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Hydrogen production via biomass gasification: Simulation and performance analysis under different gasifying agents

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Abstract

This study develops a new simulation model by ASPEN Plus for gasification integrated with water-gas shift reactors and product recovery unit for hydrogen production. Timber and wood waste (T&WW) as a lignocellulosic biomass was also considered as the input feedstock to the system. Then, the model is applied to investigate the effect of two agents of air and a mixture of air-steam under different operating conditions of temperature and steam to biomass ratio (SBR). The results reveal that the produced hydrogen through the air-steam gasification is at the highest points for all studied temperatures and it would be maximum (44.37 Kmol/hr per 1 ton T&WWs) at 700 ˚C. The hydrogen production efficiency (HPE) can be also raised, stemming from the growth of H_2. It values 39.2% at SBR = 0.1 that grows to 70% at SBR = 0.9. The optimum SBR lies between 0.7-0.8 that specific mass flow rate of hydrogen would be higher than 0.1 $kg_{hydrogen}/kg_{T\&WW}$.

Keywords: Hydrogen production, Biomass gasification, Water-gas shift reactor, Process simulation, Gasifying agents.

Introduction

Growing concerns about the depletion of fossil fuels, energy security and environmental impacts due to burning of the fossil fuels have encouraged the decision makers in the energy sector to substitute fossil fuels with renewable and sustainable energy alternatives [1-5]. Among the renewable energies, biomass and hydrogen have received significant attention as they can increase the global energy sustainability and reduce greenhouse gas emissions [6-10]. Globally, biomass has the third widest energy source after coal and oil [11] and it includes plenty advantages such as it is inexhaustible, it can be easily stored, and its CO_2 emissions is considered climate-neutral, since the CO_2 released through the biofuel combustion is almost equal to the CO_2 value absorbed by biomass during its lifetime [12,13].

There are various technologies for conversion of biomass to product gas, including thermochemical, biochemical and mechanical extraction methods. Thermochemical conversion methods can be classified into: combustion, gasification, pyrolysis and liquefaction [14,15]. Among these methods, biomass gasification is a promising technology to convert different feedstocks for various energy purposes [16-18]. This complex thermochemical process converts the lignocellulosic materials into a more valuable gas known as syngas by a series reactions at high temperatures [19-21]. The gasification process takes place in the presence of gasification agents such as air, steam, oxygen, or a mixture of them. Air gasification produces syngas with LHV in the range of 4-7 MJ/Nm^3 and if steam is used instead of air the syngas produced has a LHV in the range of 10-15 MJ/Nm^3 and the hydrogen yield is higher, as a result of water gas shift reaction [22,23]. However, it would be more beneficial to consider a mixture of air and steam as the oxidizing agent because biomass steam gasification requires external heat due to the endothermic steam reforming reactions involved [24].

The gasification process consists different steps of drying of the wet feedstocks, pyrolysis of the dried feedstocks and the reaction part containing oxidation, reduction and cracking [15,25]. Syngas as a result of biomass gasification, contains mainly carbon monoxide, hydrogen, carbon dioxide, methane and traces of higher hydrocarbons, can be used for polygeneration purposes such as thermal heat, power generation or to produce hydrogen fuel [26-28]. Hydrogen has the highest energy density among all hydrocarbons fuels which is about 122 kJ/kg [29] and it can be used as a clean energy source for fuel cells, clean energy carrier for heat supply, and transportation purposes [30-32]. Several technologies were developed to produce hydrogen, like conventional methane steam reforming, biological processes, biomass gasification, biomass pyrolysis, electrolysis, and thermochemical water splitting [19,33].

Biomass gasification as an attractive technology for conversion of various types of biowastes to energy, has been known as a clean and efficient way of producing hydrogen [34,35]. Biomass gasification is of significant interests due to the facts that (a) the process is fast, (b) the process is efficient, (c) biomass is environmentally friendly, (d) biomass is renewable, etc. [36,37]. Performance analysis of biomass gasification systems has been studied in many researches [4,27,38-46]. However, there are just a few studies on performance analysis of integrated gasification-hydrogen production [10,28,47].

