Review on effects of gasifying agents, temperature and equivalence ratio in biomass gasification process

F N Sidek, N A F Abdul Samad* and S Saleh

Faculty of Chemical & Process Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Pahang, Malaysia.

*E-mail: asmafazli@ump.edu.my

Abstract. Biomass gasification is one of the promising technologies for converting biomass into gaseous fuels. It is crucial to fully understand the influence of operation parameters and types of gasifier on the performance of biomass gasification. It also can provide useful information for a better design and operation of gasification process. The general overview on each types of gasifier are discussed where it can be classified into fixed bed and fluidized bed gasifiers. Most of the review from literature focuses more on the effects of temperature and equivalence ratio rather than gasifying agent. However, the review on the effect of gasifying agent is still limited whereas the effect of gasifying agent is also important as it influences the yield and composition of product gas. In the present work, the effects of gasifying agent, temperature and equivalence ratio on the gasification process were reviewed. Firstly, this article highlights the advantages and disadvantages of each gasifiers which consists of fixed bed and fluidized bed. Based on review, a detailed comparison was made in terms of syngas composition obtained by using steam, air, oxygen and carbon dioxide as gasifying agents in order to provide basic knowledge regarding the selection of gasifying agents. The effects of temperature and equivalence ratio (ER) on the gas composition, tar content and reaction rate were discussed and analyzed. Finally, guidelines on the operation parameters in terms of gasifying agent, temperature and equivalence ratio are suggested in the summary review.

1. Introduction

The world is depending on fossil fuels for energy and about 80% of the world energy source is being fulfilled by these fuels which contributing to serious environmental problems such as global warming [1]. There has been a growing concern towards the environmental issues as well as depletion of fossil fuels in the future. Therefore, to secure the energy supply while reducing the effect of global warming, the shifting of energy from fossil fuel to renewables energy is essential. Among the renewables energy source, biomass is considered as promising source since it is widely available and it is derived from living matters. The utilization of biomass for energy give positive impacts on the environment, as it is carbon neutral while the availability of biomass is abundance and uniform all over the world [2]. The examples of biomass are forest and agricultural wastes, municipal organic wastes and animal wastes [3].

Biomass can be converted into useful product in many different ways based on the characteristics and the condition of the product as well as its applications [4]. The most common application for biomass utilization is thermochemical conversion routes. Thermochemical conversion routes consist of three ways, which are gasification, liquefaction and pyrolysis [4]. The biomass gasification is an attractive process routes for energy conversion due to its conversion efficiency for various end product such as heat and electricity. In gasification process, the solid biomass is converted into combustible fuel through
thermochemical conversion with the help of oxidant in a reactor known as gasifier [4]. The product of biomass gasification may undergo further processing step before it can be utilized for different applications such as power generation and cooking. Gasifier can be divided into two principle types namely fixed bed and fluidized bed [2]. Fixed bed gasifiers are the most common reactor use in gasification due to its simplicity and ease of operation in terms of design and operation. However, the fluidized bed is considered as the best due to its flexibility in terms of efficiency and type of fuels.

Many researchers have investigated the influence of operating parameters and types of feedstock on the gasification performance. Current reviews tend to focus more on the effect of temperature as well as equivalent ratio (ER) because it is easy to be varied and measured. However, the review on the effect of gasifying agent is still limited whereas the selection gasifying agent is also important. This is because different types of gasifying agent will influence the yield and composition of syngas. Therefore, it is necessary to understand how these factors influence the gasification reactions, which can provide useful information as it influence the composition of product gas [5]. In the present work, the effects of gasifying agents, temperature and equivalence ratio on the gasification process are reviewed. This information is selected due to the fact that gasification temperature significantly influences the composition of syngas, yield of tar content as well as reaction rate. The selection of gasifying agent is usually based on the desired quality or composition of syngas [3]. Furthermore, the equivalent ratio (ER) is considered one of the crucial variables that affect gasifier performance [6]. The correct ratio of ER will contribute to the good blending of feedstock over gasifying agent, which in turn affects the quality of syngas and the stability of the operation. This article also reviews the feasibility of fixed bed and fluidized bed by highlighting the advantages and disadvantages of each gasifier as well as the effects of different gasifying agents, temperature and ER on gasification performance.

