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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 $\sim$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 a steam–biomass ratio range of 0.17–0.51 kg steam/kg biomass, respectively. Here is a brief summary to explain how the present work differs from the literature works and earlier studies:

- The present model provides a full picture on the effects of steam–biomass ratio and gasification temperature on energy and exergy efficiencies.
- This approach allows evaluating of the energy and exergy efficiencies of the steam gasification process.
- The computation of individual profiles from parametric study allows avoiding inefficient situations during the gasifier operation and having safe design.
- The modeled approach from earlier work is utilized to support the obtained results.
- The present results assist efforts to understand the thermodynamic analysis to improve both energy and exergy efficiencies for hydrogen production from biomass gasification.

2. Analysis

Before starting the analysis of biomass gasification process, there is a need to make some assumptions as follows:

- The flow is steady-state.
- Potential and kinetic energies are negligible.
- Reference state is chosen as $T_0 = 298$ K and $P_0 = 1$ atm.
- Dry gases obtained from gasification are: H_2, CO, CO_2 and CH_4.
- Ash residue that remains behind gasification process is negligible.
- Gasifier accepts biomass moisture content.
- The gases are treated as ideal gases.
- The char represents a 5% [19] of carbon available in the biomass.
- C_6H_6 represents the tar.
- The gasifer is operated at isothermal and at equilibrium conditions.
- The products from gasification process are delivered at the gasifier temperature.
- There is sufficient residence time to let the gasifier reach the equilibrium mode.

The schematic diagram of the system is shown in Fig. 1 to represent a gasifier for analysis purposes.

2.1. Reaction mechanisms

Carbon, hydrogen and oxygen are the major components in biomass. These and negligible elements like sulfur and nitrogen represented the ultimate analysis. The chemical formula of biomass is represented by $C_lH_mO_n$. The biomass is gasified according to the following global reaction:

$$\alpha C_lH_mO_n + \gamma H_2O + \text{heat} \rightarrow aH_2 + bCO + cCO_2 + dCH_4 + eC + f\text{Tar} \tag{1}$$

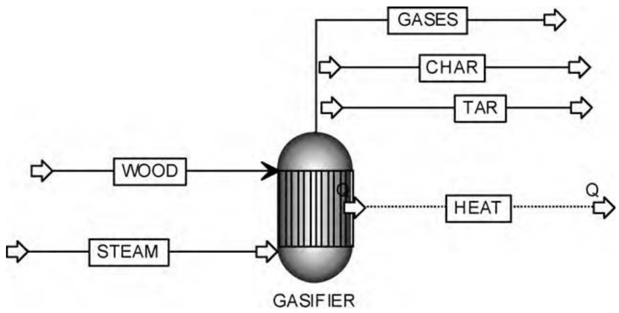

Fig. 1. Schematic diagram of the gasifier considered.

Table 1
Ultimate and proximate analysis of sawdust wood.

Element	Weight on dry basis (%)
C	48.01
H	6.04
O	45.43
N	0.15
S	0.05
Ash	0.32
HHV (MJ/kg)	18.4
Volatile matter	76.78
Fixed carbon	18.7
Ash	0.32

Source: Ref. [11].

where $C_lH_mO_n$ is the chemical representation of biomass. l, m and n are the number of atoms of carbon, hydrogen and oxygen in the feedstock respectively determined from the ultimate analysis of biomass; α is the amount of biomass; and γ is the amount of supplied steam. a, b, c, d, e and f are the number of moles of H_2, CO, CO_2, CH_4, C and tar respectively which they are found from the approach discussed in the previous paper [10]. Same assumptions are made regarding tar and char in this paper.

