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

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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.

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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 (m³ 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/m³ stp.), but the separation cost of pure oxygen
The process of biomass gasification requires a high energy input. 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
fluidized bed achieves the highest hydrogen product. However, the cost of hydrogen production from the downdraft process is the lowest due to the highest exergy efficiency for three different hydrogen production processes.

As described above, the effect of methane co-feeding and the use of different agents for biomass gasification on the hydrogen content have been widely reported. However, the energy and cost analysis of the hydrogen production of biomass gasification, which provides important indicators for the decision to select the proper guidelines, is still a matter for further investigation. Thus, the main objectives of this work are to study the impact of methane co-feeding in biomass gasification and the suitable gasifying agents using an exergoeconomic analysis. The effects of the preheating temperature of the agents, equivalence ratio and steam to biomass ratio are considered first to find the proper conditions for biomass gasification. In the next section, a comparison of different gasifying agents and the addition of methane for the exergy and economic analysis are investigated.

2. Simulation and model

2.1. Assumptions of the model

Biomass gasification is considered in the downdraft reactor. The downdraft fixed bed gasification includes four zones; drying, pyrolysis, combustion, and gasification. In this study, the combustion and gasification were combined in same zone. The flowsheet of the biomass gasification is shown in Fig. 1. The basic assumptions for the simulation of the biomass gasification are as follows:

1. biomass gasification operates at steady-state conditions;
2. the system is assumed to be adiabatic;
3. all gases behave as ideal gases; and
4. the reactions in the gasifier are at an equilibrium state.

2.2. Aspen Plus model description

The biomass used in this study is rubber wood. The proximate and ultimate analyses of the rubber wood are shown in Table 1 [28]. The proximate analysis reveals the contents of fixed carbon (FC), volatile matter (VM), moisture content (MC), and ash (ASH). The ultimate analysis reveals the elemental contents of carbon, hydrogen, nitrogen, oxygen, and ash. Fig. 1 shows the unit operations of the biomass gasification process simulated in an Aspen Plus flowsheet. For the downdraft gasification process, the biomass is fed into a drying zone. RSTOIC and FLASH3 blocks were used for drying zone. An RSTOIC block was used to convert the raw biomass into dry biomass and steam. The reaction for biomass drying is as follows.

\[
\text{Biomass}^{(\text{wet})} \rightarrow \text{Biomass}^{(\text{dry})} + \text{H}_2\text{O}^{(\text{steam})}
\]  

The dry biomass and steam was separated with the FLASH3 block. In the decomposition or pyrolysis zone, the RYIELD block was used to convert the nonconventional component into the constituent elements of carbon, nitrogen, oxygen, hydrogen, sulphur, and ash. The yield distribution is highly dependent on the biomass feedstock as evaluated by the ultimate analysis. Before feeding the dry biomass into the RGIIBBS block, the heat of reaction (QDCOMP) associated with the decomposition of the biomass must be considered in the biomass gasification. In the gasification zone, the RGIBBS block based on the chemical and phase equilibria was used as a reactor. The reactions occurring in the gasification zone were included in Table 2 [29]. The dry biomass was fed with various gasification agents and fuel, such as air, steam, and methane. To preheat the gasifying agent and fuel, the HEATER block was employed. In the final zone, the separation of the syngas product from the ash used the SSPPLIT block.

According to the Aspen Plus simulator, the physical properties of the conventional component can be calculated using the Peng-Robinson-Boston-Mathias (PR-BM) model. This thermodynamic property model can describe both pure and mixed components. Naveed et al. [30] showed that this model is quite appropriate for high ranges of temperature and pressure. In this simulation, the HCOALGEN and DCOALIGT property models were used to calculate the enthalpy and density of the biomass and ash, which are non-conventional components.

![Aspen Plus flowsheet used for simulation of biomass gasification process in downdraft fixed bed.](image-url)
3. Energy and exergy analysis

3.1. Energy analysis

The energy analysis consists of four types of energy, which are kinetic energy ($E_k$), potential energy ($E_p$), physical energy ($E_{ph}$), and chemical energy ($E_{ch}$), as follows:

$$ E_{total} = E_k + E_p + E_{ph} + E_{ch} $$  \hspace{1cm} (2)

The kinetic and potential energies have very low values compared with the total energy [22,31] so they can be neglected. The simplified equation for the total energy is shown below.

$$ E_{total} = E_{ph} + E_{ch} $$  \hspace{1cm} (3)

$$ E_{ph} = \sum_i n_i h_i $$  \hspace{1cm} (4)

In Eqs. (3) and (4), $h_i$ is the specific enthalpy (kJ/kmol) and $n_i$ is the molar yield of gas component $i$ (mol/kg). The specific enthalpy, specific entropy, standard chemical exergy, and higher heating value of the component of gases at the dead state (temperature $T_0 = 25$ °C and pressure $P_0 = 1$ atm) are shown in Table 3.

The chemical energy is calculated from the higher heating value (HHV) of gas component $i$, which can be obtained from Eq. (5).

$$ E_{ch} = \sum_i n_i HHV_i $$  \hspace{1cm} (5)

The energy of the biomass is calculated from the equation as follow:

$$ E_{ch} = mHHV_{biomass} $$  \hspace{1cm} (6)

where $m$ is the mass flow rate of the biomass in kg/s and $HHV_{biomass}$ represents the higher heating value of the biomass in MJ/kg. The higher heating value of rubber wood is 19.6 MJ/kg [28].

