Thermodynamic analysis of steam gasification for syngas production in Biomass renewable energy using parametric investigation

Ziyu Wang [1,*], Charalampos Baniotopoulos [2]

[1] *School of Civil Engineering, University of Birmingham, Birminghan ,Edgbaston , B15 2TT, UK*
[2] *Central Arizona College, Coolidge 85128, AZ, United States*

Highlights

➢ Considering optimal placement and sizing of distributed generations in power market-based systems with using optimal power flow
➢ Considering local margin price as a factor of power market factor besides customer payment factor
➢ Applying the fast optimization method to find the optimal place and size of distributed generations
➢ Considering operation and economic factors in the optimal model to achieve the best point
➢ Analysis of both operation and economic factors after placement to illustrate the method's robustness.

Article Info

Abstract

The need for renewable energy sources has increased due to pollution caused by fossil fuels and increased energy demand. Biomass is considered as a clean renewable energy source that releases zero carbon dioxide. But it is not common to use it because of its low energy density. Therefore, it is converted into syngas using processes such as gasification. Gibbs free energy minimization approach is used in this investigation. This study has investigated the impacts of biomass flow rate, temperature of gasification, and steam flow rate on mole fraction and mass flow rate of carbon monoxide, hydrogen, carbon dioxide, methane and steam gases. Also, the amount of heat consumed or produced in drying, pyrolysis and Gibbs reactors was also studied in this investigation. According to the results, an enhancement of 13.8% in hydrogen molar fraction can be observed with increasing gasification temperature from 700℃ to 900℃. Steam flow rate and biomass flow rate have a noticeable effect on the quality of syngas. As biomass flow rate increases, the heat consumed in the drying reactor increases and the heat produced in the pyrolysis reactor increases. As the steam flow rate increases, the heat consumed in the Gibbs reactor increases. Also, the hydrogen mole fraction is maximum at a steam mass flow rate of 5000 kg/h and biomass flow rate of 1000kg/h..

1. Introduction

Today, the destructive effects caused by the combustion of fossil fuels have disrupted the order of nature , created environmental pollution and serious dangers for humans and other living beings[1−4]. Therefore, in recent years, scientists are trying to replace fossil fuels with clean fuels that are produced from renewable and available sources [5−8] . For decades, researchers have introduced new methods for energy production [9,10] . One of these methods is the use of biomass, one of the most important renewable resources that can be utilized to produce clean energy carriers.

Biomass steam gasification let us produce gaseous such as hydrogen with high-value energy[11,12]. The generated gas can be used in lots of processes to produce different products. hydrogen can be used directly in fuel cell technology or combustion engines. Furthermore, in the generation of gasoline, methanol, and other valuable materials, it has important role[13−15]. Given the above-

---

* Corresponding Author: Ziyu Wang
Email: ZXW264@student.bham.ac.uk

mentioned information, some of the most recent studies conducted in this field are reviewed.

Campoy et al [16] investigated the influence of oxygen concentration in the gasification enhanced−air−steam biomass. In the enriched air, the oxygen portion was changed from 21% to 40% at inlet mixture temperature 400 °C. The results shows that enhancement of air from 21% to 40% led to enhance the LHV of the gas from $5 MJ/Nm^3$ to $9.3 MJ/Nm^3$ and the efficiency of gasification from 54% to 68%. The maximum carbon conversion is reached to 97%. In the range 0.25–0.35 of steam-to-biomass ratio, the best scenario are happened.

Nipattummakul et al [17] investigated steam gasification of oil palm trunk waste in a batch-type gasifier at 800 °C. In the process, more than half of the syngas were produced within the first five minutes, and the steam flow rate was increased to accelerate the gasification reactions and reduce the processing time. Gasification process of oil palm trunk waste have been compared to mangrove wood, paper and food waste. Oil palm trunk waste produced more syngas, energy and hydrogen than mentioned biomasses.

Mazumder & Lasa [18] studied the influence of La2O3 promoted Ni/-Al2O3 fluidizable catalysts steam gasification of biomass. The results show that enhancing the La2O3 up to 5 wt% improves the BET surface area and the CO2 adsorption potential, as well as reduces acidity support. By increasing mass fraction of to the La2O3 up to 10 wt%, syngas production decreases, furthermore, producing higher coking than the supported catalyst. In specific case, gasification with catalyst using 20% Ni shows 95% carbon conversion of glucose to stable gases without tar formation and very low coke production.

D'Orazio et al [19] experimentally investigated syngas production by biomass steam gasification. They used noncatalytic candles with new support, filter candles with catalytic layer, and filter candle with a new integrated catalytic foam system as ceramic filters in the temperature range of 800-815 °C. It's observed that theoretical water conversion ratio of 0.88 and H2 volume content of 56% was obtained with the catalytic filter with a cycled olivine bed. It was able to produce gas yields of 1.80 Nm3/kgdaf and a gas yield of 1.80 Nm3/kgdaf.

The citrus peel residues and steam gasification process are used by Chiodo et al [20] to generate hydrogen. The influence of synthetic and minerals catalysts on the gasification process was examined in terms of hydrogen formation tendency, efficiency, and outlet stream composition. The gasification efficiencies of carbon and hydrogen can both be increased with dolomite, magnesium oxide, and nickel/alumina in the reactor (from 43.7% to 54.9% and 34.3% to 54.1%, respectively).

Perondi et al [21] used a tubular reactor for pyrolysis experiments of poultry litter, using an N2 atmosphere in the temperature range of 800-900 °C. In the first 15 minutes of the reaction, the maximum hydrogen (H2) reaction rate was observed, and with increasing temperature, the maximum reaction rate changed to lower reaction times. It's reported that the increased H2 may be led to potassium (K) present in the biochar. The (H2 + CO) gained from steam gasification of this biomass presented high capacity to decrease iron ore by IR in the furnaces, or in DRI processes.

Li & Chen [22] inserted palm empty fruit bunch in a fixed-bed, batchfed gasifier as fuel. Their study examined the effects of four control parameters on syngas production, including fuel pretreatment temperatures, gasification temperatures, carrier-gas flow rates, and steam flow rates. Analysis revealed that the temperature of gasification of biomass and flow rate of steam has the lowest, and biggest impact on syngas production, respectively. Additionally, they found that when the temperature increases from 680°C to 780°C, the ratio of H2/CO increases by approximately 50%.

As part of the biomass steam gasification in a fixed-bed reactor, Yan et al. [23] A feeder was used for the production of hydrogen using CeO2-CaO/Ca12Al14O33. In their study, they reported that when the CaO/Ca12Al14O33/CeO2 mass ratio is 75:10:15, the CaO/Ca12Al14O33 captures CO2 at 0.48 g/g, 30% higher than CaO/Ca12Al14O33. Additionally, CeO2 helps stabilize pores that are 10-100 nm in diameter and improves the cyclic stability of CaO/Ca12Al14O33.

During plasma gasification of wood sawdust, Ma et al [24] investigated the influence of polyethylene content, input power, and steam/carbon ratio on tar changes. Increased input power positively influences the reduction of light tars and the conversion to heavy tars, according to the sensitivity analysis. A turbulent variation in tar concentration can be observed with the S/C ratio increasing between 0.87 g and 2.76 g. According to response surface methodology model, the minimum tar concentration of 0.54 g·Nm- 3 can be gained under the best conditions, which is significantly lower than that from conventional gasification (1–100 g·Nm -3).

Salaudeen et al [25] investigated the gasification of sawdust with a CO2 capture unit. As a CO2 sorbent and calcined eggshell bed material, the gasification process was tested in a bubbling fluidized bed reactor. In a thermogravimetric and X-ray diffraction study of the eggshell, 900°C was found to be sufficient for converting calcium carbonate to calcium oxide. In the best case and in temperature of 650°C, the maximum hydrogen

concentration and minimum CO_2 volumetric concentration was 78% and 3.3%.

Singh et al [26] examined food waste steam gasification with torrefaction. Torrefaction has used for one-hour in the temperatures range of 230 °C- 290 °C. Furthermore, the impact of torrefaction on energy and mass yields, density of energy and, density of mass was investigated. The rate of steam flow kept constant at 0.625 ml/min at temperature 700 °C. A high heating value of 12.19 MJ/Nm3 was found for syngas, which ranged from 0.95 to 3.49 m3/Kg and 0.6 to 2.15 m3/Kg.

Huang et al [27] Research two-stage pyrolysis/gasification reactor unit for gasification of leftover rice at temperatures between 600°C and 1000°C. During the pyrolysis process at 600 degrees Celsius, volatile products are appeared in conversion of raw rice, producing high yields of gas (69.2%) and tar (21.1%). The tar yield decreases at 700°C, resulting in 88.1% gas efficiency. The increase in pyrolysis temperature reduces the gas efficiency regarding the production of coke due to an increase in the pyrolysis temperature. Reaching the temperature of gasification to 1000°C, led to increases the reactions of char gasification.

