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Article

Performance Analysis of an Integrated Fixed Bed Gasifier Model for Different Biomass Feedstocks

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Abstract: Energy recovery from biomass by gasification technology has attracted significant interest because it satisfies a key requirement of environmental sustainability by producing near zero emissions. Though it is not a new technology, studies on its integrated process simulation and analysis are limited, in particular for municipal solid waste (MSW) gasification. This paper develops an integrated fixed bed gasifier model of biomass gasification using the Advanced System for Process ENngineering (Aspen) Plus software for its performance analysis. A computational model was developed on the basis of Gibbs free energy minimization. The model is validated with experimental data of MSW and food waste gasification available in the literature. A reasonable agreement between measured and predicted syngas composition was found. Using the validated model, the effects of operating conditions, namely air-fuel ratio and gasifier temperature, on syngas production are studied. Performance analyses have been done for four different feedstocks, namely wood, coffee bean husks, green wastes and MSWs. The ultimate and proximate analysis data for each feedstock was used for model development. It was found that operating parameters have a significant influence on syngas composition. An air-fuel ratio of 0.3 and gasifier temperature of 700 °C provides optimum performance for a fixed bed gasifier for MSWs, wood wastes, green wastes and coffee bean husks. The developed model can be useful for gasification of other biomasses (e.g., food wastes, rice husks, poultry wastes and sugarcane bagasse) to predict the syngas composition. Therefore, the study provides an integrated gasification model which can be used for different biomass feedstocks.

Keywords: gasification; fixed bed; Aspen Plus; syngas

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1. Introduction

The demand for energy security has been increasing globally to meet the vital needs of humans' daily lives: producing electricity, powering vehicles, heating or air-conditioning homes, producing life-saving medicines and processing food, *etc.* A recent study predicted that oil and gas prices would be double by 2050 [1]. Renewable energy is thus taking on an increasingly vital role to provide the balance between energy demand and supply. Renewable energy can be obtained from different sources. Biomass is an important renewable energy source with near zero CO_2 emissions through the use of gasification processes, which may provide a new way of increasing energy utilization while also satisfying the requirements of sustainable development [2].

Biomass comprises carbon based materials and are composed of mixtures of organic materials, such as municipal solid wastes (MSWs), wood wastes, green wastes, sugarcane bagasse, rice husks, coffee bean husks, food wastes and poultry wastes. Biomass gasification is one of the popular processes that produces energy in the form of synthesis gas and at the same time reduces the environmental hazards of raw biomasses. It can reduce the dependency on imported energy and would thus help ensure energy security. Gasification is a thermochemical process which converts the carbonaceous materials of biomass into a combustible syngas [3]. Biomass gasification is a continuous substoichiometric [oxygen (O_2) starved] burning process which burns biomass (e.g., solid waste) in a reactor generating a syngas and pyrolysis liquids (tars) as fuels. It takes place in the presence of a limited amount of oxidizer (air, O_2 or steam). The composition of the end product, syngas, varies with operating conditions and types of oxidizers used. Syngas mainly consists of carbon monoxide (CO) and hydrogen (H_2). The remaining components of syngas are carbon dioxide (CO_2), methane (CH_4), O_2 and nitrogen (N_2). Syngas plays a significant role in industrial and household applications. Nowadays, gasifiers are not only utilized for the chemical and petrochemical industries, but also applied in many other fields. The gasification process is comprised of three linked processes; pyrolysis (decomposition), gasification, and partial combustion. Partial combustion is necessary because it supplies the heat required by the endothermic gasification reactions [4].

Recently, Ma *et al.* [5] performed an investigation into combined catalyst and O_2 carrier systems for the partial oxidation of naphthalene as a model tar from biomass gasification. In their research, catalytic partial oxidation is applied as a thermo-chemical method to remove tar (naphthalene) from syngas and convert it into fuel gas by using a combined catalyst and O_2 carrier system. Another recent study was carried out by Font Palma and Martin [6] on a model based evaluation of six energy integration schemes applied to a small-scale gasification process for power generation considering the use of spent poultry litter as a fuel for on-site power generation. They found the preferred configuration of the proposed 200 kW process can achieve electrical efficiencies ranging between 26% and 33.5%.