2. Biomass gasification
A variety of biomass gasifier types have been performed in experimental and simulation works for representing the gasification process. It can be categorized into two major classifications which are fixed bed gasifier and fluidized bed gasifier [7].

2.1. Fixed bed gasifier
The most common type of gasifier used for biomass is the fixed bed gasifier. The fixed bed gasification is one of the earliest and most frequent reactor used for the production of syngas [2]. The fixed bed gasifier gain interest of researchers and industrial people due to its simple design and operation with no or few moving parts, but the syngas produced is a low gas calorific value with high tar content [4]. The fixed bed gasifier can be classified into three types which are updraft, downdraft and cross flow [8]. The first type of fixed bed gasifier is updraft gasifier. The major difference between the gasifier is depending upon the direction and the doorway of the airflow where for updraft gasifier the entry of the gasifying agent is from the bottom of the gasifier while the biomass is fed from the top of the gasifier [2]. However, the produced gas from the updraft gasifier contains huge amount of tar and moisture where the gas was vented at the top of the gasifier. In the case of downdraft gasifier, both biomass and gasifying agent were fed from the top of the gasifier while the direction is downward which is towards the lower section of gasifier unit while product gases leave just under the grate of gasifier [2]. This will allow the product gases to undergo partial cracking where the tar content is lower. The downdraft gasifier is divided into four zones, which are drying, pyrolysis, oxidation and reduction zone. The biomass with a high moisture and ash content will complicate the process of handling the biomass with a low overall thermal efficiency. For cross flow gasifier, the biomass moves downward from the top of the gasifier and the gasifying agent is supplied from the side of the gasifier [2]. The product gases exited from the top of the cross flow gasifier are expected to have high tar content with low overall energy efficiency.

2.2. Fluidized bed gasifier
Fluidized bed is considered as an attractive selection because of its flexibility in terms of fuel and efficiency [2]. The gasifiers are broadly used in coal gasification for many years. One of the advantages
of fluidized bed over the fixed bed is the temperature in the reduction zone is uniform with the help of fine granular particle, which helps to fluidize the bed [9-10]. However, the downside of the fluidized bed gasifier is the complicated design with high operation and energy requirement. In addition, the major concern is the syngas from the gasifier has high tar content where gas cleaning is required. Fluidized bed is economical for 5 to 10 MW scale since the plant costs is high. Fluidized bed can be classified into two types, which are circulating fluidized bed and bubbling bed. The circulating fluidized bed is conducted based on the mechanism of continuous circulation of the bed material between the reaction vessel and cyclone separator. The advantages of a circulating fluidized bed are its ability to perform well with a high capacity of biomass throughputs and can be operated at high pressure [2]. In the bubbling bed, the gasifying agent enters the reactor from the bottom which is through the grate whereas the fine bed material is located above the grate where the biomass feed is fed. The bed material reacts with the high molecular weight tar to produce a syngas with lower tar content [2].

2.3. Advantages and disadvantages of different gasifiers

The advantages and disadvantages of each gasifier are highlighted in tables 1 and 2. There are numerous comparisons between fixed bed and fluidized bed gasifiers based on many aspects such as technology

| Advantages | Cross-flow gasifier |
|------------|---------------------|
| Simple and low cost process | Ease of operation |
| Suitable for high moisture and high inorganic content | Simple glass cleaning train (cyclone and bed filter) |
| Proven technology | High tar content |

| Disadvantages | Cross-flow gasifier |
|---------------|---------------------|
| Tar content is about 10 to 20% of tar by weight | Low overall energy efficiency |
| Intensive cleaning is required | |

| Advantages | Downdraft Gasifier |
|------------|---------------------|
| Required minimal or no tar cleanup as about 99.9% of tar formed is consumed [11] | |
| Minerals remain with char or ash, reduce the need of cyclone | |
| Proven technology, simple and low cost process | |

| Disadvantages | Downdraft Gasifier |
|---------------|---------------------|
| The feed needs to be dry to lower the moisture (<20%) | |
| The high temperature of syngas exits from gasifier require cooling before use | |
| Unconverted carbon of 4 to 7% [12]. | |

