Energy Conversion and Management 140 (2017) 228–239

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Exergoeconomics of hydrogen production from biomass air-steam gasification with methane co-feeding

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ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form 14 February 2017
Accepted 1 March 2017

Keywords:
Biomass
Air–steam gasification
Exergy
Exergoeconomic
Methane co-feeding

ABSTRACT

Biomass is one of the most promising energy sources for hydrogen production. However, biomass gasification has a low hydrogen content in the producer gas. To increase the hydrogen yield, the co-feeding of methane into biomass gasification is proposed in this study. The type of gasifying agent is a key factor in the determination of the content of the hydrogen product. To compare the designs and find the best performance criteria of a process, not only energy and exergy analyses but also a cost analysis of the process should be investigated. In the present study, the effects of various types of gasifying agent, i.e., air and both steam and air, for the biomass gasification with/without methane co-feeding are investigated through an exergoeconomic analysis. It is observed that the air-steam used as an agent achieves high energy and exergy efficiency. Methane co-feeding can improve the energy and exergy efficiency. In exergoeconomic analysis, the specific exergy cost (SPECO) method is applied to investigate the unit cost of hydrogen. The economic reveal that the biomass gasification using air-steam as an agent with methane co-feeding also presented the lowest unit hydrogen cost of 2.69 $/kg. The unit exergy cost of hydrogen is 0.068 $/kW h.

1. Introduction

The consumption of fuels and chemicals continuously grows. Hydrogen plays an important role in the chemical industry as a fuel and chemical reactant due to its high energy density and low emission [1–3]. Most synthesis gas is produced from fossil sources. The combustion of fossil fuel leads to environmental problems such as the greenhouse effect and air pollution [4–6]. Additionally, fossil sources are limited in quantity. To develop sustainable strategies for energy production, renewable resources have been investigated as substitutes for fossil sources [7]. Biomass has been considered to be an alternative fuel for hydrogen production because it is an organic material that comes from various green sources including agricultural residues and waste from industrial production processes [8,9]. Although conversion biomass into fuels releases carbon dioxide in the atmosphere, biomass utilization is carbon dioxide neutral due to growth of the crops taking carbon dioxide out of the atmosphere.

Biomass can be converted to synthesis gas via a gasification process. The main challenges regarding large-scale biomass gasification are the low hydrogen content in the synthesis gas product and the high energy input required. The quality of the hydrogen content in the syngas depends upon the type of biomass used, the gasifier reactor, gasifying agent, and operating condition of the gasifier. To increase the hydrogen content and reduce the tar content in the fuel gas, preheating of the gasification agent was proposed in publications [10,11].

The most common gasifying agent is air because of its abundance and inexpensiveness. However, the large proportion of inert nitrogen gas in ambient air directly causes the low quality, with a higher heating value (HHV) of 4–6 MJ per cubic metre at standard temperature and pressure (m^3 stp; 25 °C, 1 atm). Furthermore, the use of air as a gasification agent obtains low hydrogen content of the product gas. The gas product from biomass gasification with pure oxygen has a higher product gas quality than that with air (HHV = 10–15 MJ/m^3 stp.), but the separation cost of pure oxygen

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http://dx.doi.org/10.1016/j.enconman.2017.03.002

Nomenclature

a, b, c, d	empirical coefficients
ex	standard exergy (kJ/kmol)
i	interest rate
E	energy (kJ/kg)
Ex	exergy (kJ/kg)
$\dot{E}x$	exergy rate (MW)
m	mole of air to mass of biomass ratio (mol/kg)
$\dot{m}$	mass flow rate of the biomass (kg/s)
c	unit exergy cost ($/GJ)
$\bar{c}_p$	constant pressure specific heat capacity (kJ/kmol K)
C	initial investment cost ($)
$\dot{C}$	cost rate ($/h)
$C\dot{A}$	annual capital cost ($/yr)
n	molar yield (mol/kg), lifetime of equipment (yr)
T	temperature (K)
P	pressure (Pa)
R	universal gas constant (kJ/kmol K)
h	specific enthalpy (kJ/kmol)
s	specific entropy (kJ/kmol K)
S	salvage value ($)
y	mole fraction of gas component
$\dot{Z}$	sum of capital investment and operation and maintenance cost rates ($/h)