Meramo-Hurtado et al., [48] addressed the modeling and evaluation of a biomass gasification topology for hydrogen production, employing process simulation along with an environmental and inherent safety analysis. The presented pathway considered for cassava and rice waste as renewable raw materials based on their vast availability in north Colombia regions. they employed Aspen Plus process simulation software to model the process, setting biomasses and ash content as nonconventional solids in the software and inclusion of FORTRAN subroutines for handling solid properties. However, their focus is mainly on environmental evaluation applying based on the waste reduction algorithm (WAR) and safety assessment that involve a comprehensive approach based on the inherent safety index (ISI) and the process route index (PRI) methods. Marcantonio et al., [28] studied the gasification of hazelnut shells within a circulating bubbling fluidized bed gasifier through a quasi-equilibrium approach developed in the Aspen Plus environment and used to validate and improve an existing bubbling fluidized bed gasifier model. The gasification unit was integrated with a water-gas shift (WGS) reactor to increase the hydrogen content in the outlet stream and with a pressure swing adsorption (PSA) unit for hydrogen separation. The amount of dry H_2 obtained out of the gasifier was 31.3 mol%, and this value increased to 47.5 mol% after the WGS reaction. Shayan et al., [10] investigated the hydrogen production from biomass gasification using various agents and compared theoretically, from the viewpoints of the first and second thermodynamics laws. Gasification of wood and paper, were assessed using four gasification agents of air, oxygen-enriched air, oxygen and steam. A parametric study was also conducted to assess the effects of key operating parameters on the hydrogen concentration and calorific value of product gas, energy and exergy efficiencies of the process and exergy destruction rate at different operating conditions. The results indicate that the higher values of hydrogen production is associated respectively with using steam, oxygen, oxygen-enriched air and air as the gasification agents. Also, it is concluded that for the gasification process the highest value of sensible energy efficiency is obtained for air gasification, while the highest exergy efficiency, as a rational criterion, is obtained for steam gasification for which the calorific value of the producer gas can reach to higher than 11 MJ/Nm^3. Nakyai et al., [49] studied, the effects of various types of gasifying agent, i.e., air and steam for the biomass gasification with/without methane co-feeding through an exergoeconomic analysis. It is observed that the methane co-feeding can improve the energy and exergy efficiency. In exergoeconomic analysis, the specific exergy cost method was applied to investigate the unit cost of hydrogen. The economic reveal that the biomass gasification using air-steam as an agent with methane co-feeding presented the lowest unit hydrogen cost of 2.69 $/kg and the unit exergy cost of hydrogen is 0.068 $/kWh. Although there have been several studies on hydrogen production by using biomass gasification, the authors are not aware of any reported works on effect evaluation and sensitivity analysis of different agents and critical operating parameters on gasification performance and hydrogen production. Therefore, the objective of the present study is development of a new simulation model by using ASPEN Plus for the integrated gasification with hydrogen production from timber and wood waste (T&WW) as the feedstock. Then, the model is used to investigate the effect of two agents of air and a mixture of air-steam on the system performance. Moreover, two sensitivity analyses are carried out to study the impacts of the gasifier temperature and the steam to biomass ratio (SBR) on the syngas composition, low heating value (LHV) of syngas, hydrogen production and its efficiency. Thus, this study could provide a framework for defining the gasification, and hydrogen production plants to support equipment specification, and will be the basis for a future comprehensive environmental and techno-economic assessments.

Material and methods

System description

The system considered in this work is shown in Fig. 1. Timber and wood wastes (T&WW) were used as the biomass feedstock. The characteristics of T&WWs are brought in Table 1. Typically, the moisture in the biomass ranges from 5–60% that during drying, it is reduced to below 5%. In the pyrolysis step, the biomass is heated from with limited oxygen or air and under these conditions the volatile components in the biomass are vaporized. The oxygen supplied to the gasifier reacts with the combustible substances, producing CO_2 and H_2O. Some of this CO_2 and H_2O subsequently are reduced to CO and H_2 upon contact with the char produced from pyrolysis [50]. Moreover, the hydrogen in the biomass can be oxidized, generating water. The reduction reactions occurring inside the gasifier are endothermic, and the energy required for these reactions is provided by the combustion of char and volatiles. Reduction of the biomass yields combustible gases such as hydrogen, carbon monoxide, and methane through a series of reactions; the main reactions in this category are as follows (Table 2) [51,52]:

After gasification, the produced syngas undergoes the water-gas (W-G) shift reaction:

$$CO + H_2O \rightarrow H_2 + CO_2 \qquad (1)$$

Which occurs in two reactors of high temperature shift and low temperature shift [53]. The gas from the W-G shift contains mainly H_2, CO_2, residual steam, and traces of CH_4 and CO; then to produce pure hydrogen, these gases is fed into the PSA system to obtain pure hydrogen.

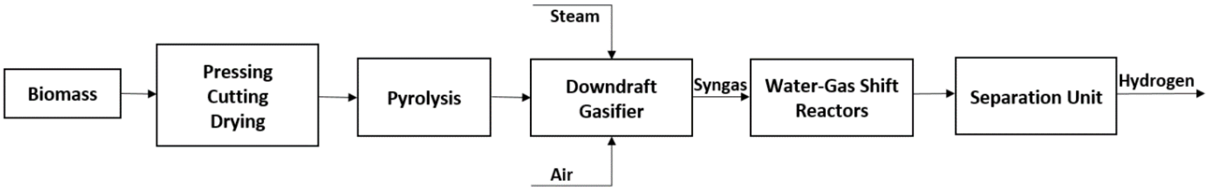

Fig.1: Structure of the biomass gasification-hydrogen production process.

Table 1. Ultimate and proximate analysis of feedstock [4,39]

	Timber & wood waste
Proximate analysis	
Proximate analysis (wt%)	
Moisture	5.01
Volatile matter (VM)	93.06
Fixed carbon (FC)	6.38
Ash	0.56
Ultimate analysis	
Elemental analysis (wt%-dry basis)	
C	56.8
H	7.28
N	0.18
Cl	0.82
S	0.07
O	34.29

Table 2: Main gasification reactions [51,52]

