Energy Conversion and Management 130 (2016) 34–43

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance evaluation at different process parameters of an innovative prototype of biomass gasification system aimed to hydrogen production

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ARTICLE INFO

Article history:
Received 29 July 2016
Received in revised form 23 September 2016
Accepted 14 October 2016

Keywords:
Bioenergy process
Thermochemical process
Gasification
Catalytic filters
Hydrogen production

ABSTRACT

Gasification is currently considered one of the most effective technologies to produce power and hydrogen from biomass and the scope of this work is to determine performances of such an energy system in terms of production of pure hydrogen. The overall plant has been simulated by means of ChemCAD® software. It is composed of a dual fluidized bed biomass gasifier with Catalytic Filter candles (CF), innovatively integrated within the gasification reactor, Water Gas Shift reactor (WGS), equipped with a desulphurization reactor (DeS), and Pressure Swing Adsorber system (PSA), coupled with a micro gas-turbine system (mGT) as an auxiliary power generator aimed to supply inner needs of electricity. Research and pilot scale tests on gasifier, CF, WGS reactor and PSA unit allowed to validate the model. The components have been integrated in a relatively small size and innovative plant (1 MW_{th} as biomass input). This integration entails highly pure H_2 and major efficiency. The model allowed a sensitivity analysis of basic parameters as WGS temperature, residence time and steam to biomass ratio (SB). Important results have been generated reaching a maximum hydrogen yield of 75.2 g_{H2}/kg_{bio} and a maximum efficiency, HHV based, of 55.1%. Optimal compromise of results was obtained with SB equal to 2, WGS reactor temperature at 300 °C and residence time at 0.8 s. Finally, even the chance to generate hydrogen without consumption of auxiliary fuel (by exploiting off gas and waste heat recovery) has been investigated.

1. Introduction

Nowadays, the industrial technologies utilizing energy sources cause negative environmental impact, such as depletion of fossil fuels, global warming due to greenhouse gases and air pollution. Improving the production of energy from biomass can lead to a more sustainable production [1,2]. New energy vectors are, anyway, required to solve problems related to the variability, the uncertainty and the difficulty of straightforward utilization of renewable energy sources. Hydrogen is a promising option for the future, since it can be used in various applications, as conventional internal combustion engines or, in a more efficient way, by fuel cells both for residential and transportation uses [3–10]. A potential low cost process to produce hydrogen is the biomass waste gasification technology, coupled with gas cleaning and purification processes [11–17]. Many works [18–21] consider gasification the dominant biomass conversion technology, as the gases from biomass gasification are intermediates in the high-efficient power production or the synthesis from chemicals and fuels. Gasification is a thermo-chemical conversion process, which produces a fuel gas rich in hydrogen, carbon monoxide, methane and carbon dioxide [22,23], but, unfortunately, also organic (tars) and inorganic (H_2S, HCl, NH_3, alkali metals) impurities that need to be removed. Use of steam as gasifying media, instead of air, in dual fluidized bed reactor allows to obtain fuel gas with reduced amount of N_2 [24–26] and greater H_2 content (up to 50%). The product gas, however, needs to be upgraded to synthesis gas in an efficient way, and this is possible even if the content of tar [27] and particulate is potentially high. A gas-cleaning step is generally necessary on the raw gas produced by the gasification process [28,29]. Among alternative hot gas cleaning and conditioning methods, catalytic cracking and steam reforming of low and high molecular weight hydrocarbons offer several advantages, such as thermal integration with gasification reactor, high tar conversion and hydrogen rich syngas production [30–33]. This was confirmed also by the results of the UNIQUE concept [34], which integrates both the fluidized bed and the hot gas cleaning system into a single

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http://dx.doi.org/10.1016/j.enconman.2016.10.039
0196-8904/

Nomenclature

Latin letters

A	Arrhenius parameter [1/s]
c	concentration [mol/m^3]
cc	cost of capital [%]
c_p	specific heat [J/mol K]
E	activation energy [kJ/mol]
$\dot{G}_i$	normalized mass flow rate
ΔH	specific enthalpy [J/mol]
k	rate constant for reaction [1/s]
$\dot{m}$	mass flow rate [kg/s, kg/h]
N	years of depreciation
n	molar flux per unit area [mol/m^2 s]
$\dot{n}_i$	normalized compressor and turbine rotating speed
Δp	pressure drop [mbar]
p	pressure [Pa]
p_i	partial pressure [bar]
r	rate of reaction [mol/m^3 s]
X	conversion rate [%]