| Advantages | Circulating fluidized beds |
|------------|---------------------------|
| Yields a uniform syngas | Suitable for fast reactions |
| Uniform temperature distribution | High heat transport rates possible due to high heat capacity of bed material |
| Accept wide range of fuel | High conversion rate with low tar and unconverted carbon |
| High rates of heat transfer between the inert material, fuel and gas | |
| High conversion with low tar and unconverted carbon | |

| Disadvantages | Circulating fluidized beds |
|---------------|---------------------------|
| Gas bypass through the bed due to large bubble size | Temperature gradients occur in direction of the solid flow |
| | Size of fuel particles determine minimum transport velocity |
| | Heat transfer less efficient than bubbling fluidized bed |

| Advantages | Bubbling beds |
|------------|--------------|
| Suitable for fast reactions | |
| High heat transport rates possible due to high heat capacity of bed material | |

| Disadvantages | Bubbling beds |
|---------------|--------------|
| Suitable for fast reactions | |
| High heat transport rates possible due to high heat capacity of bed material | |
| Temperature gradients occur in direction of the solid flow | |
| Size of fuel particles determine minimum transport velocity | |
| Heat transfer less efficient than bubbling fluidized bed | |
and economy. The selection of gasifier will be depending on numbers of factors such as the feedstock, the product of producer gas required, and also operating condition. However, the complex design and operation as well as high energy consumption in fluidized bed is not favorable factor for gasifier selection. In addition, the tar content in a syngas of a fluidized bed is usually high where extra gas cleaning is required. In comparison to fluidized bed, the fixed bed gasifier appears to be more feasible for small scale plant application. This is due to the operation simplicity and cost-effective operation.

3. Effects of different gasifying agents

The most common gasifying agents used are air, steam, carbon dioxide and also pure oxygen. Usually the gasifying agent is selected based on the required quality of the syngas used in the downstream applications [3]. Ahmed et al. investigated woodchips char gasification by using steam and CO\(_2\) as gasifying agent [13]. The gasification was conducted in a fixed reactor temperature and pressure of 900 °C and 2 bars. The variation of partial pressure of gasifying agents is from 0.6 to 1.5 bars with intervals of 0.3 bars. The steam and CO\(_2\) flow rates were chosen in order to have an equal amount of oxygen in both of gasifying agents where the flowrates are 4.42 g/min of steam or 5.4 g/min of CO\(_2\). The reactivity of steam is higher compared to CO\(_2\) as the gasifying agent. The results show that the duration of gasification experiments for steam is approximately 22 minutes while the duration of CO\(_2\) is approximately 60 minutes. Based on the findings, it shows that the reactivity of steam is approximately three times faster than that of CO\(_2\). Therefore, as the reaction time faster, the time to produce syngas also shorter.

Xu et al. evaluated the gasification performance of municipal solid waste (MSW) by using thermodynamic equilibrium model [14]. Three type of gasifying agents were considered which are steam, hydrogen and air. In order to compare the performance of the gasifying agents, the temperature of the reactor and the mass flowrate of MSW are fixed at 1273 K and 100 kg/h. Based on the results, hydrogen gasifying agent contributed to highest mole fractions of CO and H\(_2\) with smallest mole fractions of CO\(_2\) and H\(_2\)O. As for steam gasifying agent, the mole fractions of H\(_2\) and H\(_2\)O is the larger and smaller mole of fractions of CO\(_2\) compared to air gasifying agent. This is due to the presence of oxygen content in the gasifying agent where hydrogen gasifying agent has the lowest oxygen content followed by steam gasifying agent and air gasifying agent. The presence of oxygen will contribute to the products composed of CO\(_2\) rather than CO and H\(_2\). Therefore, the selection of gasifying agent is depending on the product requirement. In this case, hydrogen gasifying agent is suitable to be used if H\(_2\) and CO are needed with a lowest mass flowrate. On the other hand, air gasifying agent can be used in order to get high energy efficiency when there is no required quality and yield of the end products. However, the steam gasifying agent falls between the other two agents as the oxygen content of steam gasifying agent is higher than hydrogen gasifying agent but lower than air gasifying agent.