Piazzi et al [28] Experimentally studied the retrofitting of available small-size gasifiers to produce hydrogen using steam and biomass residues. The tests were implemented at different steam flows and temperature ranges of 700°C and 800°C. In order to provide 80 percent of the H_2 for bio methanation and MeOH synthesis, lower steam flows can be used, which can provide 10 NLpg/gchar. The producer gas compositions are in the range of 2-6 % CH_4 ,9-29 % CO, 46-70 % H_2, and 12-27 % CO_2.

Vikram et al [29] numerically optimized CO_2-steam based gasification system in Aspen hysis software. Several factors were taken into account when analyzing the results, including the temperature, the reaction temperature, and the composition of the gas agent, including CO and H_2 concentration and tranformation, the H_2 / CO ratio, as well as the efficiency of the syngas process. As a result of replacing H_2O with CO_2 in the gasification process, global greenhouse emissions can be reduced, however, the gasification efficiency is not affected.

In bubbling fluidized bed gasifier, Ruivo et al [30] studied Fe2-xMnxO3 catalyst biomass gasification. Catalytic impact was evaluated by assessment with simple tests. They investigated the effect of the equivalence ratio, catalyst temperature, and velocity of gas space on decomposition of tar. According to the thermogravimetric analysis and structural analysis, the catalyst is the most important factor in the conversion of tar (83 %), carbon conversion efficiency and cold gas efficiency enhance.

Ali et al [31] used palm waste for feedstock in biomass gasification and investigated polygeneration power and syngas system. Among the most important parameters were steam/biomass ratio, temperature, compression ratio, and flow rate of air. The conclusion consisted of two sections; the power generation and syngas production. Using 850°C and a steam/biomass ratio of 1.0, the composition of the syngas was CH_4 0.001 vol%, CO 14.24 vol%, H_2 37.88 vol%, and CO_2 11.29 vol%. The power generation enhanced from 3.2 MW to 3.6MW from the gas turbine with a temperature increase.

In gasification process, Li et al [32] experimentally investigated the influence of CBA bed material on tar catalytic reforming properties. In biochar/steam gasification reactivity, they used a fixed bed furnace. The results shows that syngas and tar conversion efficiency reached maximum at 594.3 mL/g and 92.39% at the temperature of 900°C.

In this study, the steam gasification of biomass (food wastes) is simulated and the effects of biomass flow rate, steam mass flow rate of steam gasification, and gasification temperature are studied on synags and heat productions by implementing Aspen hysys software.

2. Methodology adopted

Aspen plus is good thermodynamic software for steam gasification simulation. The temperature of steam gasification is high and PR-BM function is used for state equation. To solve equations, the assumptions need to simplify [29]:

Isothermal, thermodynamic equilibrium conditions, and adiabatic.

Ideal gas behavior is seen in all the gaseous compounds.

Atmospheric conditions are used in reactor operations.

Net volatile yield equivalent to volatile content of char and biomass content corresponds to fixed carbon.

Ash as an inert material.

Negligible formation of other heavy hydrocarbons and tar.

To analyze the biomass gasification process, the Gibbs free energy (GFE) minimization viewpoint are utilized. The chemical equation for biomass steam gasification is represented in below equation [29]:

$$CH_aN_bO_c + dH_2O \rightarrow e\,H_2 + f\,CO + g\,CO_2 + h\,H_2O + i\,CH_4 + m\,N_2 \tag{1}$$
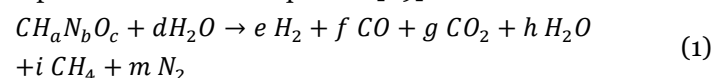
Where $CH_aN_bO_c$ is empirical formula of biomass, and d, e, f, g, h, i, and m depict the number of moles of H_2O, H_2, CO, CO_2, H_2O, CH_4, and N_2. GFE is a function of

temperature and pressure, and it attains minima when thermodynamic equilibrium is attained [29].

$$G^t = \sum_{J=1}^{N} n_j \emptyset_j \tag{2}$$

Where $\emptyset_j$ and n_j denote the chemical potential and number of moles of species j. The general chemical potential is below equation:

$$\emptyset_j = G_j^0 + RTln(\frac{f_j}{f_j^0}) \tag{3}$$

Where G_j^0, f_j and f_j^0 denote the standard GFE, fugacity, and standard fugacity of the species j. In Table 1, the gasification reactions are shown.

Table 1. The equilibrium analysis is employed in gasification reactions

Reaction symbol	Reaction name	Gasification reactions	Heat of reaction [kJ/mol]
R1	Partial oxidation	$C + 0.5O_2 \rightarrow CO$	$\Delta H = -111$
R2	Char combustion	$C + O_2 \rightarrow CO_2$	$\Delta H = -394$
R3	Boudouard reaction	$C + CO_2 \leftrightarrow 2CO$	$\Delta H = 172$
R4	Char reforming reaction	$C + H_2O \leftrightarrow CO + H_2$	$\Delta H = 131$
R5	Water gas-shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	$\Delta H = -41$
R6	Methanation reaction	$C + 2H_2 \leftrightarrow CH_4$	$\Delta H = -75$
R7	Steam-methane reforming reaction	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	$\Delta H = 206$

Three stages are seen in design of steam gasification system: pyrolysis, gasification, and drying, as shown in Figure 1. The first stage of gasification was performed in the DRIER block, where the content of moisture of the biomass was decreased. The produced heat of reaction and dried biomass were fed into the PYROL reactor for decomposition. The GASIFY reactor signifies the final phase of the process of gasification in which the minimization of GFE predicted the composition of the product gas to achieve chemical equilibrium of multiphase. In Table 2, the diagram blocks are described [29].

Table 2. Description of unit blocks in Figure 1

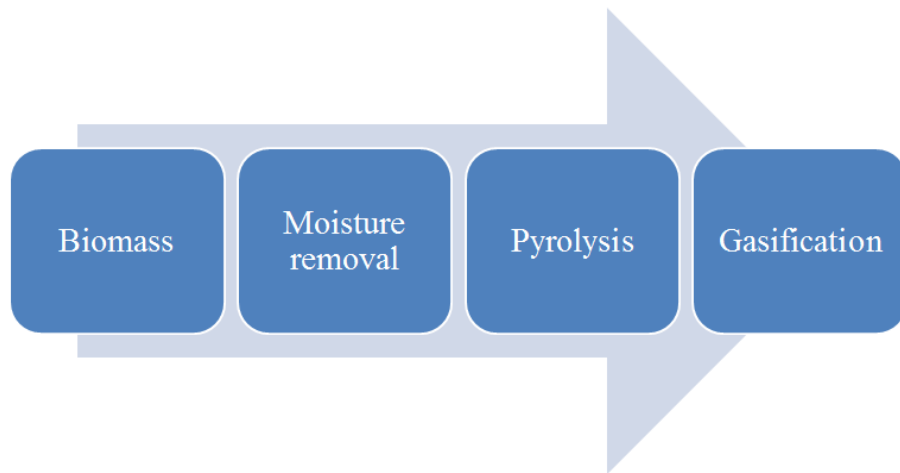| Block name	Description
DRIER	Reduce moisture content to reasonable extent
PYROL	Conversion of non-conventional components into conventional
GIBS	Gibbs reactor for gasification reactions
SEP	To separate moisture and dry feed
SEP1	To separate solids and volatile matters

Fig 1. Gasification process diagram

3. Model validation

The validation of the numerical solution shows that the solution has or does not have the ability to simulate the problem. Therefore, validation is very important. Gasification is a useful method for producing syngas due to the limitation of fossil energy and environmental pollution. Fremaux et al [33] experimental results are used to validate steam gasification. They used wood waste as feed in gasification. The ultimate and proximate analyzes of wood waste are listed in Table 3. The gasification temperature in the study of Fremaux et al [33] is considered to be 700℃, and the gaseous compounds from the results of Fremaux et al [33] and the results of the present solution are shown in Table 4. The following two terms are used to simulate Steam gasifiction:

Thermodynamic equilibrium

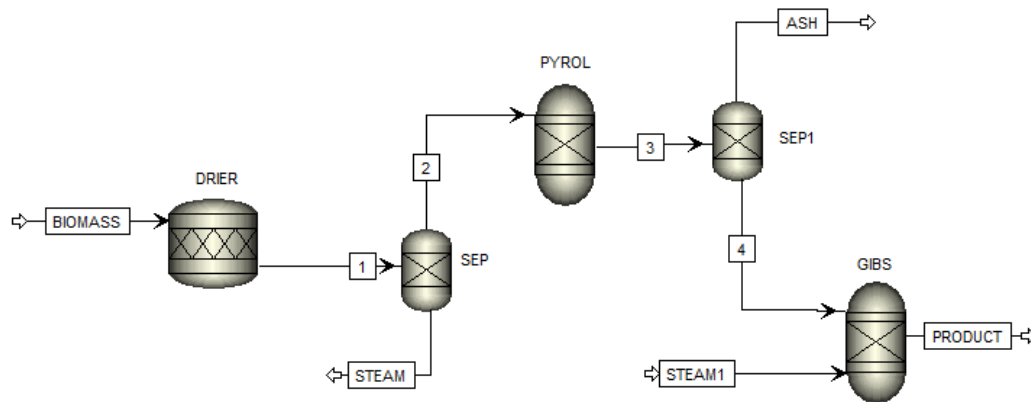The reaction time is sufficient to reach thermodynamic equilibrium.

