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Efficiency evaluation of dry hydrogen production from biomass gasification

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ABSTRACT

The hydrogen production from biomass gasification needs to be improved through investigation of the operating parameters and thermodynamic efficiencies (energy and exergy). A comprehensive study is conducted to predict H_2 production with a gasifier using a quantity of 14.5 kg/s from biomass (wood sawdust) and an amount of 6.3 kg/s of steam at 500 K and evaluate system performance through energy and exergy efficiencies for hydrogen production from biomass. The gasification process takes place in a temperature range of 950–1500 K and steam–biomass ratio of 0.17–0.51. The results indicate that an improvement in exergy efficiency from 33 to 37% is possible during hydrogen production only. It becomes more sensitive if the temperature goes beyond 1000 K. In this regard, the exergy efficiency increases from 42 to 47% when all of the product gases are taken in consideration and from 47 to 52% when all of the products from the gasification process are taken in consideration. Over a range of gasifier temperatures, the gasification ratio is 97–105 g H_2/kg of biomass while hydrogen yield reaches 1.5 kg/s for the studied biomass.

1. Introduction

Gasification is a process that converts carbon-containing feedstock into H_2, CH_4, CO, CO_2 and others in the presence of gasification agents. Steam gasification gives a medium heating value gas of ~15–20 MJ m^{-3} which is higher than that from air gasification and less cost comparing to oxygen gasification [1]. Gasification adds value to low or negative-value feed stocks by converting them to marketable fuels and products. It is theoretically modeled in series steps but there is no sharp boundary between them and they often overlap.

There has been and will be a considerable increase in fossil fuel consumption which leads to depletion of fossil fuel in near future and makes the world highly worried regarding carbon emission issue. In addition, it is important to note that as fossil fuels become depleted, their costs will certainly escalate [2]. As matter of fact that needs more efforts to provide alternative or substantial resources that is friendly regarding pollution and green house gas emissions. Biomass is a resource which has more attention these days and it classified energy wise as third energy resource after coal and oil [3]. Gasification of biomass to produce hydrogen as energy carrier is a part of the effort to combat this threat. Hydrogen is a clean fuel; it can be existed in atmosphere without causing any air pollution [4]. Gasification process appears to offer attractive technology and friendly to utilize biomass in energy generation [5].

Many gasification studies have been carried out to predict hydrogen and few predicting hydrogen production by addressing gasifier via a studying parameters influencing the hydrogen production. Many parameters were considered influencing gasification process in regard to hydrogen production such as: composition, moisture content, gasifier temperature, gasifier pressure, geometry, amount of oxidant present, and the mode of gas–solid contact. Walawender et al. [6] considered the gasifier temperature as the most important parameter. The conducted experiments on gasification of biomass showed that the results were affected by the pressure. Mahishi and Goswami [7] and Hanaoka et al. [8] reported that an increasing of the gasifier pressure reduces the hydrogen yield and the highest hydrogen yield occurred at atmospheric pressure. This leads to conduct this study on biomass gasified in atmospheric gasifier. The gasification temperature and steam–biomass ratio were reported to be the dominant experimental parameters (e.g. Florin and Harris [9]), influencing both the concentration of H_2 in the product gas and the total yield. That also recently observed by Abuadala et al. [10]. Most of researches discussed related issues to gasifier from equilibrium analysis view and this makes us do not discuss how much that will affect results from different type of gasifiers and one can make comparisons easily.

Hydrogen is expected to be the most important energy carrier in a sustainable energy system. Turn et al. [11] reported there was no emphasis on hydrogen production by past experimental work done on steam gasification of biomass. Recently, Abuadala et al. [10] emphasized on dry hydrogen production from gasification of

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Nomenclature

a	molar flow rate of hydrogen (kmol/s)
A	gasifier area (m^2)
b	molar flow rate of carbon monoxide (kmol/s)
c	molar flow rate of carbon dioxide (kmol/s)
C	carbon content in biomass (wt%)
C_P	specific heat at constant pressure (kJ/kmol K)
d	methane moles (kmol/s)
e	char product (kmol/s)
Ex	exergy (kJ/kg or kJ/kmol)
$\dot{E}x$	exergy rate (kW)
f	tar yield (kmol/s)
H	hydrogen content in biomass (wt%) or total enthalpy (kW)
h	specific enthalpy (kJ/kg or kJ/kmol)
I	irreversibility (kW)
LHV	lower heating value (kJ/kg)
O	oxygen content in biomass (wt%)
P_0	ambient pressure (atm)
PI	improvement potential (kW)
$\dot{Q}$	heat transferred to ambient (kW)
k	thermal conductivity (W/m K)
$\dot{m}$	mass flow rate (kg/s or kmol/s)
R	universal gas constant (8.314 kJ $kmol^{-1}$ K^{-1})
s	specific entropy (kJ $kmol^{-1}$ K^{-1} or kJ kg^{-1} K^{-1})
$\dot{S}$	entropy (kW/K)
T	gasifier temperature (K)
T_0	ambient temperature (K)
T_w	wall temperature (K)
U_0	wind velocity (m/s)
U	overall heat transfer coefficient between gasifier wall and ambient (W m^{-1} K^{-1})
x	insulation thickness (m)
X	mole fraction