Process simulation studies on gasification are limited, though there have been substantial research involving gasification of MSWs, sugarcane bagasse and other different types of wastes. Recently, Mavukwana *et al.* [7] performed simulation of sugarcane bagasse gasification using the Advanced System for Process ENgineering (Aspen) Plus software and they compared the model data with experimental results published in the literature. The overall data were found to be in good agreement. Most recently, Kuo *et al.* [8] performed a study on gasification performances of raw and torrefied biomass in a downdraft fixed bed gasifier using thermodynamic analysis. In their study, the gasification performances of three biomass materials: raw bamboo, bamboo torrefied at 250 °C and bamboo torrefied at 300 °C, in a downdraft fixed bed gasifier were evaluated through thermodynamic analysis. Two parameters of Modified Equivalence Ratio and Steam Supply Ratio were considered to account for their impacts on biomass gasification. Ramzan *et al.* [9] developed a steady state model using Aspen Plus to study the gasification of MSWs, food wastes and poultry wastes. They validated the model with experimental data obtained through a hybrid biomass gasifier. They also investigated the effect of equivalent ratio (ER), gasification temperature and moisture content on gasification performance. Another study has been done by Chen *et al.* [10] on two different types of fixed bed reactor for MSW simulation. They discussed the effect of flue gas from the combustion section on the composition and lower heating value (LHV) of syngas, heat conversion efficiency, and carbon conversion at different gasification temperatures and air equivalence ratios. It is to be noted that these researchers developed simulation models for their specific feedstocks, therefore an integrated model which can be used for a number of feedstocks is necessary. The novelty of this study is to develop an integrated and generalised model applicable for different feedstocks.

The objective of this study is to develop an integrated fixed bed gasifier model for different biomass feedstocks, more practically for MSWs, wood wastes, green wastes and coffee bean husks for predicting the steady-state performance of the model. Initially the developed simulation model was validated with MSW data measured by Naveed *et al.* [11] and then used to perform analysis for other feedstocks. This paper presents details of the modelling approaches taken to obtain a process simulation model and its validation, including performance analysis of different feedstocks. Then the model is extended to study the impact of operating variables, such as air-fuel ratio and gasifier temperature on syngas production.

2. Simulation Model Development

2.1. Process Model Simulator

Recently, a number of processes modeling software package have become available to develop computational model of gasification process and to perform simulation and validation studies. Generally, researchers and professionals use Aspen Plus, Computational Fluid Dynamics (CFD, composed of GAMBIT and FLUENT), ChemCAD and MatLab software packages to develop and optimize their gasification models. Although CFD is powerful software, the programs have high computational requirements. On the other hand, Aspen Plus is one of the sophisticated processes modeling computer software packages which is familiar to many users and has proven its capacity for gasification model development and simulation. Due to its vast capability and precise outcomes in process modeling, Aspen Plus was used in this study to develop and simulate a fixed bed gasification process for different feedstocks (MSWs, wood wastes, green wastes and coffee bean husks).

The simulations of the biomass gasification process were based on the mass-energy balance and chemical equilibrium for the overall process. Aspen Plus is based on "blocks" related to unit operations as well as chemical reactors, through which most industrial operations can be simulated. It comprises several databases containing physical, chemical and thermodynamic data for a wide variety of chemical compounds, as well as a selection of thermodynamic models required for the accurate simulation of any given chemical system [12]. In this study, the developed Aspen Plus model for a fixed bed gasifier involves the following sequential steps:

(1) stream class specification;
(2) property method selection;
(3) system component specification (from databank) and identifying conventional and non-conventional components;
(4) defining the process flowsheet (using unit operation blocks and connecting material and energy streams);
(5) specifying feed streams (flow rate, composition, and thermodynamic condition);
(6) specifying unit operation blocks (thermodynamic condition, chemical reactions, *etc.*).