### 3.2. Exergy analysis

Based on the second law of thermodynamics, the exergy can be defined as the maximum work obtainable between the system and reference states. In this section, the evaluation of the exergy for biomass gasification is obtained from Eq. (7).

$$ Ex_{total} = Ex^i + Ex^{ep} + Ex^{ph} + Ex^{ch} $$  \hspace{1cm} (7)

where $Ex_{total}$ is the total exergy of the gas product (kJ/kg) and $Ex^i$, $Ex^{ep}$, $Ex^{ph}$, and $Ex^{ch}$ are the kinetic exergy, potential exergy, physical exergy, and chemical exergy, respectively. Previous studies have been reported that the values of the kinetic and potential exergies are very low and can be neglected [22]. Thus, the simplified total exergy can be written as:

$$ Ex_{total} = Ex^{ph} + Ex^{ch} $$  \hspace{1cm} (8)

The physical exergy can be calculated as:

$$ Ex^{ph} = \sum_i n_i Ex_{ph} $$  \hspace{1cm} (9)

where $Ex^{ph}$ denotes the physical exergy of component $i$ in the gas product, which can be obtained Eq. (10) [18,32].

$$ Ex^{ph} = (h - h_0) - T_0(s - s_0) $$  \hspace{1cm} (10)

where $h_0$ and $s_0$ are the specific enthalpy and entropy at the reference state.

$$ h - h_0 = \int_{T_0}^{T} c_p dT $$  \hspace{1cm} (11)

and

$$ s - s_0 = \int_{T_0}^{T} c_p dT - R \ln \frac{p}{P_0} $$  \hspace{1cm} (12)

where $c_p$ is the specific heat capacity at constant pressure (kJ/kg K). The coefficient of the heat capacity for each component can be obtained from [33], as shown in Table 3.

$$ c_p = a + bT + cT^2 + dT^3 $$  \hspace{1cm} (13)

where $a$, $b$, $c$, and $d$ are empirical coefficients.

The chemical exergy is similarly calculated as

$$ Ex^{ch} = \sum_i n_i (Ex^{ch}_i + RT_0 \ln Y_i) $$  \hspace{1cm} (14)

where $Ex^{ch}_i$ is the standard chemical exergy of gas component $i$ as shown in Table 3 and $Y_i$ is the mole fraction of gas component $i$.

The feed exergy of the biomass is given by the correlation equation as below [34]:

$$ Ex^{biomass} = \mu (HHV_{biomass} + |MC| h_{ash}) + 9683[S] + Ex_{ash}[ASH] + Ex_{H_2O}[MC] $$  \hspace{1cm} (15)

### Table 2
Reactions in the gasifier.

<table>
<thead>
<tr>
<th>Reaction number</th>
<th>Reaction name</th>
<th>Reaction equation</th>
<th>Heat of reaction (MJ/kmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Char gasification</td>
<td>C + H₂O → CO + H₂</td>
<td>+131</td>
</tr>
<tr>
<td>R2</td>
<td>Methanation</td>
<td>C + 2H₂ → CH₄</td>
<td>-75</td>
</tr>
<tr>
<td>R3</td>
<td>Boudouard</td>
<td>C + CO₂ → 2CO</td>
<td>+172</td>
</tr>
<tr>
<td>R4</td>
<td>Char partial oxidation</td>
<td>C + 0.5O₂ → CO</td>
<td>-283</td>
</tr>
<tr>
<td>R5</td>
<td>Char combustion</td>
<td>C + O₂ → CO₂</td>
<td>-393</td>
</tr>
<tr>
<td>R6</td>
<td>Methane shift</td>
<td>CH₄ + H₂O → CO + 3H₂</td>
<td>+206</td>
</tr>
<tr>
<td>R7</td>
<td>Water gas shift</td>
<td>CO + H₂O → CO₂ + H₂</td>
<td>-41</td>
</tr>
<tr>
<td>R8</td>
<td>Hydrogen partial oxidation</td>
<td>H₂ + 0.5O₂ → H₂O</td>
<td>-242</td>
</tr>
</tbody>
</table>

### Table 3
Specific enthalpy, specific entropy, standard chemical exergy, and higher heating value of the components at the dead state.

