Exergoeconomic comparison of syngas production from biomass, coal, and natural gas for dimethyl ether synthesis in single-step and two-step processes

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ABSTRACT

Dimethyl ether (DME) as a promising alternative fuel can be produced through two-step and single-step processes with differently suitable H_2/CO ratio in syngas. Natural gas, coal, and biomass are potential energy sources for syngas production to synthesize the DME. In order to analyze the proper process of syngas production for the DME synthesis, this work aims to compare the syngas production processes from biomass gasification, coal gasification, and methane tri-reforming for the sinle-step and two-step processes through the exergoeconomic analysis. The results showed that from the coal gasification achieves the highest energetic efficiencies of the syngas production for both single-step and two-step processes while the methane tri-reforming shows the highest exergetic efficiencies at H_2/CO of 2. In the exergoeconomic analysis, the air-steam coal gasification showed the lowest syngas unit cost of 0.65 $/kg for the two-step process, while biomass gasification with air-steam agent presents the lowest unit cost of syngas of 0.54 $/kg for the single-step process. When considering the environmental point of view, the intensity of CO_2 emission of biomass gasification with oxygen-steam agent for the single-step process of DME synthesis is the lowest about 2.83 tonne CO_2/tonne syngas.

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1. Introduction

Dimethyl ether (DME) is one of the most promising alternative energy sources because it is an environmentally benign fuel and chemical intermediate. DME also can be used for different purposes such as household fuel, diesel replacement, chemical feedstock, and fuel for electricity generation. The global market of the DME was expected to increase about 20 million metric tons in 2020 (as increased 15.67%) (Dimethyl ether Market, 2015). Therefore, the development in order to increase DME productivity and process efficiency is essential.

The DME can be manufactured by either two-step or single-step processes. The two-step process comprises two reactors with different catalysts for methanol and DME syntheses. The single-step process of the DME production is the methanol synthesis and methanol dehydration in a single reactor using a bi-functional catalyst (Chen et al., 2012). DME in the two-step and the single-step processes produces from H_2 and CO in a syngas. The H_2/CO ratio is a main factor on the DME yield. Lu et al. (2004) indicated that the H_2/CO of 1 in syngas was suitable for the single-step of DME synthesis using fluidized bed reactor. Ju et al. (2009) found that the $H_2/CO = 1$ provided the maximum yield and DME selectivity of 0.37 and 0.91, respectively. These are consistent with the results of Ogawa et al. (2004) and Huang et al. (2015). Peng et al. (1999) obtained the optimum H_2/CO ratio for methanol and DME syntheses are 2 and 1, respectively. Moradi et al. (2008) found that the methanol productivity increased at H_2/CO ratio of 2, and thereby increasing the DME yield. As aforementioned above, the proper ratio of H_2/CO for single-step and two-step processes are between 1 and 2.

The composition of H_2/CO ratio as syngas depends on the feedstock, gasifying agent, and operating condition. Several feedstocks, i.e., natural gas, coal, and biomass have been studied for producing syngas. Traditionally, the natural gas is used to produce H_2-rich syngas as feedstock for many chemical productions (Fan et al., 2016; Zhang et al., 2013). The most common processes of the syngas production from natural gas are steam reforming and dry reforming. Nevertheless, the drawbacks of steam reforming and

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dry reforming processes are the need of high energy to provide the endothermic reaction in the reformer and the easy occurrence of coke formation resulting in deactivation of catalyst (Rahnama et al., 2014; García-Vargas et al., 2015). To overcome the weakness of both processes, tri-reforming of methane is interesting process because of its energy efficient process (Song and Pan, 2004). It is a combination of steam reforming, dry reforming, and partial oxidation of methane. Many researches have been used the tri-reforming of methane for producing syngas and hydrogen (Chein and Hsu, 2018). Zhang et al. (2014) suggested that the operation at high temperature and low pressure in the reformer encouraged hydrogen yield as well as carbon dioxide conversion.

Among these feedstocks, coal is widely used for syngas production because of abundant energy resource and low cost (Liszka et al., 2012). For syngas production via renewable resources, biomass is a potential energy source to replace the fossil fuels because it is relatively plenty and CO_2 neutral (Van der Heijden and Ptasinski, 2012). The process for conversion of coal and biomass to syngas is gasification (Huang and Dincer, 2014). The gasifying agents, such as air, steam, carbon dioxide, are vital factor that has influence on the syngas yield and process performance (Colpan et al., 2010). The utilization of steam can enhance the syngas yield, while the use of oxygen can help to supply the necessary heat for the endothermic reactions in the coal and biomass gasifiers (Sharma and Sheth, 2016).

The H_2 and CO ratio in the syngas has not only the effect on the DME yield, the others, i.e., CO_2, H_2O, and H_2S, contain in the syngas are also effect on the DME production. Huang et al. (2015) reported that the CO_2 co-feeding between 0 and 10 vol% in the feed reduced the CO conversion and DME yield. Similarly, Mevawala et al. (2017) found that the CO_2 content about 3 mol % with the fresh feed of syngas reduced the DME productivity. Kung (1992) pointed out that the sulphur content in the feed stream should be reduced to below 0.5 ppm because it deactivated the activity of catalyst in the methanol synthesis. As previously mentioned from the literature, the composition of syngas is directly affected the methanol and DME yields. To investigate the preparation of the syngas production for DME synthesis in the two-step and single-step processes, the processes for CO_2, H_2O, and H_2S removals from syngas should be taken into account.

To improve and design the efficient syngas production for DME synthesis in both two-step and single-step processes, the energy, exergy, economic, and environmental analyses are important deep-going evaluation. Energy and exergy approaches have been studied in many thermochemical processes. Energy analysis is based on the first law of thermodynamics and used to analyze the energy utilization, whereas the exergy analysis is a useful method that is based on the first and second laws of thermodynamics (Zhang et al., 2015). Exergy is used to identify the source, type and magnitude of energy losses in a system (Szargut et al., 1988). Therefore, energy and exergy efficiencies are currently used to indicate and compare the system performance of the hydrogen and syngas productions from coal (Liszka et al., 2012), rice husk (Zhang et al., 2015), natural gas (Simpson and Lutz, 2007), and biomass (Iribarren et al., 2014). Additionally, the economic analysis is an important criterion on decision to find the suitable process for syngas production. Exergoeconomic is a powerful method which combines of the exergetic and economic analyses in order to evaluate and improve the performance systems (Tsatsaronis and Moran, 1997).

The various studies have been conducted on the exergy, energy, and exergoeconomic analyses of hydrogen production by using different gasification systems (Chen et al., 2012), co-feeding fuels, and gasifying agents (Nakyai et al., 2017). Liszka et al. (2012) studied energy and exergy analyses of hydrogen production from coal gasification. Their studies revealed that the overall exergy

efficiency of the coal-to-hydrogen system of 57% and the gasifier is the majority (~18%) of the exergy loss. The performance of the methane steam reforming for hydrogen production was studied by Simpson and Lutz (2007). They proposed that the most exergy destruction takes place in the reformer and furnace.

As mentioned earlier, there is a little research applied the exergoeconomic on syngas production for two-step and single-step DME production. Exergoeconomic evaluation and optimization of syngas production via tri-reforming of methane was studied by Sadeghi et al. (2018). Nevertheless, this study did not cover the gas cleaning units which are required to remove CO_2 and impurity before being fed into DME reactor. Therefore, additional studies are necessary to further investigate this matter. Moreover, there is no available research that explicitly compares the efficiency and performance of syngas production integrated the gas cleaning unit using natural gas, coal, and biomass for the two-step and single-step processes or their operation and maintenance.

Recently, environmental and climate change concerns have been emphasized. Thus, the environmental analysis is another key criterion for the decision to find the most suitable processes. The CO_2 emission intensity has been proposed for considering CO_2 emission of such processes. The sources of CO_2 emission, i.e., the use of feedstock, energy consumption, and unreacted gases are usually included to find the CO_2 emission intensity.

Therefore, the aims of the present study are to determine the proper processes of syngas production derived from natural gas, coal, and biomass for manufacturing DME in both two-step and single-step processes. Firstly, the influences of the steam-to-fuel ratios and air-to-fuel ratios on H_2/CO ratios are investigated. Secondly, to indicate the performance of the three different syngas production processes including syngas cleaning (CO_2 and water removal), and syngas preparation, the energetic and exergetic efficiencies are carried out. Thirdly, the unit costs of the syngas based on the exergoeconomic method are considered. Finally, the CO_2 emission intensity of each system is analyzed to investigate the environmental-friendliness of syngas production processes.

2. Process description

2.1. Syngas production

In this study, syngas derived from three different processes, namely, biomass gasification, coal gasification, and methane tri-reforming using air, oxygen, steam, and CO_2 as agent are analyzed. The composition of syngas product was fixed at the H_2/CO ratio of 1 for the single-step process and at H_2/CO ratio of 2 for the two-step process. The assumptions of the three processes are summarized as follows:

(1) The simulation is in a steady state conditions;
(2) The biomass and coal gasification processes are operated in adiabatic, while the methane tri-reforming is operated in isothermal;
(3) Methane, instead of natural gas, is used as feedstock;
(4) Atmospheric air contains approximately 21% of oxygen and 79% of nitrogen on a volume basis;
(5) The environmental state is at 25 °C and 101.325 kPa.

2.2. Biomass and coal gasification processes

Biomass gasification and coal gasification processes are the conversion of the carbonaceous substance to synthetic gas. The proximate and ultimate analyses of rubber wood and coal are shown in Table 1. Flowsheet of syngas production processes

Table 1
Proximate analysis, ultimate analysis, and higher heating value (HHV) of biomass and coal.

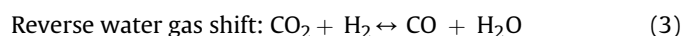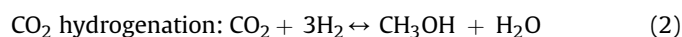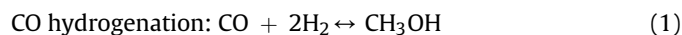| Fuel	Biomass	Coal
Proximate Analysis (wt%)		
FC	19.20	67.84
VM	80.10	22.43
MC	18.50	4.12
ASH	0.70	5.61
Ultimate Analysis (wt% dry basis)		
C	50.60	75.69
H	6.50	5.29
O	42.00	7.91
N	0.20	1.58
Cl	–	2.35
S	–	1.57
ASH	0.70	5.61
Caloric value		
HHV (MJ/kg)	19.60	30.63

modeled in Aspen plus is shown in Fig. 1. In a downdraft gasifier, the biomass or coal is fed into the top of the gasifier, and the preheated air, oxygen, and steam are fed into the side of the gasifier. The ash is removed from the bottom of the gasifier. As can be seen in Fig. 1(a), the biomass or coal gasification processes comprises four zones: the drying, decomposition, gasification and combustion, and separation. In the drying zone, the moisture is eliminated by using RStoic and Flash2 blocks. RYield block is used to simulate the decomposition zone. In this zone, biomass or coal as non-conventional components are converted to the conventional components, i.e. hydrogen, carbon, nitrogen, sulphur, and water, by their ultimate analysis (see Table 1). For gasification and combustion zones, the preheated gasifying agents are reacted with the conventional components from the decomposition zone. The chemical reactions that take place in the gasification and combustion zones are summarized in Table 2. In Aspen Plus model, the RGibbs block is utilized to determine chemical and phase equilibria based on the minimization of Gibbs free energy. The outlet stream from RGibbs block consists of H_2, CO, CO_2, CH_4, N_2, H_2O, other impurities (NH_3, H_2S and HCl), and ash. Then, all components from RGibbs are being fed into the separator to remove ash using the SSpit block. The syngas stream without solid particles was cooled (Hx-3) to 120 °C prior fed into the gas cleaning unit. The physical property method is the Peng-Robinson equation of state with Boston-Mathis (PR-BM). The HCOALGEN and DCOALIGT models are selected to investigate the enthalpy, specific heat capacity, and density of biomass and coal.

