Energy Conversion and Management 143 (2017) 326–337

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Analysis of a gas turbine based hybrid system by utilizing energy, exergy and exergoeconomic methodologies for steam, power and hydrogen production

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ARTICLE INFO

Article history:
Received 29 January 2017
Received in revised form 12 March 2017
Accepted 3 April 2017

Keywords:
Exergy
Energy
Tri-generation
Hydrogen production
PEM electrolyzer

ABSTRACT

Energetic, exergetic and exergoeconomic assessments are performed for a novel cogeneration system of power, steam and hydrogen production, including a gas turbine (to produce power), a heat recovery steam generator (to produce steam) and an organic Rankine cycle equipped with a proton exchange membrane electrolyzer (to produce hydrogen). A comprehensive parametric study is reported and effects of such significant variables as air compressor pressure ratio, evaporator temperature, the pinch point temperature difference in the evaporator and degree of the superheat at the ORC turbine inlet on the exergy efficiency, rate of produced hydrogen and sustainability index of the proposed system investigated. Using direct search method by the EES software, the combined system is optimized to achieve the maximum exergy efficiency. It is observed that the rate of produced hydrogen decreases with an increase in superheating degree of ORC turbine and takes the maximum value with change in evaporator temperature. Under the base condition, the corresponding cost values for the power, steam and produced hydrogen are 4.811 cents/kWh, 20.56 $/ton, and 3.967 $/kg H_2, respectively. Moreover, under the optimized condition, exergy efficiency, rate of the produced hydrogen and sustainability index of the proposed cogeneration system is 52.09%, 8.723 kg/hour and 2.162, respectively.

1. Introduction

Currently, energy consumption is rising due to population growth and CO_2 emission caused by the utilization of fossil fuels [1]. In order to reach an advisable and efficient way to produce several kinds of energy from an energy source, multi-generation systems are very attractive. Furthermore, hybridization is a novel opinion in which a waste-to-energy technology enhances system production capacity [2]. It is necessary to evaluate various integrated hybrid multi-generation systems in order to clarify the importance and benefits of such systems. There are wide research items in this field. Eveloy et al. [3] developed an integrated hybrid system that comprises of two main parts: SOFC-GT and organic Rankine power generation. The organic Rankine cycle is proposed to obtain the exhaust thermal energy of the SOFC-GT part. By using waste-to-energy method, SOFC-GT subsystem energy efficiency has been increased about 6%. Kalinci et al. [4] employed a co-generation hybrid system to produce power and hydrogen. In this study, an energy-exergy methodology was conducted to investigate proposed system performance. In another study, an Exergy Life Cycle Assessment (ELCA) method was applied by Rocco et al. [5] to utilize the energy embodied in the proposed power plant exhaust. The ELCA analysis allowed to make better the overall thermodynamic performance of the power plant and reduce the non-renewable energy source demand, significantly. Also, this study revealed that the exergy efficiency of the proposed system was increased about 1%, corresponding to utilize the waste-to-energy technology. Consequently, utilizing the waste-to-energy technology is a very sobering alternative to improve hybrid energy system performance. Experienced ways that we can take this idea from concept to reality are: utilizing an organic Rankine cycle (ORC) and Kalina cycle (KC). These solutions trap the low grade heat potential of system waste output to power generations in order to utilize in desalination, cooling and other possible purposes which are more profitable than using the fossil fuel [6–9]. Therein, one of the best-known systems that its thermodynamic performance can be improved with this approach, is gas turbine based hybrid systems [10–12]. Among the all, CGAM is a gas turbine based cogeneration plant producing 30 MW power and 14 kg/s of

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http://dx.doi.org/10.1016/j.enconman.2017.04.020
0196-8904/