Fig 2. Steam gasification diagram

Table 3. Ultimate and proximate analysis of wood residue [22].

Ultimate Analysis	(wt %)	Proximate Analysis	(wt %)
Oxygen	42.66	Volatile Matter	77.71
Carbon	50.26	Fixed Carbon	16.94
Hydrogen	6.72	Ash	0.34
Nitrogen	0.16	Moisture content	5.01

Table 4. Validation of numerical method

17

	SBR=0.5		SBR=0.6		SBR=0.7		SBR=0.8		SBR=0.9		SBR=1.0	
	exp	num	exp	num	exp	num	exp	num	exp	num	exp	num
H_2	37.47	48.3	41.65	49.1	45.15	49.15	47.49	48.8	49.61	48.2	51.03	47.5
CO	35.4	29	29.71	27.3	24.91	24.55	21.74	22.1	19.72	20	18.85	18.17
CO_2	9.42	9.1	11.77	10	13.42	11	14.85	11.8	16.05	12.4	16.32	12.8
CH_4	9.42	2.9	9.93	2.3	10.43	1.7	10.94	1.26	11.45	0.9	12.41	0.7
RMS	7.08		5.53		4.95		5.11		5.62		6.37	

But there is a significant difference between the actual conditions of gasification and the conditions mentioned above. According to the results of Fremaux et al [33], with the rise in the ratio of steam to biomass, the volume fraction of methane, carbon dioxide and hydrogen increases, and the volume fraction of carbon monoxide gas decreases. In an operational gasification, the rate of reaction and the reduction zone length affect the conversion of H2O to H2, and the laboratory results showed that the length of the reduction zone is sufficient for the conversion of hydrogen gas. However, according to the results of thermal balance analysis, with the increase of steam to biomass ratio up to 0.8, the volume fraction of hydrogen gas increases and after that, the volume fraction of hydrogen decreases.

Excess steam in the reactor leads to an increase in partial pressure and the reactions of R7, R4 and R5 increase in the reactor. Hydrogen and carbon monoxide gases are produced from Char reforming reaction and Steam-methane reforming reaction, and carbon dioxide and hydrogen gases are produced from Water gas-shift reaction. On the other hand, with the increase in the ratio of steam to biomass, CO is consumed in the R5 reaction and CO_2 increases. One of the reasons for the difference in the amount of methane is that thermal balance is not provided in the gasifier. The average RMS for each experimental condition was calculated in Table 4, and its value is acceptable for validation.

4. Results

This study was conducted with the aim of investigating the effect of biomass flow rate, gasification temperature and injection steam flow rate on the composition of produced gases. Food waste is used as feedstock. Ultimate and proximate analyzes of food waste are listed in Table 5. In the process of pyrolysis, with the decomposition of food waste, the amount of carbon, hydrogen, oxygen and nitrogen is 56.65%, 8.76%, 23.54 and 3.95%, respectively. In this study, it is assumed that the temperature of the pyrolysis reactor and the temperature of the Gibbs reactor are the same, and they are the same as the gasification temperature. Gasification pressure is atmospheric pressure.

Table 5. Proximate and Ultimate Analysis of Food wastes

Proximate analysis	(wt.%, dry)
Volatile matter	72.41
Fixed carbon	20.68
Ash	6.91
Ultimate analysis	(wt.%, dry)
C	56.65
H	8.76
O	23.54
N	3.95
S	0.19
CI	-
ASH	6.91
Moisture	29.3

4.1. Investigating the effect of biomass flow rate on gas composition

The effect of biomass input flow rate on the mole fraction of gas composition, the mass flow rate of gas composition and the heat produced and the heat consumed by the reactors are shown in this section. Biomass flow rate was considered from $5000 kg/h$ to $15000 \, kg/h$. The gasification temperature is 800℃ and the steam flow rate is $5000 \, kg/h$. The effect of biomass flow rate on the mole fraction of gas composition is shown in Figure 3.
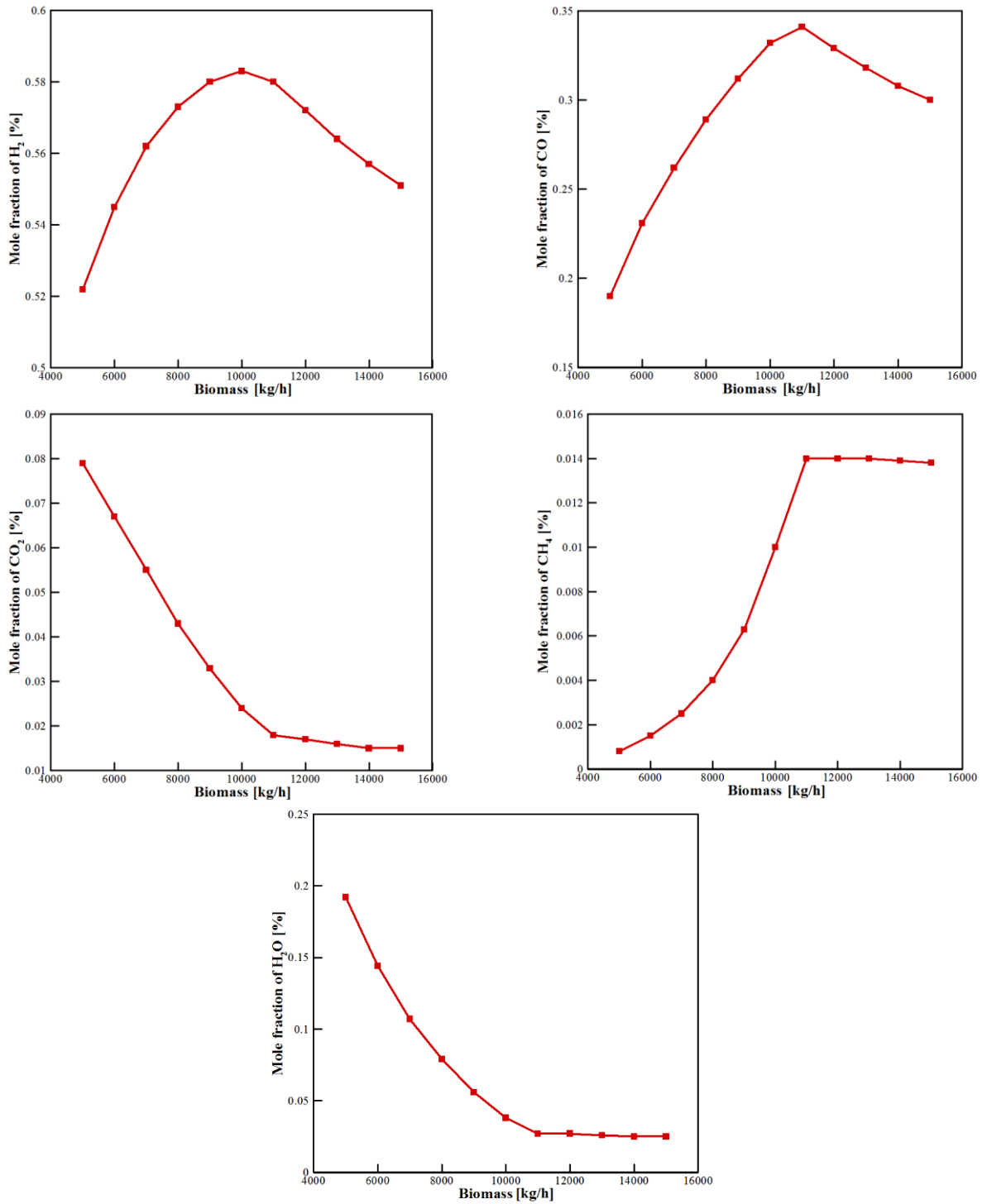
Fig 3. Effects of Biomass mass FR on mole fractions of H_2, CO, CO_2, CH_4 and H_2O

With the change of biomass flow rate from 5000 kg/h to 10000 kg/h, hydrogen mole fraction changes from 0.522 to 0.583, and an increase of 11.6% in hydrogen mole fraction is seen. Then the mole fraction of hydrogen decreases. With changes in biomass flow from 5000 kg/h to 11000 kg/h, the carbon monoxide mole fraction changes from 0.19 to 0.341 and a 79% increase is observed. As the biomass flow rate increases again, the mole fraction of carbon monoxide and water decreases. The effect of biomass flow rate on mass flow rate of gas composition is shown in Figure 4. As biomass increases, the mass flow rate of hydrogen, carbon monoxide and methane gas increases, and the mass flow rate of carbon dioxide and steam decreases almost. With changes in biomass flow rate om