### 2.3. Methane tri-reforming

Methane tri-reforming is a unification of the three reforming process, i.e., steam reforming, partial oxidation, and dry reforming, in a single reactor to convert the methane into hydrogen-rich gas. Process flowsheet of methane tri-reforming is depicted in Fig. 1(b). In the present study, pure CO_2 separated from the exhaust gas after the post combustion using the MEA-solvent absorption is chosen as a gasifying agent for methane tri-reforming. In Fig. 1(b), methane as fuel and air or oxygen, steam, and CO_2 as gasifying agents are preheated by the Heater block (Hx-1 to Hx-4) before being fed to the reformer. The temperature of reformer was kept constant at 1000 °C. The chemical reactions inside the reformer are listed in Table 2. The syngas leaving the reformer is cooled down (Hx-5) to 120 °C. Then, it is sent to the gas cleaning unit.
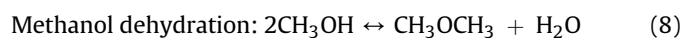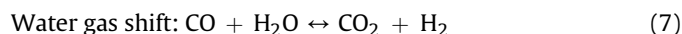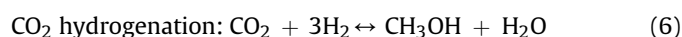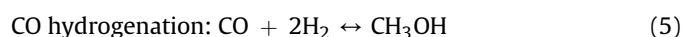
2.4. Gas cleaning unit

In the gas cleaning unit, the Rectisol process is carried out to remove CO_2 and other impurities (NH_3, HCl, and H_2S) in the syngas stream. The process is suitable for removing CO_2 and/or H_2S at low temperature and high pressure. A chilled methanol was used as a solvent. In Fig. 1, the Rectisol process comprises absorber, flash, and stripper. The cooled syngas is mixed with the unreacted gases from recycle stream. The remaining water in the syngas is removed using the flash tank (Flash-1 block). The uncleaned syngas is compressed and cooled before being fed to the bottom of the absorber (RadFrac block) and then contacted with the counter-current chilled methanol. The CO_2 and other impurities are absorbed and then removed from the bottom of the absorber. The rich solvent containing H_2, CO, CO_2, and other impurities are then sent into the flash tank (Flash-2 block) in order to recover H_2 and CO to the feed stream of absorbing process. After that, this stream is then sent into the stripper (RadFrac block) to regenerate and recycle the solvent to the absorber column. The syngas leaves from the top of the absorber column, and then the clean syngas is compressed, preheated, and fed into the DME synthesis unit. The reactions involved the two-step of DME synthesis via syngas are expressed as follows.

CO hydrogenation: $CO + 2H_2 \leftrightarrow CH_3OH$ (1)

CO_2 hydrogenation: $CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$ (2)

Reverse water gas shift: $CO_2 + H_2 \leftrightarrow CO + H_2O$ (3)

After the methanol synthesis and purification of methanol, the DME synthesis can be produced from the methanol dehydration reaction, which is expressed as.

$2CH_3OH \leftrightarrow CH_3OCH_3 + H_2O$ (4)
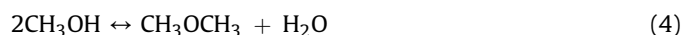
In the single-step of DME synthesis, the four reactions from syngas occurring in a single reactor are presented in Eqs. (5)–(8).

CO hydrogenation: $CO + 2H_2 \leftrightarrow CH_3OH$ (5)

CO_2 hydrogenation: $CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$ (6)

Water gas shift: $CO + H_2O \leftrightarrow CO_2 + H_2$ (7)

Methanol dehydration: $2CH_3OH \leftrightarrow CH_3OCH_3 + H_2O$ (8)

3. Performance analysis

3.1. Energetic and exergetic analyses

The total energy is the sum of the physical (E^{ph}) and chemical energies (E^{ch}), which are defined as (Zhang et al., 2015):

$$E_{total} = E^{ph} + E^{ch} \tag{9}$$

$$E^{ph} = \sum_{i=1}^{n} n_i h_i \tag{10}$$

$$E^{ch} = n_i HHV_i \tag{11}$$

where n_i, h_i, and HHV_i are the molar yield, the specific enthalpy,
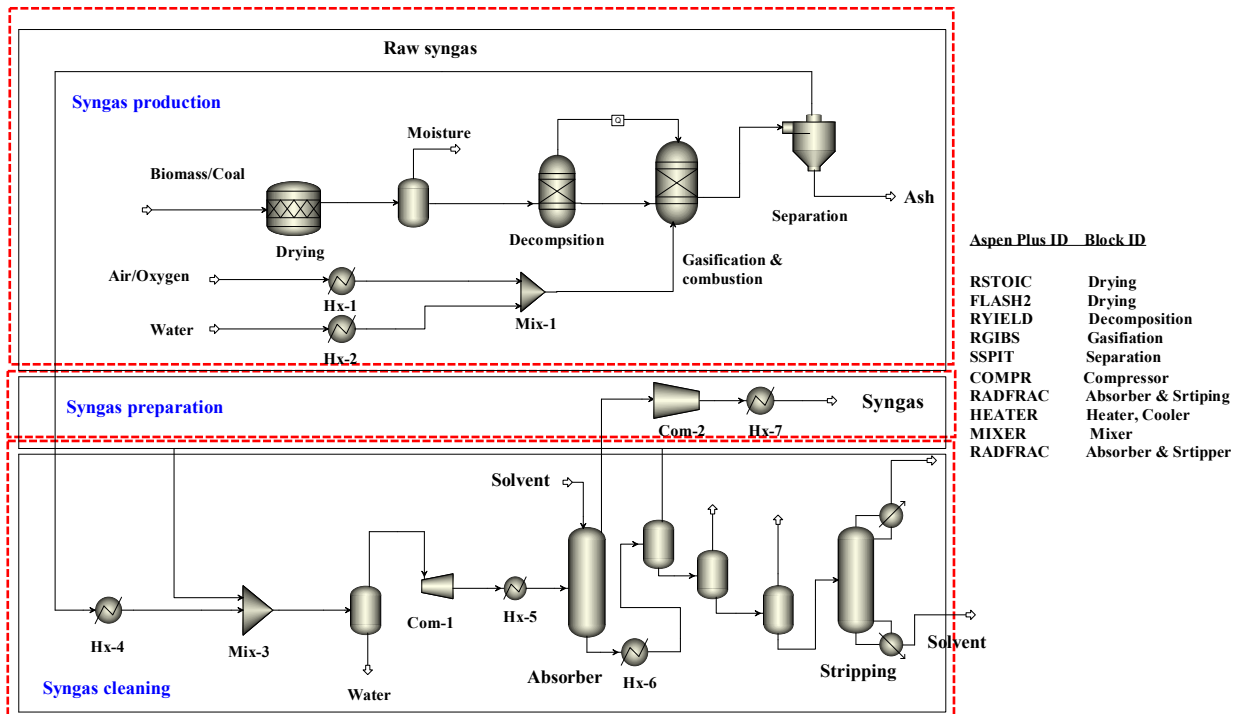
(a)
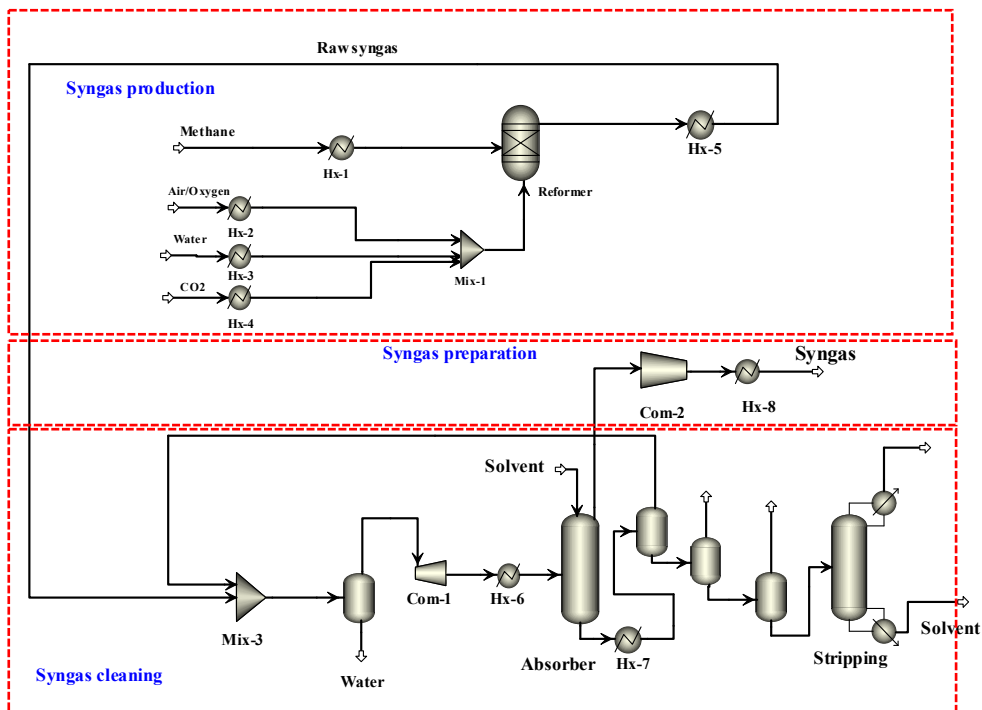
(b)

Fig. 1. Flowsheets for process simulation of (a) air-steam biomass and air-coal gasification and (b) methane tri-reforming.

Table 2
Main reactions in the gasifier and reformer.

Reaction No.	Reaction	Reaction name	ΔH (kJ/mol)
Biomass and coal gasification			
R1		Char partial oxidation	−283
R2		Char combustion	−393
R3		Boudouard	+172
R4		Methanation	−75
R5		Char gasification	+131
R6		Hydrogen partial oxidation	−242
R7		Water gas shift	−41
Methane tri-reforming			
R8		Steam methane reforming	+206
R9		Dry reforming of methane	+247
R10		Partial oxidation of methane	−36

and the higher heating value of component i in the syngas, respectively.

The overall energetic efficiency of the syngas production process (η_E) can be calculated as:

$$\eta_{E,\text{system}} = \frac{E_{\text{syngas}}}{E_{\text{fuel}} + Q_{\text{con}} + P_{\text{con}}} \times 100 \tag{12}$$

where E_{syngas} is the energy of syngas, E_{fuel} is the energy of fuel (i.e. biomass, coal, and methane), Q_{con} is thermal energy consumption, and P_{con} is electrical consumption. In Eq. (12), the chemical energy of biomass, coal, and methane as fuel are calculated as follows (Zhang et al., 2011).

$$E_{\text{fuel}} = m\text{HHV}_{\text{fuel}} \tag{13}$$

where HHV_{fuel} denotes the higher heating value of fuels, which are 19.60, 30.63 and 55.64 MJ/kg for biomass, coal, and methane, respectively.