<table>
<thead>
<tr>
<th>Component</th>
<th>Enthalpy, $h_0$ (kJ/kmol)</th>
<th>Entropy, $s_0$ (kJ/kmol K)</th>
<th>Exergy, $Ex^{ch}$ (kJ/kmol)</th>
<th>Higher heating value, HHV (kJ/kg)</th>
<th>Empirical coefficients for specific heat capacities</th>
<th>Temperature range (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>8468</td>
<td>130.57</td>
<td>236,100</td>
<td>285,840</td>
<td>$a = 29.11, b = -0.19, c = -0.04, d = -0.87$</td>
<td>273–1800</td>
</tr>
<tr>
<td>CO</td>
<td>8669</td>
<td>197.54</td>
<td>275,100</td>
<td>282,900</td>
<td>$a = 28.16, b = 0.17, c = 0.53, d = -2.22$</td>
<td>273–1800</td>
</tr>
<tr>
<td>CO₂</td>
<td>9364</td>
<td>213.69</td>
<td>19,870</td>
<td>19,290</td>
<td>$a = 22.26, b = 5.98, c = -3.50, d = 7.47$</td>
<td>273–1800</td>
</tr>
<tr>
<td>CH₄</td>
<td>-</td>
<td>186.16</td>
<td>831,650</td>
<td>890,360</td>
<td>$a = 19.89, b = 5.02, c = 1.27, d = -11.01$</td>
<td>273–1800</td>
</tr>
<tr>
<td>N₂</td>
<td>8669</td>
<td>191.50</td>
<td>720</td>
<td>-</td>
<td>$a = 28.90, b = -0.16, c = 0.81, d = -2.87$</td>
<td>273–1800</td>
</tr>
<tr>
<td>O₂</td>
<td>8682</td>
<td>205.03</td>
<td>3970</td>
<td>-</td>
<td>$a = 25.48, b = 1.52, c = -0.72, d = 1.31$</td>
<td>273–1800</td>
</tr>
<tr>
<td>H₂O (g)</td>
<td>9904</td>
<td>188.72</td>
<td>9500</td>
<td>-</td>
<td>$a = 32.24, b = 0.19, c = 1.06, d = -3.60$</td>
<td>273–1800</td>
</tr>
<tr>
<td>Air</td>
<td>-</td>
<td>69.94</td>
<td>900</td>
<td>-</td>
<td>$a = 28.11, b = 0.20, c = 0.48, d = -1.97$</td>
<td>273–1800</td>
</tr>
</tbody>
</table>
where \( h_w \) is the evaporation enthalpy of moisture in the biomass, \( \beta \) is a correlation factor, which can be defined as Eq. (16). However, according to Eq. (15) the exergy of ash is neglected. This is due to there is relatively small effect on the total exergy.

\[
\beta = 1.0412 + 0.2160[H/C] - 0.2499[O/C](1 + 0.7884[H/C]) + 0.0450[N/C]/1 - 0.3035(O/C)
\]

(16)

\[ LHV_{\text{biomass}} \] is the lower heating value of the biomass in MJ/kg. This parameter is calculated from the following equation:

\[
\]

(17)

The mass percentages of the C, H, O, and S elements in the biomass can be obtained from ultimate analysis, as shown in Table 1. The relationship between the lower heating value (LHV) and the higher heating value (HHV) can be calculated using the following equation [35]:

\[
\text{HHV} = \text{LHV} + 21.978 \, [H]
\]

(18)

The physical exergy of the biomass at the initial state is zero [20].

The physical exergy and chemical exergy of the gasification agent are evaluated using equations Eqs. (9) and (14). The physical exergy and the chemical exergy of air can be calculated from Eq. (19).

\[
Exh_{\text{air}} = m_{\text{air/biomass}} \left[ \frac{\text{ex}^h_{O_2} + 3.76 \text{ex}^h_{N_2} + RT_o (\ln y_{O_2} + \ln y_{N_2})}{y_{O_2} + y_{N_2}} \right]
\]

(19)

where \( m_{\text{air/biomass}} \) is the moles of air to mass of biomass ratio, \( \text{ex}^h_{O_2} \) and \( \text{ex}^h_{N_2} \) are the standard chemical exergies of oxygen and nitrogen, respectively, \( y_{O_2} \) and \( y_{N_2} \) are moles fraction of oxygen and nitrogen in air and \( R \) is the universal gas constant.

3.3. Energy and exergy efficiencies

The energy and exergy efficiencies of the product gas in a biomass gasification are calculated using the following equations:

\[
\eta_E = \frac{E_{\text{gas}}}{E_{\text{biomass}} + E_{\text{agent}} + E_{\text{methane}}} \times 100%
\]

(20)

\[
\eta_{Ex} = \frac{Ex_{\text{gas}}}{Ex_{\text{biomass}} + Ex_{\text{agent}} + Ex_{\text{methane}}} \times 100%
\]

(21)

The overall energy efficiency is defined as the ratio of the energy of the syngas at the output to the energy inputs which comprise the energy flow in with gasified fuels and agents. In addition, the energy efficiency of the system is considered as follows:

\[
\eta_{E_{\text{sys}}} = \frac{E_{\text{gas}}}{E_{\text{fuel}} + Q_{\text{sup}}} \times 100%
\]

(22)

where \( Q_{\text{sup}} \) is the heat supplied in the preheating of gasifying agents and fuels. Similarly, the exergy efficiency of the overall system is presented as the following equations:

\[
\eta_{Ex_{\text{sys}}} = \frac{Ex_{\text{gas}}}{Ex_{\text{fuel}} + Ex_{\text{q}}}
\]

(23)

where \( Ex_q \) is the exergy due to the heat transfer for each equipment and according to the following equation:

\[
Ex_q = \left( 1 - \frac{T_o}{T} \right) Q_{\text{sup}}
\]

(24)

3.4. Exergoeconomic analysis

The cost balance for downdraft gasification operating at steady state is calculated by Eq. (25) [5,36,37].

\[
\dot{C}_p = \dot{C}_f + \frac{Z_k^f}{T_k}
\]

(25)

where \( \dot{C}_f \) is cost rate of the product stream ($/h), Z is sum of capital investment cost and the operating and maintenance costs of the system ($/h) of component k, and \( \dot{C}_f \) is the cost rate of the feed stream ($/h), calculated from following equation.

\[
\dot{C}_f = e\dot{Ex}
\]

(26)

where e is the unit exergy cost of the stream (heat, or work stream) at the inlet and outlet in the biomass gasification system and \( e\dot{Ex} \) is the exergy rate.