Prabawo et al. explored the high thermal efficiency in thermal gasification by replacing the steam gasifying agent by CO\(_2\) gasifying agent [15]. The lab scale downdraft gasifier was used to study the effect of the gasifying agent on gas evolution and thermal efficiency. A list of biomass pyrolysis and CO\(_2\) steam gasification experiments were conducted with or without the presence of O\(_2\). The results show that CO\(_2\)-steam gasification with and without the present of O\(_2\) produced a larger amount of combustible gas compared to pyrolysis. The yield of H\(_2\) decreases while the yield of CO increases, as the steam is substituted by CO\(_2\) gasifying agent. The advantage of CO\(_2\) mixing ratio in terms of thermal efficiency was observed at the temperature greater than 850 °C. The efficiency of gasification process with CO\(_2\) as a gasifying agent is higher if compared to the pyrolysis with N\(_2\) in syngas production. Moreover, it is more efficient to use CO\(_2\) than steam in the N\(_2\) free syngas production.

Shayan et al. investigated and compared hydrogen production by using different gasifying agents [16]. Four gasifying agents were used which are air, oxygen-enriched air, oxygen and steam in gasification of wood and paper. The effect of key operating parameters on the yield of hydrogen, calorific value of producer gas, energy efficiencies of the process and energy destruction rate at different operating conditions. The gasification temperature and moisture content used are 1073 K and 10%. The highest amount of hydrogen produced when steam is used as the gasifying agent, which is higher than
air gasifying agent. The reason for this finding is due to the fraction of nitrogen in steam gasification is zero where it leads to a shift in chemical equilibrium of the gasification reaction, which cause the yield of hydrogen to increase. Besides, molar fraction of hydrogen is higher by using oxygen enriched air and oxygen instead of environmental air due to lesser concentration of nitrogen to the gasifier. The results also show that the yield of CO in the producer gas is the highest when O\(_2\) is used. The effect of gasification temperature on the yield of hydrogen of the producer gas for different gasifying agents also was investigated for both biomass wood and paper. The amount of hydrogen produced by using steam gasifying agent is the highest for all the gasification temperature ranges from 1000 to 1400 K for both biomass. On the other hand, the yield of hydrogen in the producer gas is the lowest for all the gasification temperature when air is used as the gasifying agent. The optimum gasification temperature by using steam gasifying agent for production of hydrogen is around 1050 K and 1075 K for wood and paper. As for the effect of gasification temperature on calorific value of producer gas, the results indicate that higher calorific value when using steam and O\(_2\) gasifying agent. This is due to the amount of hydrogen and carbon monoxide content where it responsible for the calorific value of syngas. However, as the gasification temperature decreases, the calorific value of the syngas decreases for all types of gasifying agent.

4. Effects of gasification temperature

The most crucial parameters in biomass gasification are temperature where it will affect the gas composition, tar content, and reaction rate [3]. Xu et al. accessed the effect of steam temperature on the concentration of syngas, which are CH\(_4\), CO, CO\(_2\) and H\(_2\) as well as the reactor temperature [14]. The steam temperature is varied from 973 to 2273 K and the steam to municipal solid waste ratio is set at 2. The effect of steam temperature on the concentration of syngas can be divided into two different regions. As the steam temperature is set below 1650 K, the concentration of H\(_2\) increases up to 0.45 Nm\(^3\).kg\(^{-1}\) while the concentration of CO\(_2\) increases from 0.09 to 0.19 Nm\(^3\).kg\(^{-1}\). On the other hand, the concentration of CH\(_4\) decreases from 0.12 to 0 Nm\(^3\).kg\(^{-1}\) and the concentration of CO remains unchanged. However, as the temperature of the steam rises above 1650 K, the concentration of H\(_2\) and CO\(_2\) reduce slightly, while the concentration of CO slightly increases. On the other hand, the reactor temperature increases as the steam temperature increases. He et al. studied the production of hydrogen rich gas or syngas by using catalytic steam gasification of MSW in a bench-scale downstream fixed bed reactor [17]. The catalyst used is calcinated dolomite where the effect of catalyst and reactor temperature was studied. The effects of temperature on the product distribution (char, tar and gas) and gas fraction were investigated. The temperature of gasifier was varied from 700 to 950 °C. As the temperature increases, the conversion rate of MSW into hydrogen-rich gas increases from 27.01 to 53.29%. However, an increase in temperature results in decrease in the yield of char and tar while the composition of dry gas increase. The yield of char decreased from 21.68 to 8.12% whereas the composition of dry gas increased from 81.84 to 104.16%.