The exergy is a maximum theoretical work possible during the process that takes the process into equilibrium with the environmental state. The exergy analysis is an extremely useful tool for designing and optimizing the systems, and also for evaluating the system performance. The total exergy is sum of the physical (Ex^{ph}) and chemical (Ex^{ch}) exergies (Zhang et al., 2015).

$$Ex_{\text{total}} = Ex^{\text{ph}} + Ex^{\text{ch}} \tag{14}$$

$$Ex^{\text{ph}} = \sum_{i=1}^{n} n_i ex_i^{\text{ph}} \tag{15}$$

The specific physical exergy (ex_i^{ph}) of components i in the inlet and outlet streams is defined as:

$$ex_i^{\text{ph}} = (h - h_0) - T_0(s - s_0) \tag{16}$$

where h_0 and s_0 are the specific enthalpy and entropy of syngas components at the environmental states, while h and s are the specific enthalpy and entropy of syngas components as a function of temperature and pressure, respectively. The chemical exergy (Ex^{ch}) can be calculated from Eq. (17).

$$Ex_i^{\text{ch}} = \sum_{i=1}^{n} n_i \left(ex_i^{\text{ch}} + RT_0 \ln y_i \right) \tag{17}$$

where ex_i^{ch} is the standard chemical exergy of gas components i, which is obtained from Zhang et al. (2011) and y_i is the mole fraction of gas component i in liquid and vapor phases. The chemical exergy of the biomass can be calculated as:

$$Ex_{\text{biomass}}^{\text{ch}} = \beta_{\text{biomass}} \left(\text{LHV}_{\text{biomass}} + [\text{MC}]h_{\text{fg}} \right) + 9683[\text{S}] + ex_{\text{ash}}[\text{ASH}] + ex_{\text{water}}[\text{MC}] \tag{18}$$

where β_{biomass} is a correlation factor of biomass, which can be computed in Eq. (19). h_{fg} is the specific enthalpy of water vaporization, ex_{water} and ex_{ash} are the specific chemical exergy of water and ash, respectively. Due to the very small value of ash, the chemical exergy of ash can be neglected in the present study (Song et al., 2011; Zhang et al., 2016).

$$\text{for } [\text{O/C}] \leq 2.67 \tag{19}$$

The chemical exergy of coal can be determined from Eq. (20) (El-Emam et al., 2012).

$$Ex_{\text{coal}}^{\text{ch}} = \left(\text{LHV}_{\text{coal}} + [\text{MC}] + h_{\text{fg}} \right)\beta_{\text{coal}} + 9417[\text{S}] \tag{20}$$

where LHV_{coal} is lower heating of coal. The coefficient correlation (β_{coal}) of coal is expressed as:

$$\beta_{\text{coal}} = 1.0437 + 0.1882[\text{H/C}] + 0.061[\text{O/C}] + 0.0404[\text{N/C}] \text{ for } [\text{O/C}] \leq 0.677 \tag{21}$$

The overall exergy efficiency of the overall system can be calculated as:

$$\eta_{Ex,\text{system}} = \frac{Ex_{\text{syngas}}}{Ex_{\text{fuel}} + Ex_{\text{heat}} + Ex_p} \times 100 \tag{22}$$

where Ex_{syngas} is the exergy of syngas, Ex_{fuel} is the exergy of fuel (i.e. biomass, coal, and methane), Ex_p is exergy of electricity for compressor, and Ex_{heat} is thermal exergy for preheater. The thermal exergy associated the equipment (Ex_{heat}) can be calculated as:

$$Ex_{\text{heat}} = Q_{\text{con}}\left(1 - \frac{T_0}{T}\right) \tag{23}$$

where T is the average temperature and T_0 is temperature at the environmental state.

3.2. Economic estimation

From the economic point of view, the specific exergy costing method (SPECO) is used to determine an exergoeconomic of syngas production based on three different processes. The SPECO method is a combination of exergy and economic analyses for designing and improving the overall system. The balance cost of the syngas production at steady state is expressed as follows (Kalinci et al., 2012):

$$\dot{C}_p = \dot{C}_f + \dot{Z}_k^T \tag{24}$$

In Eq. (24), the cost rate of the product stream ($\dot{C}_p$) is the sum of cost rate of the feed stream ($\dot{C}_f$) and the sum of the capital investment and the operating and maintenance cost rates of the system ($\dot{Z}_k^T$). The cost rate of each stream can be written in terms of the cost per unit of exergy ($\dot{c}$) and exergy rate ($\dot{Ex}$) as shown in Eq. (25).

$$\dot{C} = c\dot{Ex} \tag{25}$$

The sum of the capital investment ($\dot{Z}_k^{\text{CI}}$) and the operating and maintenance ($\dot{Z}_k^{\text{OM}}$) cost rates for the component kth in the syngas production processes is defined as (Kalinci et al., 2012):

$$\dot{Z}_k^T = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{26}$$

where $\dot{Z}_k^T$ can be rewritten as the follows:

$$\dot{Z}_k^T = \frac{\varphi \left(C\dot{A}_{process}^{CI} + C\dot{A}_{process}^{OM} \right)}{\tau} \frac{PEC_k}{\sum PEC_k} \tag{27}$$

where ϕ is the operating and maintenance factor, $C\dot{A}$ is the annualized capital cost, τ is the annual operating time of equipment at full load, and PEC is the purchased equipment costs of the kth component. The economic assumptions for syngas production processes can be obtained in our previous work (Nakyai et al., 2017). Table 3 presents the capital investment costs and their reference years. The gasifier and reformer costs are calculated based on a maximum capacity of 400 MW HHV of the fuel (Tijmensen et al., 2002), while preheater, cooler, and compressor costs are obtained from the available literature (Rafati et al., 2017). The cost of Rectisol unit is scaled based on the CO_2 capture in ton per day (Chiuta et al., 2016). However, the estimation of the capital investment cost in the different capacities and different years, the six-tenths rule method is utilized to investigate the cost of equipment (Ng and Sadhukhan, 2011). To calculate the cost of equipment at the reference year (2018), the cost indexes (CI) are obtained from Chemical Engineering Plant Cost Index (CEPCI) (Cost Index, 2018). The equipment cost at reference year (C_2) can be calculated from equipment cost (C_1) as the following equation:

$$C_2 = C_1 \left(\frac{CI_2}{CI_1} \right) \tag{28}$$

where CI_1 and CI_2 are the cost indexes for year 1 and year 2, respectively.

The unit cost of biomass and coal are 2.0 and 1.15 \$/GJ (Abuadala and Dincer, 2011; Bartels et al., 2010), respectively, while the unit cost of natural gas of 3.04 \$/GJ based on Henry Hub spot price is taken from the U.S. Energy Information Administration (EIA) (Nakyai et al., 2017). The unit costs of oxygen and water as gasifying agents are 25 and 4.59 \$/ton (Kalinci et al., 2012), respectively. The cost of pure CO_2 is set as 35 \$/ton CO_2 (Herzog, 2012). The specific heat duty of reboiler for regeneration of MEA and total electrical power consumption are 5.112 MJ/kg CO_2 and 65.5 MW_e.

3.3. Environmental analysis

In this section, the CO_2 emission intensity is used to indicate which process has the least CO_2 emission resulted in the most environmental friendliness. The sources of CO_2 emission from the different processes of syngas production comprise: (1) the CO_2 emission from combustion of fuel, (2) CO_2 emission associated with heat and electricity duty of utilities, and (3) the CO_2 emissions involved in the syngas production. In consideration of the CO_2 emission due to the combustion of fuel, the CO_2 emission from biomass combustion is not taken into account owing to biomass as

a part of natural cycle. It does not increase or decrease CO_2 in the atmosphere (Schakel et al., 2018). Therefore, the total CO_2 emission intensity for syngas production processes is calculated as:

$$CO_2 \text{ emission intensity} = \frac{\text{tonne } CO_2 \text{ emission}}{\text{tonne syngas production}} \tag{29}$$

4. Results and discussions

This work investigates the syngas production derived from different feedstocks, i.e. biomass, coal, and methane for the two-step and single-step processes of DME synthesis. Six cases of syngas production are analyzed as follows:

- Case 1: air-steam biomass gasification (B + A + S)
- Case 2: oxygen-steam biomass gasification (B + O + S)
- Case 3: air-steam coal gasification (C + A + S)
- Case 4: oxygen-steam coal gasification (C + O + S)
- Case 5: methane tri-reforming with using air (M + A + S + CO_2)
- Case 6: methane tri-reforming with using oxygen (M + O + S + CO_2)

Process block diagram of syngas production for all cases are presented in Fig. 2. All cases of syngas production for DME synthesis via two-step or single-step processes are studied based on energy, exergy, exergoeconomic, and environmental analyses.

4.1. Validation of the model

To predict the performance and cost of the syngas production via three different processes, the model validation is required to verify the accuracy and the reliability of the results from the simulation model. The gasification model was validated with the experiment data reported by Jayah et al. (2003). The rubber wood and air are used as feedstock and gasifying agent, respectively. The condition for the validation of gasifier model is at 1000 K and 1.013 kPa. The comparison of syngas composition between the simulation result and experiment data are shown in Table 4. The relative errors between simulation and experiment of syngas productions are in the range 0–2.53%. It can be seen that the model predictions are in good agreement with experimental data. For the tri-reforming of methane, the syngas compositions from the reformer are compared with the experiment data of Jang et al. (2016), as shown in Fig. 3. The simulation results show a good agreement with experimental results.

4.2. Influences of air and steam to fuel ratios on H₂/CO ratio

To determine the influences of air and steam to fuel ratios on H_2/CO ratio, the air to fuel ratio (A/F) was varied between 2.0 and 5.0 at different steam to fuel ratios (S/F) in range of 0.5–2.0 for three feedstocks. Fig. 4 shows the influences of steam to fuel ratios on H_2/CO ratio in product gas from biomass gasification, coal gasification,

Table 3
Capital investment cost for syngas production processes.

Component	Scaling parameter	Base cost (million US$)	Base capacity	Scaling exponent	Reference year	Source
Gasifier	HHV (MW)	28.9[a]	400	0.7	1999	Tijmensen et al. (2002)
Preheater	Heat duty (MW_{th})	9.2[a]	138.1	0.6	2007	Hamelinck et al. (2004)
Syngas cooler	Heat duty (MW_{th})	12.5	110	0.6	2002	Rafati et al. (2017)
Compressor	Power (MW_e)	6.3	10	0.67	2007	Clausen et al. (2010)
Rectisol unit[a]	CO_2 capture (t/d)	185.5	13296	0.7	2007	Chiuta et al. (2016)

[a] The exchange rates are taken from European Central Bank (1 Euro = 1.1369 dollars).
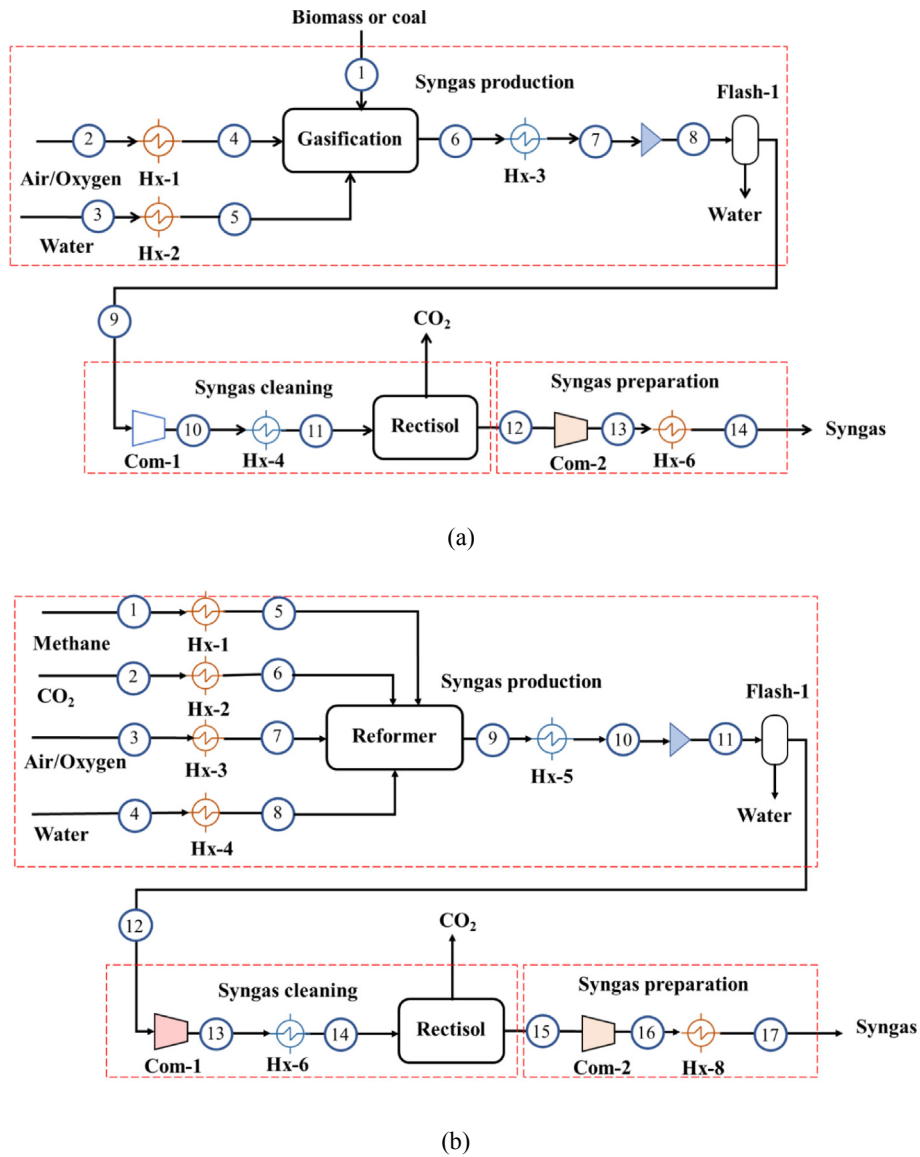
(a)

(b)

Fig. 2. Schematic diagrams of (a) biomass and coal gasification (air-steam and oxygen-steam) and (b) methane tri-reforming (air-steam and oxygen-steam).