Heterogeneous reactions		
$C+O_2 \rightarrow CO_2$+394 kJ/mol	Complete combustion	R1
$C+0.5O_2 \rightarrow CO$+111 kJ/mol	Partial combustion	R2
$C+CO_2 \rightarrow 2CO$-172 kJ/mol	Boudouard	R3
$C+H_2O \rightarrow CO+H_2$-131 kJ/mol	Water-gas	R4
$C+2H_2 \rightarrow CH_4$+75 kJ/mol	Methanation	R5
Homogeneous reactions		
$CO+0.5O_2 \rightarrow CO_2$+283 kJ/mol	CO partial combustion	R6
$H_2+0.5O_2 \rightarrow H_2O$+242 kJ/mol	H_2 combustion	R7
$CO+H_2O \rightarrow CO_2+H_2$+41 kJ/mol	Water-gas shift (WGS)	R8
$CH_4+H_2O \rightarrow CO+3H_2$-206 kJ/mol	Reforming	R9
H_2S and NH_3 formation reactions		
$H_2+S \rightarrow H_2S$	H_2S formation	R10
$3H_2+N_2 \rightarrow 2NH_3$	NH_3 formation	R11

Simulation model

An equilibrium simulation model has been developed for biomasses gasification integrated with W-G shift unit and separation unit for ethanol production by using ASPEN Plus version 10. Penge Robinson equation of state with Boston-Mathias alpha function (PR-BM) was applied to calculate physical properties of the conventional components in the gasification process. HCOALGEN and DCOALIGT models were also employed for enthalpy and density of biomass and ash which are non-conventional components. MCINCPSD stream comprising three substreams of MIXED, CIPSD and NCPSD class, was also considered to define the biomass structure and ash streams which are not available in Aspen Plus component database [27,39,41,54,55]. The flow chart of the system simulated by using ASPEN Plus is shown in Fig. 2.

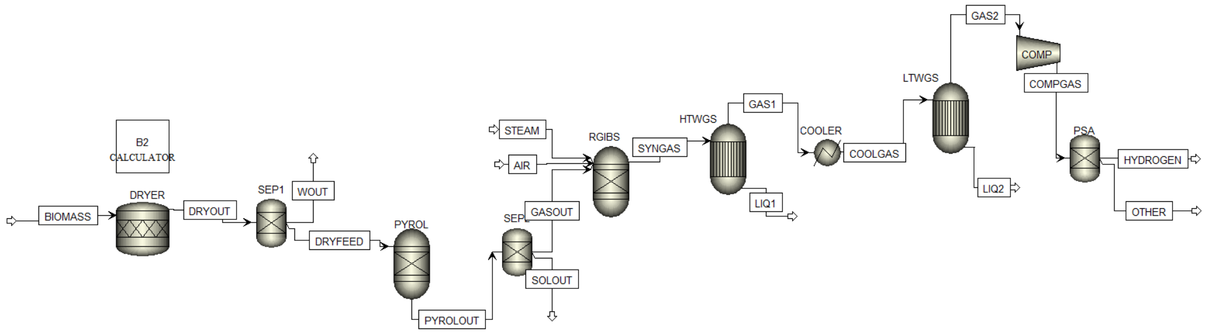

Fig. 2: Aspen Plus flow chart of the system.

Gasification module

The BIOMSS stream was defined as a nonconventional stream and it was created by specifying the elemental and gross compositions of feedstock obtained from proximate and elemental analyses given in Table 1. Drying occurs at 150 °C to achieve the moisture reduction to 5 wt.% of the original sample. This step is directed by the stoichiometric reactor RSTOIC in the Aspen Plus. This particular module is used to perform chemical reactions of known stoichiometry [42]. After drying, RYIELD, the yield reactor is brought to simulate the feed pyrolysis. In this step, the feedstock is converted to volatile materials (VM) and char. VM contains carbon, hydrogen, oxygen and nitrogen; Char is also converted into ash and carbon, by specifying the product distribution based on the proximate and ultimate analysis of the feedstock. Then RGibbs is used to simulate the biomass gasification. The decomposed feed, and gasifying agent (air or air-steam) enter to the RGibbs reactor where partial oxidation and gasification reactions occur. The reactor calculates the syngas composition by minimizing the Gibbs free energy and assumes complete chemical equilibrium [56].

Water-gas shift module

For this part, two water-gas shift reactors were considered because W-G shift reaction is moderately exothermic, and it tends to shift to the left side at high temperature. One at higher temperature (HTWGS) and the other at lower temperature (LTWGS). In the HTWGS reactor, there is a first low conversion of CO with quick kinetics, but it is not possible to go beyond the equilibrium curve, thus the LTWGS reactor was used [57]. In the LTWGS reactor, by reducing the operation temperature, it was possible to obtain higher conversion. HTWGS and LTWGS have been simulated at 400 °C and 200 °C with two Requil reactors, respectively [28]. Requil is equilibrium reactor for which the chemical and phase equilibrium are determined by stoichiometric calculations.

Separation unit module

In order to reach a high purity of hydrogen, a PSA unit is applied [58,59]. A separation efficiency of 70% for hydrogen and an input pressure of 7 bar for simulation of PSA were considered from the optimal values found in the literature [60-63]. Pressurization was achieved with a compressor, COMP in Fig. 2, before the PSA. The PSA outlet stream, denoted as HYDROGEN in Fig. 2.

Methodology

The developed model for waste biomass gasification integrated W-G shift and separation unit for hydrogen production is used to investigate the gasification performance of timber and wood waste as a lignocellulosic biomass. The effect of gasifier temperature, and steam to biomass ration (SBR) on syngas composition, lower heating value (LHV) of produced gas, hydrogen production efficiency (HPE) and the amount of hydrogen production are investigated. The lower heating value of product gas is calculated as [22,64]:

$$LHV_{syngas}(KJ/Nm^3) = 4.2 \times (30 \times y_{CO} + 25.7 \times y_{H_2} + 85.4 \times y_{CH_4}) \quad (2)$$

where y is the mole fraction of gas species in the syngas (dry basis) that can be extracted from the simulation results.

