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Exergoeconomic and thermodynamic analyses of an externally fired combined cycle with hydrogen production and injection to the combustion chamber

Anahita Moharamian [a], Saeed Soltani [a,*], Marc A. Rosen [b], S.M.S. Mahmoudi [a]

[a] Faculty of Mechanical Engineering, University of Tabriz, 16471 Tabriz, Iran

[b] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

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ABSTRACT

A hydrogen production unit is successfully integrated with an externally fired combined cycle using biomass fuel. The hydrogen produced in an electrolyzer can be used for other purposes, but when there is temporarily no market for it is injected into the combustion chamber of an externally fired combined cycle. Injecting hydrogen into the combustion chamber was found to reduce fuel consumption by almost 27%. Moreover, hydrogen injection decreased the energy efficiency and exergy efficiency by 45%, and decreased both the exergy loss and exergy destruction rates. Meanwhile, CO_2 emissions decreased by 32%. However, there are some disadvantages to hydrogen injection, especially from the viewpoint of exergoeconomics. The total unit product cost for the externally fired combined cycle with hydrogen injection is almost 27% more than the unit without hydrogen injection, although the exergy loss and destruction costs decreased with hydrogen injection. The value of the relative cost difference with hydrogen injection rises by 40%. Also the exergoeconomic assessment demonstrates that the cost of components (purchase and maintenance) are higher than cost of components' exergy destruction for both cycles, i.e., with and without hydrogen injection. As the compressor pressure ratio increases, optimal points are identified for biomass flow rate, energy and exergy efficiencies, exergy destruction and loss rates, exergy destruction and loss exergy cost rates, total unit product cost and relative cost difference.

Introduction

Population growth and industrial development in many countries lead to environment impacts and ecosystem damage to (e.g., climate change due to greenhouse gas emissions). The use of renewable energy can help mitigate greenhouse gas emissions. Research on renewable energy technologies can improve their capabilities, and environmentally sensitive energy

* Corresponding author.
E-mail addresses: a.moharamian92@ms.tabrizu.ac.ir (A. Moharamian), soltani929@gmail.com (S. Soltani), marc.rosen@uoit.ca (M.A. Rosen), s_mahmousi@tabrizu.ac.ir (S.M.S. Mahmoudi).

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Nomenclature

$\dot{C}$	Cost rate ($/h)
c	Cost per unit exergy ($/GJ)
D	Membrane thickness (μm)
$\dot{E}$	Exergy rate (kW)
$E_{act,a}$	Activation energy of anode (kJ/mol)
$E_{act,c}$	Activation energy of cathode (kJ/mol)
EFCCH	Externally fired combined cycle with PEM electrolyzer
EFCCHI	Externally fired combined cycle hydrogen injection
F	Faraday constant (C/mol)
G	Gibbs free energy (J/mol)
H	Specific enthalpy
HHV	Higher heating value (kJ/kg)
J	Current density (A/m^2)
J_0	Exchange current density (A/m^2)
J_a^{ref} (A/m^2)	Pre-exponential factor of anode (A/m^2)
J_c^{ref} (A/m^2)	Pre-exponential factor of cathode (A/m^2)
$\dot{m}$	Mass flow rate (kg/s)
LHV	Lower heating value (kJ/kg)
P_i	Pressure at state i (bar)
r_p	Compressor pressure ratio
R_{PEM}	Proton exchange membrane resistance **(Ω)**
T	Temperature (K)
TIT	Gas turbine inlet temperature (K)
$\dot{W}$	Work rate (kW)
$\dot{W}_{PEM}$	Electrical power required to split water in the electrolyzer (kW)
V_0	Reversible potential (V)
$V_{act,a}$	Anode activation over potential (V)
$V_{act,c}$	Cathode activation over potential (V)
V_{Ohm}	Ohmic overpotential (V)
X	Steam quality
Z	Investment expense of component ($)
$\dot{Z}$	Investment expense rate of component ($/h)

Greek letter

η	Energy efficiency
$\eta_{is,C}$	Isentropic efficiency of compressor
$\eta_{is,GT}$	Isentropic efficiency of gas turbine
$\eta_{is,T}$	Isentropic efficiency of steam turbine
$\eta_{is,pump}$	Isentropic efficiency of pump
ε	Exergy efficiency
σ (x)	Local ionic PEM conductivity (S/m)
σ_{PEM}	Proton conductivity in PEM (S/m)
λ_c	Water content at cathode-membrane interface
λ_a	Water content at anode-membrane interface
λ (x)	Water content in location x in membrane
β	Ratio of chemical exergy of organic reaction of biomass

Subscripts

a	Anode
act	Activation
AP	Air preheater
HRSG	Heat recovery steam generator
C	Cathode
Comp	Compressor
CC	Combustion chamber
CI	Capital investment
D	Destruction
Cond	Condenser
G	Gasifier
GT	Gas turbine
in	Inlet condition
i	Index for thermodynamic state point
is	Isentropic
PEM	Proton exchange membrane
out	Outlet condition
0	Reference
OM	Operation and maintenance
ohm	Ohmic
ST	Steam turbine

policies can support the utilization of renewable energy. In addition renewable energy mitigates many environmental consequences and enhances energy security for countries which are dependent on imported non-renewable fuels. Therefore non-fossil energy resources such as biomass can be appropriate alternatives to fossil fuels, in large part because biomass resources are scattered throughout the land. Also, biomass, a common material on Earth, has numerous advantages as an energy resource. It can be utilized directly or converted into various energy products such as biofuels [1]. The most common approach of utilizing biomass for energy is its direct combustion with coal [2]. Several technologies such as gasification and pyrolysis exist for converting biomass, but there remain challenges to its widespread use [3,4]. One approach to overcoming the weaknesses of biomass is to utilize it as a fuel in an externally fired gas turbine [5]; a diverse set of methods for doing so have been recommended [6,7]. Biomass based cogeneration systems and power plants have been evaluated in several studies. Al-Sulaiman et al. [8] considered biomass trigeneration using an organic Rankine cycle (ORC), and found advantages to using biomass for trigeneration instead of electrical generation. Soltani et al. [9] demonstrated that biomass can be used without filtering in an externally fired combined cycle (EFCC) and that it has some advantages over internal fired units when utilized in this manner but also has some disadvantages such as low efficiency.

Hydrogen is the product of some cogeneration or multigeneration power plants. Hydrogen is not an energy source but rather is an energy carrier. Its use causes little pollution provided it is produced from clean energy sources. Hydrogen has been investigated extensively as an energy carrier that can help address numerous global energy issues, in large part by facilitating the use of renewable energy [10]. One device to produce hydrogen from water is an electrolyzer, which uses

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