Table 4
Simulation and experimental results for rubber wood gasification.

| Syngas composition (% vol)	ER = 0.35			ER = 0.38		
	Simulation	Experiment[a]	Relative Error	Simulation	Experiment[a]	Relative Error
H_2	20.86	19.6	1.26	21.31	20.20	1.11
CO	21.04	17.20	3.84	20.83	18.30	2.53
CO_2	10.07	9.90	0.17	9.70	9.70	0
CH_4	0.009	1.40	1.39	0.04	1.10	1.06

[a] Jayah et al. (2003).

and methane tri-reforming. The results reveal that the effects of S/F and A/F on the syngas product of all processes show the same trends. The increase in S/F ratios increases the H_2/CO ratio. This can be explained that the molar flow rate of hydrogen increases while the molar flow rate of carbon monoxide decreases with increasing S/F ratios. This is because the char gasification (R5), water gas shift (R7), and steam methane reforming (R8) reactions take place in the gasifier for the biomass and coal gasification processes as shown in Fig. 4(a)–(d). According to the char gasification reaction, the solid

carbon (C) reacts with steam to form hydrogen and carbon monoxide. For the water gas shift reaction, hydrogen and carbon dioxide are produced from the carbon monoxide with steam. In addition, the methane as product gas reacts with steam to generate more hydrogen and carbon monoxide via steam methane reforming reaction. For methane tri-reforming process (Fig. 4(e)–(f)), the H_2/CO ratio increases when the S/M ratio is increased because of the occurrence of steam methane reforming (R8) resulting in the increase of hydrogen content. In opposite, the amount of carbon
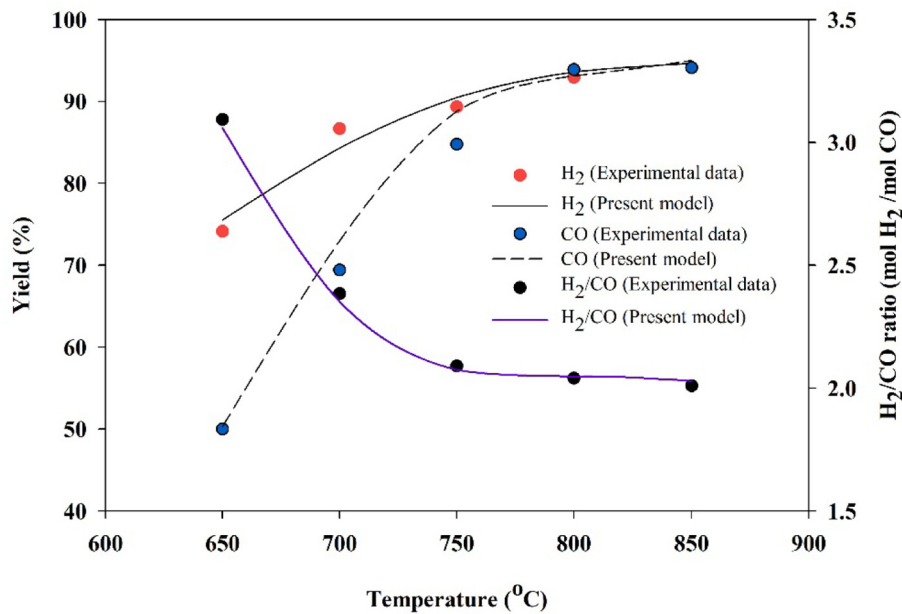
(a)
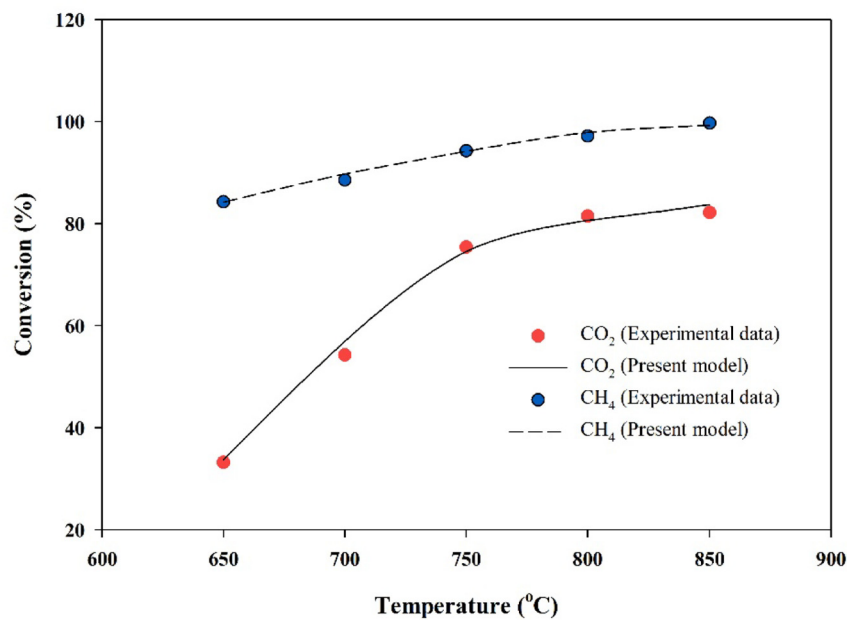
(b)

Fig. 3. Comparison of the simulation results and experiment data in the tri-reforming of methane (a) yield of syngas and H_2/CO ratio and (b) conversion of CO_2 and CH_4 as a function of reformer temperature at an $(CO_2 + H_2O)/CH_4$ ratio of 1.2 and $CO_2:H_2O$ ratio of 1:2.1.

monoxide slightly decreases when the S/M ratio is raised due to carbon monoxide consumed in the water gas shift reaction to produce carbon dioxide and hydrogen.

Considering the influences of the A/F ratio, the H_2/CO ratio decreases for all processes at a higher the A/F ratio. This can be explained that the char partial oxidation (R1), char combustion (R2), and hydrogen partial oxidation (R6) reactions are more dominant in the biomass and coal gasification processes. In char partial oxidation reaction, the solid carbon is converted into carbon monoxide by reacting with oxygen. At the same time, the oxygen also reacts with solid carbon to produce carbon dioxide in R2.

Moreover, the decline in H_2/CO molar ratio is caused by the fact that some hydrogen further reacts with oxygen resulting in water. For the methane tri-reforming process, the H_2/CO ratio decreases when the A/F is increased because of the occurrence of the partial oxidation of methane (R10) and hydrogen partial oxidation (R6) reactions.

The DME syntheses in the two-step and single-step processes require the H_2/CO ratio of 2 and 1, respectively. H_2/CO ratios in syngas were controlled by adjusting the amount of fuel and agents. Table 5 presents the suitable amount of agents in each case to achieve the highest syngas yield at H_2/CO ratios of 1 and 2. When
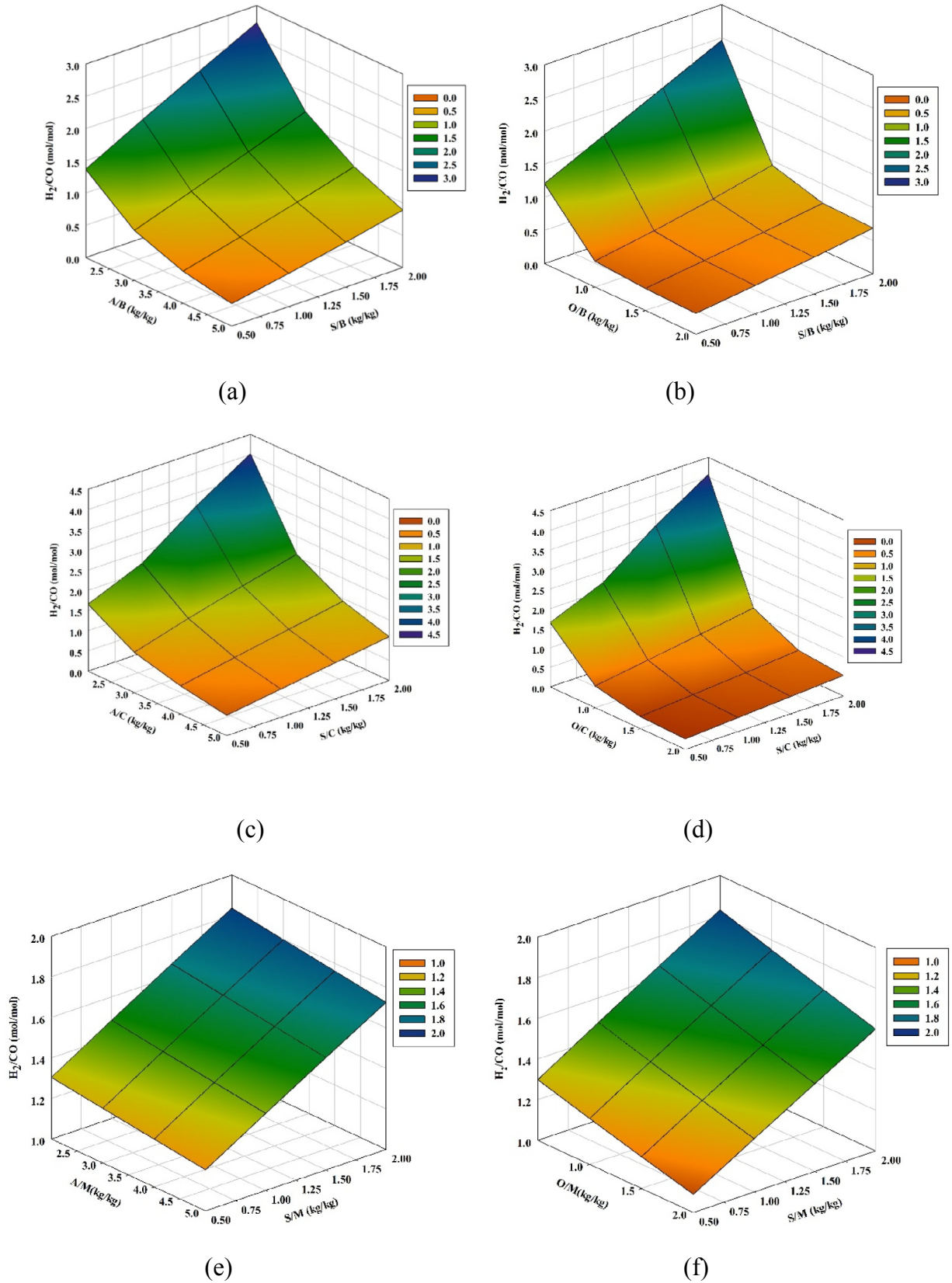
Fig. 4. Influences of air and steam on the H_2/CO molar ratio and molar flow rate of H_2 and CO in syngas product of (a) air-steam biomass gasification, (b) air-steam coal gasification, and (c) air-methane tri-reforming ($CO_2/M = 2$, $T = 1000\ ^{\circ}C$).

Table 5
Syngas composition and syngas yield for all cases to produce H_2/CO of 1 and 2.