Pu et al. studied the biomass gasification of a pine with air and oxygen/steam atmosphere in a fixed bed reactor [18]. The effect of different reaction temperature on the gas composition and lower heating value (LHV) was investigated. The variation of reaction temperature is from 650 to 950 °C. The results show that, higher reaction temperature leads to higher H\(_2\) content. The maximum value of reaction temperature is at 850 °C before the H\(_2\) content started to decrease gradually. This is due to the water gas shift reaction and steam reforming reaction, which is endothermic. Therefore, the increase in reaction temperature is conducive for the yield of H\(_2\) initially. However, some of H\(_2\) may take part in oxidation reaction when the reaction temperature is further increased which contributes to decrease in the yield of H\(_2\). Besides, the H\(_2\) content also affect the LHV values. This is because, at reaction temperature range of 650 – 750 °C, as the H\(_2\) content increases, the LHV also increases. Therefore, it can be concluded that, H\(_2\) content plays an important role in LHV. Yan et al. carried out an experiment of biomass gasification in a fixed bed reactor [19]. The influence of temperature on the hydrogen yield was investigated. The variation of temperature used is from 600 to 850 °C. As the temperature increases, the yield of H\(_2\) increases from 29.54 to 52.41%. It can be concluded that, an increase in temperature
contributes to a sharp increase of hydrogen yield. Jamin et al. developed the thermodynamic equilibrium and predicted the composition of product gas based on the food and wood waste in a fluidized bed gasifier [20]. The gasification temperature used is in the range of 650 to 1000 °C. It was found that, as the temperature increases up to 1000 °C, the percentage of H₂ and CO gas increase which is from 29.58% to 34.03% and 31.85 to 45.78% for food waste. Meanwhile, the percentage H₂ and CO gas show the same trend where it increases from 31.25 to 39.87% and 26.33 to 34.81% for wood waste. Furthermore, LHV also exhibits the same trend as the product gas yield for both food and wood waste.

5. Effect of equivalence ratio (ER)

The equivalence ratio (ER) is defined as mass ratio of gasifying agent to fuel/biomass in any combustion unit [3]. Stoichiometric ratio is the minimum ratio of gasifying agent to fuel/biomass which is exactly enough to burn the fuel completely. The difference between combustion and gasification is combustion uses minimum stoichiometric ratio of gasifying agent to fuel whereas gasification uses gasifying agent-fuel ratio lower than stoichiometric ratio. On the other hand, the ratio between the gasifying agent-fuel ratio of the gasification process and the gasifying agent-fuel ratio for complete combustion is defined as equivalence ratio. Xu et al. investigated the effect of steam to MSW ratio on the concentration of syngas, which are CH₄, CO, CO₂ and H₂ and the reactor temperature [14]. The steam to MSW ratio (STMR) varied from 1 to 5 while the temperature is set to 1273 K. The result from the effect of the STMR is very identical to the effect of steam temperature. The results indicate that an increase of STMR will increase the reactor temperature that is cause by the energy balance. Guo et al. studied the effect of design and operating parameters on the gasification of corn straw [21]. The gasification was performed in a downdraft gasifier under atmospheric pressure and the gasifying agent used was air. Total of seven experiments were conducted by varying only the air feeding rate while the biomass feeding rate is kept constant. The equivalence ratio ranges from 0.18 to 0.37. The results show as the ER increases, the operating temperature in the gasifier increases, as high value of ER will enhance the combustion reactions to release heat. However, at the upper part of the gasifier, which is pyrolysis zone, the temperature is relatively low where the peak temperature only occurs at oxidation zone. The high temperature of gasifier caused by the high value of ER also led to higher tar cracking which in turn reduces tar yield. However, as ER increases above 0.32, the tar yield started to increase gradually. The lowest tar yield produced is 0.52 g/Nm³ where the ER is at 0.32.