Nomenclature

AC	air compressor
AP	air preheater
CC	combustion chamber
COND	condenser
D_P	depletion number
ex	specific physical exergy [kJ/kg]
Eva	evaporator
Ex	exergy flow rate (kW)
$E_{act,i}$	activation energy in cathode or anode (kJ)
$E_{electric}$	electric energy input rate (kW)
$Ex_{electric}$	electric exergy input rate (kW)
F	Faraday constant (C/mol)
G	Gibbs free energy (J/mol)
GT	gas turbine
h	specific enthalpy [kJ/kg]
HRSG	heat recovery steam generator
J	current density [A/m^2]
J_0	exchange current density (A/m2)
J_i^{ref}	pre-exponential factor (A/m2)
LHV	lower heating value [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
$\dot{N}$	molar mass flow rate (mol/s)
ORC	organic Rankine cycle
ORCP	organic Rankine cycle pump
ORCT	organic Rankine cycle turbine
PR_c	pressure ratio
$\dot{Q}$	heat transfer rate [kW]
R	gas constant (kJ/kg K)
R_{PEM}	proton exchange membrane resistance (Ω)
SI	sustainability index
T	temperature
V_0	reversible potential (V)
V_{act}	activation overpotential (V)
$V_{act,a}$	anode activation overpotential (V)
$V_{act,c}$	cathode activation overpotential (V)
$\dot{W}$	power [kW]

Greek letters

η	energy efficiency
ε	exergy efficiency
$\sigma(x)$	local ionic PEM conductivity (s/m)
σ_{PEM}	proton conductivity in PEM (s/m)
$\lambda(x)$	water content at location x in the membrane (Ω^{-1})
λ_a	water content at the anode-membrane interface (Ω^{-1})
λ_c	water content at the cathode-membrane interface (Ω^{-1})

Subscripts

ch	chemical
D	destruction
E	evaporator
in	inlet condition
L	loss
ohm	ohmic
out	outlet condition
ph	physical
PEM	proton exchange membrane
pp	pinch point
sup	superheating degree
T	turbine
0	ambient condition

saturated steam. CGAM consists of a high temperature gas turbine and an air preheater to use a part of thermal energy of the hot gases leaving the gas turbine as well as a heat recovery steam generator in which the saturated steam is produced [13]. In fact, CGAM was named after the first initials of the participating researchers including C. Frangopoulos, G. Tsatsaronis, A Valero and M. von Spakovsky [11–16].

The next step in this study is focused on finding the suitable option for the use of waste energy of energy converting systems. Over the last decade, several different options (as mentioned above) are introduced by researchers [17–20]. Among the options available, promising method that can produce green and environmental friendly energy is hydrogen production. Progress in this regard could herald to achieve some ways to control CO_2 emissions and consequently, reduce global warming concerns. A variety of processes can be applied to hydrogen production. Water electrolysis is a very pervasive method whereby water is split into its feedstock. Also, the well-known technology is applied to this purpose is the proton exchange membrane (PEM) electrolyzer [21]. Khalid et al. [22] conducted a renewable hybrid system in order to produce hydrogen. Their proposed system was investigated by energy-exergy methodology. The results revealed that the energy and exergy efficiency of the system are 26 and 26.8%, respectively, and the rate of produced hydrogen is 1523 kg/year. Moreover, a novel hybrid multi-generation energy system based on the solar energy was introduced by Yuksel et al. [23] in order to produce hot water, cooling, heating, power and hydrogen. The influence of the solar intensity and the temperature of absorber pipes inner surface on the hydrogen production was studied. The results show that there is a direct effect between the proposed parameters. By applying the energy-exergy methodology, Ahmadi et al. [24] has also studied the combination of solar-boosted ocean thermal energy conversion (OTEC) and PEM electrolyzer. They reported that the amount of produced hydrogen by the PEM is 1.2 kg/hour while the exergy efficiency of the PEM electrolyzer is about 56.5%. Ahmadi et al. proposed a novel multi-generation energy system based on the solar energy to produce power, hydrogen and fresh water. They reported that under the optimized condition the combined proposed system has the exergy efficiency of 60% and the total cost rate of the 154 $/hour [25].

From the other hand, economic analyzing of hydrogen production systems is a growing technology and there are wide researches in this field. Yilmaz studied a geothermal based hydrogen production system and optimized his proposed system from the viewpoint of economics [26]. He considered the flash binary geothermal power plant as the power source of the electrolyzer. His results revealed that the produced hydrogen has the cost of 1.149 $/kg. Taheri et al. presented a novel biomass based multi-generation system to produce power, cooling and hydrogen [27]. They showed that the mass flow rate of fuel in the system is the most effective parameter on the system overall performance. Based on their results, an increase of 6 kg/s in mass flow rate of fuel leads to 122.8% of the increase in total cost rate.

In summary, masses of studies have been done on the integrated multi-generation energy systems, until now. Nonetheless, in authors' knowledge, the integration of a CGAM/ORC system with a PEM electrolyzer has not been scrutinized by using the energy-exergy methodology to produce electricity, steam and hydrogen,