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Hydrogen production from biomass gasification; a theoretical comparison of using different gasification agents

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ABSTRACT

In the present paper hydrogen production from biomass gasification using various agents is investigated and compared theoretically, from the viewpoints of the first and second thermodynamics laws. Gasification of wood and paper, as two types of common biomass feedstocks, is assessed using four gasification agents namely: air, oxygen-enriched air, oxygen and steam. Thermodynamic equilibrium model is employed to simulate the gasification process, the results of which are validated using available theoretical and experimental data in literature. The NO_x and SO_x emissions from the biomass gasification are also considered in the model and a sensitivity analysis is performed to determine the accuracy of the results regarding to the uncertainties of the input data. A parametric study is conducted to assess the effects of key operating parameters on the hydrogen concentration and calorific value of producer gas, energy and exergy efficiencies of the process and exergy destruction rate at different operating conditions. The results indicate that the higher values of hydrogen production is associated respectively with using steam, oxygen, oxygen-enriched air and air as the gasification agents. Also, it is concluded that for the gasification process the highest value of sensible energy efficiency is obtained for air gasification, while the highest exergy efficiency, as a rational criterion, is obtained for steam gasification for which the calorific value of the producer gas can reach to higher than 11 MJ/Nm^3.

1. Introduction

In recent years, increasing global energy demand, depletion of fossil fuels and increasing environmental concerns arising from fossil fuels have urged researchers to substitute fossil fuels with clean energies that come from renewable resources. Among the renewable energy sources, biomass and hydrogen have received significant attention as they can increase the global energy sustainability and reduce greenhouse gas emissions [1].

Different technologies are developed to convert biomass to producer gas, including thermochemical, biochemical and mechanical extraction methods. Thermochemical conversion methods can be classified into: combustion, gasification, pyrolysis and liquefaction [2]. Among these methods, biomass gasification is considered as a prominent conversion route for producing a clean feedstock for power generation and is preferred as it has lower pollutant emissions and higher efficiency of power and heat generation [3,4]. Various types of biomass fuels such as wood, paper, sawdust and municipal solid waste [5], are used in gasification process by which biomass fuel is converted to syngas that primarily contains carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), water vapor (H_2O) and methane (CH_4). The composition of syngas derived from biomass gasification depends mainly on the biomass fuel, gasifier type and gasification agent [6,7]. Various gasifier types for gasification are used and the selection of the gasifier type depends on the capacity of the unit [8]. Advantages and disadvantages of each gasifier type can be found in Ref. [8]. In addition to different types of the gasifiers, different gasification agents including air, oxygen, oxygen-enriched air and steam can also be employed for gasification process, each of which brings about different composition of the produced syngas.

Recent scientific literature on investigation of gasification process includes assessment of different aspects of the concept applied for power or hydrogen production. Seyitoglu et al. [9] developed an integrated coal based gasification system for hydrogen production and power generation. Energy and exergy analyses on their proposed system showed that the overall energy and exergy efficiencies of the system reaches to 41% and 36.5%, respectively. The effect of biomass packing factor and employing oxygen-enriched air as gasifying agent on fixed bed biomass gasification is studied by Lenis et al. [10], who concluded that the efficiency slightly increases when the packing factor is

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Nomenclature

n_{H_2}	hydrogen moles (kmol)
n_{CO}	carbon monoxide moles (kmol)
n_{CO_2}	carbon dioxide moles (kmol)
n_{H_2O}	water moles (kmol)
n_{CH_4}	methane moles (kmol)
n_{N_2}	nitrogen moles (kmol)
n_{O_2}	oxygen moles (kmol)
n_C	carbon moles (kmol)
Ex	exergy (kJ $kmol^{-1}$)
C	carbon content in biomass (w%)
H	hydrogen content in biomass (w%)
O	oxygen content in biomass (w%)
K	equilibrium constant
ΔG	change in Gibbs function
s	entropy (kJ $kmol^{-1}K^{-1}$)
h	enthalpy (kJ $kmol^{-1}K^{-1}$)
LHV	lower heating value (kJ kg^{-1})
n	kmol of oxygen per kmol of biomass
m	kmol of steam per kmol of biomass
T	temperature (K)
P	pressure (bar)

Subscripts

biomass	biomass
0	reference state
ch	chemical
ph	physical
gen	generation
en	energy
ex	exergy
prod	related to produced gases
agent	related to agent gasification
H_2O	related to steam
f	formation
D	destruction