2.1.1. Biomass equations

The chemical exergy of biomass was calculated according to the method proposed by Szargut et al. [20], for the evaluation of the exergy of solid fuels as follows:

$$Ex_{biomass} = \beta LHV_{biomass} \tag{2}$$

where the coefficient β is given in terms of oxygen–carbon and hydrogen–carbon ratios and according the following equation:

$$\beta = \frac{1.0414 + 0.0177[\mathrm{H/C}] - 0.3328[\mathrm{O/C}]\{1 + 0.0537[\mathrm{H/C}]\}}{1 - 0.4021[\mathrm{O/C}]} \tag{3}$$

and the biomass lower heating value is given by [21]:

$$LHV_{biomass} = 0.0041868(1 + 0.15[\mathrm{O}]) \times \left(7837.667[\mathrm{C}] + 33888.889[\mathrm{H}] - \frac{[\mathrm{O}]}{8}\right) \tag{4}$$

where C, H and O are respectively carbon, oxygen and hydrogen elements in saw dust wood and are obtained from wood ultimate analysis. The fuel data that were used, which correspond to saw dust wood, and includes the ultimate and proximate analysis of the used wood are given in Table 1.

2.2. Energy efficiencies

The first law efficiency or energy efficiency is defined based on conservation of energy, which states the energy lost is the difference in energy supplied to the gasifier and the energy content in the products from the gasification process, and is represented through the following balance equation:

$$\mathrm{H}_{biomass} - H_{gas} - H_{char} - H_t = Q_{lostwa} \tag{5}$$

where H is the enthalpy, Q_{lostwa} is the energy lost during the gasification process and subscripts *biomass*, *gas*, *char* and *t* refer to biomass, gas, char and tar, respectively.

In this analysis, three types of energy efficiencies, η_{en1}, η_{en2} and η_{en3} are defined as follows:

$$\eta_{en1} = \frac{En_{H_2}}{En_{biomass} + En_{stream}} \tag{6}$$

where the output energy is only considered for hydrogen, and

$$\eta_{en2} = \frac{En_{gas}}{En_{biomass} + En_{steam}} \tag{7}$$

where the output energy is only considered for all product gases, and

$$\eta_{en3} = \frac{En_{gas} + En_{char} + En_{tar}}{En_{biomass} + En_{steam}} \tag{8}$$

where the total output energy is considered for all products. Here, En_{H_2} is the energy content in the hydrogen product, En_{gas} is the energy flow-out with gases, En_{char} is the energy flow-out with char, En_{tar} is the energy flow-out with tar, En_{steam} is the energy flow in with injected steam, and $En_{biomass}$ is the energy flow in with biomass.

2.3. Exergy efficiencies

Since exergy analysis is an effective method using conservation of both mass and energy with the second law of thermodynamics for design, analysis and performance improvement of biomass gasification for hydrogen production, it is practically important to assess the exergetic performance of such systems. In his regard, the second law or exergy efficiency is defined as the ratio between desired exergy output(s) from the gasifier to the necessary exergy input to the gasifier. In this exergy efficiency assessment, three forms of rational exergetic efficiencies, η_{ex1}, η_{ex2} and η_{ex3} are defined as follows:

$$\eta_{ex1} = \frac{\dot{E}x_{H_2}}{\dot{E}x_{biomass} + \dot{E}x_{steam}} \tag{9}$$

where exergy rate content of hydrogen is the only output,

$$\eta_{ex2} = \frac{\dot{E}x_{gas}}{\dot{E}x_{biomass} + \dot{E}x_{steam}} \tag{10}$$

where total exergy rate content of all gases is the only output, and

$$\eta_{ex3} = \frac{\dot{E}x_{gas} + \dot{E}x_{tar} + \dot{E}x_{char}}{\dot{E}x_{biomass} + \dot{E}x_{steam}} \tag{11}$$

where total exergy rate contents of all gases, tar and char will make the output.

Here, $\dot{E}x_{H_2}$ is the exergy flow rate of the product hydrogen, $\dot{E}x_{tar}$ is the exergy flow rate with tar, $\dot{E}x_{char}$ is the exergy flow rate with char, $\dot{E}x_{steam}$ is the exergy flow rate with steam and $\dot{E}x_{biomass}$ is the exergy flow rate with biomass. From the thermodynamics point of view, the gasification process has to satisfy both the first and the second laws of thermodynamics. The exergy balance leads to the following equation when a gasifier is taken as a system:

$$\dot{E}x_{biomass} + \dot{E}x_{steam} - \dot{E}x_{gas} - \dot{E}x_{tar} - \dot{E}x_{char} = I \tag{12}$$

where the exergy flow rate is primarily calculated from the following equation:

$$\dot{E}x_i = \dot{m}_i \cdot Ex_i$$

where the subscript *i* represents fuel or agent or product. The exergy content depends primarily on the matter composition, which is known as chemical exergy, Ex_{ch} and for a mixture is given by [22] as

$$Ex_{ch} = \sum_i X_i Ex_{0,i} + RT_0 \sum_i X_i \ln X_i \tag{13}$$

where X_i is the mole fraction of component *i* and Ex_0 is standard exergy and for different compounds is summarized in Table 2. The other part of exergy depends on the matter temperature and mater pressure.

