Renewable and Sustainable Energy Reviews 91 (2018) 869–887

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Model development and energy and exergy analysis of the biomass gasification process (Based on the various biomass sources)

Mehdi Mehrpooya[a,b,*], Maryam Khalili[a], Mohammad Mehdi Moftakhari Sharifzadeh[c]

[a] Renewable Energies and Environment Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
[b] Hydrogen and fuel cell laboratory, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
[c] Department of Chemical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

ARTICLE INFO

Keywords:
Gasifier
Gasification
Biomass
Hydrogen
Energy
Exergy efficiency

ABSTRACT

Worldwide growing demand for energy consumption in recent years arising from industrialization development and increasing earth population has caused more environmental concerns to emerge. On the other hand, specific issues related to the use of fossil fuels as a nonrenewable source of energy has been caused alternative fuels like biomass to be investigated with more concern. Generally, gasification is a process which converts organic matter to gas and tar. Also, through the gasification, biomass as a fuel is converted to the combustible gas (syngas). In this study, modeling and simulation of the biomass gasification process is investigated and analyzed considering 23 different kinds of the biomass sources. The proposed model is based on the Gibbs free energy minimization and the restricted equilibrium method is used for calibration. The process operating performance is analyzed thermodynamically based on the hydrogen production yield. In this regard, effective parameters like temperature of the gasification, air-fuel ratio, steam-biomass ratio and temperature of the air and steam streams are investigated. Gasification temperature and steam-biomass ratio affect the syngas compositions and the heating value significantly. Biomass moisture has the most significant impact on the syngas production efficiency. Also, other parameters which are not very intensive but still have an effect on the syngas production efficiency, are examined. Finally, the process performance is analyzed based on the energy and exergy analysis methods. The obtained results show that, exergy efficiency of drying stage is the highest (about 90.0%) in all cases. Nonetheless, exergy destruction rate for this stage is a great value against the others. Among the selected biomasses, Rice husk type has the greatest exergy destruction rate which is related to the tar combustion and decomposition reactors; respectively.

1. Introduction

After coal and oil, biomass as a renewable source is one of the largest sources of energy that is extracted from the organic materials and natural resources [1]. Biomass includes a wide range of materials that agricultural residue and forest residue have the biggest portion in it. Agriculture residues are from resources such as husk, bagasse, straw and forest residues are like bark, sawdust and wood chips [2,3]. Municipal solid wastes is another source of biomass fuel. Depending on the potentiality of different countries, variety range of different biomass sources are known as the renewable resources for fuel production. Because the net carbon dioxide (CO_2) emission from the biomass is zero, so it is quite clean in comparison with other sources of energy. In the thermochemical gasification process, CO_2 is one of the emission gaseous while in the biomass gasification, CO_2 is consumed by biomass in the photosynthesis process [4]. Hydrogen (H_2) is known as an effective and clean fuel for the fuel cells and combustion engines. Biomass is one of the important resources to produce hydrogen and biofuel. Different method have been produced for production of Hydrogen. Steam reforming of the natural gas, water (H_2O) electrolysis and coal gasification are of the most common methods. But they are not known as a sustainable procedure to produce hydrogen, because electricity or fossil fuels are gained from the non-renewable sources. Gasification and pyrolysis, as alternative thermochemical method and bio-photolysis, water-gas shift reaction and fermentation as biological method are more sustainable than conventional methods [5,6]. Several researches have been conducted regarding the technologies of hydrogen production from the biomass [7–9]. One of the most important sections of

Abbreviations: C, Carbon; CO_2, Carbon dioxide; CO, Carbon monoxide; CH_4, Methane; CCHP, Combined cooling, heat and power; E, Heat Exchanger; H_2, Hydrogen; H_2O, Water; H_2S, Hydrogen sulfide; N2, Nitrogen; NH_3, Ammonia; NO_2, Nitrogen dioxide; O_2, Oxygen; S, Sulfur; SO_2, Sulfur dioxide; SOFC, Solid oxy fuel cell

* Corresponding author at: Renewable Energies and Environmental Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran.
E-mail address: mehrpooya@ut.ac.ir (M. Mehrpooya).

https://doi.org/10.1016/j.rser.2018.04.076
Received 14 March 2017; Received in revised form 15 March 2018; Accepted 14 April 2018
1364-0321/