The hydrogen production efficiency (HPE) is an important index to account for the performance of biomass gasification for H_2 production that it is calculated by using equation (3):

$$HPE(\%) = \frac{\dot{m}_{H_2} \times LHV_{H_2}}{\dot{m}_{Biomass} \times HHV_{Biomass}} \times 100 \quad (3)$$

Where $\dot{m}_{H_2}$ is the mass flow rate of hydrogen (kg/hr) that comes from the simulation results, LHV_{H_2} is lower heating value of hydrogen that is 120.1 MJ/kg, $\dot{m}_{Biomass}$ is the mass flow rate of input biomass (kg/hr), $HHV_{Biomass}$ is the higher heating value of the biomass (MJ/kg); It is calculated by using the following equation [38,65]:

$$HHV_{fuel}(MJ/kg) = 0.312 \times (FC) + 0.1534 \times (VM) \quad (4)$$

According to the equation (4), heating value is a function of weight fractions of fixed carbon and volatile matter in the dry and ash-free conditions.

Specific mass flow rate of the produced hydrogen (SHP) is the ratio of the mass flow rate of the product hydrogen per mass flow rate of the entering biomass into the system, calculated as below:

$$SHP = \frac{\dot{m}_{H_2}(kg/hr)}{\dot{m}_{biomass}(kg/hr)} \quad (5)$$

Validation

To validate the developed simulation model, the syngas compositions gained from ASPEN simulations were compared with the experimental results of Jayah et al., [66]. In their work, rubber wood was fed in a down draft gasifier operated at atmospheric pressure and gasification temperature of 900 ˚C. Six different air to fuel mass flow rate ratios (AFRs) were took in account and the comparisons of CO_2, H_2, CO, and N_2 concentrations are shown in Fig. 3. It can be seen that the present model shows very great agreement with the experimental results. The deviation of the model results from experimental values is quantified by mean absolute error that is around 6.5% for all data.

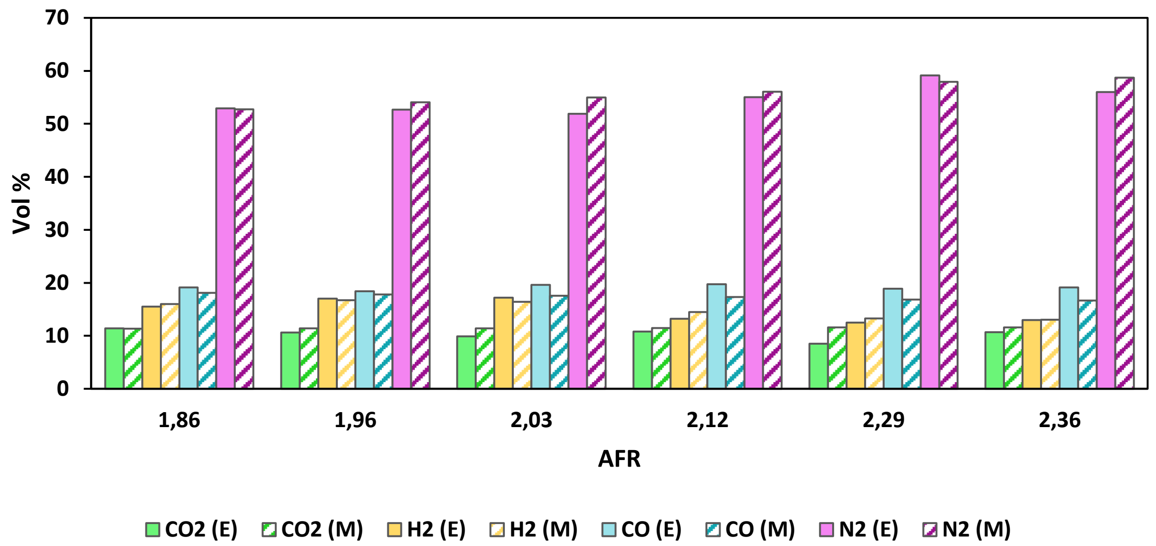

Fig. 3: Comparison of CO_2, H_2, CO, and N_2 concentrations between the simulation model (M) and experimental results (E)

Results and discussion

Effect of temperature on gasification performance and hydrogen production

At the first of this part the effects of the gasification temperature on the syngas compositions under different gasifying agents of air and mixing of air-steam are investigated. In fact, syngas compositions in the form of molar flow rates are evaluated. Temperature varies in the span of 500 to 1500 °C, while the mass flow rate of air to fuel ratio (AFR), steam to biomass ratio (SBR) and biomass feeding rate are fixed at points of 1.8, 0.4, and 1000 kg/hr, respectively. The considered range of 500 to 1500 °C for temperature is based on different literatures focusing on biomass gasification [23,67,68] as well as our previous works that were properly confirmed and evaluated [27,38,41]. Moreover, 1.8 was considered as AFR for the gasification system derived by timber and wood waste (T&WW) since this value is the optimal AFR for this biomass. This matter has been studied and proved in our pervious works [27,39]. The selection of 0.4 as a fixed point through the temperature analysis is also based on the research work conducted by Marcantonio et al., (2019) [28].