The total cost rate of operation and maintenance can be obtained as follows (\( Z_k^f \)) [38,39].

\[
Z_k^f = Z_k^i + Z_k^{OM}
\]

(27)

According to Eq. (27), the total operation and maintenance cost for the \( k \)th equipment in a gasification process is the sum of the capital investment cost (\( Z_k^i \)) and the hourly operating and maintenance cost (\( Z_k^{OM} \)), which can be determined using Eqs. (28) and (29).

\[
Z_k^i = \frac{\phi CA_{\text{process}}}{\tau} \frac{PEC}{\sum_{\text{process}} PEC_k}
\]

(28)

\[
Z_k^{OM} = \frac{\phi CA_{\text{process}}}{\tau} \frac{PEC}{\sum_{\text{process}} PEC_k}
\]

(29)

where \( CA_{\text{process}} \) is the annual capital investment cost, \( CA_{\text{process}}^{OM} \) is the annual operating and maintenance factor, \( PEC \) is the purchased equipment cost, and \( \tau \) is the annual operation time of equipment \( k \).

In Eqs. (28) and (29), the annualized capital cost (\( CA \)) can be calculated using the capital recovery factor (CRF) and present worth (PW) of the process.

\[
CA_{\text{process}} = PW_{\text{process}} CRF
\]

(30)

Using the interest rate \( i \), the capital cost recovery factor (CRF) is

\[
CRF = \frac{i(i + 1)^n}{(1 + i)^n - 1}
\]

(31)

The present worth of the considered process (PW) is

\[
PW_{\text{process}} = C - S_p PWF
\]

(32)

where C is the initial investment cost of equipment.

The present worth factor (PWF) is

\[
PWF = \frac{1}{(1 + i)^n}
\]

(33)

where \( i \) is the interest rate, \( n \) is the lifetime of the equipment in years, and \( S_p \) is the salvage value at the end of the equipment life. In this study, both the interest rate and salvage value are taken to be 10% [26]. The economic data based on the biomass gasification process and the criteria for calculating the operation annualized costs are shown in Tables 4 and 5. The annual labor cost estimation assumes fulltime operation [25,40].

The cost rate of fuel can be calculated using the following equation [41]:

\[
\dot{C}_{\text{Fuel}} = m_{\text{fuel}} LHV_{\text{Fuel}}
\]

(34)
where $\text{LHV}_{\text{fuel}}$ is the lower heating value of fuels (biomass and methane). The lower heating value of the methane is 50,050 kJ/kg [42], while the lower heating value of biomass can be calculated from Eq. (17).

The unit cost of gasification agents, including air and steam, are shown in Table 5 [24,25]. The unit of methane cost is taken from literatures are 2 $/\text{GJ}$ and 4.59 $/\text{t}$, respectively [26,27].

The total capital investment cost of equipment in each system depends on the size and capacity of the equipment. Thus, the rule of six-tenths method was applied for calculating the total capital investment cost, which is given by:

$$C_i = C_0 \left( \frac{S_i}{S_0} \right)^{0.6}$$

(35)

where $C_i$ is actual cost of component, $C_0$ is the reference cost having size $S_0$, and $f$ is scaling factor. The scaling factor is commonly used in the range of 0.3–1. In this work, the value of scaling factor assumed to be 0.6 [44]. Additionally, not only the size and capacity of equipment have effect on the total capital investment cost, but also the reference year should be regarded. The cost at the reference year can be calculated from the Chemical engineering Plant cost index (CEPCI). In this study, the reference year was 2016. The cost at reference year can be obtained as the following equation:

Cost at the reference year = Original cost

$$\times \left( \frac{C_l \text{ for reference year}}{C_l \text{ when original cost was obtained}} \right)$$

(36)

The values of CI are 390.6, 395.6 and 536.5 for years 1999, 2002, and 2016, respectively [45]. The case-based cost of gasifier and heater were adapted from previous work [46].

### 3.5 Model validation

The rubber wood chips as biomass and an air gasification agent are fed into a downdraft gasifier to produce the syngas. The downdraft gasification for syngas production was validated with the experimental data of Jayah et al. [28]. The ultimate and proximate analyses of the biomass fuel are given in Table 1. The operating conditions of the biomass gasification process for the validation of the model are included in Table 6. Table 7 shows the predicted syngas composition, including hydrogen, carbon monoxide, carbon dioxide, and methane, compared the experimental data at the equivalence ratios of 0.35 and 0.38 [28]. It can indicate that the results from the model and experiment are in good agreement.

### 4. Results and discussion

#### 4.1 Gasification of biomass

##### 4.1.1 Influence of the preheating temperature of the gasification agent and equivalence ratio on the syngas composition

The influences of the equivalence ratio (ER) and preheating temperature on the syngas composition are illustrated in Fig. 2 (a)-(d). In this study, the inlet mass flow rate of biomass to the gasifier is 266.7 kg/h. The preheating temperature was varied from 100 to 1000 °C, while the equivalence ratio (ER) was studied in the range of 0.15–0.45. Fig. 2(a) shows the effects of the preheating temperature and ER on hydrogen production. As seen, increasing the preheating temperature can enhance hydrogen production and decrease methane and carbon dioxide production. This is because the char gasification reaction (R1), Boudouard reaction (R3), and methane shift reaction (R6) as endothermic reactions are favoured at higher preheating temperatures. Additionally, the carbon monoxide content gradually increases from 19.88% to 22.88% as the preheating temperature is elevated from 100 to 1000 °C.