Pratik et al. explored biomass gasification of waste wood based on production of hydrogen energy [22]. The experiment was conducted in a downdraft gasifier where the effect of ER on the producer gas composition is evaluated. The ER was varied from 0.15 to 0.4. As the ER increases, the concentrations of H₂ and CO are also increased. However, as the ER is further increased up to 0.205, the concentrations of H₂ and CO are decreased. On the other hand, the CO₂ and N₂ show opposite trends to H₂ and CO concentrations. Furthermore, the result shows that the increase of ER will increase the production rate of producer gas. The optimum value of ER based on the production of producer gas point of view is 0.205, thus resulting to a maximum of yields of H₂ and CO. Gai et al. conducted a study on biomass gasification of corn straw in downdraft gasifier [23]. The study was carried out in downdraft fixed bed gasifier where air is used as gasifying agent. The influence of ER on the main gas composition is investigated where the range of ER is from 0.18 to 0.41. It was found as the ER increase, the temperature of gasifier increased. The results of ER can be divided into 2 categories, which is from 0.18 to 0.32 and above 0.32. The increase in ER, which is from 0.18 to 0.32 resulting the yield of CO₂ to decrease from 23.93 to 11.58% whereas the yield of CO increase from 11.35 to 19.81%. On the other hand, the yield of H₂ and CH₄ increases from 6.9 to 13.51% and from 1.27 to 3.96% respectively. When ER is greater than 0.32, the yield of CO₂ was observed to increase from 11.58 to 18.41% whereas the yield of CO gradual decrease from 19.81 to 15.16%. Moreover, the yield of H₂ and CH₄ reduced from 13.51 to 10.58% and from 3.72 to 1.57% respectively. Furthermore, as the ER increases from 0.18 to 0.32 the LHV increased from 2.69 to 5.39 MJ/m³. However, as the ER increase above 0.32, the LHV started to reduce to 3.69 MJ/m³.
6. Review summary

The summary of effects of gasifying agent, temperature and equivalence ratio (ER) and its remarks are described in the table 3. It can be concluded that the uses of different types or combination of gasifying agent have their own advantages and disadvantages. The gasifying agent should be selected based on application, required quality or composition product gas as well as the end use of the product gas. Based on the review, the usage of air as a gasifying agent will results in higher yield of CO$_2$ rather than CO or H$_2$. Therefore, making it suitable to be used for refrigeration and cooling application as the composition of CO$_2$ is high in the product gas. Next, in order to produce hydrogen rich gas, it is recommended to use steam as gasifying agent rather than air gasifying agent. The high amount of H$_2$ is suitable to be used in the fuel cell application. For example, power generation by using the H$_2$ as an input for proton exchange membrane fuel cell (PEMFC) [24]. Utilization of pure oxygen as gasifying agent will increase the composition of CO and H$_2$ while reduces the tar content in the product gas but the cost of the gasifying agent is high.

Table 3. Summary of parameters affecting the gasifier operation.

| Parameters          | Remarks                                      |
|---------------------|----------------------------------------------|
| Gasifying Agent     |                                              |
| Air                 | • Higher composition of CO$_2$ rather than CO or H$_2$ rather than CO or H$_2$. |
| Steam               | • Favorable in hydrogen rich gas             |
| Pure Oxygen         | • Higher composition of CO and H$_2$         |
|                     | • Reduce tar content                         |
|                     | • Cost of the gasifying agent high           |
| Temperature         | • For the production of hydrogen rich gas or syngas (above 850 °C) |
|                     | • Temperature ↑, LHV ↑, yield of char and tar ↓. |
|                     | • Temperature of biomass should not exceed 1000°C, as it will melt the ash |
|                     | • Reactor temperature ↑, ER ↑, tar yield ↓. |
| Equivalence Ratio   | • ER ↑, yield of H$_2$, CO and CH$_4$ ↑ while yield of CO$_2$ ↓ |
| (ER)                | • ER ↑ further to a certain ER value (ER>0.32), the yield of H$_2$, CO and CH$_4$ ↓, yield of CO$_2$ ↑ |