19

5000 kg/h to 15000 kg/h, the mass flow rate of hydrogen and carbon monoxide increases by approximately 114% and 208%.
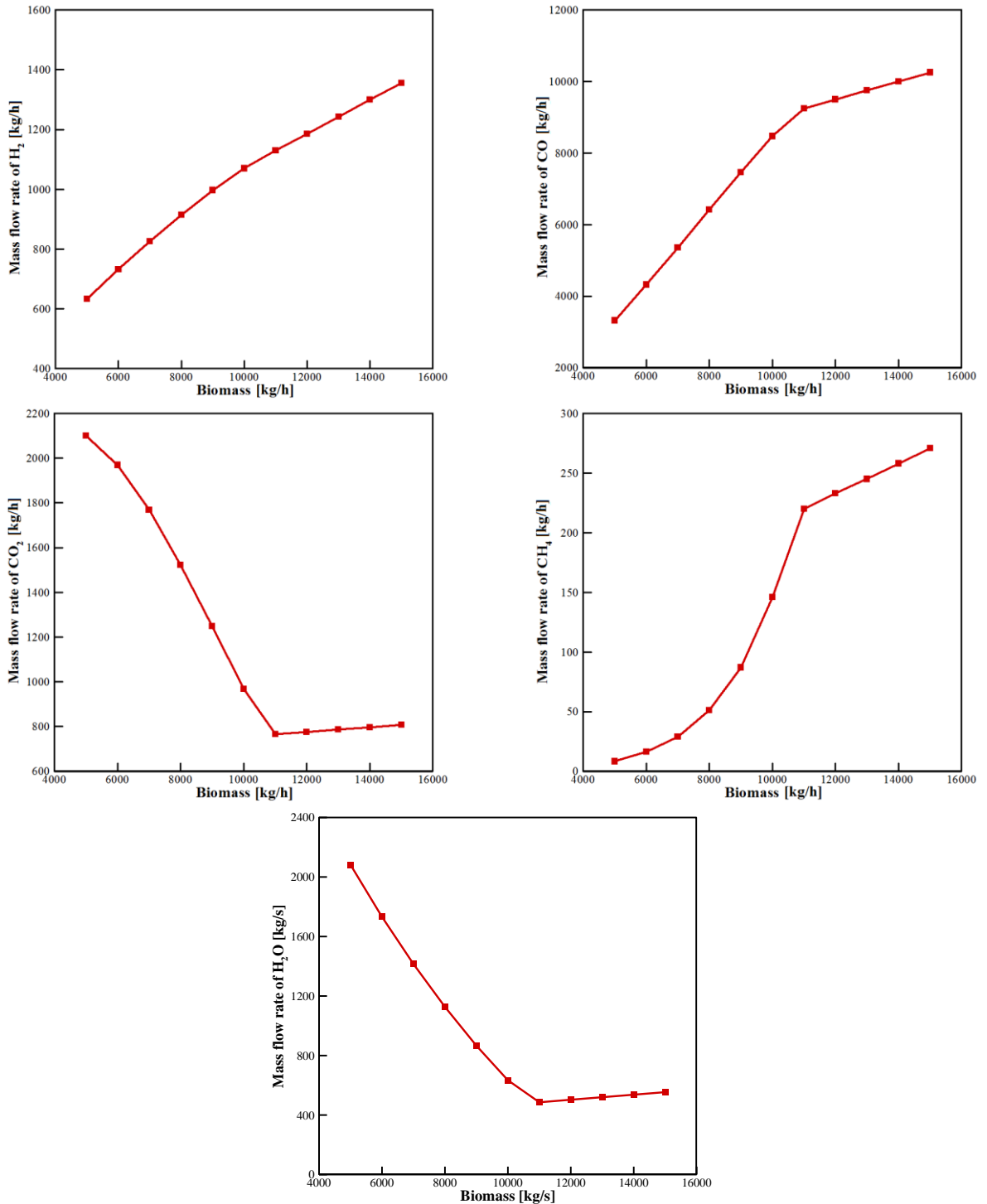

Fig 4. Effects of Biomass mass FR on FR of H_2, CO, CO_2, CH_4 and H_2O

Drying, pyrolysis and Gibbs reactors are used in the gasification process. Moisture makes up 29.3% of biomass (food). The amount of moisture reaches zero in the drying reactor. The amount of heat consumed for dehumidification is $442kW$ at a biomass flow rate of 1000 kg/h. In the pyrolysis reactor, biomass is decomposed into ultimite with proximate components, and a lot of heat is released. In the Gibbs reactor, heat is

consumed, and the reactions in Table 2 are carried out in thermal equilibrium. It can be seen that with changes in biomass flow rate from 5000 kg/h to 15000 kg/h, the heat consumed by the drying reactor and the heat produced by the pyrolysis reactor increase (Figure 5). In the Gibbs reactor, an increasing-decreasing trend can be seen with increasing biomass flow rate (Figure 5).
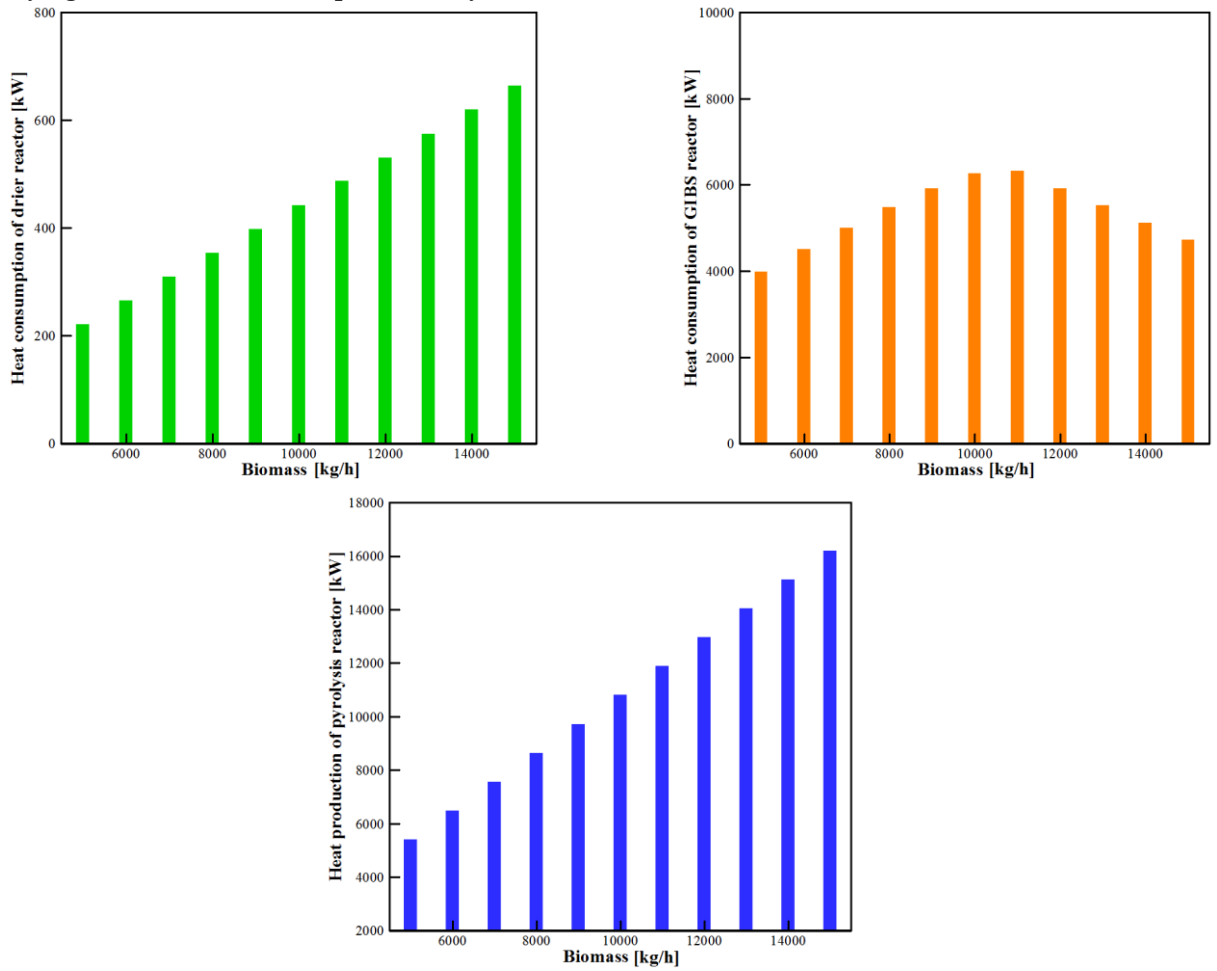