A drawback of using Aspen Plus is the lack of a library model to simulate fixed bed unit operations. However, it is possible for users to input their own models, using FORTRAN codes and reactions nested within the Aspen Plus input file, to simulate the operation of a fixed bed.

2.2. Assumptions

The following assumptions were considered in this study:

(1) the model is steady state, kinetic free and isothermal;
(2) chemical reactions take place at an equilibrium state in the gasifier, and there is no pressure loss;
(3) all elements except sulphur contact at uniformly and take part in the chemical reaction;
(4) all gases are ideal gases, including H_2, CO, CO_2, steam (H_2O), N_2 and CH_4;
(5) char contains volatile matters composed of carbon, H_2 and O_2;
(6) tars are assumed as non- equilibrium products to reduce the hydrodynamic complexity [13].

2.3. Model Description

A number of steps comprise the overall gasification process: (1) drying; (2) decomposition; (3) gasification; and (4) combustion. A process flowchart and an Aspen Plus simulation flowchart of biomass gasification are shown in Figures 1 and 2, respectively. Feed is specified as a non-conventional component in Aspen Plus and defined in the simulation model by using the ultimate and proximate analysis.

Figure 1. Process flowsheet of gasification in fixed bed gasifier.

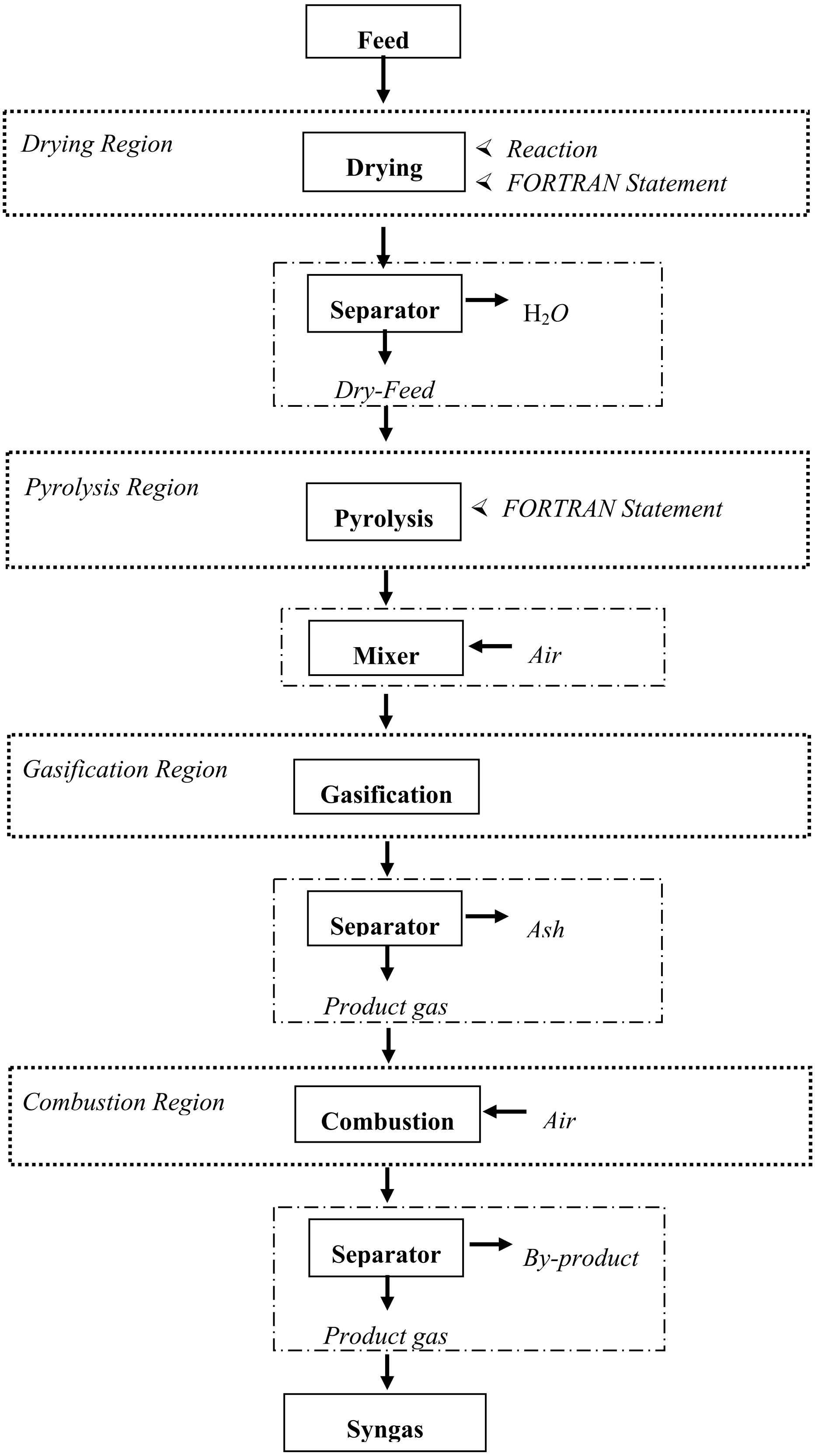
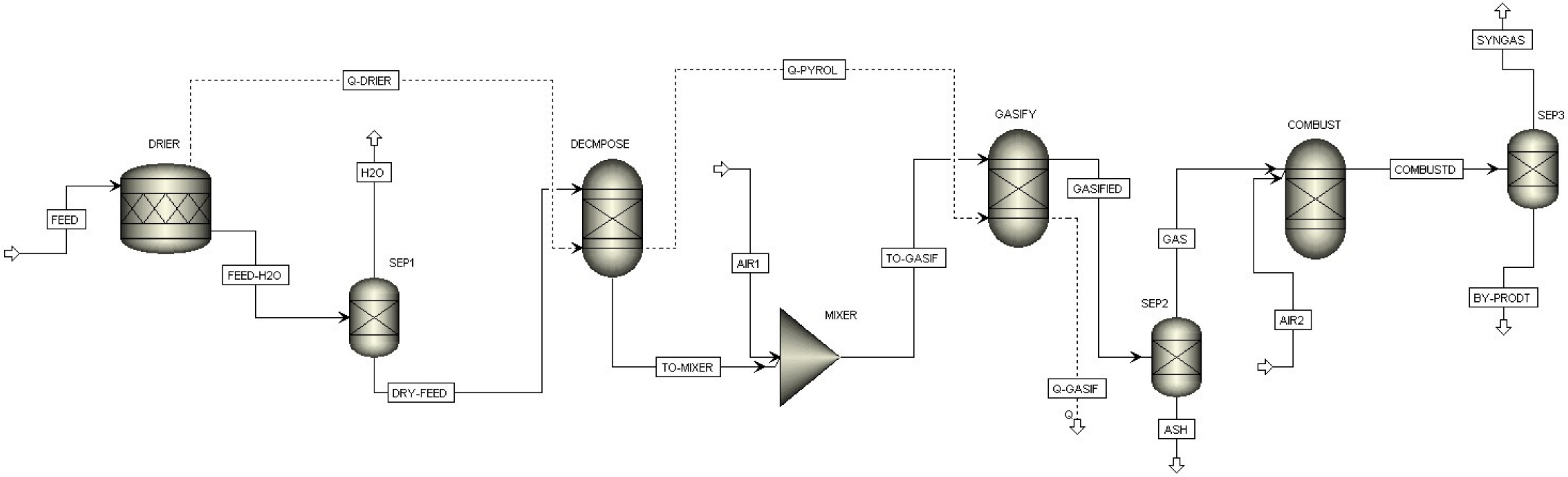


Figure 2. Advanced System for Process ENgineering (Aspen) Plus simulation flowchart.



The characteristics of different feedstocks (MSWs, wood, green wastes and coffee bean husks) sourced from the literature (BEST Energies Australia Pty Ltd. Report [14], Wilson *et al.* [15], Naveed *et al.* [11] and Chen *et al.* [10]) are given in Table 1. The model is based on minimization of the Gibbs free energy at equilibrium. This simulation is developed under the assumption that the residence time is long enough to allow the chemical reactions to reach an equilibrium state.