For the effect of temperature on the composition of product gas, the findings indicate that for the production of hydrogen rich gas or syngas, high temperature is favorable. The high reactor temperature will help in reducing tar yield. However, as the temperature increase to a certain temperature above 850 °C, the composition of hydrogen decreases gradually. Therefore, it is important to study the optimal temperature in order to achieve high amount of hydrogen rich gas or syngas since the optimal temperature of every biomass is different. Furthermore, optimal temperature also contributes to optimal LHV and reduces the yield of char and tar. Despite the advantages of using high temperature, the temperature of biomass should not exceed 1000 °C as it will melt the ash especially the biomass with high ash content such as wheat straw. Besides, this requirement is to adhere to the reactor specification. On the other hand, as the ER increases, it will attribute to higher yield of H$_2$, CO and CH$_4$ and lower yield of CO$_2$. However, as the ER increase further to a certain ER value, the yield of H$_2$, CO and CH$_4$ will start to reduce gradually while the yield of CO$_2$ will start to increase.

7. Conclusion

In this paper, the advantages and disadvantages of each gasifier were discussed. However, the selection of particular gasifier types and its design are depending on the properties of biomass feedstock and quality of product gas. The fixed bed gasifier is favorable for small-scale plant due to its design simplicity, easy to operate and economically feasible. On the other hand, the fluidized bed is more suitable for medium scale plant application due to its ability to achieve uniform yield and temperature distribution. The effects of gasifying agent, temperature and equivalence ratio on the performance of gasification process were also reviewed. As discussed above, the use of air gasifying agent will result in
highest yield of CO\(_2\) whereas steam gasifying agent will result in hydrogen rich syngas. On the other hand, the use of oxygen gasifying agent produced lower tar yield and higher composition of CO and H\(_2\). In terms of gasification temperature and ER, it is favorable to use high reactor temperature in the range of 850 – 1000 °C and ER in the range of 0.2 – 0.32 in order to produce hydrogen rich syngas with a yield around 50%. The yield of H\(_2\), CO and CH\(_4\) increases while yield of CO decreases as the reactor temperature increases.