Fig 5. Effects of Biomass mass FR on heat production or consumption by reactors

According to Figure 6, as biomass flow rate increases from 10000 kg/h, the mole fraction and mass flow rate of carbon increase. The reason for this is that the amount of steam is not enough for the carbon reaction. For this reason, some of the carbon does not participate in the reactions and is found in the output products of the Gibbs reactor.
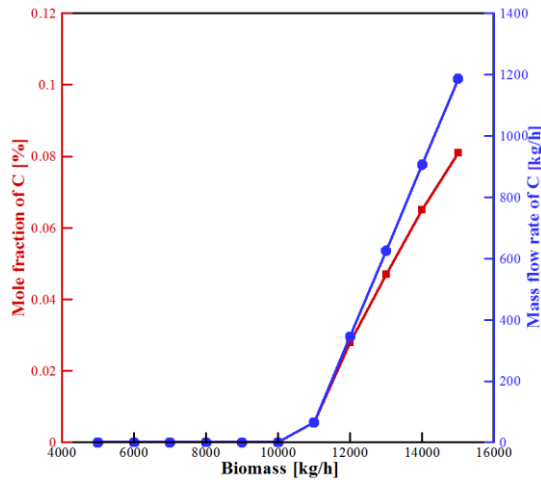
Fig 6. Effects of Biomass mass FR on mole fraction and mass FR of C

4.2. *The impact of temperature of gasification on the composition of gases*

This section has investigated the effect of gasification temperature on the syngas composition. Food waste is used for biomass, and biomass flow rate and steam flow rate are $5000 kg/h$ and $5000\ kg/h$, respectively. The range of gasification temperature changes was considered from 700℃ to 1200℃. Figure 7 shows the effect of gasification temperature on mole fraction of hydrogen, carbon monoxide, carbon dioxide, methane and steam. As the gasification temperature increases from 700℃ to 900℃, the mole fraction of hydrogen changes from 0.52 to 0.587, and an increase of 13.8% can be seen. By increasing the gasification temperature again, the mole fraction of hydrogen gas decreases and up to the temperature of 1200℃, a decrease of 0.8% is observed. A decreasing trend can be seen in carbon dioxide gas with changes in

gasification temperature. From the temperature of 900℃ to 1200℃, hydrogen reacts with carbon dioxide because the exothermic water gas shift reaction is reversed. The products of this reaction are water and carbon monoxide. For this reason, the molar fraction of carbon monoxide and the molar fraction of water increase from 900℃ to 1200℃. Figure 8 shows the effect of gasification temperature on the mass flow rate of hydrogen, carbon monoxide, carbon dioxide, methane and water. The process of changes in Figure 8 is similar to Figure 7. At the temperature of 900℃, which is the maximum hydrogen, the mass flow rate of each of hydrogen, carbon monoxide, carbon dioxide, methane and water are: 1104 kg/h, 8871 kg/h, 683 kg/h, 19.58 kg/h and 609 kg/h. At a temperature higher than 900℃, the amount of methane gas is almost negligible. is, and methane is not expected to have an effect on hydrogen production.
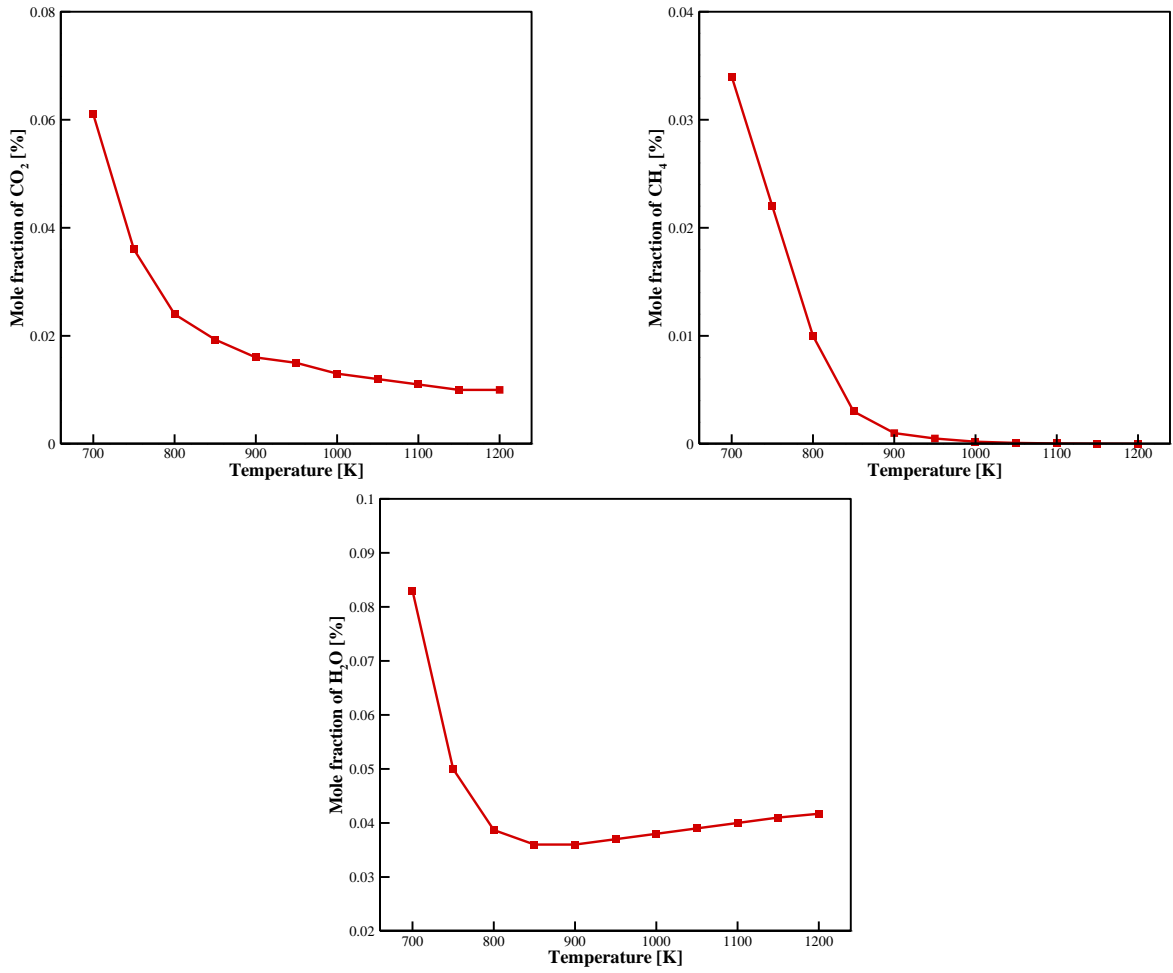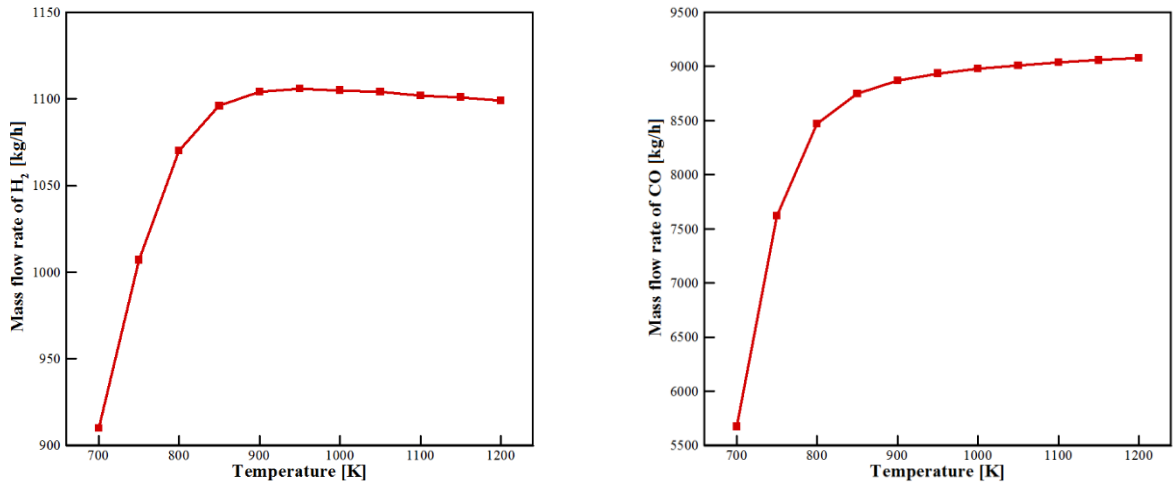

