of woody biomass is discussed from the view of the environmental problem [1–3]. In Japan, the utilization as a woody biomass fuel of thinned wood or building scrap wood is investigated. Authors are evaluating the test Stirling engine (WB-SEG) that burns these woody biomasses directly [4]. The theoretical thermal efficiency of a Stirling cycle is higher than a Diesel cycle at heat for the same input temperature level. However, in actual WB-SEG, the heat transmission control between combustion gas and the engine is difficult and heat supply temperature are limited [4]. In the experiment, the heat released down stream of the engine represents at least 60% in total loss [4]. As far as exergy efficiency of an energy system is concerned, loss in the combustor is large [5]. Therefore, the high-temperature heat released when woody biomass needs to be used effectively for utilization of WB-SEG. However, when such release is used for space heating and hot water supply, it is not effective from the view of energy cascade utilization. So, in this study, the combined system of WB-SEG and PEM-FC is proposed. There are very few reports of research regarding the WB-SEG and PEM-FC combined system [6]. The study on the complex system of a fuel cell and an engine is uncivilizedness, and the example of the system especially using a Stirling cycle is few. The burning exhaust heat of WB-SEG is used for the heat source of a steam generator (vaporizer), and a reforming unit for steam reforming of city gas in this system. The exhaust heat of each unit can be used for preheating of fuel and combustion air in this system. However, low-temperature exhaust heat, such as engine-cooling water of WB-SEG and cell stack exhaust heat of PEM-FC, is used for space heating and hot water supply. There are many methods to optimize the leading of different efficiency level. In the

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Nomenclature

A_r	surface area of the combustion chamber, m^2
C_a	mean specific heat of exhaust gas, J/(kg K)
C_w	specific heat of engine-cooling-water, J/(kg K)
$\dot{E}$	power, W
E_s	generating end output, W
e	exergy, W
K	the rate of overall heat transfer, W/(m^2 K)
L_b	calorific value of the woody biomass, J/g
$\dot{q}_a$	exhaust gas quantity of heat, W
$\dot{q}_b$	the amount of combustion heat of the woody biomass, W
q_r	the amount of heat release from the combustion chamber surface, W
q_w	engine-cooling-water quantity of heat, W
R	power load factor, %
r_{ce}	utilization rate of anode gas, %
r_{fa}	utilization rate of cathode gas, %
Δt_a	difference of exhaust gas temperature and room temperature, K
Δt_r	difference of combustion-chamber temperature and room temperature, K
Δt_w	difference of engine-cooling-water and room temperature, K
V_a	exhaust gas flow rate, m^3/s
V_f	supply of the woody biomass, g/s
V_w	engine-cooling-water flow rate, g/s
$\dot{H}$	heat, W
h	enthalpy, J/mol
$\dot{I}$	exergy loss, W
L_b	lower calorific value of woody biomass, J/kg
L_{CH_4}	lower calorific value of city-gas, J/kg
$\dot{m}$	molar flow rate, mol/s
$\dot{q}$	heat quantity, W
$\dot{q}_{lhv}$	lower calorific value, J/mol
T	temperature, K

Greek letters

η	efficiency
ρ_a	mean density of emission
ρ_w	density of engine-cooling water

Subscript

a	exhaust gas of the combustion chamber
br	combustion gas
c	CO oxidation unit
ca	air supplied to the combustor unit
cb	burning
ce	reformed gas of the CO oxidation equipment unit
ch	chemical
cr	CO oxidation heat
en	energy
ex	exergy
f	cell stack
fa	air supplied to the cell stack
fe	exhaust gas of the cell stack
fr	cell stack heating valve
ga	air supplied to the combustor unit
gc	city-gas supplied to the combustor unit
gv	city-gas supplied to the vaporizer unit
r	reformer unit
ra	reforming heat
rb	combustion gas
re	reformed gas of the reformer unit
rm	heat release of the combustion chamber
rw	water supplied to the vaporizer unit
s	shifter unit
sa	shifting heat
sc	cell stack
se	reformed gas of the shifter unit
si	output to the Stirling engine
sys	system
tc	thermomechanical
v	vaporizer unit
va	amount of heat of vaporization
ve	reformed gas of the vaporizer unit
vo	exhaust heat of the vaporizer unit
w	cooling-water of the Stirling engine
wb	woody biomass
0	standard reference

WB-SEG/PEM-FC combined system, because PEM-FC is operated using the exhaust heat of WB-SEG, exergy efficiency should improve. Therefore, in this study, the energy flow and the exergy flow are investigated in both of WB-SEG, PEM-FC, and the WB-SEG/PEM-FC combined system including preheating of fuel and combustion air.

2. System configuration

2.1. *Stirling engine generator*

Fig. 1(a) is the block diagram of WB-SEG. Woody biomass fuel (chips) and combustion air are supplied to the combustor. A heat exchanger is introduced and this is exchangeable for the heat of the exhaust gas. The heat generated in the combustor is supplied to the engine heat exchanger. As exhaust heat, there is exhaust gas from burning and engine-cooling water. The heat of the engine-cooling water is supplied to a heat storage tank, and can be supplied to the demand side with a time shift. On the other hand, the combustion gas can select preheating of the biomass fuel and the combustion air, or supply to the heat storage tank. As shown in Fig. 1(b), engine power is transmitted to the power generator using a belt. The power outputted with the power generator is converted into a regular frequency by the inverter, and supplies stable voltage power and frequency to the grid. The output characteristics of WB-SEG shown in Fig. 1(c) are introduced into this analysis. These output characteristics were taken by examining an engine of the specification shown in Fig. 1(b). The heat of each