The variation of molar flow rate of syngas and its compositions by increasing temperature under two agents of air and air-steam mixture, were shown in Fig. 4 and Fig. 5, respectively. For both systems by growing the gasifier temperature, H_2 and CO flow rates are also increased. However, in such this condition, the flow rates of CO_2 and CH_4 show a reverse trend. Moreover, growth of the flow rates of CO and H_2 in the range of 500 to 800 °C is because of the combined effect of boudouard, steam methane reforming and water-gas reaction. These are endothermic reactions in nature, hence they are favored with higher temperature. Obviously, H_2 flow rate lessens after 800 °C that it can be attributed to the combined effect of all the reactions occurring in the reduction zone. At low temperatures, water gas shift reaction contributed to hydrogen production, but this reaction was hindered at high temperatures.

In fact, at the higher temperature, the reactions of water gas shift and steam methane reforming contribute majorly to H_2 production. However, the steam methane reforming reaction is limited due to the absence of CH_4 as the main reactant. Therefore, it can be concluded that water gas shift reaction mainly controls the H_2 production.

Furthermore, reduction in CO_2 flow rate by increasing of temperature is due to the boudouard reaction which utilizes CO_2 to produce CO and it is endothermic in nature that is favored at higher temperatures. Methane is also produced through the methanation reaction that is an exothermic reaction and it is favored at lower temperatures. Thus, decrease in CH_4 flow rate is observed when the temperature is increased.

Referring to Fig. 5, the value of hydrogen product from the system derived by air-steam agent is at the highest statues for all studied temperatures. It can be also observed that over the temperature range of 800-1500 °C, the hydrogen production by applying the air-steam based gasification decreases from a maximum value of 44.3 to 38.3 Kmol/hr. Moreover, this indicator for the air based system decreases from 34.4 to 33.7 Kmol/hr.

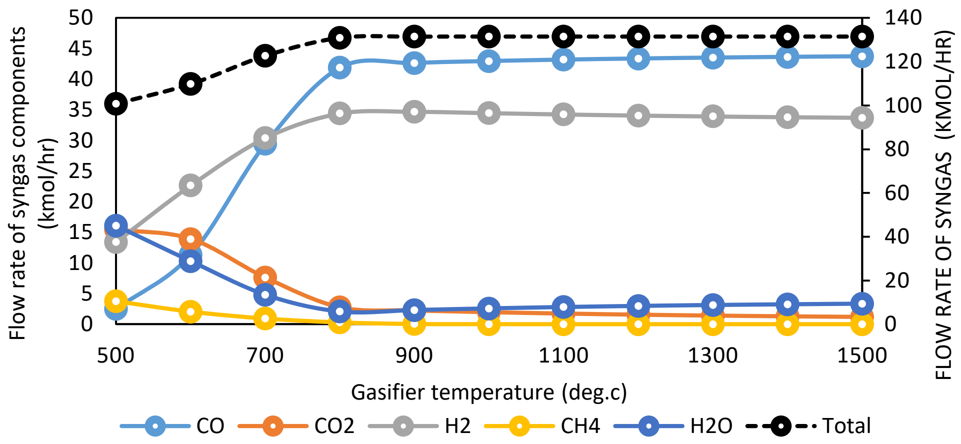

Fig. 4: Effect of gasification temperature on molar flow rates of syngas constituents- air is only gasifying agent.

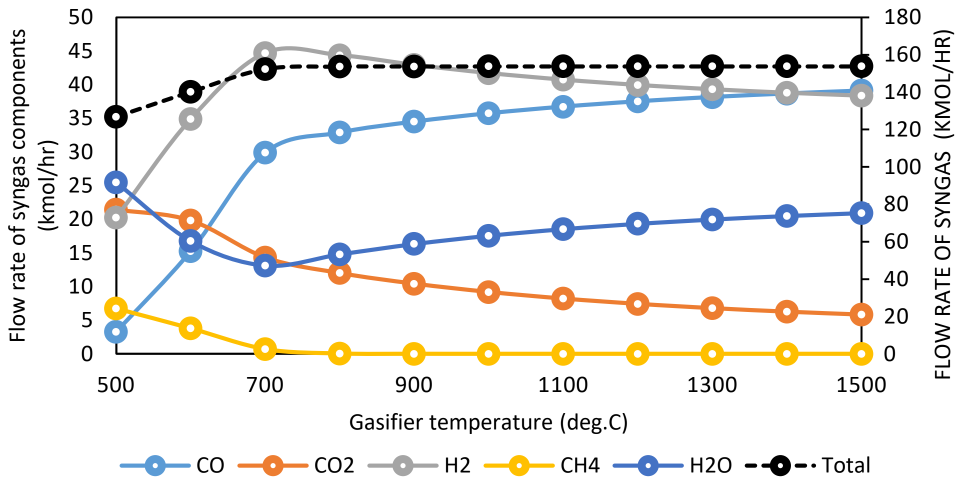

Fig. 5: Effect of gasification temperature on molar flow rates of syngas constituents- mixing of air-steam is gasifying agent.

