Energy Conversion and Management 171 (2018) 287–297

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance assessment of a combined heat and power system: A novel integrated biomass gasification, solid oxide fuel cell and high-temperature sodium heat pipe system part I: Thermodynamic analysis

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ARTICLE INFO

Keywords:
Biomass gasification
Solid oxide fuel cell
Heat pipes
Cogeneration
Thermodynamic analysis

ABSTRACT

In this study, a thermodynamic assessment of an integrated solid oxide fuel cell (SOFC) with a steam biomass gasification and high-temperature sodium heat pipes for combined heating and power production as a cogeneration system is conducted. In this regard, rice husk is used as feedstock. The modeling and analysis of the system is performed using mass and energy conservation laws and equilibrium constants. The results of the extended model are confirmed by experimental results. The effect of steam to biomass ratio (STBR) on the performance of the system is investigated. According to the results, more number of heat pipes and higher heat rate of gasification are needed at high STBR. Also, the effects of key parameters including the current density, the fuel utilization ratio (U_f), and the fuel cell temperature are studied on the produced power and electrical, thermal, and total efficiencies. The results indicate that the produced power and electrical and total efficiencies of the integrated system enhance by increasing temperature whiles increasing the current density decreases the total efficiency. By selecting the processing parameters at their optimum levels, the outputs are achieved as the power of 208 kW, the electrical efficiency of 43.71%, the thermal efficiency of 30.6%, and the total efficiency of 74.31%.

1. Introduction

Nowadays using renewable energies such as solar, biomass, wind and hydrogen energies instead of fossil fuels is necessary due to the increasing demand for energy, limitation of fossil fuels, pollution of the environment, global warming, the greenhouse phenomenon effect and the necessity of balancing emission of carbon dioxide.

Biomass includes any substance in the nature that is produced by living creatures or their residues and excreta. These substances can be changed to energy using physical, mechanical, biological and thermal processes [1]. Gasification is one of the most effective methods of utilization of biomass energy. During this process, decomposition is performed by heating and the final potential efficiency of this method is higher than combustion [2]. Gasifiers are designed and produced in different capacities and dimensions for various purposes. Gasification processes are classified into three categories including fixed bed, fluidized bed, and continuous laminar flow according to their reactor design and mass transfer [3]. Steam and air can be used as gasification agents in order to perform biomass gasification during an auto-thermal process. Air gasification is an exothermic process while steam gasification is an endothermic process which needs an external heat source.

Fuel cells are highly efficient as they convert the fuel's chemical energy directly into electrical energy without being subjected to the limitation of Carnot efficiency [4]. Solid oxide fuel cells (SOFCs) have many special advantages such as higher efficiency, the possibility of shifting the input fuel, no need for expensive catalysts, and lesser corrosion problem compared to conventional fuel cells. These advantages make SOFCs more applicable than other fuel cells [5].

The heat pipe is a two-phase heat transfer equipment which can be produced in both tubular and plain forms [6]. These pipes consist of three parts: condenser, adiabatic and evaporator, which working fluid is selected according to the operating temperature of the heat pipe [7]. In many cases, heat pipes are one of the best alternatives for heat transfer and recycling waste heat. Easy design and manufacturing, lower temperature drop through their length, application in a wide temperature range (4–2000 K), and higher heat transfer rate in different temperatures are among the advantages of heat pipes [8].

Different studies have been conducted in this field so far. For instance, Meisel et al. [9] designed ceramic heat pipes for high-temperature applications and used sodium as the working fluid. The temperature range was obtained from 800 to 1200 °C for high-temperature power-engineering applications. Wu et al. [10] compared a tube

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https://doi.org/10.1016/j.enconman.2018.05.096
Received 22 February 2018; Received in revised form 25 May 2018; Accepted 26 May 2018