Case	S/F (kg/kg)	A/F (kg/kg)	O/F (kg/kg)	CO_2/M (kg/kg)	H_2/CO (mol/mol)	Syngas composition (kmol/h)			Syngas yield of (mol/kg fuel)	
						H_2	CO	CO_2	H_2	CO
B + A + S	0.55	2.56	–	–	1.0	5.89	5.88	4.03	21.98	21.94
	0.37	1.42	–	–	2.0	9.18	4.59	5.47	34.63	17.24
B + O + S	0.61	–	0.58	–	1.0	5.88	5.88	4.03	22.49	22.49
	0.34	–	0.34	–	2.0	9.18	4.57	5.48	34.63	17.31
C + A + S	0.80	3.50	–	–	1.0	5.90	5.90	2.41	38.12	38.05
	0.50	1.79	–	–	2.0	9.17	4.59	3.67	57.62	29.85
C + O + S	0.62	–	0.75	–	1.0	5.90	5.90	1.97	39.45	39.45
	0.55	–	0.46	–	2.0	9.17	4.58	3.94	57.84	28.90
M + A + S + CO_2	0.14	7.30	–	2.04	1.0	5.90	5.89	3.07	71.57	71.45
	0.88	5.56	–	0.55	2.0	9.17	4.58	1.54	112.31	56.31
M + O + S + CO_2	0.14		1.70	2.04	1.0	5.90	5.89	3.07	71.57	71.45
	0.88		1.29	0.55	2.0	9.17	4.58	1.54	112.31	56.31

comparing H_2 and CO yields of three processes, the B + A + S has the lowest yield of H_2 and CO at both H_2/CO ratios of 1 and 2. The M + A + S + CO_2 process has the highest syngas yield about 71.57–112.31 mol H_2/kg methane and 56.31–71.45 mol CO/kg methane for $H_2/CO = 1$ and 2. The syngas yield of M + A + S + CO_2 is 3.24 and 1.95 times higher than those of biomass and coal gasification processes, respectively. This is because the ratio of H/C atom in methane is about 33.5%, which is higher than biomass (H/C = 12.84%) and coal (H/C = 7.05%).

4.3. Energetic and exergetic analysis

To evaluate the performance of syngas production processes of biomass gasification, coal gasification, and methane tri-reforming, the overall energetic and exergetic efficiencies of the syngas production processes for the $H_2/CO = 1$ and 2 are considered as illustrated in Fig. 5. As can be seen, the trends of energetic and exergetic efficiencies of $H_2/CO = 1$ are similar to the $H_2/CO = 2$. The use of oxygen as the gasifying agent has higher energetic and exergetic efficiencies than those of air. These results can be explained that the preheating of oxygen consumes less energy than preheating of air as shown in Table 6. Thus, using the oxygen as gasifying agent enhances the energetic and exergetic efficiencies of syngas production processes.

From Fig. 5, the C + O + S has the highest energetic efficiency at both $H_2/CO = 1$ and 2 about 68.60 and 67.78%, respectively. On the
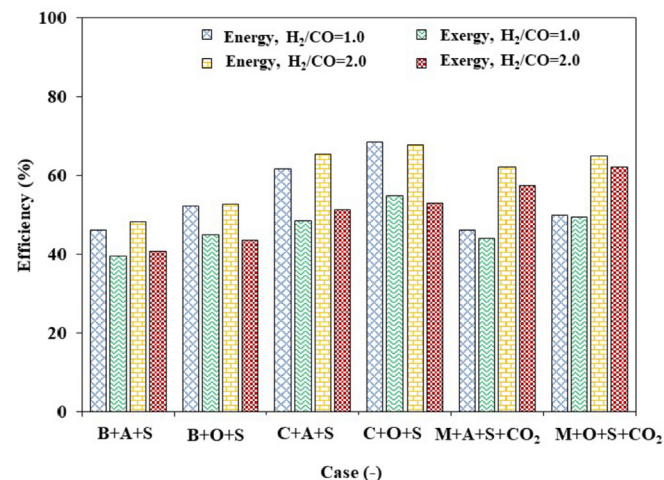
other hand, the M + O + S + CO_2 achieves the highest exergetic efficiency of 62.09% for $H_2/CO = 2$. This is because this process produces the highest yield of syngas. The higher syngas yield can increase the chemical exergy resulting in the enhancement of the system exergetic efficiency. Although all coal gasification processes are higher energetic efficiencies than the methane tri-reforming, their exergetic efficiencies are lower. This can be explained that the methane tri-reforming has less exergy input than energy input, while the coal has higher exergy input than energy input. Furthermore, the B + A + S shows the lowest energetic and exergetic efficiencies at both $H_2/CO = 1$ and 2 because of its low syngas yield.

4.4. Economic estimation

To investigate the unit cost of syngas, the SPECO method is applied. The principle of the SPECO is obtained based on the exergy rate and economic. To analyze the unit cost of syngas, the input, capital investment, operating, and maintenance cost rates are calculated. Table 7 shows the exergy, cost, and unit cost rates for fuel and gasifying agents of all cases for the H_2/CO of 1 and 2. As can be seen, the cost rates of input stream depend on the exergy rate. The cost rate of fuel is a major cost of the syngas cost rate for all cases. Also, the use of the oxygen as gasifying agent causes the higher input cost rates than those of the use of air and steam.

Fig. 6(a) and (b) display the cost rates of the capital investment and operation and maintenance for all cases. There are the cost rates in the range of 60.41–87.71 \$/h and 53.36–89.28 \$/h for H_2/CO of 1 and 2, respectively. The operating and maintenance cost rates are higher than those of the capital investment cost rates for all cases. In addition, the use of air as gasifying agent has higher operating and maintenance cost rates than the use of oxygen because the preheating of air consumes more energy than that of the oxygen. Thus, higher energy consumption leads to the increase of the capital investment and operating and maintenance cost rates. For the H_2/CO of 1, the C + A + S has the highest capital investment and operating and maintenance cost rate of 85.91 \$/h, whereas the M + O + S + CO_2 has the lowest cost rate of 60.41\$/h. For the H_2/CO of 2, the highest and the lowest capital investment and operating and maintenance cost rates are the B + A + S of 89.28 and M + O + S + CO_2 of 53.36 \$/h, respectively.

The cost rates breakdown of capital investment and operating and maintenance of each unit in the syngas production processes for H_2/CO of 1 and 2 are shown in Figs. 7 and 8, respectively. From Fig. 7(a)–(f), the largest cost rates of the H_2/CO of 1 are caused by the Rectisol unit, gasifier, and cooler of syngas, which are in the rage of 31.07–33.39%, 15.52–20.71%, and 12.64–17.89% of total cost rate,

Fig. 5. Energetic and exergetic efficiencies of the biomass gasification, coal gasification, and methane tri-reforming at $H_2/CO = 1$ and 2.

Table 6
Energy consumption for syngas production of the H_2/CO of 1 and 2.

Component	B + A + S	B + O + S	C + A + S	C + O + S	M + A + S + CO_2	M + O + S + CO_2
	$H_2/CO = 1$					
Hx-1	2747.89	585.09	3751.28	785.90	3727.41	3727.40
Hx-2	2598.63	2891.01	3610.49	3287.60		
Hx-3	–	–	–	–	7839.46	1721.29
Hx-4	–	–	–	–	2251.13	2251.12
Hx-6	956.75	371.70	1659.28	631.83	–	–
Hx-8	–	–	–	–	2854.85	1171.67
Com-1	329.58	151.43	523.18	299.80	962.22	452.01
Com-2	85.40	41.30	148.11	59.89	250.65	108.00
Stripper	4486.57	4598.09	5171.81	5361.56	13689.83	13663.26
Total (kJ/kg fuel)	11204.81	8638.62	14864.15	10426.58	31575.55	23094.74
	$H_2/CO = 2$					
Hx-1	2162.51	474.83	2775.08	657.82	3727.42	3704.14
Hx-2	5680.35	5676.58	5887.45	6463.63	–	–
HX-3	–	–	–	–	5964.21	1146.52
Hx-4	–	–	–	–	613.70	573.26
HX-6	887.31	422.40	1659.28	631.83	–	–
Hx-8					1945.84	2636.20
Com-1	322.97	181.36	523.18	299.80	864.71	864.71
Com-2	81.08	40.74	148.11	59.89	452.22	244.70
Stripper	4535.84	4535.84	5171.81	5361.56	14012.88	13960.40
Total (kJ/kg fuel)	13670.06	11331.76	16164.91	13474.53	27580.97	23129.93

Table 7
Exergy and cost rates of input stream for all cases to produce H_2/CO of 1 and 2.

Stream No.	Stream	$H_2/CO = 1$						$H_2/CO = 2$					
		Air + steam			Oxygen + steam			Air + steam			Oxygen + steam		
		$\dot{E}x$ (MW)	$\dot{c}$ ($/GJ)	$\dot{C}$ ($/h)	$\dot{E}x$ (MW)	$\dot{c}$ ($/GJ)	$\dot{C}$ ($/h)	$\dot{E}x$ (MW)	$\dot{c}$ ($/GJ)	$\dot{C}$ ($/h)	$\dot{E}x$ (MW)	$\dot{c}$ ($/GJ)	$\dot{C}$ ($/h)
	Biomass gasification												
1	Biomass	1.687	2.000	12.144	1.646	2.000	11.849	1.668	2.000	12.012	1.668	2.000	12.012
2	Air/Oxygen	0.015	0.000	0.000	0.005	201.511	3.788	0.014	0.000	0.000	0.004	201.511	3.109
3	Water	0.024	7.849	0.679	0.023	8.697	0.734	0.047	8.697	1.469	0.047	8.697	1.469
	Coal gasification												
1	Coal	0.973	1.150	4.026	1.407	1.150	5.824	0.968	1.150	4.007	0.999	1.150	4.135
2	Air/Oxygen	0.008	0.000	0.000	0.004	201.511	3.063	0.008	0.000	0.000	0.004	201.511	2.579
3	Water	0.018	8.697	0.565	0.018	8.697	0.555	0.029	8.697	0.916	0.033	8.697	1.038
	Methane tri-reforming												
1	Methane	1.190	3.040	13.027	1.190	3.040	13.027	1.179	3.040	12.900	1.179	3.040	12.900
2	Air/Oxygen	0.013	0.000	0.000	0.005	201.511	3.505	0.009	0.000	0.000	0.004	201.511	2.641
3	Water	0.002	8.697	0.055	0.002	8.697	0.055	0.011	8.697	0.333	0.011	8.697	0.333
4	CO_2	0.010	164.460	5.880	0.010	164.460	5.880	0.003	164.460	1.587	0.003	164.460	1.587

respectively. The C + A + S shows the highest cost rate of the Rectisol unit because it has the highest carbon dioxide content in the syngas. This results in the increase of the equipment capacity, leading to the increase of the capital investment and operating and maintenance costs.

As seen in Fig. 8(a)–(f), for the H_2/CO of 2, the Rectisol unit has the highest cost rates for all processes of syngas production from biomass and coal, which are similar to the H_2/CO of 1. On the contrary, the reformer in the methane tri-reforming process of both M + A + S + CO_2 and M + O + S + CO_2 show the largest cost rate. The second largest cost rate is the Rectisol unit, followed by cooler and preheating of steam. The cost rate of the Rectisol unit in methane tri-reforming at H_2/CO of 2 is less than that at H_2/CO of 1. This is because the carbon dioxide content in syngas at H_2/CO of 2 is smaller than that at the H_2/CO of 1. In addition, when the cost rate of Rectisol unit between M + A + S + CO_2 and M + O + S + CO_2 processes are compared, the results reveal that the M + A + S + CO_2 has higher cost rate about 38.10%. The reason is that the M + A + S + CO_2 process has nitrogen content. This condition requires more energy supply for separating carbon dioxide, resulting

in higher operating and maintenance cost rates.