Greek letters

β	coefficient
ε	gasifier wall emissivity
γ	supplied steam (kg/s)
α	quantity of biomass (kg/s)
η	efficiency

Subscripts

biomass	biomass
ch	chemical
char	char
desi	internal exergy destruction
deswa	external exergy destruction
en	energy
ex	exergy
gen	generation
gas	gas
H_2	hydrogen
H_2O	water, vapor
ins	insulation
lostwa	lost from gasifier wall to ambient
o	reference state or ambient
ph	physical
steam	steam
tar	tar
w	wall
wa	from wall to ambient

biomass (sawdust wood). This study is belonging to the approach that developed before but the present results are in regard to evaluation of hydrogen production efficiency. The modeled approach can be used to predict hydrogen production and also can depend on it to support results from this study. This requires knowing biomass properties, specifically, the proximate and the ultimate analysis and its heating value.

In essence, the gasifier is considered a heart of a gasification process. Ptasinski et al. [13] and Vlaswinkel et al. [12] demonstrated that the gasifier is one of the least-efficient unit operations in the whole gasification technology. Therefore, improvement of overall efficiency (energy and exergy) of gasifier will improve the whole gasification technology.

Past research was focused on effect of process parameters such as temperature, pressure, steam–biomass ratio, air to biomass ratio and biomass type on the hydrogen yield and total gas and tar yields [5,11,14]. Focus on the thermodynamics of biomass gasification has been relatively limited [7]. Ptasinski et al. [15] compared gasification efficiencies of different biofuels in ideal gasifier used air agent. They found from the calculated exergy efficiency that the exergy efficiency that was calculated at 600 °C is comparable to that calculated from coal. It was lower in case of materials which have higher moisture like Sludge. Pellegrini et al. [16] performed exergy analysis to evaluate irreversibility associated with air-gasification process based on chemical equilibrium consideration and that by minimizing Gibbs energy of the produced gas. The developed model studied an influencing of variables such as: gasification temperature, moisture content, and air temperature. Prins et al. [17] mentioned to importance of the conservation of energy as well as the energy quality. The energy and exergy losses were performed for adiabatic system at atmospheric pressure. The system used biomass and air/steam gasification medium. They found energy and exergy of product gas are maximum at the point where all carbon is consumed. They have noticed hardly thermodynamic losses happen when adding more steam than the process required. Rao et al. [18] identified the sources and magnitudes of the irreversibility and inefficiencies in terms of energy conversion and energy available of refuse derived fuel. They conducted studies on counter current fixed bed to compare refuse derived fuel pellets with other different biomasses and fuels. They developed stoichiometric empirical equation to describe the gasification process. Their results show produced gas from refuse derived fuel is higher in carbon monoxide and hydrogen content comparing to produced gas from wood chips. Also its cold gas efficiency was higher than that of wood chips.

Efficiency evaluation of hydrogen production from biomass gasification through a parametric study aims to calculate the overall efficiency (energy and exergy) for hydrogen production from gasificating a quantity of biomass in existing of an amount of steam as gasification agent. A performed parametric study will help in identifying the more efficient condition or avoid inefficient conditions of hydrogen production via biomass gasification from first- and second law of thermodynamics views.

In addition to that and under the available knowledge of the authors no any study had addressed the hydrogen production performance through exergy efficiencies in addition to energy efficiencies. Studying energy efficiencies is quite common, for example, as Mahishi and Goswami [7] studied energy efficiencies for biomass gasification in existing of air-steam medium. In the present study a comprehensive parametric study is carried out to investigate numerous factors, influencing overall efficiency of hydrogen production from biomass gasification. In this regard, the earlier work by Abuadala et al. [10] is enhanced to mainly explore the influence of steam–biomass ratio and gasification temperature on both energy and exergy efficiencies of hydrogen production. Therefore, these exergy and energy efficiencies are studied for a range of gasification temperature of 950–1500 K and