Table 1. Characteristics of feedstocks.

Feedstocks	**Data source**	**Proximate analysis (%)**				**Ultimate analysis**				
		Moisture content	**Fixed carbon**	**Volatile matter**	**Ash**	**C**	**H**	**O**	**N**	**S**
Wood	BEST Energies Australia Pty Ltd. Report [14]	25	16.3	82.6	1.1	50.3	6.03	42.33	0.21	0
Coffee bean husks	Wilson *et al.* [15]	10.1	83.2	14.3	2.5	49.4	6.1	41.2	0.7	0.07
Green wastes	BEST Energies Australia Pty Ltd. Report [14]	48	19.6	72	8.4	46.6	5.5	38.61	0.71	0.18
MSWs	Naveed *et al.* [11]	12	15.47	38.29	46.24	36.4	4.97	10.15	1.44	0.802
Food wastes	Naveed *et al.* [11]	29.3	14.6	51.1	4.9	56.65	8.76	23.54	3.95	0.19
MSWs	Chen *et al.* [10]	48	7.7	46.15	46.15	30.77	4.62	17.3	0.77	0.39

The input parameters and the corresponding operating conditions for all feedstocks are the same, and are given in Table 2.

Table 2. Gasification operating parameters for different feedstocks.

Model parameter	**Feed**	**Air**	**Gasifier**
Flow rate (kg/h)	10	1–10	-
Pressure (bar)	1	1	1
Temperature (°C)	25	25	500–1000

Method and steps used for model development are described below.

2.3.1. Physical Property Method

The Redlich-Kwong-Soave cubic equation of state with Boston-Mathias alpha function (RKS-BM) has been used to estimate all physical properties of the conventional components in the gasification process. This property method is comparable to the Peng Robinson cubic equation of state with the Boston-Mathias alpha function (PR-BM) property method. RKS-BM is recommended for gas-processing, refinery and petrochemical applications such as gas plants, crude towers and ethylene plants. This method is generally used for nonpolar or mildly polar mixtures, like hydrocarbons and light gases such as CO_2, hydrogen sulfide and H_2. Using RKS-BM, reasonable results can be expected at all temperatures and pressures. The RKS-BM property method is consistent in the critical region. The enthalpy and density model selected for both feed and ash are non-conventional components, HCOALGEN and DCOALIGT. In this study, feed was defined as non-conventional components from the perspectives of ultimate and proximate analysis (Table 1). Ashes were also defined as a non-conventional component with an ash content set to 100%.

2.3.2. Model Sequence

A number of Aspen Plus units were used to develop the model. The main processes were simulated by three reactors in Aspen plus: RStoic, RYield and RGibbs. The gasification process begins with the decomposition (pyrolysis) region and continues with the combustion region. The relevant reactions in Equations (1)–(7) considered in these processes were [6,16]:

$$C + O_2 = CO_2 \text{ (carbon combustion)} \tag{1}$$

$$C + 0.5O_2 = CO \text{ (carbon combustion)} \tag{2}$$

$$C + CO_2 = 2CO \text{ (Boudouard)} \tag{3}$$

$$C + H_2O = CO + H_2 \text{ (water-gas)} \tag{4}$$

$$CO + H_2O = CO_2 + H_2 \text{ (CO shift)} \tag{5}$$

$$C + 2H_2 = CH_4 \text{ (methanation)} \tag{6}$$

$$H_2 + 0.5O_2 = H_2O \text{ (}H_2\text{ combustion)} \tag{7}$$

$$CH_4 + H_2O = CO + 3H_2 \tag{8}$$

$$CH_4 + 2H_2O = CO_2 + 4H_2 \tag{9}$$

Major gasification reactions are water gas, Boudouard, shift conversion and methanation. In accordance with the Boudouard reaction in Equation (3), at low temperatures both unburnt carbon and CH_4 are present in the syngas but as the temperature increases carbon is converted into carbon. CH_4 is converted into H_2 by reverse methanantion reaction in Equation (6). According to the Boudouard reaction (R4), as the gasifier temperature increases the mole fraction of CO increases and that of CO_2 decreases. Water gas reaction in Equation (4) suggests that high temperature increases the production of both CO and H_2. According to the methanation reaction in Equation (6) the mole fraction of CH_4 in syngas decreases and that of H_2 increases with the increase in temperature. At higher temperatures yield of H_2 and CO starts reducing. This is also attributed to the water gas reaction in Equation (4).