Nomenclature

A_a	active surface area, m^2
b_r	extent of shift reaction, mol/s
c_p	specific heat at constant pressure, kJ/kmol K
c_r	extent of electrochemical reaction, mol/s
D_{eff}	effective gaseous diffusivity, m^2/s
E_{act}	activation energy, kJ/mol
F	Faraday constant, C/mol
$\bar{G}_i^\circ$	molar Gibbs free energy, J/mol
$\bar{h}$	molar enthalpy, kJ/kmol
$\bar{h}_f^\circ$	molar enthalpy of formation, kJ/kmol
H_l	latent heat of vaporization of heat pipe working fluid, J/kg
I	current, A
j	current density, A/m^2
j_{as}	snode-limiting current density, A/m^2
j_{cs}	cathode-limiting current density, A/m^2
j_{oa}	exchange current density of anode, A/m^2
j_{oc}	exchange current density of cathode, A/m^2
k_m	thermal conductivity, W/m K
k_w	thermal conductivity, W/m K
K	equilibrium constant
$L_{e,c}$	heat pipe length, m
LHV	lower heating value, kJ/mol
m	mole of input steam, mol
n_i	mole of gases, mol
N_{FC}	total number of fuel cells
P	pressure, kPa
P_v	vapor pressure of heat pipe working fluid, Pa
$\dot{Q}_{in}$	requested heat for gasification, kW
R_c	contact resistivity, $\Omega{\cdot}m^2$
R_i	thermal resistivity
R_{in}	internal heat pipe radius, m
R_{out}	external heat pipe radius, m
R_w	heat pipe wick internal radius, m
$\bar{R}$	Universal gas constant, J/mol K
STBR	steam to carbon ratio
T	temperature, °C
U_a	air utilization ratio
U_f	fuel utilization ratio
V	voltage, V
w	biomass moisture, mol
$\dot{W}$	power, kW
y_i	mole fraction of components

Greeks letters

ρ	electrical resistivity of cell components
η	efficiency
δ	thickness of SOFC layer, μm
γ	pre-exponential coefficient

Subscripts

0	ambient condition
a	anode
act	activation loss
AB	after burner
AC	air compressor
bio	biomass
c	cathode
conc	concentration loss
cv	control volume
C	cell
e	exit
FC	fuel cell
g	gasifier
i	input
is	isentropic
N	Nernst
ohm	ohmic loss
WP	water pump

bundles heat exchanger with a heat pipe based on heat transfer efficiency. They concluded that heat pipes have more applications due to their awesome properties and various structural characterizations while tube bundles heat exchangers are still challenging in primary investment and energy saving. Mahdavi et al. [11] studied a high-temperature heat pipe in combination with a concentrated solar power system in order to enhance the performance of the thermal energy storage system. These authors reported that the thermal resistance decreases with the increase of operating temperature and the decrease of heat input. Yu et al. [12] investigated the feasibility of usage of the solid sorbent heat pipe for heat transfer applications. They found that the highest radial thermal flux for horizontal and vertical directions is 22.1 and 12.4 kW/m^2, respectively.

Yari et al. [13] compared two new CHP systems fed by biogas and syngas. The effects of operating parameters such as the current density and the temperature difference of the fuel cell stack on the performance of the proposed systems were examined. A parametric study indicated that the total energy efficiency of the cogeneration systemsbased on gasifier and digester are 58.75 and 51.05%, respectively. A cogeneration system integrating a SOFC with a two-stage biomass gasifier was investigated by Bangmller et al. [14] forvarious operating conditions and parameters. In this study, it was shown that the highest energy efficiency is obtained almost 45% and electric power is obtained almost 1.4 MW. Gadsball et al. [15] combined a biomass gasifier with a SOFC stack. Their study showed experimentally the potential and feasibility of a SOFC-gasification system with a commercial gasifier and a SOFC stack by measuring the highest reported values of such a system, with biomass-to-electricity efficiencies up to 43%. A cogeneration plant based on a SOFC and a Stirling engine was investigated by Hosseinpour et al. [16].They evaluated the effect of the current density, the input temperature of the fuel cell and the compression ratio on the performance of the system. According to their results, the efficiency was enhanced by increasing the temperature.

El-Emam et al. [17] performed thermal modeling and efficiency assessment of an integrated biomass gasification and solid oxide fuel cell system. They showed that the steam biomass ratio has a significant effect on the hydrogen production efficiency. An integrated gasification solid oxide fuel cell and Stirling engine for CHP application was assessed by Rokni et al. [18].Their target for electricity production was 120 kW. Woodchips was used as gasification feedstock to produce syngas. The performance of the system was examined under different conditions such as the temperature of SOFC stack, the number of cells, and the fuel utilization ratio.

Santhanam et al. [19] proposed a cogeneration system of biomass gasifier, SOFC and gas turbine on a small scale. They used heat pipes to improve the performance of the system. Fryda et al. [20] integrated the heat pipes with biomass gasifier and SOFC. Their results indicated that in the current density of 3000 A/m^2, the net power was produced 170 kW and energy efficiency was obtained 34%.

In the present research, a thermodynamic analysis is carried out of a proposed new cogeneration system, under steady-state operation and using a zero-dimensional approach. In the zero dimensional models, it is assumed that the fluid state is homogenous in the control volumes. STBR, fuel utilization factor, SOFC inlet flow temperature, and SOFC