Energy Conversion and Management 161 (2018) 1–12

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermoeconomic assessment of a novel integrated biomass based power generation system including gas turbine cycle, solid oxide fuel cell and Rankine cycle

Z. Ghaffarpour[a], M. Mahmoudi[a], A.H. Mosaffa[a,*], L. Garousi Farshi[b]

[a] *Department of Mechanical Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran*
[b] *Faculty of Mechanical Engineering, University of Tabriz, Iran*

ARTICLE INFO

Keywords:
Biomass
Gasification
Solid oxide fuel cell
Thermoeconomic analysis
Power generation

ABSTRACT

In this work, a novel combined biomass based power generation system is proposed and investigated. The proposed integrated system consists of a combination of biomass gasifier, solid oxide fuel cell, gas turbine cycle and a Rankine cycle. Three different biomasses are selected: Pine Saw Dust, Municipal Solid Waste and Fowl Manure. A comprehensive thermoeconomic analysis as well as a multi-objective optimization is carried out. The effects of most important operating parameters on thermodynamic performance, unit production cost and total cost rate are investigated for the overall system and components. The operating parameters considered include biomass mass flow rate, compression ratio of air compressor, current density of solid oxide fuel cell and exit temperature of solid oxide fuel cell. The results show that the fuel mass flow rate and current density are the dominant factors affecting the variation of energy and exergy efficiencies as well as unit production cost. Moreover, the best thermodynamic and economic performances are corresponded to the Pine Saw Dust fueled system. Nevertheless, the best environmental performance is related to the Fowl Manure fueled system mainly due to the lowest content of CO_2 in flue gas leaving the system to the atmosphere.

1. Introduction

Environmental problems such as air pollution, global warming, and the reduction of unrenewable energy sources have accelerated the use of new and renewable energy sources, such as geothermal, solar, wind and biomass. Bioenergy is obtained from various biomasses, such as wood waste, agricultural and livestock residues, cereals and vegetable oil. Converting biomass energy into biofuels is performed by biochemical conversion and thermochemical conversion processes [1]. Anaerobic digestion, as biochemical conversion process, is appropriate for moist biomass to produce methane [2]. Thermochemical conversion process such as combustion, gasification and pyrolysis, takes place in a partial oxidizing atmosphere in order to produced syngas [3]. The main advantages of using biomass are utilization any type of biomass in various chemical processes and the product gases can be converted to a variety of fuels. Nevertheless, for thermochemical route, the cleaning of product gas from tar and undesirable contaminants is high costly and due to the high temperatures required is inefficient [4]. Biomass gasification is a high-tech complex process that is used to generate low cost and high efficiency syngas. In order to optimal use of syngas energy the appropriate heat engine systems such as natural gas-based, spark-ignition engine [5], solar-biomass hybrid power system [6] hybrid solar-biomass combined cycle power generation system [7], etc. are required.

In the gasification process, the gas produced during pyrolysis is partially burned, raising the internal temperature and favoring a partial tar decomposition. The gasification process is supposed to occur at ambient pressure using air as gasifying agent [8]. Depending on the kind of biomass, syngas composition will be different and the main factor for selecting biomass, considering the amount of carbon, moisture and oxygen which cause to produce high quality syngas with more methane, hydrogen and steam content that this amounts have significant effect on the bottoming systems performance. So choosing suitable biomass for achieve best operating condition for other bottoming applied systems is necessary. Shabani et al. [9] studied a hydrogen and electricity co-generation plant with rice husk as biofuel where electricity produced using two Rankin cycles. Their main purpose was to eliminate hydrogen combustion for electricity generation and reduce the production of pollutant NO_x by the Rankine cycle. Kirsanovs et al. [10] proposed a system to produced thermal energy for heating purposes through the biomass gasification. They used wood chips as biomass and due to the high amount of moisture in this type of

---

* Corresponding author.
E-mail address: mosaffa@azaruniv.ac.ir (A.H. Mosaffa).

https://doi.org/10.1016/j.enconman.2018.01.071
Received 6 November 2017; Received in revised form 8 January 2018; Accepted 27 January 2018
0196-8904/