The physical exergy, Ex_{ph}, is given by

$$Ex_{ph} = (h - h_0) - T_0(s - s_0) \tag{14}$$

where *h* and *s* are enthalpy and entropy of a specie when gasifier operates at *T* and *P* and h_0 and s_0 are enthalpy and entropy at standard operating state (i.e., $T_0 = 289\,\mathrm{K}$ and $P_0 = 1\,\mathrm{atm}$).

Table 2
Standard chemical exergy and enthalpy of formation for different components.

Component	Standard chemical exergy (kJ/kmol)	Enthalpy of formation (kJ/kmol)
CH_4	831,650	−74,850
CO	275,100	−110,530
CO_2	19,870	−393,520
H_2O	9,500	−241,820
H_2	236,100	0.0
C	410,260	0.0
C_6H_6	3,303,600	82,930

Source: Ref. [21].

The total exergy, *Ex*, then becomes

$$Ex = Ex_{ch} + Ex_{ph} \tag{15}$$

The enthalpy and entropy values are necessary to perform a thermodynamic analysis. The gases are assumed to be the ideal gas and their respective enthalpies and entropies are as follows:

$$h = h_f^0 + \int_{T_0}^{T} C_p\, dT \tag{16}$$

The enthalpy of formation values, h_f^0 for the different species is given in Table 2. The values of constant pressure specific heat for gases are a function of gasifier temperature and can be calculated using the following empirical equation [23]:

$$C_P = a' + b'T + c'T^2 + d'T^3 \tag{17}$$

where the coefficients, a', b', c' and d' of different gases are summarized in Table 3.

The system consists of a set of equations for all chemical species involved in the analysis including the equation of atomic balance for each element, the equation of the total number of moles, the equations of variation of the standard Gibbs free energy of formation of the species and the energy balance around the gasifier.

2.4. Irreversibilities (exergy destructions/losses)

In this section, exergy destructions within the system and losses in interaction with the surrounding are studied. There are internal irreversibilities causing exergy destructions during the gasification process as a result of flow of substances, physical changes in states, heat and mass transfer, and chemical reactions. It is given by the following equation:

$$\dot{E}x_{desi} = T_0 \dot{S}_{gen} \tag{18}$$

Before we present the equation for exergy losses, we need to look at the heat rejection aspects of it. Therefore, the heat rejection from the gasifier is defined as:

$$\dot{Q}_{lostwa} = U_{wa} A (T_w - T_0) \tag{19}$$

Here, the gasifier wall temperature, T_w is estimated from the energy balance made around the gasifier wall (with a thickness,

Table 3
The coefficients used in constant specific heat empirical equation.

Gas	a'	b'	c'	d'
CO	28.16	0.1675×10^{-2}	0.5372×10^{-5}	-2.222×10^{-9}
CO_2	22.26	5.981×10^{-2}	-3.501×10^{-5}	-7.469×10^{-9}
H_2O	32.24	0.1923×10^{-2}	1.055×10^{-5}	-3.595×10^{-9}
H_2	29.11	-0.1916×10^{-2}	0.4003×10^{-5}	-0.8704×10^{-9}
CH_4	19.89	5.2040×10^{-2}	1.269×10^{-5}	-11.01×10^{-9}

x_{ins} and thermal conductivity, k_{ins}) through:

$$U_{wa}(T_W - T_0) = \frac{k_{ins}}{x_{ins}}(T - T_W) \tag{20}$$

Here, the overall heat transfer coefficient, U_{wa} between the external gasifier wall at a temperature T_W and the ambient at a temperature T_0 estimated by the following empirical relation given by Isachenko et al. [24]:

$$U_{wa} = 1.9468(T_W - T_0)^{1/4}(2.8633U_0 + 1)^{1/2} + 5.75 \times 10^{-8}\varepsilon_{ins}\frac{T_W^4 - T_0^4}{T_W - T_0} \tag{21}$$

where U_0 is the average wind velocity and a value of 2 m/s, as a common one, is used in this study. The exergy loss from the gasifier wall becomes:

$$\dot{E}x_{deswa} = \dot{Q}_{lostwa}\left(1 - \frac{T_0}{T_W}\right) \tag{22}$$

Therefore, the total irreversibility (including both internal and external) results in:

$$I = \dot{E}x_{desi} + \dot{E}x_{deswa} \tag{23}$$

A potential to improve the exergy efficiency of the hydrogen production from biomass gasification is analysed by using the concept of potential improvement. It investigates how much energy available can be redirected to ward hydrogen production. The potential improvement in exergy can be calculated from the following equation [25]:

$$PI = I(1 - \eta_{ex1}) \tag{24}$$

3. System description

The study done on system considered as shown in Fig. 1 simulates an atmospheric self-heated gasifier at equilibrium state. This gasifier has internally heat to assist gasification process and operates at a temperature range of 950–1500 K and the fed biomass was 14.5 kg/s and steam flowing at a rate of 6.3 kg/s and at a temperature of 500 K. The study evaluates hydrogen production from a process of steam gasification of biomass process in two ways. In the first: gasification temperature is varied while the fed biomass and injected steam are 14.5 and 6.3 kg/s, respectively. In the second set, the amount of steam–biomass ratio is varied while the gasification temperature is kept constant.

4. Results and discussion

Here, for the case studies considered, the following data are used in the analysis.

- The ambient conditions are $T_0 = 298$ K and $P_0 = 1$ atm.
- The gasifier dimensions are 0.08 m outside diameter and 0.50 m height.
- The gasifier has a wall with insulation thickness of $x_{ins} = 5$ mm, thermal conductivity, $k_{ins} = 0.06$ W/m K and emissivity, $\varepsilon_{ins} = 0.01$.
- The average wind velocity is $U_0 = 2$ m/s.
- The gasifier operates in a temperature range of 950–1500 K and the atmospheric pressure.
- The gasifier operates in a steam–biomass ratio range of 0.17–0.51 kg steam per kg biomass.

The study evaluates hydrogen production from a process of biomass steam gasification in two ways. In the first case, steam–biomass ratio is varied while the gasification temperature is kept constant. In the second case, gasification temperature is varied while the fed biomass and the injected steam are 14.5 and 6.3 kg/s, respectively. The present model is constructed in the EES (Engineering Equation Solver) for parametric studies.

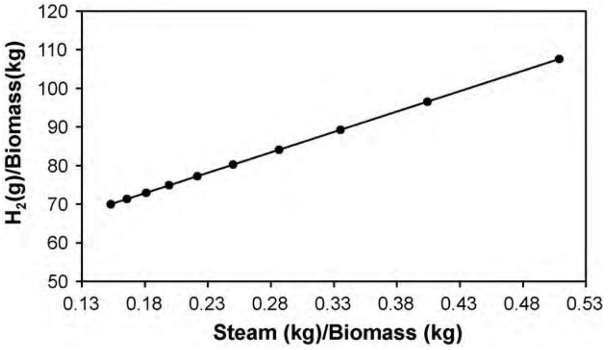

Fig. 2. Hydrogen yield from different steam–biomass ratios and at 1023 K.