22
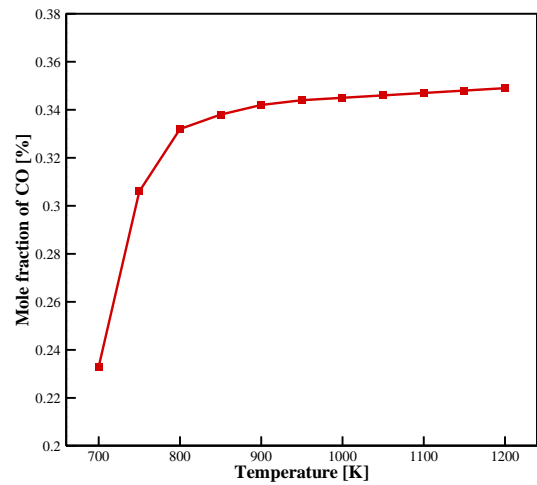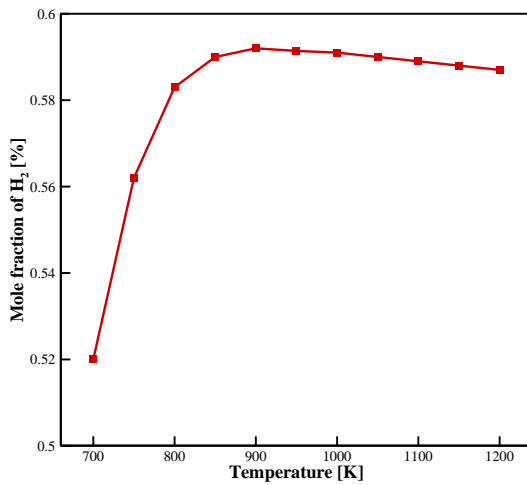
Fig 7. Effects of gasification temperature on mole fractions of H_2, CO, CO_2, CH_4 and H_2O
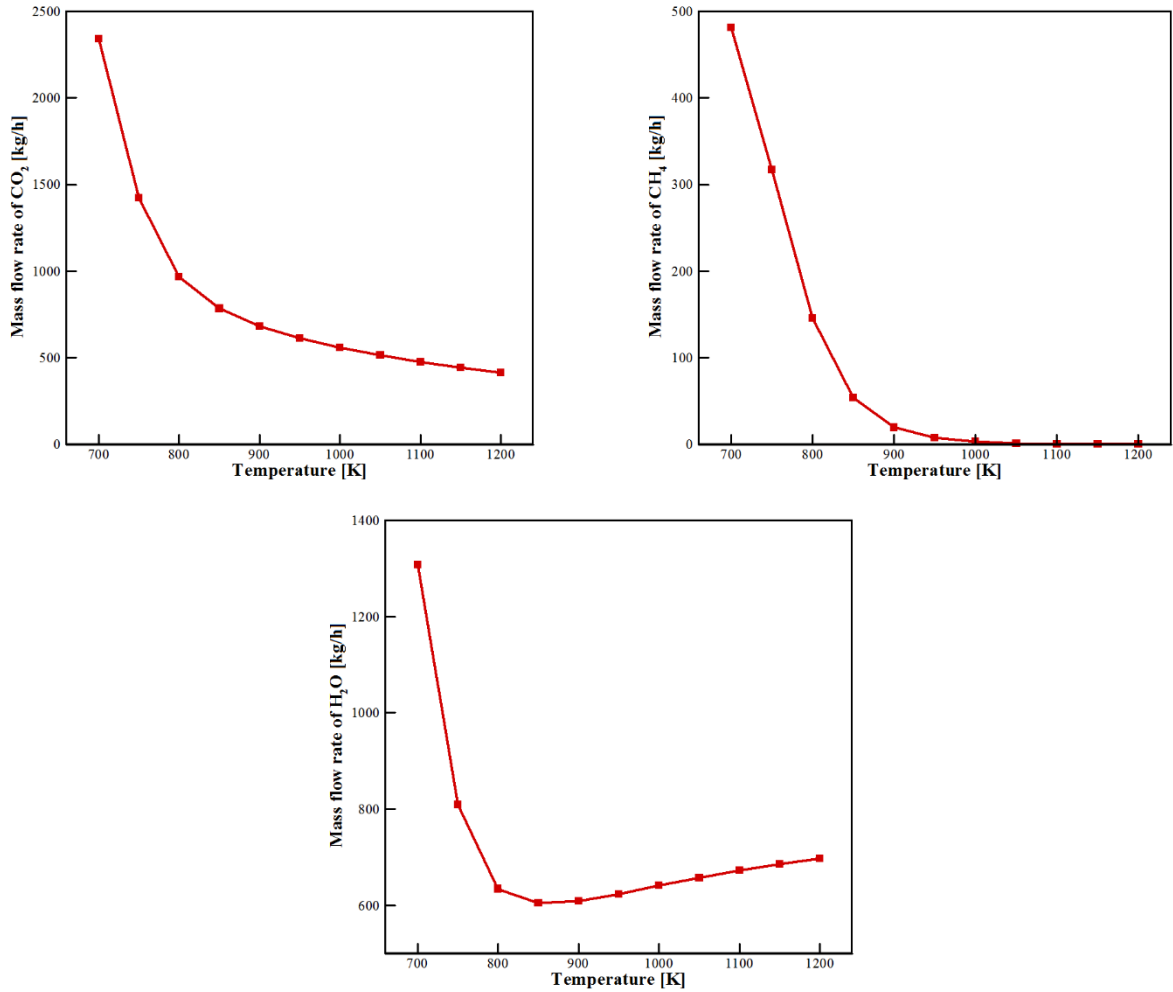
Fig 8. Effects of gasification temperature on mass FR of H_2, CO, CO_2, CH_4 and H_2O

The impact of temperature of gasification on the heat produced in the pyrolysis reactor and the heat consumed in the Gibbs reactor is shown in Table 6. As the gasification temperature increases, the heat in the reactors increases. With changes in gasification temperature from 700°C to 1200°C, the heat in pyrolysis and Gibbs reactor increases by 34.5% and 183.5%, respectively.

Table 6. Effects of gasification temperature on Heat production of pyrolysis reactor and Heat consumption of GIBS reactor

Temperature [K]	Heat production of pyrolysis reactor [kW]	Heat consumption of GIBS reactor [kW]
700	10171	2669
850	10483	5047
800	10804	6264
850	11134	6762
900	11473	7010
950	11820	7158
1000	12177	7268
1050	12542	7358
1100	12916	7437
1150	13299	7508
1200	13690	7570

4.3. The effect of steam flow rate on the composition of gases

The effect of steam flow rate on the composition of Syngas is investigated in this section. Gasification temperature is 800°C and biomass flow rate is 10000kg/h.