The ER is the ratio of the air flow supplied relative to the air flow needed for the stoichiometric complete combustion of the biomass. From Fig. 2(a)-(d), the yield of hydrogen slightly increases upon increasing the ER from 0.15 to 0.21. However, increasing the ER from 0.21 to 0.45 causes the yield of hydrogen to be reduced from 24.11% to 9.66%. The increment of the ER over 0.21 provides a benefit of the air excess to the system, resulting in the enhancement of the char partial oxidation (R4) and hydrogen partial oxidation (R8) reactions. Thus, the composition of the combustible gases, including hydrogen, carbon monoxide, and methane, are diminished as the ER is raised (see Fig. 2(b)-(d)). For the content of carbon dioxide in product gas, the carbon dioxide can be produced from the char combustion reaction (R5). However, the content of the carbon dioxide decreases at higher ER, resulting from carbon dioxide consumed in the Boudouard reaction (R3). It can be explained that the
increasing of the ER raises the oxidation and combustion taken place in the gasification process. This leads to the increase in the temperature of the biomass gasification system due to the biomass gasification as adiabatic process. Therefore, the increase in the ER drives the Boudouard reaction (R3) as the endothermic reaction in forward direction. Simultaneously considering the effects of the preheating temperature and the equivalence ratio, the maximum hydrogen production that can be achieved is 24.11% at the preheating temperature of 1000 °C and ER of 0.21.

4.1.2. Influence of the steam to biomass ratio on the syngas composition

The addition of steam to biomass gasification can enhance the hydrogen yield. Therefore, the influence of additional steam on the product composition was studied in this section. The optimum preheating temperature and ER are 1000 °C and 0.21, respectively. Fig. 3 presents the additional steam to biomass ratio from 0 to 2.0 at a preheating temperature of 1000 °C and an ER of 0.21. In the steam to biomass ratio (S/B) range of 0–1.0, the hydrogen, carbon monoxide, carbon dioxide, and methane fractions were calculated.
dioxide and methane increase, whereas the carbon monoxide decreases. This can be explained by steam driving the char gasification (R1), methane shift (R6), and water gas shift (R7) reactions. In the char gasification, the solid carbon reacts with steam to form hydrogen and carbon monoxide, leading to the enhancement of the hydrogen yield. In addition, the methane produced in the gasification chamber can be reacted with the steam to produce the hydrogen and carbon monoxide in the syngas product from the methane shift reaction (R6). However, the carbon monoxide content in the syngas is decreased with increasing S/B owing to the water gas shift reaction. In the S/B range of 1.0–2.0, it can be observed that the component contents of hydrogen, carbon monoxide, carbon dioxide, and methane decrease. This is because the introduction of excessive steam to the biomass gasification results in the decrease in the reaction temperature, leading to the reduction in the syngas contents in product gas. Moreover, the decrease in all components in the product also arises from the dilution due to the excessive steam in the biomass gasification. Thus, the optimum ratio of steam to biomass at the maximum yield of hydrogen is 1.0.

### 4.2. Gasification of biomass at different gasifying agents with and without methane co-feeding

#### 4.2.1. Influence of different gasifying agents with and without methane co-feeding on H₂/CO ratio

In this section, the influence of the use of air and/or steam as the gasifying agent with the co-feeding of methane on the yield of the gas product was studied. The various gasifying agents in four cases are used at a preheating temperature of 1000 °C and equivalence ratio of 0.21. The steam and methane to biomass ratios were set to 1.0 and 0.36 kg/kg biomass, respectively. Table 8 compares the product gas compositions using different agents in biomass gasification with and without methane co-feeding. The various gasifying agents are divided into four cases: air (A), air with methane co-feeding (A + M), air and steam (A + S), and air and steam with methane co-feeding (A + S + M). It can be observed that utilizing a mixture of air and steam as a gasifying agent can improve the syngas quality compared to the case of using air alone, without methane co-feeding. This is because the oxygen content in the air provides the energy for exothermic reactions in biomass gasification. The addition of steam also has the effect of driving the water gas shift reaction (R7), resulting in increases in the hydrogen and carbon dioxide contents. The hydrogen production can be also increased with adding steam from the char gasification reaction (R1).

In addition, the influence of the C species of CH₄ can be divided to two cases: the air as gasification agent with co-feeding of methane (A + M) and air-steam with co-feeding of methane (A + S + M). Firstly, the Boudouard (R3) and char partial oxidation (R4) reactions can occur when using the methane co-feeding with biomass for the gasification with air. This result leads to the increase in the carbon monoxide, whereas the concentration of carbon dioxide becomes lower. Secondly, when using steam with methane co-feeding, the contents of hydrogen and carbon monoxide increase as a result of the char gasification (R1) and methane shift reaction (R6) reactions. Furthermore, the carbon dioxide and hydrogen are increased by the reaction between carbon monoxide and steam from the water gas shift (R7). The mixture of air and steam as an agent with methane co-feeding can enhance the hydrogen yield from 23.26 to 67.31 mol/kg biomass.

#### 4.2.2. Influence of different gasifying agents with and without methane co-feeding on system performance

The performances of biomass gasification processes are indicated by the energy and exergy efficiencies. The total energy can be determined from the physical and chemical energy. Physical energy is the change of enthalpy from the environmental state, while the chemical energy values of the product gases are evaluated from Eq. (5). The energy efficiency is the ratio of energy outputs to energy inputs.

A comparison of the energy and exergy efficiencies of different gasifying agents for biomass gasification is illustrated in Fig. 4. From Fig. 4, the exergy efficiency is lower than the energy efficiency because the entropy occurred in the system is taken into consideration of exergy efficiency. The range of energy efficiency of the product gas with various gasifying agents is 66.41–87.14%. The air-steam with co-feeding of methane has the highest energy efficiency of the product gas because of the high yields of hydrogen, carbon dioxide, and methane in this case.