4.1. Effect of steam–biomass ratio on hydrogen production

In this section, a parametric study for combined effects of steam amount and biomass quantity is performed. Here, the steam–biomass ratio refers to mass of steam inject per mass of biomass fed. The displayed trend in Fig. 2 shows an increase in H_2 corresponding with an increase in steam–biomass ratio. Such trend was also observed by Mahishi and Goswami [7] and is consistent with their results. Hydrogen yields range from 70 to 107 g H_2/kg biomass. This is also partly in consistent with the literature experimental data. For example, Turn et al. [11] reported some hydrogen production results using different gasifier types, namely batch-type reactor, bubbling fluidized beds and dual fluidized bed technologies as ranging from 30 to 80 g H_2/kg biomass, and they did not give a specific reason for such a large difference. The difference could be attributed to the differences in circumstances and hydrogen potentials with the different technologies and different gasifiers used. Circumstances and features are different with differences in types of gasification technology as well. The hydrogen yield potential is defined as the total hydrogen theoretically is formed by considering possible side reactions like shift-reaction and reforming reaction. To predict potentials to increase gasification ratio, the gases concentration against steam–biomass ratio are plotted in Fig. 3. From the first look on the graph, one can observe that the hydrogen concentration increases with increasing in the steam–biomass ratio. Also, for this set of results CO concentration becomes negligible after a steam–biomass ratio of ~0.50 kg steam kg^{-1} biomass. Therefore, theoretically one can expect enhanced hydrogen will come from the wood conversion and side reactions that using other species.

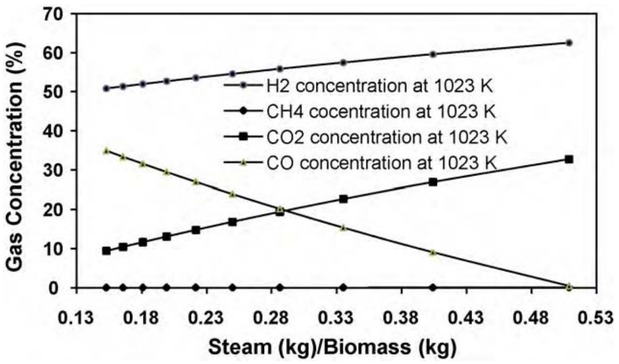

Fig. 3. Concentration of gases from gasification at different steam–biomass ratios.

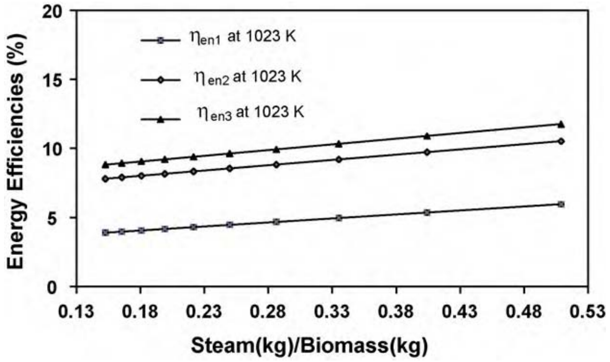

Fig. 4. Energy efficiencies for different steam–biomass ratios.

4.2. *Effect of steam–biomass ratio on energy efficiency*

It is found that energy efficiencies considered have low sensitivity to the studied range of steam–biomass ratio. Fig. 4 shows the efficiencies versus steam–biomass ratio have similar trends. A little variation, ~3% in these efficiencies appears within the studied steam–biomass ratio range at a gasification temperature of 1023 K. All the products from gasification process leave the gasifier at the gasification temperature. Therefore, some improvement in gas efficiency is expected if their energy content is extracted. At higher gasification temperature the fuel released energy in form of gases. As an increase of the higher hydrogen production is observed and as the hydrogen has higher energy content compared to other gases. It is logical to expect that the higher hydrogen yield gives indication to higher energy content in the product gas which in turn leads to higher energy efficiency.

4.3. *Effect of steam–biomass ratio on exergy efficiency*

Three exergy efficiencies were defined in the analysis section earlier and according to the desired outputs and plotted in Fig. 5. The exergy efficiency, η_{ex1} that considers hydrogen production is increasing as steam–biomass ratio increases and that because there is available energy increases as hydrogen increases. The other two efficiencies, η_{ex2} and η_{ex3} have similar trends. The exergy efficiency, η_{ex3} has the highest value because it considers all the products from the gasification process. It is noticed there is a point where the exergy efficiencies η_{ex2} and η_{ex3} are minimum. This can refer to the same reason that it was mentioned in our previous work [10]. The entropy generation per unit mass of biomass was plotted in Fig. 6. It is obvious from the graph the specific entropy generation is maximum at the state corresponding to the minimum exergy efficiency. At lower steam–biomass ratio there is insignificant change in specific entropy generation (Fig. 6). However, in this case the results show that there is a minimum exergy efficiency point, belonging to η_{ex3} curve and corresponding to maximum specific entropy generation point. It is important to clarify that considering η_{ex3} where gasifier temperature is constant, the external irreversibility is related to the thermal losses from the gasifier wall and internal irreversibility that is calculated from entropy generation. The former is function of gasifier wall temperature and this is constant as gasifier temperature is kept constant. Therefore, one can attribute that to the internal irreversibility.