The variation of the syngas LHV by increasing of the gasification temperature under two gasifying agents were drawn in Fig. 6. Abruptly, LHV increases from 3.7 to 7.05 MJ/Nm^3 in span of 500 to 800 ˚C for the air-based system. The increasing trend of this factor for air-steam gasifications is from 4.9 to 6.3MJ/Nm^3 in temperature range of 500 to 700 °C. However, for both conditions it almost became constant. At lower temperatures (500-700 °C), syngas LHV obtained from the air-steam gasification is much higher than the air gasification. However, by increasing the temperature, this indicator for the air agent based system goes upper than the system derived by air-steam agent. This is due to the sum of hydrogen and carbon monoxide content is mainly responsible for the LHV value of the syngas. According to equation (2), the LHV of syngas is function of H_2, CO, and CH_4 mole fractions, so it increases till 700 °C because of the increase in H_2, CO, and CH_4 concentrations. After 700 °C, LHV does not show so much variation due to decreasing in H_2 concentration and slightly increasing of CO concentration.

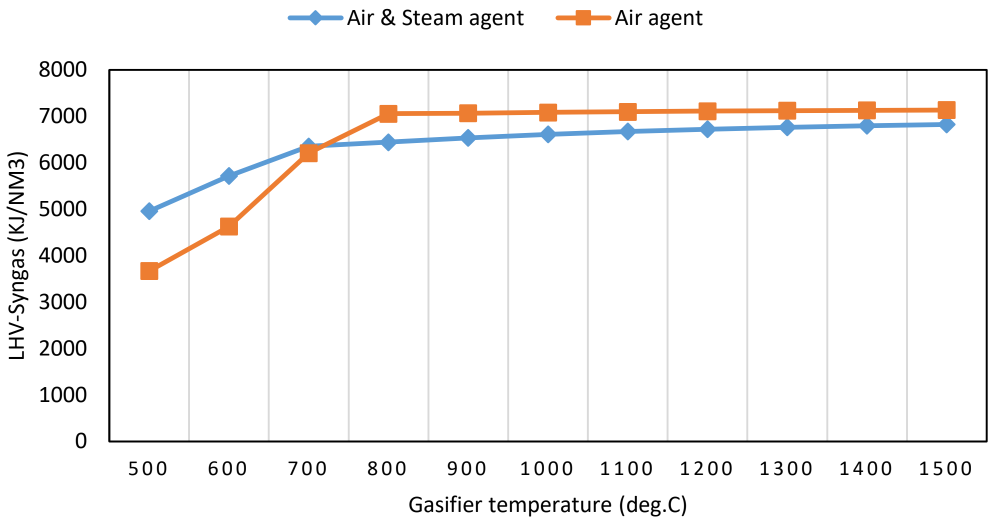

Fig. 6: Effect of gasification temperature on syngas LHV under two different agents.

At the next step, the effect of the gasifier temperature on the hydrogen production efficiency (HPE) and the specific mass flow rate of hydrogen production (SHP) are evaluated. The results of this part based on the functional unit of 1000 kg/hr from timber and wood waste entering to the system have been brought in Fig. 7 and Fig. 8.

As the gasifier temperature is grown (till 800 ˚C), the syngas production is also increased; then it approximately became constant. Hydrogen production also follows such this trend since it is affected mainly by the input syngas to its process. Fig. 7 reveals that, the HPE values by the air-steam gasification show the highest statues for all the studied temperatures. HPE is also maximum for both systems over the temperature of 800°C, it values 54 and 33% for the air-steam gasification and the air based system, respectively. Moreover, Fig. 8 shows the process of the air-steam gasification yields 33 kg/hr hydrogen product from 1000 kg/hr timber and wood waste at 500 ˚C, then it can be increased to 83 kg/hr at 800 ˚C. However, the SHP for the gasification based on only air agent varies from 0.022 to 0.052 $kg_{hydrogen}/kg_{T\&WW}$ in the considered range of temperature.

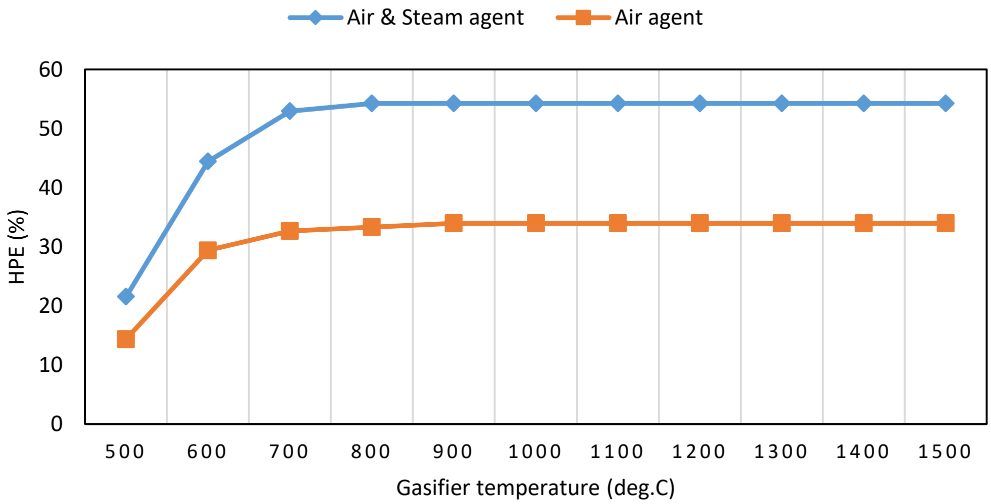

Fig. 7: Effect of gasification temperature on hydrogen production efficiency.