Fig. 9(a) and (b) show the unit of syngas of H_2/CO of 1 and 2 for all cases. As can be seen, the unit costs of syngas are in the ranges of 0.54–0.79 $/kg. The results indicate that the use of oxygen as gasifying agent increases the syngas unit cost of $H_2/CO = 1$ and 2 between 1.77 and 17.57% of total syngas unit cost for biomass, air-coal gasification, and methane tri-reforming processes. The use of oxygen has higher unit cost than that of air because of the cost input of oxygen although it has a lower operating and maintenance cost. In contrast, the use of the oxygen instead of air in the coal gasification at the $H_2/CO = 2$ is not different. The unit cost breakdown of all processes is considered from Fig. 9(a) and (b). The syngas unit cost of the process is divided into the syngas production, gas cleaning, and syngas preparation units. It is found that the unit cost of all cases at H_2/CO of 1 is similar to that of all cases at H_2/CO of 2. The cost of syngas production has the main impact on the unit cost of syngas for B + O + S, M + A + S + CO_2, and M + O + S + CO_2, both the $H_2/CO = 1$ and 2. This is due to the cost of fuel (biomass and methane) and gasifying agents (oxygen and carbon dioxide). On the other hand, the cost of syngas cleaning unit
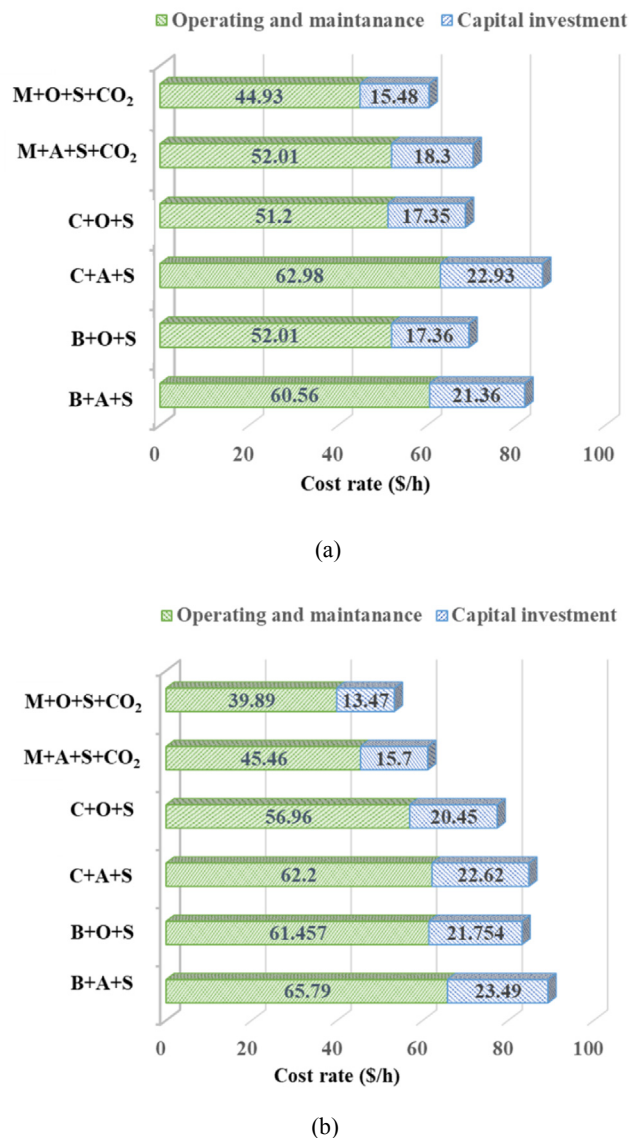
(a)

(b)

Fig. 6. Cost rates of capital investment and operating and maintenance at syngas ratios of (a) $H_2/CO = 1$ and (b) $H_2/CO = 2$ for all cases.

has the greatest effect on the unit cost of syngas for $B + A + S$, $C + A + S$, and $C + O + S$, both the $H_2/CO = 1$ and 2. Furthermore, the cost of syngas preparation before feeding into the DME reactor such as costs of compressor and heater are less than 7% of total unit cost for all cases, which has a slight effect on the unit costs of syngas when compared to unit costs of syngas production and gas cleaning units.

When considering the unit costs of syngas at H_2/CO of 1, the $B + A + S$ has the lowest unit cost of syngas of 0.54 $/kg, whereas the $M + O + S + CO_2$ has the highest of 0.77 $/kg. This indicates that the $B + A + S$ is appropriate for producing the syngas in single-step process of DME production ($H_2/CO = 1$). In the syngas production for two-step process of DME production ($H_2/CO = 2$), the $C + A + S$ and $C + O + S$ are preferred. Furthermore, the $M + A + S + CO_2$ has lower syngas unit costs than the use of biomass at the H_2/CO of 2.

The comparison of the syngas unit cost for H_2/CO ratio of 1 and 2 with the different feedstocks and processes is shown in Table 8. The syngas production processes consist of co-electrolysis and biomass gasification (fixed bed and entrained bed gasification). From

Table 8, the syngas unit costs of $H_2/CO = 1$ are in range of 0.39–1.45 $/kg. The downdraft biomass gasification has the lowest unit cost of 0.24 $/kg which is not included the cost of the gas cleaning unit. When considering the unit cost of syngas production from the biomass gasification with different technologies, the syngas unit cost of the entrained bed biomass gasification using oxygen as agent has 1.63 times higher than that of the downdraft biomass gasification (Trippe et al., 2011). In addition, the co-electrolysis of water and CO_2 has 2.63 times higher syngas unit cost than the downdraft biomass gasification (Redissi and Bouallou, 2013). It is clear that the syngas production from the air-steam biomass gasification is appropriate for single-step of DME production.

For the syngas unit cost for the two-step of DME production ($H_2/CO = 2$), the coal gasification from Section 4.4 was selected to compare the syngas unit cost with different sources. In Table 8, the result was found that the syngas unit cost of the entrained bed biomass gasification has 1.95 times higher than the air or oxygen-steam downdraft coal gasification (Trippe et al., 2011). Compared to the high-temperature steam/CO_2 co-electrolysis (Redissi and Bouallou, 2013), the air or oxygen-steam downdraft coal gasification without gas cleaning unit (0.20 $/kg) still has a lower syngas unit cost than that of a high-temperature steam/CO_2 co-electrolysis (0.88 $/kg) of 77.27%. It can be observed that the syngas production via co-electrolysis has not been able to compete with the thermal process and still needs to be developed in the future. This is because the high costs of stack investment and electricity consumption. As mentioned above, it can be indicated that the coal gasification can be competitive in the syngas production for the two-step of DME production.

4.5. Environmental assessment

To determine the environmental friendliness of syngas production processes, the emissions of the CO_2 from three different processes of syngas production are compared. The sources of CO_2 emission in the syngas production process derives from fuel utilization, gas cleaning unit, and utilities. Fig. 10(a)-(b) illustrate the CO_2 emission intensities for syngas production at the H_2/CO of 1 and 2 from the biomass gasification, coal gasification, and methane tri-reforming. As can be seen, the use of air as gasifying agent produces higher CO_2 emission intensity than the use of oxygen for all processes of the syngas production. The use of oxygen as gasifying agent reduces the CO_2 emission intensities in the ranges of 0.67–19.83% of total CO_2 emission intensity of all feedstocks, when compared with the use of air. This is because the systems supplying oxygen as gasifying agent require less heat duty than those using air.

In biomass gasification processes of syngas production, the energy inputs of utilities are the major source of CO_2 emissions for $B + A + S$ and $B + O + S$. Moreover, the biomass gasification feedstock is the highest CO_2 emissions due to the energy input of utilities, compared to the other fuels using the same agents. However, the $B + O + S$ shows the lowest total CO_2 emission intensity for the syngas production of H_2/CO ratio = 1 (see in Fig. 10(a)). For the $H_2/CO = 2$, the $M + O + S + CO_2$ produces the lowest CO_2 emission intensity, as shown in Fig. 10(b). This can be explained that the case of $M + O + S + CO_2$ requires the least heat duty of utilities and gas cleaning unit than other cases, resulting in the lowest release of CO_2. On the other hand, the $C + A + S$ produces the highest CO_2 emission intensity in both syngas productions at $H_2/CO = 1$ and 2. This can be described that the CO_2 emission associated with coal combustion causes about 49.83–55.38% of total emission intensity. The comparison of syngas production for single-step and two-step productions shows that the $B + O + S$ for the production of $H_2/CO = 1$ produces lower CO_2 emission intensity
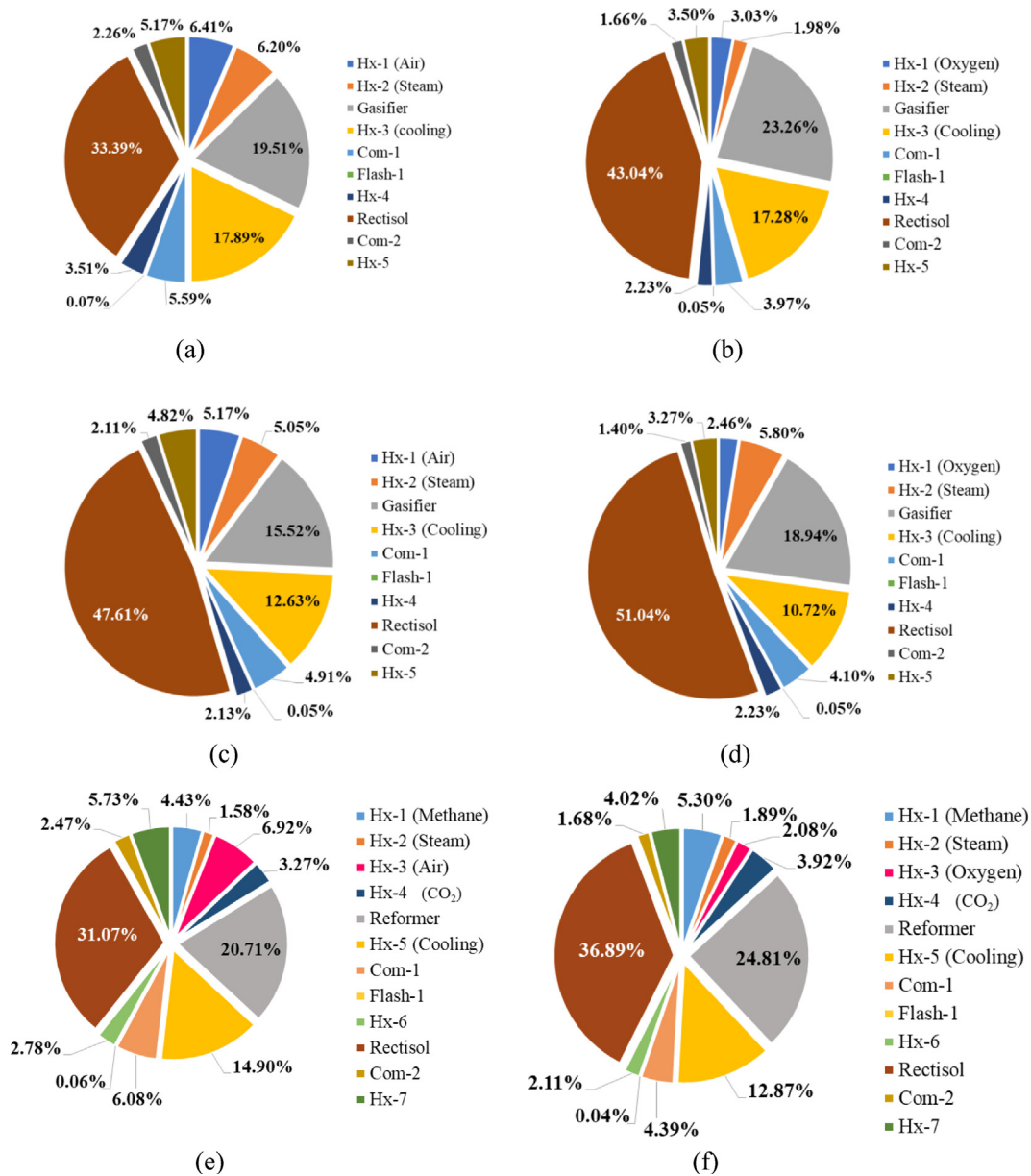
Fig. 7. Cost rate breakdown of the capital investment and operating and maintenance at the $H_2/CO = 1$; (a) B + A + S, (b) B + O + S, (c) C + A + S, (d) C + O + S, (e) M + A + S + CO_2, and (f) M + O + S + CO_2.

than the M + O + S + CO_2 of $H_2/CO = 2$ about 14.24%. This indicates that the syngas production from B + O + S for single-step process of DME synthesis produces the lowest CO_2 emissions.