Greek letters

η_i	chemical hydrogen efficiency
$\dot{\eta}_i$	normalized compressor and turbine efficiency
ν	stoichiometric coefficient
$\dot{\pi}_i$	normalized pressure ratio

Abbreviations

CAPEX	total capital costs
CF	catalytic filters candles
DeS	desulphurization reactor
daf	dry and ash free
Eco	economizer
WGS	water gas shift
HHV	higher heating value
LHV	lower heating value
mGT	micro gas-turbine system
OPEX	operation and maintenance costs
PEM	proton exchange membrane
ppi	pores per inch
ppm	parts per million
PPS	portable purification system
PSA	pressure swing adsorber
SB	kg of steam fed per kg of biomass
SBR	moles of steam fed per mole of biomass
SH	superheater
Vap	vaporizer

Subscripts

bio,daf	biomass dry and ash free
c	compressor
e	electric
eq	equilibrium
in	input
nom	nominal
t	turbine
th	thermal

and compact gasifier. It has been possible by virtue of a bundle of ceramic filter candles operating at high temperature directly in the gasifier freeboard, producing a syngas free of tars and allowing remarkable plant simplifications and reduction of costs [34–36]. In this way, the coupling of UNIQUE technology with WGS and PSA, aimed at H_2 separation from residual gases, is, thus, feasible with a high hydrogen yield. Conventional WGS reactors operate at high pressure and thus they are not suitable to be coupled with atmospheric pressure gasification (suitable for small-scale applications). Ceramic foams impregnated of specific catalyst are fundamental in order to realize a WGS reactor operating at atmospheric pressure and to increase the efficiency of the gas-solid contact (catalytic surface area). The gas, rich of hydrogen at the outlet of the WGS reactor, could be then cooled down to ambient temperature to remove condensable and then compressed at relatively low pressure to feed PSA unit, obtaining pure hydrogen to store.

Hydrogen production by biomass gasification has been widely analysed. Cohce et al. [37] and Spath et al. [38] have analysed a system to produce hydrogen based on a Battelle Columbus Indirectly heated gasifier working at a pressure close to the atmospheric. The main difference between these works is in the way to operate tar and methane steam reforming. Neither of them, in fact, has studied a steam methane and tar reforming system integrated inside the gasifier reactor as the UNIQUE concept suggests. Moreover, in both the works cited, a high PSA efficiency of 85% was assumed and the power and steam for the plant was obtained by a steam power plant coupled with the hydrogen production plant: both of these choices are suitable only for large scale applications. On the contrary, the interest of the scientific community and institutions regarding the biomass to hydrogen technologies, at the moment is addressed on small/medium scale application. For example, an expected outcome according to the EU target [39] is that reactors for hydrogen production from biomass should be in the forecourt size range for a hydrogen filling station (100–500 kg/day), that means biomass systems of the order of 1 MW_{th} (200–250 kg/h as lignocellulosic biomass input). New simulations are therefore required to verify the feasibility to produce hydrogen from biomass with different assumptions more suitable for small/medium scale applications. Furthermore, the analyses carried out in these papers are based on thermodynamic considerations, while gasification, steam reforming and WGS reactions are affected by kinetic. New analyses with experimental validation are thus necessary, for the optimization of the operating conditions that influence the reaction kinetic, like residence time and operating temperature, and for a more feasible design of the plant and its subsystems.

As regards the steam to biomass ratio (SB), in these works, it was set at 0.4 and Spath et al. hinted the possibility to increase this ratio. Mahishi and Goswami [40], instead, studied the effects of SB increasing. They determined that operating at very high SB might not be energy efficient, since additional H_2 produced may not justify the high cost of producing steam. In that case, at gasification temperature of 1000 K, ER of 0.1 and at a gasifier pressure of 1 atm, an optimum SB of 2.1 (SBR = 3 where SBR refers to moles of steam fed per mole of biomass) has been determined. Moreover, Kalinci et al. [41] identified the range of 0.6–10 for SBR optimum values in gasification. On the contrary, Inayat et al. [42] found that maximum hydrogen efficiency is provided at SB of 2 and gasification temperature of 850 K, while the maximum H_2 concentration in the product gas is obtained with a gasification temperature of 950 K and a SB of 3. A rise in SB to 1.0–2.0 increases the primary production of hydrogen [43] in the gasifier and would favourite the steam methane reforming and Water Gas Shift (WGS) reactions with no further steam addition, reducing the complexity of the