Nomenclature

A_{cell}	active surface area (cm^2)
AF	air–fuel ratio
c	unit cost of mass ($\$\ \mathrm{kg}^{-1}$)
$\dot{C}$	cost rate ($\$\ \mathrm{s}^{-1}$)
CRF	capital recovery factor
$\dot{E}x$	exergy rate (kW)
$\overline{ex}^0$	specific standard chemical exergy ($\mathrm{kJ\,kmol}^{-1}$)
F	Faraday constant ($=96{,}486\ \mathrm{C\,mol}^{-1}$)
$\Delta\overline{G}^0$	Gibb's free energy ($\mathrm{kJ\,kmol}^{-1}$)
GTC	gas turbine cycle
h	specific enthalpy ($\mathrm{kJ\,kg}^{-1}$)
$\Delta\bar{h}_f^0$	enthalpy of formation ($\mathrm{kJ\,kmol}^{-1}$)
HRSG	heat recovery steam generator
i_{r}	annual interest rate
i	current density ($\mathrm{A\,cm}^{-2}$)
K_{p}	equilibrium constant
LHV	low heating value ($\mathrm{kJ\,kg}^{-1}$)
$\dot{m}$	mass flow rate ($\mathrm{kg\,s}^{-1}$)
M	molecular weight ($\mathrm{kg\,kmol}^{-1}$)
$\dot{n}$	molar flow rate ($\mathrm{kmol\,s}^{-1}$)
N	operational hours in a year (h)
N_{cell}	number of cell
P	pressure (kPa)
PEC	purchased equipment cost
$\dot{Q}$.	heat rate (kW)
r	compression ratio
r_{r}	recirculation ratio
$\overline{R}$	universal gas constant ($\mathrm{kJ\,kmol}^{-1}\,\mathrm{K}^{-1}$)
RC	Rankine cycle
s	specific entropy ($\mathrm{kJ\,kg}^{-1}\,\mathrm{K}^{-1}$)
SF	steam-fuel ratio
SOFC	solid oxide fuel cell
T	temperature (K)
ΔT_{lm}	logarithmic mean temperature difference (K)
U	utilization factor
v	specific volume ($\mathrm{kg\,m}^{-3}$)
V	voltage (V)
$\dot{W}$	power (kW)
x	molar fraction
y	system life time (year)

Greek symbols

β	extraction fraction of steam turbine
γ	specific heat ratio
η	Efficiency

Subscripts and superscripts

0	ambient
a, b	coefficients
AC	air compressor
cond	condenser
CI	capital investment
D	destruction
el	electrical
env	environmental
G	generator
GT	gas turbine
is	isentropic
M	maintenance
rec	recuperator
rel	relative
ST	steam turbine
stoi	stoichiometric

biomass downdraft gasifier was employed to reach higher temperature for syngas. The results show that the highest gasifier efficiency was obtained under nominal operating conditions. A model based on a Gibbs free energy reactor is considered by Fernandez-Lopez et al. [11] for The gasification of Fowl Manure in a dual gasifier. They evaluated the effects of using the steam and CO_2 as the gasifying agents on the composition, the gasifying/biomass ratio, the gasification temperature and the low heating value (LHV) of the produced syngas. Their results show that the H_2 production is higher when steam is used as the gasifying agent and the formation of CO is enhanced when CO_2 is considered as gasification agent. To simulate steady state and transient state of gasification process, a mathematical model is developed by Jia et al. [12]. They studied the effects of the equivalence ratio, steam to biomass ratio and mass flow rate of biomass on the steady and transient characteristics of gasifier.

In the recent years, the integration of biomass gasifier with fuel cells is highly mentioned. Fuel cells are the new electrochemical technology that converts the chemical energy from a fuel into electricity through an electrochemical reaction of hydrogen-containing fuel with oxygen or another oxidizing agent [13]. Among different types of fuel cell, the solid oxide fuel cell (SOFC) is chosen due to its benefits [14]. For example, different types of fuels such as biogases, methanol, hydrogen sulfide and hydrocarbons can be used in SOFC. Moreover, high temperature SOFCs could be integrated with thermodynamics cycles such as Brayton, organic Rankine cycle (ORC) and refrigeration systems to rise the overall efficiency [15].

Colpan et al. [16] presented a thermodynamic model for the direct internal reforming SOFC where the syngas form the gasifier has been used as the fuel enters anode. They also investigated the effects of SOFC operating parameters such as fuel utilization ratio, recirculation ratio on the biofuel mass flow rate, inlet temperature of fuel, electrical efficiency, network and cell voltage. They concluded that at higher current densities, by increasing the recirculation ratio, the electrical efficiency and output power of the SOFC decrease. Mortazaei and Rahimi [17] analyzed two different trigeneration systems integrated gasifier and digester based SOFC to produce cooling, heating and power from thermodynamic and environmental points of views. They showed that the energy efficiency of digester based SOFC system is 11.1% higher than gasifier based SOFC system, while the gasifier based SOFC system has higher thermal and cooling capacity due to higher mass flow. Gadsbøll et al. [18] experimentally studied a combined power plant consists of gasification and SOFC to examine the potential of the commercial agent of these two technologies. They showed that by employing a two-stage gasifier an electrical efficiency of 46.4% is achieved. Ebrahimi and Moradpoor [19] presented a new power generation system combining three technologies of SOFC, micro gas turbine and ORC. They investigated the effects of variation of operating parameters include current density, steam to carbon ratio, reformer temperature, fuel utilization factor and minimum and maximum pressure of the ORC on electrical efficiency.

In the present research, a novel biomass fueled power generation system is proposed and a comprehensive thermoeconomically assessment is carried out. The proposed power plant consists of a gasifier, a syngas based SOFC, a syngas based gas turbine cycle (GTC) and a Rankine cycle (RC) to produce electricity. In this system, syngas produced in gasifier at different pressure is fed to the SOFC and combustion chamber of GTC. The required high pressure steam for gasification process is supplied from RC which is run by heat recovery from flue