5. Conclusion

In this present study, a comparison of syngas production via three different processes, i.e., biomass gasification, coal gasification, and methane tri-reforming to produce DME in single-step ($H_2/CO = 1$) and two-step ($H_2/CO = 2$) processes was studied through exergoeconomic analysis and CO_2 emission assessment. The following conclusions were drawn:

- The B + A + S achieves the lowest energetic and exergetic efficiencies at $H_2/CO = 1$ and 2. The coal gasification shows the highest energetic efficiency in all cases. However, the methane

tri-reforming achieves the highest exergetic efficiency at the $H_2/CO = 2$.
- Using of oxygen-steam as agent has more energetic and exergetic efficiencies than that of air-steam because of more energy intensive. Nevertheless, the use of air-steam is more economically feasible than the use of oxygen-steam.
- The lowest unit costs of syngas production for the single-step and two-step processes are the B + A + S of 0.54 \$/kg and coal gasification process of 0.65 \$/kg, respectively.
- When concerning environmental point, the biomass gasification process produces the lowest CO_2 emissions when required to produce $H_2/CO = 1$, while the methane as a fuel contributes the least amount of CO_2 emissions at $H_2/CO = 2$.
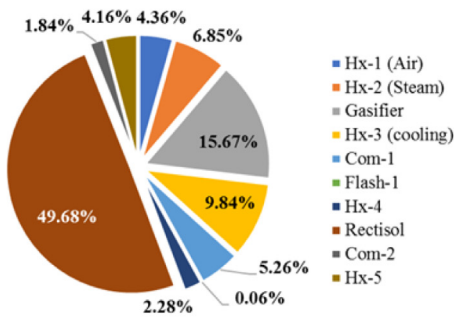
From all results, the suitable processes of syngas production for single-step and two-step processes of the DME synthesis were in-
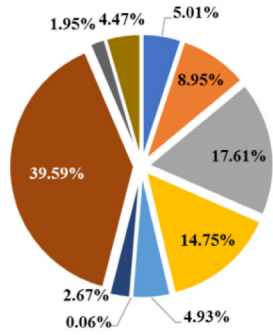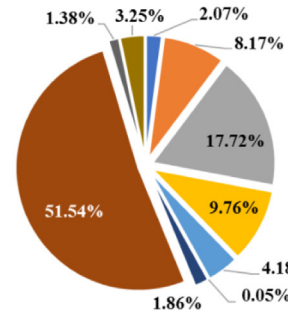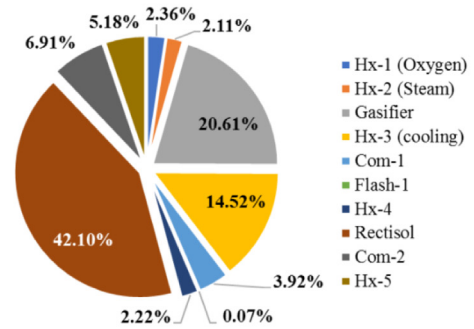
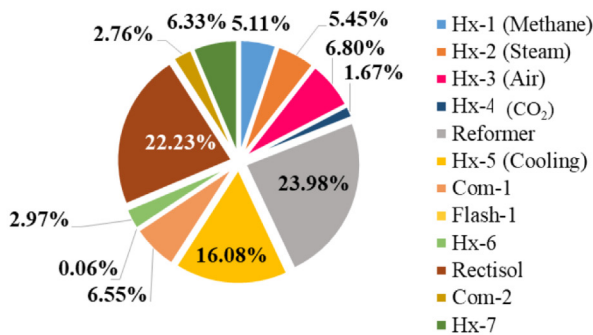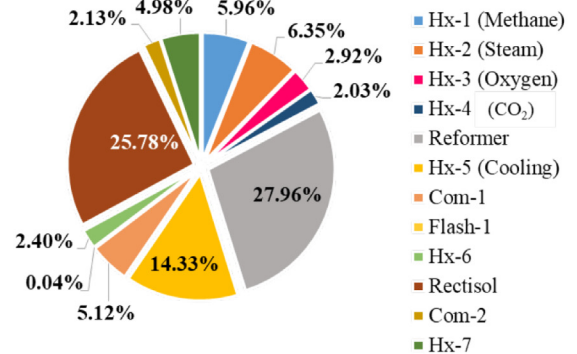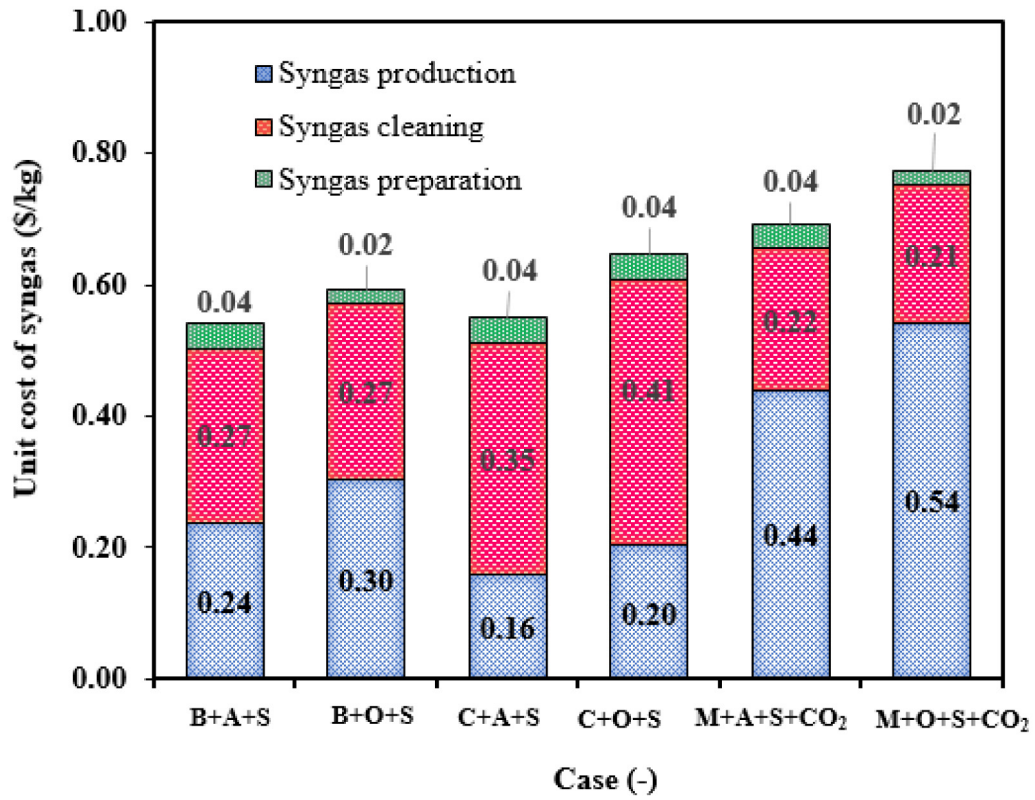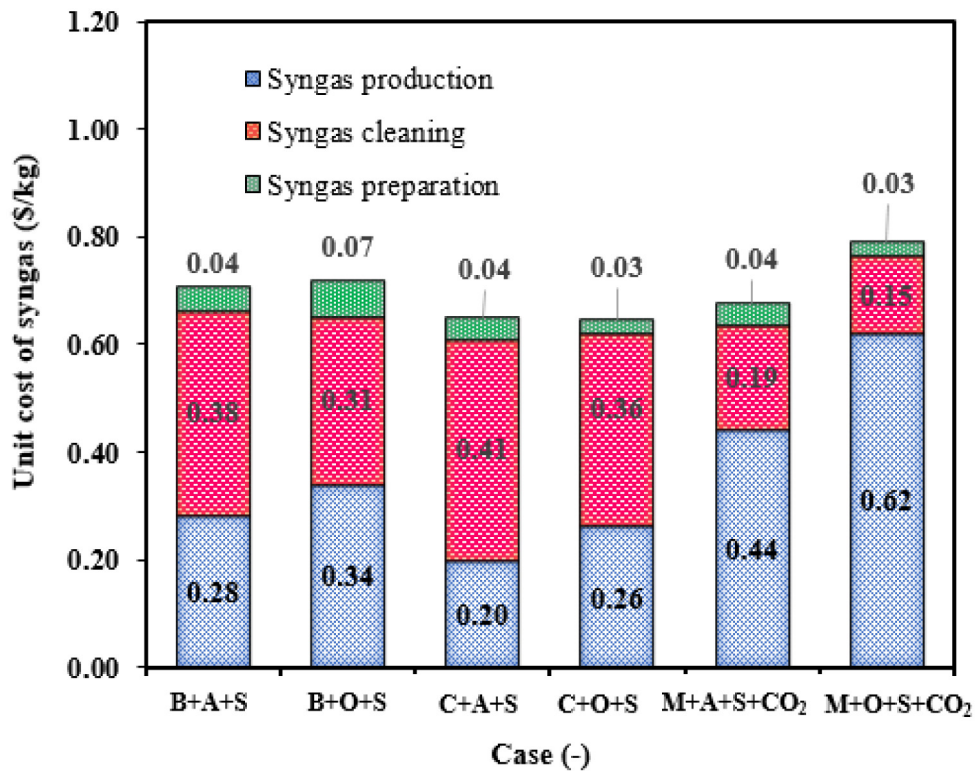**Fig. 8.** Cost rate breakdown of the capital investment and operating and maintenance at the $H_2/CO = 2$; (a) B + A + S, (b) B + O + S, (c) C + A + S, (d) C + O + S, (e) M + A + S + CO_2, and (f) M + O + S + CO_2.

(a)

(b)

Fig. 9. Unit cost of syngas ratios of $H_2/CO = 1$ and $H_2/CO = 2$ for all cases.

Table 8
Comparison the syngas unit costs of the $H_2/CO = 1$ and 2 with different feedstocks and processes.

Feedstock	Gasifying agent	Process	Unit cost ($/kg)	Ref.
$H_2/CO = 1$				
Biomass	Oxygen	Entrained bed gasification	0.39 (Not included CO_2 capture)	Trippe et al. (2011)
Hydrogen, CO, and H_2O	–	Co-electrolysis	1.45 (Not included CO_2 capture)	Redissi and Bouallou (2013)
Biomass	Air-steam	Fixed bed downdraft gasification	0.54	This study
$H_2/CO = 2$				
Biomass	Oxygen	Entrained bed gasification	0.39 (Not included CO_2 capture)	Trippe et al. (2011)
Hydrogen, CO_2, and H_2O	–	High-temperature steam/CO_2 co-electrolysis	0.88 (Not included CO_2 capture)	Fu et al. (2010)
Coal	Air, oxygen, and steam	Fixed bed downdraft gasification	0.65	This study
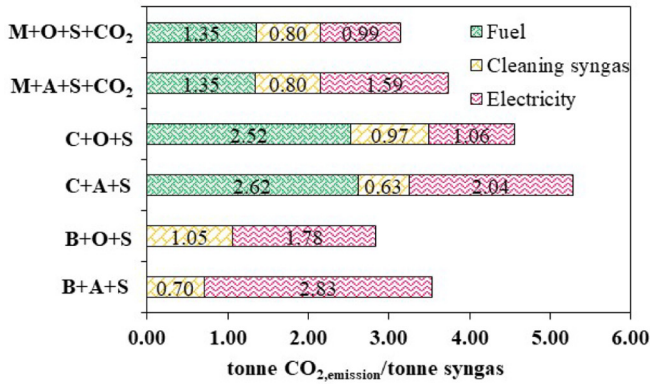
(a)
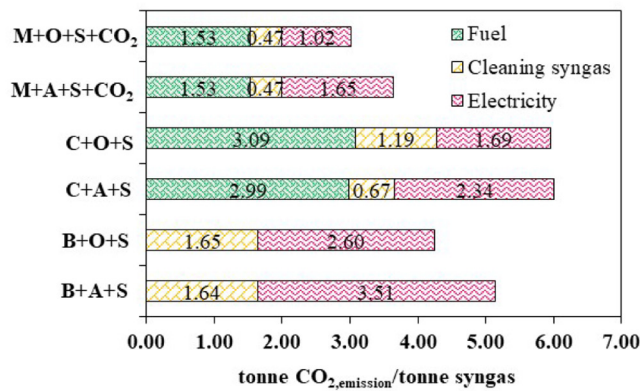
(b)

Fig. 10. CO_2 emission intensity at syngas ratios of (a) $H_2/CO = 1$ and (b) $H_2/CO = 2$ for all cases.

depth considered in this work. The authors look forward to presenting the combined processes of syngas production, gas cleaning, and DME synthesis to compare the single-step and two-step processes and find the best process for the DME synthesis in the near future.