According to the second law of thermodynamics, the exergy efficiency in the product gas can be investigated using Eq. (21), which is the work output compared to the potential of the input to do work. As can be seen Fig. 4, the exergy efficiency shows similar trend with the energy analysis. The exergy efficiency of product gas is 46.16%, 57.90%, 57.52% and 71.80% for air (A), air with methane co-feeding (A + M), air and steam (A + S), and air and steam with methane co-feeding (A + S + M), respectively. The use of air-steam as a gasifying agent with methane co-feeding shows the highest exergy efficiency. This is because this case produces the highest yields of hydrogen of all of the agents as shown in

---

### Table 8

<table>
<thead>
<tr>
<th>Cases</th>
<th>Gasification agents</th>
<th>Fuels</th>
<th>Gas composition (mol/kg biomass)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>H₂</td>
</tr>
<tr>
<td>A</td>
<td>Air</td>
<td>Biomass</td>
<td>23.26</td>
</tr>
<tr>
<td>A + S</td>
<td>Air-steam</td>
<td>Biomass</td>
<td>46.82</td>
</tr>
<tr>
<td>A + M</td>
<td>Air</td>
<td>Biomass with methane co-feeding</td>
<td>49.07</td>
</tr>
<tr>
<td>A + S + M</td>
<td>Air-steam</td>
<td>Biomass with methane co-feeding</td>
<td>67.31</td>
</tr>
</tbody>
</table>

---

**Fig. 4.** Energy and exergy efficiencies of biomass gasification using various gasification agents and methane co-feeding; A (air), S (steam), and M (methane).
The increased amount of syngas product in the process can improve the chemical exergy as well and thereby the total exergy. The addition of steam and methane to the gasifier requires more energy consumption for the preheating. Thus, the energy and exergy efficiencies of the overall system using various gasification agents and methane co-feeding should be considered. Fig. 5 shows the overall energy and exergy efficiencies of A, A + S, A + M, and A + S + M, which are in the range of 66.36–84.25% for energy efficiency and in the range of 45.12–66.12% for exergy efficiency. The results indicate that the tendencies of the overall energy and exergy efficiencies are the same as the energy and exergy efficiencies of product gas. The air-steam co-feeding of methane also has the highest energy and exergy efficiencies of the overall system. This result indicates that the increment of energy consumption for the preheating of steam and methane has less influence on the energy and exergy efficiencies of overall system.

### Table 8

<table>
<thead>
<tr>
<th>Gasification agents</th>
<th>Overall energy</th>
<th>Overall exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>66.36%</td>
<td>45.12%</td>
</tr>
<tr>
<td>A + S</td>
<td>84.25%</td>
<td>66.12%</td>
</tr>
<tr>
<td>A + M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A + S + M</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.** Overall energy and exergy efficiencies of biomass gasification using various gasification agents and methane co-feeding: A (air), S (steam), and M (methane).

## 4.3. SPECO analysis

The specific exergy cost (SPECO) was used to calculate the hydrogen unit costs using the exergy-related costs in thermal systems. In this study, the unit costs of the four cases using different gasifying agents with and without methane co-feeding were obtained. To calculate the cost rate of the input stream, the exergy of the steam input in Section 4.2 was used. The mass flow rate, temperature, pressure, unit cost rate, and cost rate of the input stream are given in Table 9. It can be seen that the exergy rate stream has a direct effect on its cost rate. From Table 9, the cost rate of biomass and methane as fuel are higher than that of the gasifying agent due to the high exergy rate of the biomass and methane streams.

For the capital investment cost, the main equipment in the biomass gasification process, including the downdraft gasifier and heat exchanger, were calculated using Eqs. (27)–(33). An interest rate of 10% was specified. Therefore, the CRF can be determined using Eq. (31) and a value of 0.11. Consequently, the purchased equipment, operation and maintenance, and total costs of the biomass gasification and its components are shown in Table 10. The results were found that the cost rate of the capital investment cost is lower than operating and maintenance cost. The largest cost rate of capital investment, operating, and maintenance are the gasifier about 53% of total cost rate of the process. Considering the cost rate of the heaters, which are used to preheat the gasifying agents and fuels, the cost rate of heater (Heat Ex 2) for preheating of steam is higher than that for preheating the air and methane (Heat Ex 1 and Heat Ex 3). This can be described that the preheating of steam needs more energy than air and methane at the same temperature. In addition, the operating cost rate depends on the several parameters such as the labor cost, catalyst, interest rate, maintenance, and other. Also, the interest and maintenance mainly affect the operating and maintenance cost rate.