The range of steam flow rate changes is considered from 2000 kg/h to 10000 kg/h. The effect of steam flow rate on the mole fraction and mass flow rate of hydrogen, carbon monoxide, carbon dioxide, methane and water, is shown in Figure 9 and Figure 10.
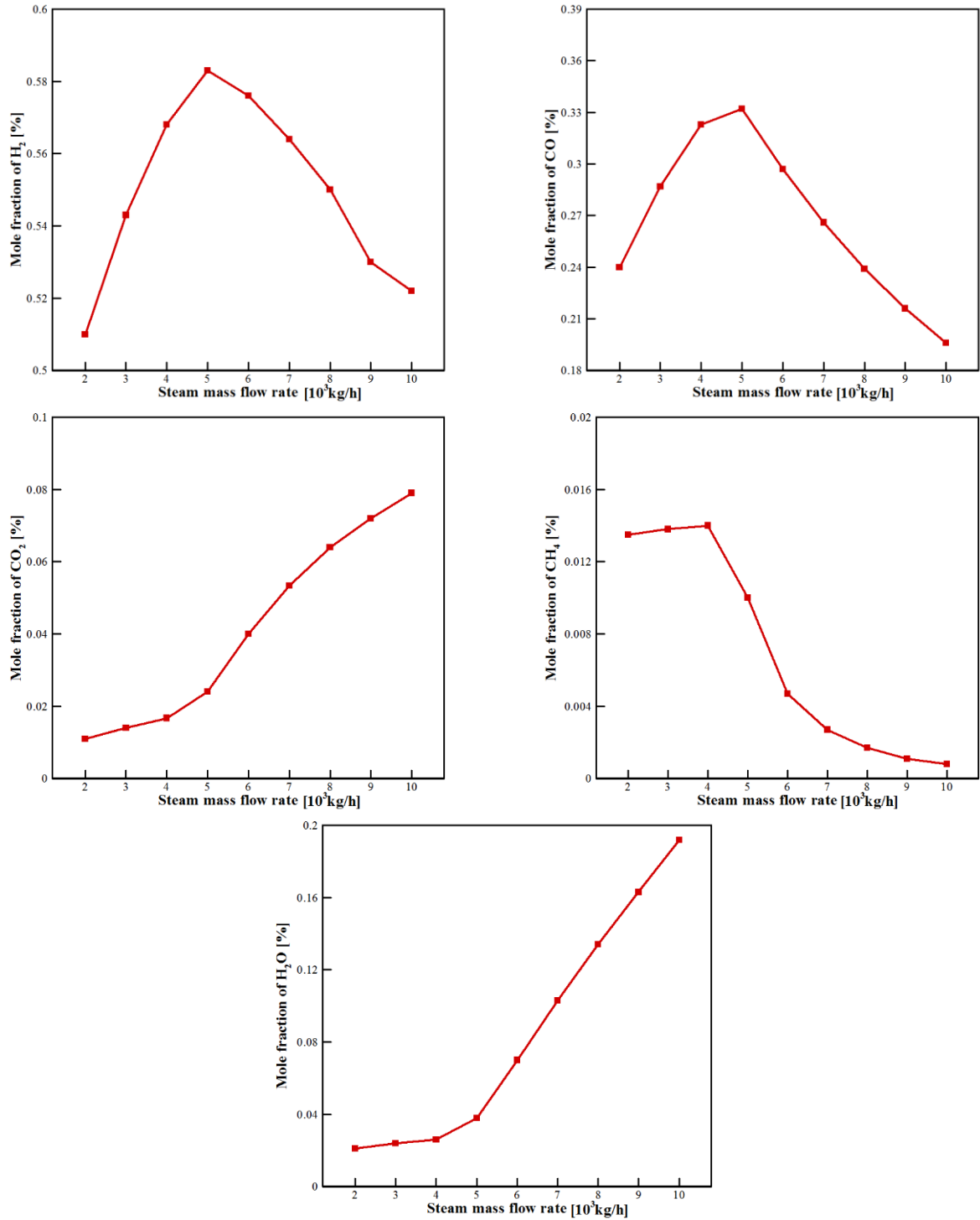
Fig 9. Effects of steam mass FR on mole fractions of H_2, CO, CO_2, CH_4 and H_2O
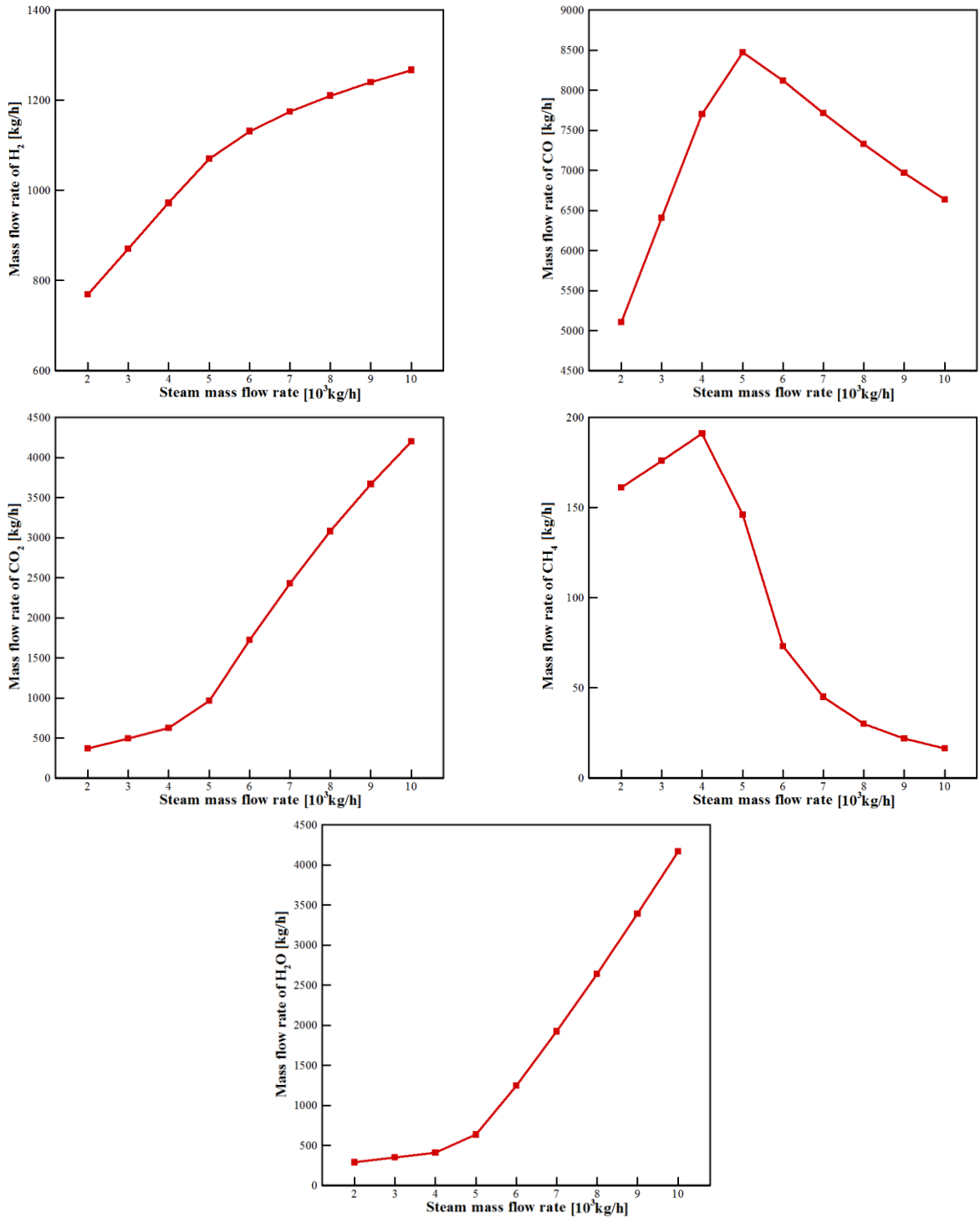
25

Fig 10. Effects of steam mass FR on mass FR of H_2, CO, CO_2, CH_4 and H_2O

The first noteworthy point is that the mole fraction and mass flow rate of steam increases. with changes in steam flow rate in output products. Steam reacts with carbon, carbon monoxide and methane, and produces hydrogen, carbon dioxide and carbon monoxide. The mole fraction and mass flow rate of carbon dioxide increases due to the reaction of water with carbon monoxide. The mole fraction

of hydrogen and carbon monoxide is maximum at a steam mass flow rate of $5000\ kg/h$, and its value is 0.583 and 0.332, respectively. The effect of the steam flow rate on the heat consumption in the Gibbs reactor is shown in Figure 11. The required heat of the Gibbs reactor increases with changes in the steam flow rate.
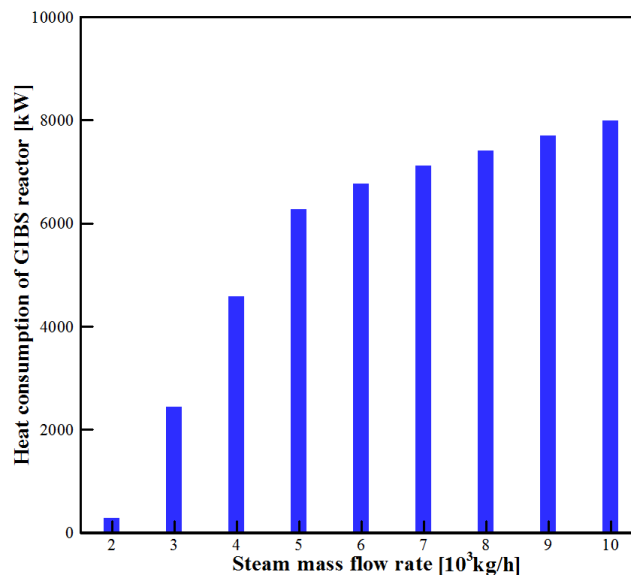
26

Fig11. Effects of steam mass FR on heat consumption of GIBS reactor

5. Conclusion

This study carried out a numerical investigation of the quality of syngas in steam gasification of biomass and examined the impact of biomass flow rate, gasification temperature and steam flow rate on the composition of gases and the heat of the reactors. Gibbs free energy minimization approach is used in this investigation. Food waste was used for biomass. First, the results of the numerical solution were validated with the existing experimental results and a good agreement between the results was observed. The following findings were obtained by examining the effect of biomass flow rate, gasification temperature and steam flow rate:

If the parameters such as steam flow rate and gasification temperature remain constant, the input flow rate has a significant effect on the output products and the heat of the reactors. With biomass flow changes from $5000 kg/h$ to $10000 kg/h$, hydrogen mole fraction changes from 0.522 to 0.583 and carbon monoxide mole fraction changes from 0.19 to 0.341, and an 11.6% increase is observed in hydrogen mole fraction and a 79% increase in carbon monoxide mole fraction. With the increase of biomass flow rate, the heat consumed in the drying reactor increases, and the heat produced in the pyrolysis reactor increases.

Gasification temperature is considered as a very important parameter in Gibbs reactor. Because increasing the temperature from a certain value causes the reversal of the water-gas shift reaction, and causes a decrease in hydrogen and an increase in carbon monoxide. As the gasification temperature increases from 700℃ to 900℃, the mole fraction of hydrogen changes from 0.52 to 0.587, and an increase of 13.8% is seen in it. As the gasification

temperature increases again, the mole fraction of hydrogen gas decreases.

The inlet steam flow rate to the Gibbs reactor is considered as an important and influencing parameter on the quality of syngas. The molar fraction of hydrogen and carbon monoxide is maximum at a steam mass flow rate of $5000 kg/h$, and its value is 0.583 and 0.332, respectively.