References
[1] D. Baruah and D. C. Baruah, 2014 “Modeling of biomass gasification: A review,” vol. 39, pp. 806–815.
[2] T. K. Patra and P. N. Sheth, 2015 “Biomass gasification models for downdraft gasifier: A state-of-the-art review,” vol. 50, pp. 583–593.
[3] M. Asadullah, 2014 “Barriers of commercial power generation using biomass gasification: A review,” vol. 29, pp. 201–215.
[4] S. K. Sansaniwal, K. Pal, M. A. Rosen, and S. K. Tyagi, 2017 “Recent advances in the development of biomass gasification technology: A comprehensive review,” vol. 72, no. December 2015, pp. 363–384.
[5] E. Madadian, V. Orsat, and M. Lefsrud, 2017 “Comparative Study of Temperature Impact on Air Gasification of Various Types of Biomass in a Research-Scale Down-draft Reactor,” Energy and Fuels, vol. 31, no. 4, pp. 4045–4053.
[6] W. Ngamchompoo and K. Triratanasirichai, 2017 “Experimental investigation of high temperature air and steam biomass gasification in a fixed-bed downdraft gasifier,” Energy Sources, Part A: Recovery, Utilization and Environmental Effects, vol. 39, no. 8. pp. 733–740.
[7] V. S. Sikarwar et al., 2016 “An overview of advances in biomass gasification,” Energy Environ. Sci., vol. 9, no. 10, pp. 2939–2977.
[8] M. B. Muslim, S. Saleh, and N. A. F. A. Samad, 2017 “Effects of purification on the hydrogen production in biomass gasification process,” Chem. Eng. Trans., vol. 56, pp. 1495–1500.
[9] P. Lahijani and Z. A. Zainal, 2011 “Bioresource Technology Gasification of palm empty fruit bunch in a bubbling fluidized bed: A performance and agglomeration study,” Bioresour. Technol., vol. 102, no. 2, pp. 2068–2076.
[10] X. Ku, H. Jin, and J. Lin, 2017 “Comparison of gasification performances between raw and torrefied biomasses in an air-blown fluidized-bed gasifier,” Chem. Eng. Sci., vol. 168, pp. 235–249.
[11] M. B. Muslim, S. Saleh, and N. A. F. Abdul Samad, 2017 “Torrefied Biomass Gasification: A Simulation Study by Using Empty Fruit Bunch,” MATEC Web Conf., vol. 131, pp. 0–5.
[12] N. Couto, A. Rouboa, V. Silva, E. Monteiro, and K. Bouziane, 2013 “Influence of the biomass gasification processes on the final composition of syngas,” Energy Procedia, vol. 36, pp. 596–606.
[13] I. I. Ahmed and A. K. Gupta, 2011 “Kinetics of woodchips char gasification with steam and carbon dioxide,” Appl. Energy, vol. 88, no. 5, pp. 1613–1619.
[14] P. Xu, Y. Jin, and Y. Cheng, 2017 “Thermodynamic Analysis of the Gasification of Municipal Solid Waste,” Energy, vol. 3, no. 3, pp. 416–422.
[15] B. Prabowo, K. Umeki, M. Yan, M. R. Nakamura, M. J. Castaldi, and K. Yoshikawa, 2014 “CO2–steam mixture for direct and indirect gasification of rice straw in a downdraft gasifier: Laboratory-scale experiments and performance prediction,” Appl. Energy, vol. 113, pp. 670–679.
[16] E. Shayan, V. Zare, and I. Mirzaee, 2018 “Hydrogen production from biomass gasification: a theoretical comparison of using different gasification agents,” vol. 159, no. December 2017, pp. 30–41.
[17] M. He et al., 2009 “Hydrogen-rich gas from catalytic steam gasification of municipal solid waste (MSW): Influence of catalyst and temperature on yield and product composition,” vol. 34, pp.
195–203.

[18] G. Pu, H. Zhou, and G. Hao, 2013 “Study on pine biomass air and oxygen / steam gasification in the fixed bed gasifier,” vol. 8, pp. 1–7.

[19] F. Yan, S. Luo, Z. Hu, B. Xiao, and G. Cheng, 2010 “Bioresource Technology Hydrogen-rich gas production by steam gasification of char from biomass fast pyrolysis in a fixed-bed reactor: Influence of temperature and steam on hydrogen yield and syngas composition,” Bioresour. Technol., vol. 101, no. 14, pp. 5633–5637.

[20] N. A. Jamin, N. A. F. A. Samad, and S. Saleh, 2019 “Synthesis gas production of food and wood wastes in a fluidized bed gasifier using thermodynamic equilibrium model,” 6TH Int. Conf. Environ. Empower. Environ. Sustain. Eng. Nexus Through Green Technol., vol. 2124, no. July, p. 020041.

[21] F. Guo, Y. Dong, L. Dong, and C. Guo, 2014 “ScienceDirect Effect of design and operating parameters on the gasification process of biomass in a downdraft fixed bed: An experimental study,” Int. J. Hydrogen Energy, vol. 39, no. 11, pp. 5625–5633.

[22] P. N. Sheth and B. V Babu, 2010 “Production of hydrogen energy through biomass ( waste wood ) gasification,” Int. J. Hydrogen Energy, vol. 35, no. 19, pp. 10803–10810.

[23] C. Gai and Y. Dong, 2012 “Experimental study on non-woody biomass gasification in a downdraft gasifier,” Int. J. Hydrogen Energy, vol. 37, no. 6, pp. 4935–4944.

[24] F. R. A. Abdul Wahid, M. B. Muslim, S. Saleh, and N. A. F. Abdul Samad, 2016 “Integrated gasification and fuel cell framework: Biomass gasification case study,” ARPN J. Eng. Appl. Sci., vol. 11, no. 4, pp. 2673–2680.

[25] S. Safarian, R. Unnþórsson, and C. Richter, 2019 “A review of biomass gasification modelling,” Renew. Sustain. Energy Rev., vol. 110, no. May, pp. 378–391.