Nomenclature

$a_1,\ldots,a_6$	Coefficients in entropy equation [dimensionless]
A	Gasifier area in m^2 or pre-exponential constant [s^{-1} or min^{-1}]
C	Carbon content in biomass [wt%]
C_P	Specific heat capacity at constant pressure [kJ/kg °C]
E	Activation energy [$kJ\,mol^{-1}$]
$\dot{E}$	Energy flow rate [kJ/h]
Ex	Exergy [kJ/kg or kJ/kmol]
Ex_o	Standard exergy [kJ/kmol]
$\dot{Ex}$	Exergy rate [kW]
h	Specific enthalpy [kJ/kg or kJ/kmol]
H	Hydrogen content in biomass (wt%) or total enthalpy [kJ]
$\dot{I}$	Irreversibility [kW]
k	Rate constant or kinetic constant [s^{-1}]
LHV	Lower heating value [kJ/kg or kJ/kmol]
$\dot{m}$	Mass flow rate [kg/s]
MW	Molecular weight [kg/kmol]
N	Nitrogen content in biomass [wt%]
O	Oxygen content in biomass [wt%]
P	Pressure or partial pressure [Pa or atm]
PI	Improvement potential [kW]
$\dot{Q}$	Heat transferred to ambient [kW]
R	Universal gas constant [8.314 KJ/kmol K]
T	Gasification temperature [K]
T_0	Reference temperature [298 K]
s	Specific entropy [KJ/kmo K or KJ/kg K]
$\dot{s}$	Entropy [kW/K]
S	Sulfur content in biomass (wt%) or total entropy [kJ]
t	Time [s]
$\dot{W}$	Electrical power [W or kW]
X	Molar fraction of component [dimensionless]
x	Thickness [m]
U_0	Wind velocity [m/s]

Greek letters

η	Efficiency [-]
β	Coefficient
ε	Gasifier wall emissivity [-]

Subscripts

BCL	Battelle Columbus Laboratory
ch	Chemical
cg	Syngas
des	Exergy destroyed
deswa	Exergy loss
drybio	Dry biomass
e	Exit
En	Energy
gen	Generation
i	Inlet or Component "i"
ins	Insulation
j	Component "j"
lostwa	Lost from gasifier wall to ambient
o	At reference or ambient or outlet
ph	Physical
prodg	Produced gas
P	Number of products
R	Number of reactants
w	Wall
wa	From gasifier wall to ambient

hydrogen production is gasifier that has been investigated so much [5,6]. In different studies, Aspen plus process simulator has been used to investigate and simulate the coal conversion in different processes like methanol synthesis, integrated coal gasification combined cycle power plants [3], coal hydro-gasification process and simulation [10], compartmented fluidized bed coal gasifiers [11], coal hydro-gasification processes [12] and coal gasification simulation [13]. A research is done on biomass gasification [14]. In biomass gasification, gasifier is the main stage of the process. [15]. The gasification, featured with a limited oxidation, can be used in various clean energy processes like hydrogen production via biomass gasification. Gasifier modeling and simulation is done in some researchers by Aspen plus [3,9,16]. Some researchers have claimed that biomass gasification in supercritical H_2O can be considered as a superior technology in H_2 production [7,8]. In this regard, energy and exergy efficiencies and also operating performance improvement along with data availability with experimental studies [6] have received the most attention in recent studies [17–19].

Various integrated processes have been proposed and analyzed to improve the operating performance efficiency of the biomass gasification process. Kalina et al. [20] presented a mathematical concept model of a small-scale combined electrical power generation cycles integrated with thermal gasification of the biomass. The obtained results show that biomass to electricity conversion efficiency in the best case is at the range of 22.3–37.7%. Taheri et al. [21] proposed a novel integrated multi-generation energy system with hydrogen production from biomass and liquefied natural gas regasification cycle. The process is examined based on the energy, exergy and economic analyses. The results indicate that, with increasing the biomass flow rate as the fuel from 4 kg/s to 10 kg/s, overall energy efficiency decreases 8.50% and total cost rate of the process increases of 123%. Santhanam et al. [22] evaluated a thermodynamic model of integrated biomass gasification and solid oxide fuel cell (SOFC) and small-scale gas turbine system (100 kWe). Based on the exergy analysis results, highest exergy loss belongs to gasifier, gas turbine and waste heat recovery system respectively. To decrease the exergy losses and increase the system performance efficiency, a new strategy for heat pipe integration is proposed. This development leads to increase the electrical efficiency from 55% to 72% by decreasing exergy losses in the gasifier. Wang et al. [23] analyzed the cost allocation of two integrated structures of the combined cooling, heat and power (CCHP) system based on the modified exergoeconomic method. Moharamian et al. [24] investigate a comparative thermoseconomic evaluation of three biomass and biomass-natural gas-fired combined cycles using organic Rankine cycles. The proposed structures are biomass integrated co-fired, post-firing and externally fired combined cycles. The highest and lowest energy and exergy efficiencies are illustrated by the biomass integrated post-fired (37.0% and 34.0%) and externally fired (36.0% and 21.0%) combined cycles, respectively. Tan et al. [25] analyzed a novel integrated structure of the hybrid system which includes electrical power generation, biomass gasification, SOFC, gas expanders and the Kalina cycle. The performance was evaluated by conducting energy and exergy analyses. The results showed that, the energy efficiency of the hybrid system can reach to 64.2% for the produced syngas lower heating value (LHV) in a system baseline operating condition. Stougie et al. [26] compared the use of livestock manure and verge grass for three different structures of electrical power generation from the biomass by using environmental and an exergetic life cycle assessments. As concluded, the differences between the environmental and exergetic sustainability assessment scores of the systems are not large. Yan et al. [27] thermodynamically analyzed a novel chemical looping electrical power generation system based on the