REFERENCES
[1]M.A.F. Aliabadi, E. Lakzian, A. Jahangiri, I. Khazaei, Numerical investigation of effects polydispersed droplets on the erosion rate and condensation loss in the wet steam flow in the turbine blade cascade, Appl. Therm. Eng. 164 (2020) 114478. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2019.114478.
[2]M. Ali Faghih Aliabadi, G. Zhang, S. Dykas, H. Li, Control of two-phase heat transfer and condensation loss in turbine blade cascade by injection water droplets, Appl. Therm. Eng. 186 (2021) 116541. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2020.116541.
[3]M.A. Faghih Aliabadi, M. Bahiraei, Effect of water nano-droplet injection on steam ejector performance based on non-equilibrium spontaneous condensation: A droplet number study, Appl. Therm. Eng. 184 (2021) 116236. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2020.116236.
[4]P. Parthasarathy, K.S. Narayanan, Hydrogen production from steam gasification of biomass: influence of process parameters on hydrogen yield−a review, Renew. Energy. 66 (2014) 570−579.
[5]E. Hosseini, Hydrogen has found its way to become the fuel of the future, Futur. Energy. 1 (2022) 11−12. https://fupubco.com/fuen/article/view/28.

[6]M. Sedaghat, A. Jahangiri, M. Ameri, A.J. Chamkha, Analysis of the effect of hot rotation cylinders on the enhancement of heat transfer in underfloor heating enclosures based on numerical and experimental results, Int. J. Therm. Sci. 188 (2023) 108218. https://doi.org/https://doi.org/10.1016/j.ijthermalsci.2023.108218.

[7]M. Sedaghat, A. Jahangiri, M. Ameri, A. Shahsavar, An experimental/numerical investigation and technical analysis of improving the thermal performance of an enclosure by employing rotating cylinders, Int. Commun. Heat Mass Transf. 138 (2022) 106370. https://doi.org/https://doi.org/10.1016/j.icheatmasstransfer.2022.106370.

[8]S.E. Hosseini, M.A. Wahid, Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development, Renew. Sustain. Energy Rev. 57 (2016) 850–866. https://doi.org/https://doi.org/10.1016/j.rser.2015.12.112.

[9]H. Singh, S. Tomar, K.A. Qureshi, M. Jaremko, P.K. Rai, Recent advances in biomass pretreatment technologies for biohydrogen production, Energies. 15 (2022) 999.

[10]S. Seker, N. Aydin, Assessment of hydrogen production methods via integrated MCDM approach under uncertainty, Int. J. Hydrogen Energy. 47 (2022) 3171–3184.

[11]B. Hejazi, Heat integration and waste minimization of biomass steam gasification in a bubbling fluidized bed reactor, Biomass and Bioenergy. 159 (2022) 106409.

[12]X. Zhang, A.C.K. Yip, S. Pang, Advances in the application of active metal-based sorbents and oxygen carriers in chemical looping biomass steam gasification for H_2 production, Int. J. Hydrogen Energy. (2022).

[13]A. AlNouss, M. Shahbaz, G. Mckay, T. Al-Ansari, Bio-methanol production from palm wastes steam gasification with application of CaO for CO_2 capture: techno-economic-environmental analysis, J. Clean. Prod. 341 (2022) 130849.

[14]S.S. Siwal, Q. Zhang, C. Sun, S. Thakur, V.K. Gupta, V.K. Thakur, Energy production from steam gasification processes and parameters that contemplate in biomass gasifier–A review, Bioresour. Technol. 297 (2020) 122481.

[15]F. Benedikt, M. Kuba, J.C. Schmid, S. Müller, H. Hofbauer, Assessment of correlations between tar and product gas composition in dual fluidized bed steam gasification for online tar prediction, Appl. Energy. 238 (2019) 1138–1149.

[16]M. Campoy, A. Gómez-Barea, F.B. Vidal, P. Ollero, Air–steam gasification of biomass in a fluidised bed: Process optimisation by enriched air, Fuel Process. Technol. 90 (2009) 677–685. https://doi.org/https://doi.org/10.1016/j.fuproc.2008.12.007.

[17]N. Nipattummakul, I.I. Ahmed, S. Kerdsuwan, A.K. Gupta, Steam gasification of oil palm trunk waste for clean syngas production, Appl. Energy. 92 (2012) 778–782.

[18]J. Mazumder, H.I. de Lasa, Ni catalysts for steam gasification of biomass: Effect of La2O3 loading, Catal. Today. 237 (2014) 100–110. https://doi.org/https://doi.org/10.1016/j.cattod.2014.02.015.

[19]A. D'Orazio, S. Rapagnà, P.U. Foscolo, K. Gallucci, M. Nacken, S. Heidenreich, A. Di Carlo, A. Dell'Era, Gas conditioning in H_2 rich syngas production by biomass steam gasification: Experimental comparison between three innovative ceramic filter candles, Int. J. Hydrogen Energy. 40 (2015) 7282–7290.

[20]V. Chiodo, F. Urbani, G. Zafarana, M. Prestipino, A. Galvagno, S. Maisano, Syngas production by catalytic steam gasification of citrus residues, Int. J. Hydrogen Energy. 42 (2017) 28048–28055.

[21]D. Perondi, P. Poletto, D. Restelatto, C. Manera, J.P. Silva, J. Junges, G.C. Collazzo, A. Dettmer, M. Godinho, A.C.F. Vilela, Steam gasification of poultry litter biochar for bio-syngas production, Process Saf. Environ. Prot. 109 (2017) 478–488.

[22]Y.-H. Li, H.-H. Chen, Analysis of syngas production rate in empty fruit bunch steam gasification with varying control factors, Int. J. Hydrogen Energy. 43 (2018) 667–675.

[23]X. Yan, Y. Li, X. Ma, Z. Bian, J. Zhao, Z. Wang, CeO2-modified CaO/Ca12Al14O33 bi-functional material for CO_2 capture and H_2 production in sorption-enhanced steam gasification of biomass, Energy. 192 (2020) 116664.

[24]W. Ma, C. Chu, P. Wang, Z. Guo, B. Liu, G. Chen, Characterization of tar evolution during DC thermal plasma steam gasification from biomass and plastic mixtures: Parametric optimization via response surface methodology, Energy Convers. Manag. 225 (2020) 113407.

[25]S.A. Salaudeen, B. Acharya, M. Heidari, S.M. Al-Salem, A. Dutta, Hydrogen-rich gas stream from steam gasification of biomass: eggshell as a CO_2 sorbent, Energy & Fuels. 34 (2020) 4828–4836.

[26]D. Singh, S. Yadav, Steam gasification with torrefaction as pretreatment to enhance syngas production from mixed food waste, J. Environ. Chem. Eng. 9 (2021) 104722.

[27]J. Huang, C. Feng, Y. Yu, D. Xie, Z. Wang, W. Hu, Y. Qiao, Contributions of pyrolysis, volatile reforming and char gasification to syngas production during steam gasification of raw and torrefied leftover rice, Fuel. 304 (2021) 121486.

[28]S. Piazzi, L. Menin, D. Antolini, F. Patuzzi, M. Baratieri, Potential to retrofit existing small-scale gasifiers through steam gasification of biomass residues for hydrogen and biofuels production, Int. J. Hydrogen Energy. 46 (2021) 8972–8985.

[29]S. Vikram, P. Rosha, S. Kumar, S. Mahajani, Thermodynamic analysis and parametric optimization of steam-CO2 based biomass gasification system using Aspen PLUS, Energy. 241 (2022) 122854.

[30]L.C.M. Ruivo, H. Gomes, D. V Lopes, A.A. Yaremchenko, C. Vilas-Boas, L.A.C. Tarelho, J.R. Frade, Catalytic O2-steam gasification of biomass over Fe2-xMnxO3 oxides supported on ceramic foam filters, Fuel. 324 (2022) 124566. https://doi.org/https://doi.org/10.1016/j.fuel.2022.124566.

[31]A.M. Ali, M. Shahbaz, K. Shahzad, M. Inayat, S. Naqvi, A.A. Al-Zahrani, M.I. Rashid, M. Rehan, A.B. Mahpudz, Polygeneration syngas and power from date palm waste steam gasification through an Aspen Plus process modeling, Fuel. 332 (2023) 126120. https://doi.org/https://doi.org/10.1016/j.fuel.2022.126120.

[32]J. Li, G. Chang, K. Song, B. Hao, C. Wang, J. Zhang, G. Yue, S. Hu, Influence of coal bottom ash additives on catalytic reforming of biomass pyrolysis gaseous tar and biochar/steam gasification reactivity, Renew. Energy. 203 (2023) 434–444. https://doi.org/https://doi.org/10.1016/j.renene.2022.12.037.

[33]Fremaux S, Beheshti SM, Ghassemi H, Shahsavan-Markadeh R. An experimental study on hydrogen-rich gas production via steam gasification of biomass in a research-scale fluidized bed. Energy Conversion and Management. 2015 Feb 1;91:427-32.
.