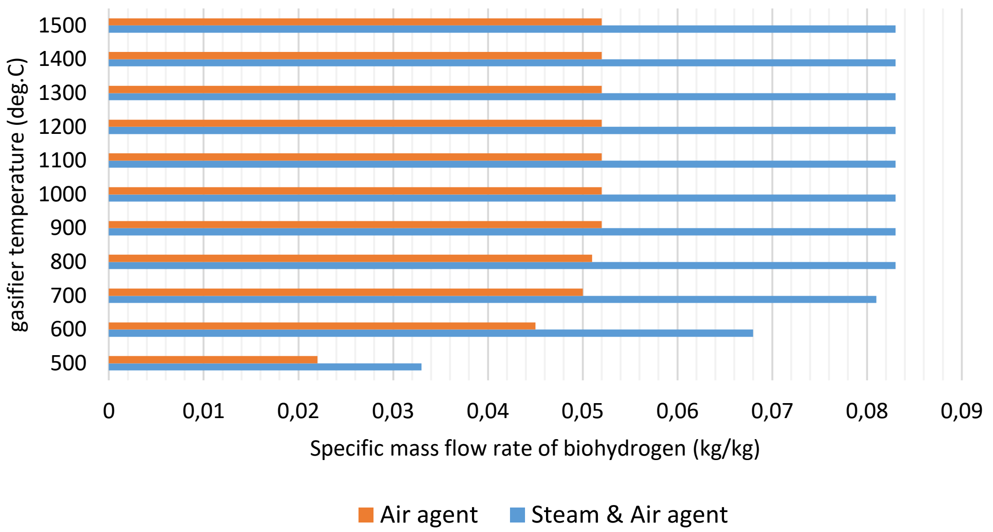

Fig. 8: Effect of gasification temperature on specific mass flow rate of hydrogen production.

Effect of SBR on gasification performance and hydrogen production

In this part, the effect of steam injection on syngas production is studied. It is assumed that the gasifier temperature is set on 800 ˚C and steam at 150 ˚C and 1 bar is injected to the system. The steam to biomass ratio (SBR) is varied from 0.1-0.9 and the result is shown in Fig. 9. The overall behavior is that the molar flow rates of H_2 and CO_2 are increased with steam injection and that of CO decreases. This can be explained due to water gas reaction; steam injection leads to rise in the molar flow rate of H_2 and CO in the syngas but stand on the CO shift reaction, the amount of H_2 is increased further and that of carbon monoxide decreases.

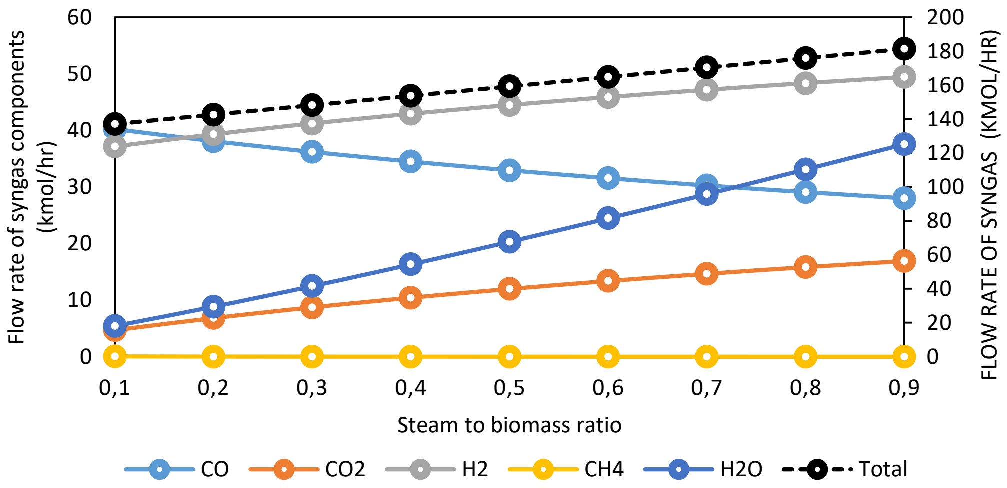

Fig. 9: Effect of SBR on molar flow rates of syngas constituents.

The effects of SBR on syngas LHV and hydrogen production efficiency were shown in Fig. 10. It can be observed that LHV of syngas decreases from 6.9 Mj/Nm^3 at SBR = 0.1 to 6.15 Mj/Nm^3 at SBR = 0.9. It was explained that by increasing steam injection, the CO production in syngas is moved down due to the water gas shift reaction, so the heating value of the syngas is reduced. Moreover, due to the W-G shift reaction, H_2 production in the product gas is grown but its degree of increase is not enough that can cover impact of the degree of CO reduction. Referring to Fig. 10, hydrogen production efficiency raises, stemming from the growth of H_2. It values 39.2% at SBR = 0.1 that grows to 70% at SBR = 0.9.