### Table 9

<table>
<thead>
<tr>
<th>Stream</th>
<th>Mass flow rate (kg/s)</th>
<th>Temperature (K)</th>
<th>Pressure (kPa)</th>
<th>Ex (MW)</th>
<th>C ($/GJ)</th>
<th>C ($/h)</th>
</tr>
</thead>
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<tr>
<td>Biomass</td>
<td>0.074</td>
<td>298.15</td>
<td>101.325</td>
<td>1.63</td>
<td>1.78</td>
<td>10.45</td>
</tr>
<tr>
<td>Air</td>
<td>0.097</td>
<td>298.15</td>
<td>101.325</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0.074</td>
<td>298.15</td>
<td>101.325</td>
<td>0.04</td>
<td>8.47</td>
<td>1.22</td>
</tr>
<tr>
<td>Methane</td>
<td>0.027</td>
<td>298.15</td>
<td>101.325</td>
<td>1.40</td>
<td>2.90</td>
<td>14.61</td>
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<tr>
<td>Pre-air</td>
<td>0.097</td>
<td>1273.15</td>
<td>101.325</td>
<td>0.07</td>
<td>23.33</td>
<td>5.53</td>
</tr>
<tr>
<td>Pre-steam</td>
<td>0.074</td>
<td>1273.15</td>
<td>101.325</td>
<td>0.13</td>
<td>27.52</td>
<td>12.64</td>
</tr>
<tr>
<td>Pre-methane</td>
<td>0.027</td>
<td>1273.15</td>
<td>101.325</td>
<td>1.46</td>
<td>3.80</td>
<td>20.03</td>
</tr>
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</table>

### Table 10

<table>
<thead>
<tr>
<th>Capital investment</th>
<th>PEC ($)</th>
<th>PEC%</th>
<th>ZC ($/h)</th>
<th>ZSM ($/h)</th>
<th>ZO ($/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasifier</td>
<td>501228.16</td>
<td>0.53</td>
<td>6.84</td>
<td>18.62</td>
<td>25.46</td>
</tr>
<tr>
<td>Heat Ex 1</td>
<td>106763.99</td>
<td>0.11</td>
<td>1.46</td>
<td>3.97</td>
<td>5.42</td>
</tr>
<tr>
<td>Heat Ex 2</td>
<td>224773.40</td>
<td>0.24</td>
<td>3.07</td>
<td>8.35</td>
<td>11.42</td>
</tr>
<tr>
<td>Heat Ex 3</td>
<td>108653.02</td>
<td>0.12</td>
<td>1.50</td>
<td>4.04</td>
<td>5.53</td>
</tr>
<tr>
<td>Total</td>
<td>941418.57</td>
<td>1.00</td>
<td>12.86</td>
<td>34.97</td>
<td>47.83</td>
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</table>

<table>
<thead>
<tr>
<th>Operation ($/yr)</th>
<th>Labor cost</th>
<th>35000.00</th>
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</thead>
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<tr>
<td></td>
<td>Catalyst</td>
<td>18828.37</td>
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<tr>
<td></td>
<td>Interest</td>
<td>9414.19</td>
</tr>
<tr>
<td></td>
<td>Insurance</td>
<td>28242.56</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>9414.19</td>
</tr>
<tr>
<td></td>
<td>Overheads/other</td>
<td>9414.19</td>
</tr>
<tr>
<td>Total</td>
<td>279768.83</td>
<td></td>
</tr>
</tbody>
</table>
methylene co-feeding (A + M + S) is highest of total cost rate. This is due to a high cost of the heater that is used to preheat the gasifying agent and fuel. Moreover, the cost rate of operation and maintenance in case of the using air-steam as a gasification agent is higher than that of using only air as a gasification agent. This situation can be described that the steam production consumes the energy more than the preheating of air and methane. The cost rate of the preheating temperature for steam is higher than that for air and methane about 16.47 and 36.85%, respectively.

In addition, the cost rates of fuel have also directly effect on the cost of hydrogen production. The case of air and steam as an agent with methane co-feeding is the highest of the cost rate for fuel cost because of the price of methane. Comparing to the gasifying agent for all case study, the cost rate of steam also prominent when compare with air. As a result, it can be indicated that the total cost rate of air-steam as an agent with methane co-feeding gives the highest total cost rate. In comparison to using air as the gasifying agent, the total cost rate of using only air as an agent without methane co-feeding are lower than those of the cases of a mixture of air and steam (A + S) and air with methane co-feeding (A + M). The total cost rate of four cases are 46.98, 71.43, 72.41, and 96.43 $/h for air (A), air and steam (A + S), air with methane co-feeding (A + M) and air-steam as an agent with methane co-feeding (A + S + M).

Table 11 shows the costs of hydrogen using different gasification agents. The cost of hydrogen production can be estimated from the cost balance at steady state from Eqs. (25) and (26). The values of the cost of hydrogen in the four cases are evaluated as 3.79, 2.84, 2.77, and 2.69 $/kg for air (A), air and steam (A + S), air with methane co-feeding (A + M), and air-steam with methane co-feeding (A + S + M), respectively. As mentioned above, the use of air as a gasification agent gives the highest cost of hydrogen production. Nevertheless, the total cost rates of the capital investment as well as the operation and maintenance are the lowest, as seen in Fig. 6. This is mainly due to the low hydrogen yield produced from the gasifier (see Table 6). The cost can be reduced by increasing the hydrogen content in the syngas. Thus, the use of air-steam with methane co-feeding (A + S + M) gives the lowest cost of hydrogen because it has the maximum mass flow rate of hydrogen of 26.17 kg/h.

In this section, the unit hydrogen production cost via different process was compared, which is the non-renewable and renewable energy sources. The non-renewable energies are the reforming of natural gas and coal gasification processes. Also, the alternative or renewable energies for the hydrogen production are electrolysis and power tower electrolysis processes [47–50]. From Table 12, it indicates that the cost of hydrogen production via the steam reforming of natural gas, which is conventional process, in the small scale (500 kg/day) is higher than that via the biomass air-steam gasification with methane co-feeding. In contrast, the hydrogen cost from the biomass air-steam gasification with methane co-feeding is not competitive with the steam reforming of natural gas process at large-scale facility (1.2 Gg/day). For coal gasification, the cost of the hydrogen production is the lowest because of a low price of the feedstock. Although the hydrogen production cost via coal gasification process is the cheapest, using coal as fuel can lead to serious environmental impacts.