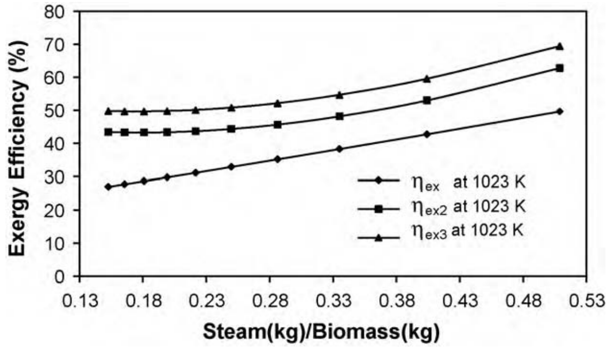

Fig. 5. Exergy efficiencies for different steam–biomass ratios.

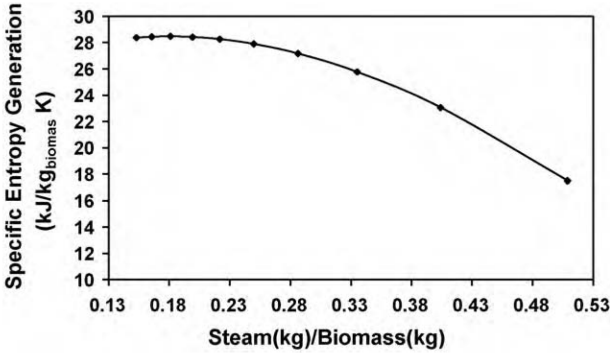

Fig. 6. Specific entropy generation corresponds to η_{ex3} at 1023 K.

4.4. *Effect of gasifier temperature on hydrogen production*

In this section, a parametric study for effects of gasification temperature is performed. The gasification temperature is a temperature at which gasification process takes place. The displayed trend in Fig. 7 shows decrease in H_2 corresponding with an increase in gasification temperature. This can be attributed to that at higher temperature other reactions take place and produces gases as by product from reaction with other species. This also observed by Florin and Harris [9]. This comparison can be considered reasonable because the not active sorbent case could fairly simulate the non-used sorbent case which is the case of this work. In the same temperature range it is found that gasification ratio increases and it was less sensitive to higher temperature. The maximum hydrogen that can be produced under this condition is ~105 g per kg of biomass gasified (Fig. 8).

4.5. *Effect of gasifier temperature on energy efficiency*

Over the studied temperature range it is observed that energy efficiency η_{en1} is less sensitive to temperature than the other efficiencies, Fig. 9. This may be attributed to that more energy content in products other than hydrogen and that also can be observed

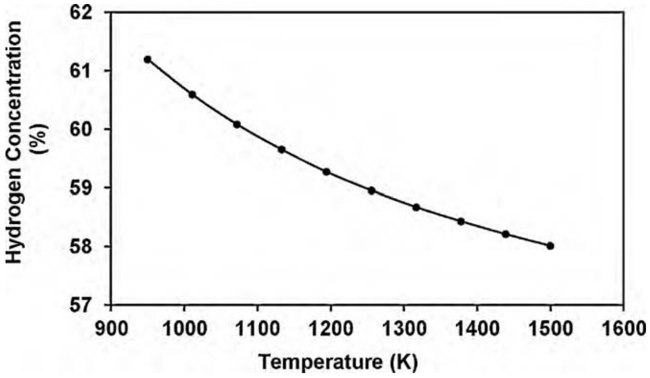

Fig. 7. Production hydrogen at different gasification temperatures for 14.5 kg/s from sawdust and 6.3 kg/s from steam.

