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Energetic and exergetic assessments of glycerol steam reforming in a combined power plant for hydrogen production

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ABSTRACT

This paper presents a thermodynamic analysis of a steam reformer coupled with a combined power plant to produce hydrogen from steam and hydrocarbon fuel. In the analysis, the steam reformer uses glycerol as a fuel and produces hydrogen for high temperature proton exchange fuel cells in which the catalyst is tolerant to the amount of carbon monoxide. The results show that increasing the steam to glycerol ratio increases the hydrogen production. However, it decreases the overall efficiency of the system because of the high heat input requirement to the system. Numerous operating conditions and plant parameters are varied and their effects on the overall energy and exergy efficiencies of the system are studied. An optimization study is performed in order to find the optimal system parameters for better performance.

Introduction

Exergy analysis is a valuable tool in both thermodynamic analysis and design of power plants. Exergy can be defined as the maximum obtainable work from a system before it reaches equilibrium with the surroundings. In order to maximize the power plant output, it is important to determine the degree of irreversibility within plant components. Exergy analysis is an efficient tool to analyze inefficiencies in various systems, ranging from thermal to chemical [1–4].

Combined power plants are used to increase the efficiency of a system. They use the exhaust gases released from Gas Turbines (GT), which mostly consist of CO_2, H_2O, N_2, and O_2 at high temperatures (around 500–600 °C) and low pressures. These temperatures are often high enough to drive a Rankine cycle. Ahmadi et al. [5] performed energy, exergy, exergoeconomic and environmental analyses of a combined power plant. The results indicated that increases in the pressure ratio cause a decrease in the steam cycle power output. This ultimately increases the overall efficiency of the system and reduces CO_2 emissions. Also, CO_2 emissions can be decreased by selecting the best component with a low fuel injection rate.

Cihan et al. [6] performed an exergy analysis of a power plant in Turkey using a parametric study of different

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Nomenclature

en	specific energy, kJ/kg
ex	specific exergy, kJ/kg
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
M	molar mass, kg/kmol
P	pressure, kPa
$\dot{Q}$	heat transfer rate, kW
$\bar{R}$	ideal gas constant, kJ K^{-1} $kmol^{-1}$
s	specific entropy, kJ/kg K
T	temperature, K
$\dot{W}$	power, kW
y	mole fraction
y_e	mole fraction in the environment
Greek letters	
η	efficiency
ρ	density of air
Acronyms	
HHV	higher heating value
LHV	lower heating value
PEMFC	proton exchange membrane fuel cell
SGR	steam glycerol reformer
SG	steam to glycerol ratio
CO	carbon monoxide
Subscripts	
C	critical
Ch	chemical
Comp	compressor
CC	combustion chamber
f	fuel
GT	gas turbine
g	generation
HPT	high pressure turbine
HX	heat exchanger
LPT	low pressure turbine
o	reference state
P	pump
Tf	thermophysical
Xd	destruction

components. Results demonstrated that the Combustion Chamber (CC), Gas Turbine (GT) and heat recovery heat exchanger are the plant components with the highest exergy destruction rates. Ahmadi et al. [5] performed energy, exergy and exergoeconomics analyses of combined power plants. Zheng et al. [7] investigated a combined power and refrigeration cycle. Their simulation results showed that the proposed cycle has the potential to produce a refrigeration effect and most of the exergy losses occur in the ejector.

In another study, Zhang et al. [8] studied a combined Brayton and inverse Brayton cycle. The results demonstrated that the optimal efficiency will be achieved by controlling the mass flow rate of air, water and fuel. Maeero et al. [9] analyzed and optimized the exergy processes of combined triple power plants. The triple analysis includes a Brayton cycle (gas-based) and two Rankine cycles (steam and ammonia-based). The results showed that the maximum exergy destruction occurs in the heat recovery heat exchanger and the use of feed water heaters results in increasing the efficiency. Also, with increases in ambient temperature, the exergy efficiency decreases. Also, with increases in pressure, the ratio of exergy efficiency increases up to a certain level and then decreases.

Steam reforming is one of the most common processes for producing hydrogen. Glycerol is a byproduct during the production of biodiesel and a considered as renewable source for hydrogen production [10]. Rabenstein et al. [11] analyzed three different processes of producing hydrogen; steam reforming, auto thermal reforming and partial oxidation. His results show that steam reforming gives the highest hydrogen production yield. Various researchers have performed both experimental [12–18] and simulation studies [19–24]. Authayanun et al. [25] discussed hydrogen production through steam reforming of steam glycerol for both high and low temperature PEM fuel cells. Results showed that the optimal reformer temperature is 1000 K and the optimal steam to glycerol ratio is 6. It was also shown that a high temperature PEM is more tolerant to the amount of CO compared to low temperature fuel cells.

Chen et al. [26] performed a detailed theoretical and experimental thermodynamic analysis of glycerol and steam reforming processes. His results showed that high temperatures, low pressures and low flow rates yield a high hydrogen yield. A high hydrogen yield was predicted for a steam to glycerol ratio of 9. Wang et al. [27] performed a thermodynamic investigation of hydrogen production from steam glycerol reforming for in situ hydrogen separation. The results showed that extraction of hydrogen in steam glycerol reforming in situ can substantially enhance the rate of hydrogen production even at a low temperature. It was shown that the optimal hydrogen yield can be achieved at atmospheric pressure and a temperature of 825 K with a steam to glycerol ratio of 9. Li et al. [28] have performed a thermodynamic analysis of hydrogen production from steam glycerol reforming with CO_2 absorption. The results showed that optimal hydrogen production can be achieved at 900 K and 1 atm with a molar steam to glycerol ratio of 4.

The objective of the present study is to thermodynamically analyze a combined system (i.e. combined Brayton and reheat Rankine cycles) coupled with a steam glycerol reformer. An exergy analysis is also performed on the overall system and individual system components. Various system parameters are investigated through parametric studies, after which the results are presented and discussed (see Fig. 1).

System description

The system consists of a combined Brayton cycle and re-heats Rankine cycle. The Brayton cycle consists of an air Compressor (Comp), Combustion Chamber (CC) and Gas Turbine (GT). The exhaust of the Brayton cycle at high temperature and low pressure is used to drive a re-heat Rankine cycle. The re-heat Rankine cycle consists of a pump (P), high and low pressure steam turbines and a heat recovery heat exchanger. The condenser is replaced with a steam reformer. Low temperature and pressure steam from a low pressure