Apart from the hydrogen production from the thermal process, the water electrolysis combined with wind or solar energy resource to produce hydrogen is also considered. The hydrogen production costs from these technologies are still currently high priced. The cost of hydrogen production from the water electrolysis combined with wind resource is 3.50 $/kg which is not included the capital cost of turbine. For the hydrogen cost from the water electrolysis combined with solar resources, this process is the highest production cost per kilogram of hydrogen (5.10 $/kg), when compared to the other sources. The cost of hydrogen production from the water electrolysis combined with the solar energy is more than 1.89 times the biomass air-steam gasification with methane co-feeding. It is clear that the hydrogen production cost via solar energy is not competitive in this time and needs to be developed for completion in the future. As mentioned in Table 12, it can be concluded that the hydrogen production costs from this study are practically application in the area of hydrogen production.

Also, in order to reduce the cost of the hydrogen production and increase the efficiency of the system, some researcher has been conducted the hydrogen and power production to reduced cost of hydrogen production [27]. The hydrogen cost from such system of 1.16 $/kg for biomass gasification process. Kohl et al. [51] investigated the performance of three different biomass upgrading process (wood pellets, torrefied wood pellets, and fast pyrolysis slurry) with a combined heat and power plant. They reported that the

Table 11 Unit hydrogen costs from different gasifying agents and methane co-feeding.

<table>
<thead>
<tr>
<th>Gasification agent</th>
<th>A</th>
<th>A + S</th>
<th>A + M</th>
<th>A + S + M</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_1$ ($/h)$</td>
<td>30.99</td>
<td>42.41</td>
<td>36.41</td>
<td>47.83</td>
</tr>
<tr>
<td>$C_{Biomass}$ ($/h)$</td>
<td>10.45</td>
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<td>10.45</td>
<td>10.45</td>
</tr>
<tr>
<td>$C_{Air}$ ($/h)$</td>
<td>5.53</td>
<td>5.53</td>
<td>5.53</td>
<td>5.53</td>
</tr>
<tr>
<td>$C_{Water}$ ($/h)$</td>
<td>-</td>
<td>12.64</td>
<td>-</td>
<td>12.64</td>
</tr>
<tr>
<td>$C_{Methane}$ ($/h)$</td>
<td>-</td>
<td>0.00</td>
<td>20.03</td>
<td>20.03</td>
</tr>
<tr>
<td>$C_{H_2}$ ($/kg$)</td>
<td>46.98</td>
<td>71.03</td>
<td>72.41</td>
<td>96.48</td>
</tr>
<tr>
<td>$H_2$ ($/h$)</td>
<td>12.40</td>
<td>24.98</td>
<td>26.18</td>
<td>35.90</td>
</tr>
<tr>
<td>$C_Needs$ ($/kg$)</td>
<td>3.79</td>
<td>2.84</td>
<td>2.77</td>
<td>2.69</td>
</tr>
<tr>
<td>$C_Needs$ ($/kWh$)</td>
<td>0.096</td>
<td>0.072</td>
<td>0.070</td>
<td>0.068</td>
</tr>
</tbody>
</table>
exergetic efficiencies of the system are improved. In addition, as mentioned previously, the operation of the biomass with air-steam as agent with methane co-feeding in the large scale process similar to reforming of natural gas may reduce the hydrogen production cost.

5. Conclusions

The hydrogen production from biomass gasification using different gasifying agent and adding methane as co-feeding studied though energy, exergy, and economic analysis has been presented. The effects of the operating parameters of biomass gasification without methane co-feeding i.e., preheating temperature, equivalence ratio, and steam to biomass, were studied in the first part. The simulation results showed that increasing the preheating temperature of the gasification agent and fuel can positively affect the hydrogen product. The equivalence ratio (ER) is affected to biomass gasification process comprising syngas compositions. High ER leads to decrease in the hydrogen yield of product gas. Additionally, the hydrogen content in syngas can be enhanced with adding steam to the biomass gasification. However, the excessive steam results in the dilution of syngas product. Considering the effect of using methane co-feeding, the addition of methane to the air-steam biomass gasification can raise the hydrogen yield and steam to the gasifier requires higher energy input, the air-steam biomass gasification with methane co-feeding achieves the highest energy and exergy efficiencies of product gas at 87.14% and 71.80%, respectively.

Considering the overall system, the overall energy and exergy efficiencies in case of the air-steam biomass gasification with methane co-feeding are also higher than other cases. It has been shown that the increment of hydrogen yield in case of adding methane and steam into the biomass gasification has significant impact on the increase in the energy and exergy efficiencies in spite of higher energy input. In the exergoeconomic analysis, the SPECO method was obtained to estimate the unit cost of hydrogen. According to the results of hydrogen unit cost, the air-steam biomass gasification with methane co-feeding provides the lowest hydrogen production cost of 2.69 $/kg which is practically applicable in the area of hydrogen production. Moreover, the hydrogen unit cost of the biomass air-steam gasification with methane co-feeding is lower than that of the steam reforming of natural gas in the small scale which is the conventional process of hydrogen production. Therefore, the air-steam biomass gasification with methane co-feeding is an attractive process for the hydrogen production.

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References