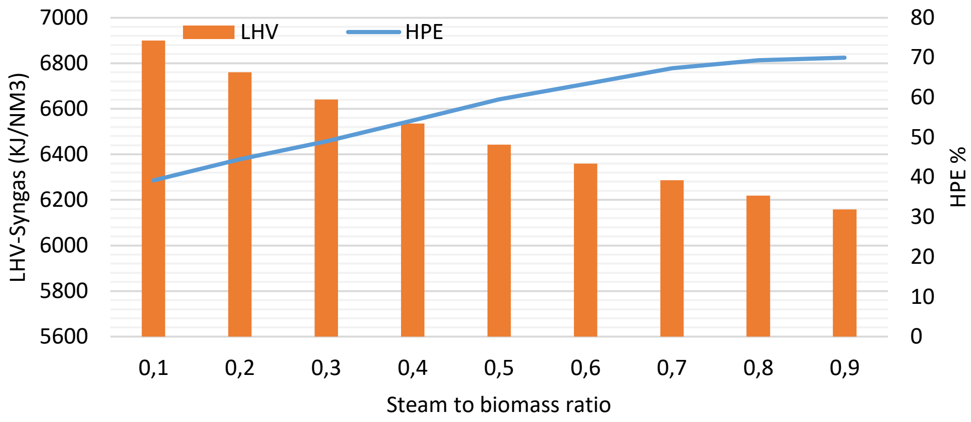

Fig. 10: Effect of SBR on syngas LHV and HPE.

Fig. 11 depicts the effect of the steam to biomass ratio on the specific mass flow rate of hydrogen production from timber and wood waste. As it can be seen, at lower SBR, the flow rate of hydrogen increases with a greater slope and then reaches to almost flatter shape. Hence, it is interesting to find the appropriate range of SBR for biomass gasification integrated with hydrogen production that has been studied in this work. As shown in Fig. 11 the optimum SBR lies between 0.7-0.8 that specific mass flow rate of hydrogen is higher than 0.1 $kg_{hydrogen}/kg_{T\&WW}$.

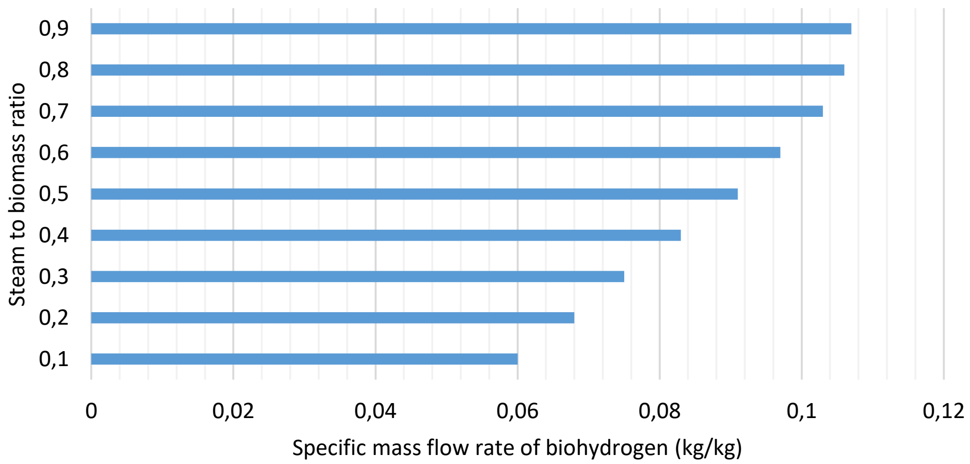

Fig. 11: Effect of SBR on specific mass flow rate of hydrogen production.

Conclusions

In this study, a simulation model by using ASPEN Plus was developed for the gasification integrated with water-gas shift reactors and separation unit for hydrogen production. Timber and wood waste as a lignocellulosic biomass was also considered as the input feedstock to the system. Then, the model was applied to investigate the effect of two agents of air and a mixture of air and steam under different operating conditions of temperature and steam to biomass ratio (SBR) on the gasification performance and hydrogen production.

The results show that the produced hydrogen through the air-steam gasification is at the highest points for all studied temperatures and it would be maximum (44.37 Kmol/hr per 1 ton T&WWs) at 700 ˚C. At lower temperatures (500-700 °C), the syngas LHV obtained from the air-steam gasification is much higher than the air-based system. However, by increasing temperature, this indicator for the air agent based system goes upper than the system derived by air-steam agent. Moreover, the hydrogen production efficiency (HPE) of the air-steam gasification is at the highest statues for all considered temperatures in comparison to the air-based system. This index would be also maximum around the temperature of 800°C for both systems. It values 54 and 33% for the air-steam gasification and the air gasification, respectively. the process of the air-steam gasification yields 33 kg/hr hydrogen product from 1 ton T&WWs at 500 ˚C, then it can be increased to 83 kg/hr at 800 ˚C. However, the specific hydrogen production (SHP) for the air agent gasification varies from 0.022 to 0.052 $kg_{hydrogen}/kg_{T\&WW}$ in the considered range of temperature.

The LHV of the syngas product decreases from 6.9 Mj/Nm^3 at SBR = 0.1 to 6.15 Mj/Nm^3 at SBR = 0.9. It was explained that by increasing steam injection, the CO production in syngas is moved down due to the water gas shift reaction, so the heating value of the syngas is reduced. Furthermore, the hydrogen production efficiency can be raised, stemming from the growth of H_2. It values 39.2% at SBR = 0.1 that grows to 70% at SBR = 0.9. The optimum SBR lies between 0.7-0.8 that specific mass flow rate of hydrogen would be higher than 0.1 $kg_{hydrogen}/kg_{T\&WW}$.

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