Acknowledgements

Nomenclature

ex	standard exergy (kJ/kmol)
E	energy (kJ/kg)
Ex	exergy (kJ/kg)
$\dot{Ex}$	exergy rate (MW)
$\dot{m}$	mass flow rate (kg/s)
c	unit exergy cost ($/GJ, $/kg)
C	initial investment cost ($)
$\dot{C}$	cost rate ($/h)
$\dot{CA}$	annual capital cost ($/yr)
n	molar yield (mol/kg)
R	universal gas constant (kJ/kmol K)
h	specific enthalpy (kJ/kmol)
s	specific entropy (kJ/kmol K)
$\dot{Z}$	sum of capital investment and operation and maintenance cost rates ($/h)

Greek letters

β	correlation factor of coal and biomass
η	efficiency (%)

Superscripts

ph	physical
ch	chemical
CI	capital cost investment
OM	operating and maintenance
T	total

Subscripts

i	component gases
0	environmental state
en	energy
ex	exergy
syngas	product gases
p	product
total	total
f	feed
kth	kth equipment

Abbreviations

PEC	purchased equipment cost ($)
LHV	lower heating value (MJ/kg or kJ/kg)
HHV	higher heating value (MJ/kg or kJ/kg)
SPECO	specific exergy cost

References

Abuadala, A., Dincer, I., 2011. Exergoeconomic analysis of a hybrid system based on steam biomass gasification products for hydrogen production. Int. J. Hydrogen Energy 36 (20), 12780–12793.

Bartels, J.R., Pate, M.B., Olson, N.K., 2010. An economic survey of hydrogen production from conventional and alternative energy sources. Int. J. Hydrogen

Energy 35 (16), 8371—8384.

Chein, R.Y., Hsu, W.H., 2018. Thermodynamic analysis of syngas production via tri-reforming of methane and carbon gasification using flue gas from coal-fired power plants. J. Clean. Prod. 200, 242—258.

Chen, W.-H., Lin, B.-J., Lee, H.-M., Huang, M.-H., 2012. One-step synthesis of dimethyl ether from the gas mixture containing CO_2 with high space velocity. Appl. Energy 98, 92-01.

Chiuta, S., Engelbrecht, N., Human, G., Bessarabov, D.G., 2016. Techno-economic assessment of power-to-methane and power-to-syngas business models for sustainable carbon dioxide utilization in coal-to-liquid facilities. J. CO_2 Util. 16, 399—411.

Clausen, L.R., Elmegaard, B., Houbak, N., 2010. Technoeconomic analysis of a low CO_2 emission dimethyl ether (DME) plant based on gasification of torrefied biomass. Energy 35 (12), 4831—4842.

Colpan, C.O., Hamdullahpur, F., Dincer, I., Yoo, Y., 2010. Effect of gasification agent on the performance of solid oxide fuel cell and biomass gasification systems. Int. J. Hydrogen Energy 35 (10), 5001—5009.

Cost Index, 2018. The Chemical Engineering Plant Cost Index (CEPCI). Chemical Engineering Report Features Report Guidebook. www.chemengonline.com. (Accessed 10 August 2018).

Dimethyl ether Market, 2015. Research and markets: dimethyl ether market 2015-global trends & Forecasts to 2020. https://www.businesswire.com/news/home/20150916005706/en/Research-%20Markets-Dimethyl-Ether-Market-2015/. (Accessed 10 November 2018).

El-Emam, R.S., Dincer, I., Naterer, G.F., 2012. Energy and exergy analyses of an integrated SOFC and coal gasification system. Int. J. Hydrogen Energy 37 (2), 1689—1697.

Fan, J., Zhu, L., Jiang, P., Li, L., Liu, H., 2016. Comparative exergy analysis of chemical looping combustion thermally coupled and conventional steam methane reforming for hydrogen production. J. Clean. Prod. 131, 247—258.

Fu, Q., Mabilat, C., Zahid, M., Brisse, A., Gautier, L., 2010. Syngas production via high-temperature steam/CO_2 co-electrolysis: an economic assessment. Energy Environ. Sci. 3 (10), 1382—1397.

García-Vargas, J.M., Valverde, J.L., Díez, J., Dorado, F., Sánchez, P., 2015. Catalytic and kinetic analysis of the methane tri-reforming over a Ni—Mg/β-SiC catalyst. Int. J. Hydrogen Energy 40 (28), 8677—8687.

Hamelinck, C.N., Faaij, A.P.C., den Uil, H., Boerrigter, H., 2004. Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential. Energy 29 (11), 1743—1771.

Herzog, H.J., 2012. The Economics of CO_2 Separation and Capture, 2012. https://sequestration.mit.edu/pdf/economics_in_technology.pdf. (Accessed 10 August 2018).

Huang, J., Dincer, I., 2014. Parametric analysis and assessment of a coal gasification plant for hydrogen production. Int. J. Hydrogen Energy 39 (7), 3294—3303.

Huang, M.H., Lee, H.M., Liang, K.C., Tzeng, C.C., Chen, W.H., 2015. An experimental study on single-step dimethyl ether (DME) synthesis from hydrogen and carbon monoxide under various catalysts. Int. J. Hydrogen Energy 40 (39), 13583—13593.

Iribarren, D., Susmozas, A., Petrakopoulou, F., Dufour, J., 2014. Environmental and exergetic evaluation of hydrogen production via lignocellulosic biomass gasification. J. Clean. Prod. 69, 165—175.

Jang, W.-J., Jeong, D.-W., Shim, J.-O., Kim, H.-M., Roh, H.-S., Son, I.H., Lee, S.J., 2016. Combined steam and carbon dioxide reforming of methane and side reactions: thermodynamic equilibrium analysis and experimental application. Appl. Energy 173, 80—91.

Jayah, T.H., Aye, L., Fuller, R.J., Stewart, D.F., 2003. Computer simulation of a downdraft wood gasifier for tea drying. Biomass Bioenergy 25 (4), 459—469.

Ju, F.D., Chen, H.P., Ding, X.J., Yang, H.P., Wang, X.H., Zhang, S.H., Dai, Z.H., 2009. Process simulation of single-step dimethyl ether production via biomass gasification. Biotechnol. Adv. 27 (5), 599—605.

Kalinci, Y., Hepbasli, A., Dincer, I., 2012. Exergoeconomic analysis and performance assessment of hydrogen and power production using different gasification systems. Fuel 102, 187—198.

Kung, H.H., 1992. Deactivation of methanol synthesis catalysts - a review. Catal. Today 11 (4), 443—453.

Liszka, M., Malik, T., Manfrida, G., 2012. Energy and exergy analysis of hydrogen-oriented coal gasification with CO_2 capture. Energy 45 (1), 142—150.

Lu, W.Z., Teng, L.H., Xiao, W.D., 2004. Simulation and experiment study of dimethyl ether synthesis from syngas in a fluidized-bed reactor. Chem. Eng. Sci. 59 (22), 5455—5464.

Mevawala, C., Jiang, Y., Bhattacharyya, D., 2017. Plant-wide modeling and analysis of the shale gas to dimethyl ether (DME) process via direct and indirect synthesis routes. Appl. Energy 204, 163—180.

Moradi, G.R., Ahmadpour, J., Yaripour, F., 2008. Intrinsic kinetics study of LPDME process from syngas over bi-functional catalyst. Chem. Eng. J. 144 (1), 88—95.

Nakyai, T., Authayanun, S., Patcharavorachot, Y., Arpornwichanop, A., Assabumrungrat, S., Saebea, D., 2017. Exergoeconomics of hydrogen production from biomass air-steam gasification with methane co-feeding. Energy Convers. Manag. 140, 228—239.

Ng, K.S., Sadhukhan, J., 2011. Techno-economic performance analysis of bio-oil based Fischer-Tropsch and CHP synthesis platform. Biomass Bioenergy 35 (7), 3218—3234.

Ogawa, T., Inoue, N., Shikada, T., Inokoshi, O., Ohno, Y., 2004. Direct dimethyl ether (DME) synthesis from natural gas. Stud. Surf. Sci. Catal. 147, 379—384.

Peng, X.D., Toseland, B.A., Tijm, P.J.A., 1999. Kinetic understanding of the chemical synergy under LPDMETM conditions-once-through applications. Chem. Eng. Sci. 54 (13), 2787—2792.

Rafati, M., Wang, L., Dayton, D.C., Schimmel, K., Kabadi, V., Shahbazi, A., 2017. Techno-economic analysis of production of Fischer-Tropsch liquids via biomass gasification: the effects of Fischer-Tropsch catalysts and natural gas co-feeding. Energy Convers. Manag. 140133, 153—166.

Rahnama, H., Farniaei, M., Abbasi, M., Rahimpour, M.R., 2014. Modeling of synthesis gas and hydrogen production in a thermally coupling of steam and tri-reforming of methane with membranes. J. Ind. Eng. Chem. 20 (4), 1779—1792.

Redissi, Y., Bouallou, C., 2013. Valorization of carbon dioxide by Co-electrolysis of CO_2/H_2O at high temperature for syngas production. Energy Procedia 37, 6667—6678.

Sadeghi, M., Jafari, M., Yari, M., Mahmoudi, S.M.S., 2018. Exergoeconomic assessment and optimization of a syngas production system with a desired H_2/CO ratio based on methane tri-reforming process. J. CO_2 Util. 25, 283—301.

Schakel, W., Hung, C.R., Tokheim, L.-A., Strømman, A.H., Worrell, E., Ramírez, A., 2018. Impact of fuel selection on the environmental performance of post-combustion calcium looping applied to a cement plant. Appl. Energy 210, 75—87.

Sharma, S., Sheth, P.N., 2016. Air—steam biomass gasification: experiments, modeling and simulation. Energy Convers. Manag. 140110, 307—318.

Simpson, A.P., Lutz, A.E., 2007. Exergy analysis of hydrogen production via steam methane reforming. Int. J. Hydrogen Energy 32 (18), 4811—4820.

Song, C., Pan, W., 2004. Tri-reforming of methane: a novel concept for catalytic production of industrially useful synthesis gas with desired H_2/CO ratios. Catal. Today 98 (4), 463—484.

Song, G., Shen, L., Xiao, J., 2011. Estimating specific chemical exergy of biomass from basic analysis data. Ind. Eng. Chem. Res. 50 (16), 9758—9766.

Szargut, J., Morris, D.R., Steward, F.R., 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, first ed. Edwards Brother, Inc.

Tijmensen, M.J.A., Faaij, A.P.C., Hamelinck, C.N., van Hardeveld, M.R.M., 2002. Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. Biomass Bioenergy 23 (2), 129—152.

Trippe, F., Fröhling, M., Schultmann, F., Stahl, R., Henrich, E., 2011. Techno-economic assessment of gasification as a process step within biomass-to-liquid (BtL) fuel and chemicals production. Fuel Process. Technol. 92 (11), 2169—2184.

Tsatsaronis, G., Moran, M.J., 1997. Exergy-aided cost minimization. Energy Convers. Manag. 14038 (15), 1535—1542.

Van der Heijden, H., Ptasinski, K.J., 2012. Exergy analysis of thermochemical ethanol production via biomass gasification and catalytic synthesis. Energy 46 (1), 200—210.

Zhang, Y., Li, B., Li, H., Liu, H., 2011. Thermodynamic evaluation of biomass gasification with air in autothermal gasifiers. Thermochim. Acta 519 (1), 65—71.

Zhang, Y., Cruz, J., Zhang, S., Lou, H.H., Benson, T.J., 2013. Process simulation and optimization of methanol production coupled to tri-reforming process. Int. J. Hydrogen Energy 38 (31), 13617—13630.

Zhang, Y., Zhang, S., Gossage, J.L., Lou, H.H., Benson, T.J., 2014. Thermodynamic analyses of tri-reforming reactions to produce syngas. Energy Fuel. 28 (4), 2717—2726.

Zhang, Y., Zhao, Y., Gao, X., Li, B., Huang, J., 2015. Energy and exergy analyses of syngas produced from rice husk gasification in an entrained flow reactor. J. Clean. Prod. 95, 273—280.

Zhang, Y., Yu, X., Li, B., Zhang, H., Liang, J., Li, Y., 2016. Exergy characteristics of woody biomass. Energy Sources A 38 (16), 2438—2446.