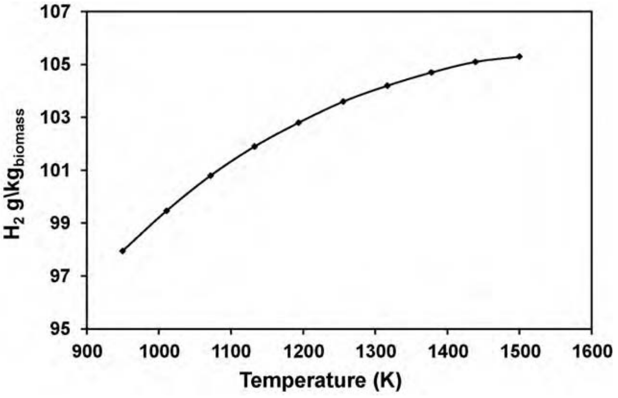

Fig. 8. Hydrogen yield at different temperatures for 14.5 kg/s from sawdust and 6.3 kg/s from steam.

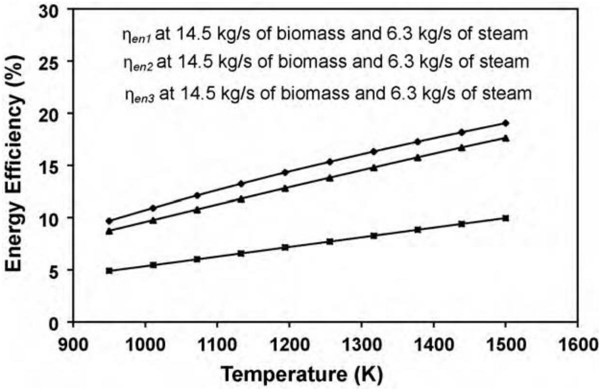

Fig. 9. Cold gas efficiencies at different temperatures.

when including more energy by including more contents in case of η_{en2} and η_{en3}.

4.6. *Effect of gasifier temperature on exergy destruction and exergy efficiency*

The exergy destroyed in the gasification process decreases after a temperature of 1000 K. This because of the available energy with gasification process products becomes dominant and this can be also seen from the exergy efficiencies graph where exergy efficiency increases. Also, it is observed from the obtained results that the exergy efficiency of hydrogen production process has minimum potential improvement at ~1000 K and was increasing beyond that temperature as well as the destroyed exergy (Fig. 10).

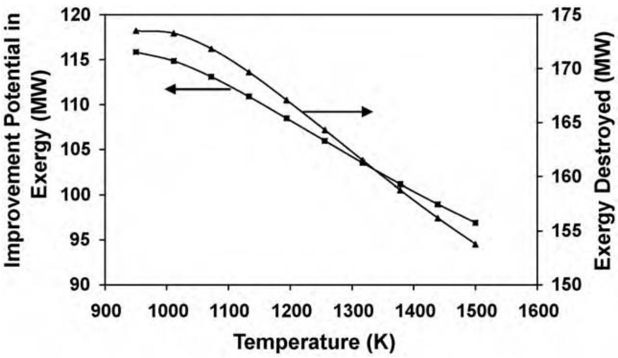

Fig. 10. Exergy destroyed and improvement potential in exergy for 14.5 kg/s from sawdust and 6.3 kg/s from steam.

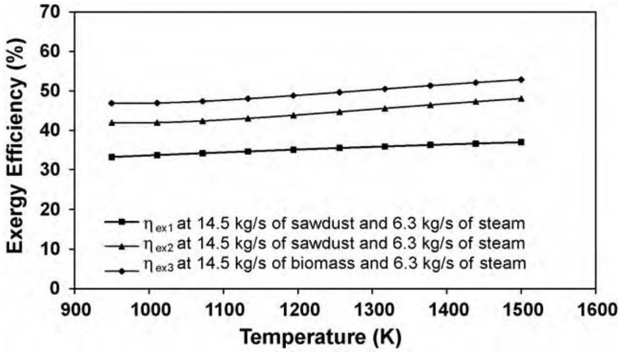

Fig. 11. Exergy efficiency at different gasification temperatures.