Greek letters

η	efficiency
ε	specific exergy (kJ $kmol^{-1}$)
β	coefficient

increased. Sepe et al. [11] investigated two advanced steam-gasification technologies of biomass: high temperature steam gasification and solar-assisted steam gasification. Their results showed that, using the high temperature gasification the process efficiency can be improved from 65% to 81% and the content of hydrogen in the syngas can be increased from 30% to 55%. A 1000 kW_{th} pilot biomass gasification plant based on a bubbling fluidized bed gasifier with internal recirculation is constructed and investigated by Barisano et al. [12] focusing on the gasifier performance and quality of the product gas. Their results showed that, using the steam/O_2 mixture as the gasification agent, the cold gas efficiency of the syngas can be increased from 50% to 70%. Song et al. [13] presented thermodynamic analysis of biomass steam gasification via interconnected fluidized bed system and showed that at a given gasification temperature and pressure, the exergy efficiency and dry syngas production have the maximum values when steam-to-biomass ratio is at the corresponding carbon boundary point. Characteristics of woody biomass conversion to syngas using a steam allothermal gasification process is investigated by Balu et al. [14] via building a lab scale apparatus to implement the experimental tests. Their results indicated that the heating value of the syngas reaches to 9–10 MJ/Nm^3. Abuadala et al. [15] studied the influences of the gasification temperature, biomass quantity and steam injection on the hydrogen production and exegetic efficiency of a self-heated gasifier. Their results showed that, hydrogen production enhancement depends on the amount of steam, quantity of biomass feeding to the gasifier and operating temperature. Gasification of agriculture waste using air and steam mixture as the gasification agent is investigated by Chang et al. [16], who showed that the maximum amount of bio-hydrogen (29.5%) and CO (23.6%) was achieved at the equivalent ratio of 0.2 and the gasification temperature of 1000 °C. Rodriguez-Alejandro et al. [17] developed a modified equilibrium model based on free Gibbs energy minimization for simulating a bubbling fluidized bed gasification process and investigated the effects of a wide range of temperatures and equivalence ratios on the produced syngas features. Effects of employing air and air-steam mixture for biomass gasification with/without methane co-feeding are investigated by Nakyai et al. [18] through an exergoeconomic analysis. Their results revealed that the biomass gasification using air-steam as the agent with methane co-feeding yields the lowest unit hydrogen cost of 2.69 $/kg. Zhang et al. [19] conducted energy and exergy analysis of syngas production from biomass gasification for different equivalence ratios and showed that the highest energy and exergy values of syngas are respectively about 10,062 and 7990 kJ per kg of fuel at the reactor temperature of 1000 °C and equivalence ratio of 0.25. A thermodynamic model to evaluate the performance of a downdraft gasifier is presented by Fortunato et al. [20], who showed that the model is able to successfully assess both the composition and heating value of the syngas, derived from several types of biomass, taking also into account the impact of its moisture content. Rao Pala et al. [21] developed a simulation model of biomass gasification for syngas production with steam as gasifying agent and subsequent syngas adjustment using Aspen Plus. Simulations were performed for different biomass feedstocks to predict their syngas composition and it is concluded that the hydrogen and CO concentrations were altered such that the H_2/CO molar ratio in the syngas is close to 2.15.

While biomass-based power and hydrogen production plants are becoming popular in recent years and a lot of studies have been devoted to this field, there is no study focusing on employing different gasification agents and comparing their influence on the producer gas and the gasification process. The present paper aims to investigate and compare the performance of gasification process employing various gasification agents. Four agents, namely: air, oxygen, oxygen-enriched air and steam, are considered and energy and exergy analyses are conducted to assess the performance of the gasification process for hydrogen production. The equilibrium model is considered for simulation of the gasifier and the effects of design and operating parameters are evaluated on the amount of produced hydrogen, calorific value of the producer gas and energy and exergy efficiencies of the process.

2. System modeling and assumptions

There are various types of biomass gasifiers among which the downdraft gasifier is the most common and commercialized one [8]. In the present work this type of gasifier is considered, a schematic of which is shown in Fig. 1. Wood, paper, municipal solid waste and sawdust matters are considered as the biomass feedstock, with the composition given in Table 1a. Also to determine the accuracy of the results regarding to the biomass composition uncertainty, a sensitivity analysis is performed. To perform the uncertainty analysis on the biomass composition, the errors are considered of ± 5%, ± 3%, ± 2%, ± 1% and ± 1% for carbon, oxygen, hydrogen, nitrogen and sulfur mass fractions (as given in Table 1b) on the basis of those elements obtained from the ultimate analysis (as given in Table 1a). Referring to Fig. 1,