Greek letters

β	correlation factor
η	efficiency (%)
τ	annual operating time of equipment (h)
ϕ	operating and maintenance factor

Superscripts

ki	kinetic
ep	potential
ph	physical
ch	chemical
CI	capital cost investment
OM	operating and maintenance
T	total

Subscripts

i	component gases
0	dead state
air	air
agent	gasifying agent
ash	ash
biomass	biomass
en	energy
ex	exergy
gas	product gases
methane	methane
n	life time of the process (yr)
process	process
p	product
total	total
F	feed
kth	kth equipment
w	water

Abbreviations

ER	equivalence ratio
CRF	capital recovery factor
PEC	purchased equipment cost ($)
PW	present worth ($)
PWF	present worth factor
LHV	lower heating value (MJ/kg or kJ/kg)
HHV	higher heating value (MJ/kg or kJ/kg)
SPECO	specific exergy cost

is relatively high [12]. The gas product of the steam reforming process has a medium caloric value and higher heating value (15–20 MJ/m^3 stp.). Although the gas product from the biomass steam gasification process is of high quality, a high energy input is required [13].

The type of feedstock is an important factor regarding the gas product quality. Several studies have been conducted by concurrently co-feeding methane or natural gas together with a carbonaceous solid [14–16]. Aaron et al. [14] reported that the addition of methane to the gasification of rice hulls affects the contents of hydrogen and carbon dioxide in the fuel gas. Moreover, some research topics have studied the addition of natural gas into the biomass gasification to generate the electricity. Pantaleo et al. [15] performed a micro gas turbine (MGT) cycle using natural gas and biomass as fuel. The combined cooling, heating and power system (CCHP) integrating biomass gasification and the co-firing of natural gas was investigated by Wang et al. [16]. Their results found that the energy efficiency of the electric power system with co-feeding of natural gas and biomass is higher than that with the use of biomass alone.

The process of biomass gasification requires a high energy input. The assessment of the energy conversion of biomass gasification systems using energy and exergy analyses should be considered to determine the optimum system and conditions [17,18]. The types of feedstocks, gasification agents, and gasifiers have the important influence on the energy and exergy efficiencies. The energy and exergy values of the biomass gasification system depend on the ultimate analysis and moisture content of feedstock [19,20]. The study of the different gasification agents on the energy and exergy efficiencies was obtained [19,21,22]. Hosseini et al. [19] found that the air used as a gasifying agent achieves higher energy efficiency than the use of steam. However, the exergy efficiency of the steam gasification is higher than that from partial oxidation gasification [22]. Moreover, the energy and exergy analyses to find the optimum condition of several gasifiers have been studied. The results of Loha et al. [23] indicated that the energy and exergy efficiencies have a maximum at the carbon boundary point. For the gasification of rice husks in an entrained flow gasifier, Zhang et al. [22] reported that the highest energy and exergy of syngas product are achieved at the gasifier temperature and equivalence ratio of 1000 °C and 0.25, respectively.

The cost of hydrogen production is also an important criterion. In an exergoeconomic analysis, the exergy and economics are combined to study a thermochemical system [24]. Various studies have been conducted on the exergoeconomic analysis of hydrogen production from biomass [25–27]. The parameters for considering the unit cost of hydrogen production are the capital investment, operation and maintenance costs. Also, the results of Lv et al. [25] indicated that the costs of electricity and the catalyst in the combined system of downdraft gasifier and a CO-shift reactor have a major impact on the hydrogen production cost. A comparison of the costs of hydrogen production from three types of gasifier reactor, i.e., downdraft, circulating fluidized bed, and plasma gasifier, was performed by Kalinci et al. [27]. They stated that the circulating