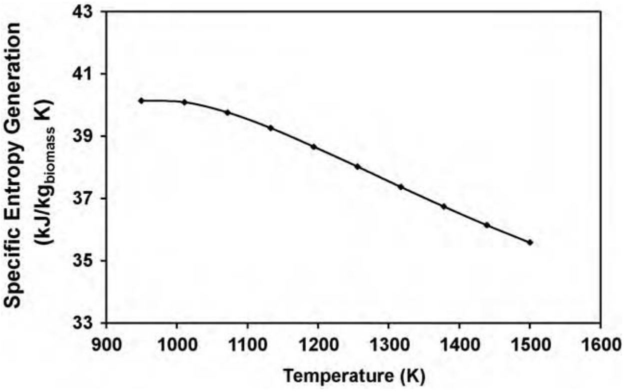

Fig. 12. Specific entropy generation corresponds to η_{ex3} at different temperatures for 14.5 kg/s sawdust and 6.3 kg/s steam.

In the studied temperature range, the same exergy trend scenario is repeated. There was improving in exergy efficiency over the studied temperature range. The sensitivity to temperature in the studied temperature range is less than the sensitivity of steam–biomass ratio. The exergy efficiency when hydrogen is taken in consideration does not exceed ~4% and it is less sensitive to temperature than the other two efficiencies. Also, it was observed from the results there is a minimum point of exergy regarding η_{ex2} and η_{ex3}, see Fig. 11. To discuss that entropy is plotted over the temperature range in Fig. 12. The same conclusion to the one drawn from the previous discussion can be said about the specific entropy generation corresponding to this phenomenon. It is difficult to declare that from Fig. 12 due to an insignificant change of specific entropy in a band of the results around a point of maximum entropy generation. In this case there is a more drastic decrease in specific entropy compare with versus gasification temperature.

5. Conclusions

The performance assessment of hydrogen production from the gasification of sawdust wood by studying the energy and exergy efficiencies shows the potential to produce hydrogen from biomass. Evaluations in regard to efficiency appear to be the ultimate option for hydrogen production in terms of optimum operating conditions studies and based on thermodynamic efficiency.

This paper shows the results of the evaluation of efficiency analysis of biomass gasification to produce hydrogen. The evaluation was focused on the influence of the gasification temperature, biomass feeding and steam injecting ratio on the energy and exergy efficiencies. The analysed gasification process was atmospheric where as the temperature range was in a range of 950–1500 K and the steam–biomass ratio was in a range of 0.17–0.51 kg steam per kg biomass.

Since there is a lack of data and under the same conditions, results from literature regarding hydrogen product will be used to verify the obtained results. Once the data regarding hydrogen product is verified, then using this data will lead to accurately reasonable results. On this path, the results showed that the hydrogen produced by following the approach from previous work reaches 70–107 g H_2 kg^{-1} biomass. While at the examined operating gasifier temperature, the hydrogen yield reaches 97–105 g H_2 kg^{-1} biomass. The hydrogen yield was consistent with the literature results and verified with a reasonable accuracy. This makes to assume the derived conclusion regarding efficiencies is on right track and supports the results from this work.

The energy efficiency in the studied steam–biomass range reaches ~15% when the product gases are taken into consideration while reaching ~8% based on hydrogen product. The exergy efficiency reaches ~50, 63 and 69% based on hydrogen, product gases and all the products, respectively. In the studied temperature range, the energy efficiency reaches ~19% when all the product gases are taken into consideration while it reaches ~10% in the case when only hydrogen product is taken into consideration. Under the same temperature range, the exergy efficiency reaches ~37, 47 and 52% based on hydrogen, product gas and all the products, respectively. The energy efficiency, or the cold gasification efficiency, is low in the case of considering hydrogen product because the other products were not taken into consideration. In addition, hydrogen or other products from the gasification process leave the gasifier at a higher temperature with energy available for further use. The sensitivity of exergy efficiency to temperature in the studied temperature range is lesser than the sensitivity of steam–biomass ratio. It can be concluded from the efficiency evaluation, biomass gasification exhibits good potential for hydrogen production in the range of the studied parameters.

At certain gasification temperature, increase in steam–biomass ratio enhances the hydrogen yield while at certain steam–biomass ratio, an increasing of the gasification temperature results increasing in energy and exergy efficiencies.

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