2.3.2.1. Drying

The purpose of this region is to reduce the moisture content of the feedstock. The Aspen Plus stoichiometric reactor, RStoic (model ID: DRIER), was used to simulate the evaporation of moisture. The drying operation was controlled by writing a FORTRAN statement in the calculator block. RStoic converts a part of feed to form water which requires the extent of reaction known as:

$$Feed \rightarrow 0.0555084\mathrm{H_2O} \tag{10}$$

The yield of gaseous water is determined by the water content in the proximate analysis of particular feedstock. In case of model validation, the moisture content of MSW is 12%; therefore, the mass yield of gaseous water is set as 12%, based on the assumption that the physically bound water is vaporized completely in this process. The mass yield of dried MSW is correspondingly equal to 100% − 12% = 88%.

In this step, the moisture of each feedstock is partially evaporated and then separated using a separator model, Sep2 (model ID: SEP1) through split fractionation of the components. The dried feedstock is placed into the next region for decomposition after being separated from the evaporated moisture. The evaporated moisture was drained out from the process. The produced heat of reaction associated with the drier (model ID: Q-DRIER) was passed by a heat stream into the RYield reactor where decomposition occurs.

2.3.2.2. Decomposition

Decomposition is one of the main steps of the gasification process where each feedstock is decomposed into its elements. The Aspen Plus yield reactor, RYield (model ID: DECMPOSE), was used to simulate the decomposition of the feed. The yield reactor converts non-conventional feed into conventional components by using a FORTRAN statement. In this step, feed is converted into its components including carbon, O_2, N_2, H_2, sulphur and ash by specifying the yield distribution according to the feedstock's ultimate analysis. The yield distribution of feed into its components was specified by a FORTRAN statement in the calculator block. The decomposed elements mixed with air at an Aspen MIXER block are ready for gasification.

2.3.2.3. Gasification

The RGibbs reactor is a rigorous reactor for multiphase chemical equilibrium based on Gibbs free energy minimisation. RGibbs was used to simulate the gasification of biomass. The Gibbs free energy of the biomass cannot be calculated because it is a non-conventional component. Therefore, before feeding the biomass into the RGibbs block it was decomposed into its elements (C, H, O, N and S, *etc.*) using the RYield reactor. The reactor calculates the syngas composition by minimising the Gibbs free energy and assumes complete chemical equilibrium. The heat of reaction associated with the decomposition (Q-PYROL) of feed was passed by a heat stream into the RGibbs reactor where gasification occurs. The decomposed feed and air enter into the RGibbs reactor where partial oxidation and gasification reactions occur. Carbon partly constitutes the gas phase, which takes part in devolatisation, and the remaining carbon comprises part of the solid phase. A very minimum heat (model ID: Q-GASIF) produced at gasification escapes from the process through a heat stream. A separator model, Sep2 (model ID: SEP2) was used to separate ash from the gas mixture using split fractionation of the components.

2.3.2.4. Combustion

To complete the gasification process, another RGibbs reactor was used in the combustion section with minimum air mixing. This combustion process is also based on the principle of minimization of Gibbs free energy. To identify the syngas components from by-products, a separator model, Sep2 (model ID: SEP3), was used.

3. Results and Discussion

3.1. Model Validation

The developed simulation model has been validated using experimental data for MSW and food waste gasification in a lab-scale hybrid gasifier published by Naveed *et al.* [11,17]. They conducted experiment in a pilot plant consisting of a gasifier, a gas cleaning and tar removal system and a flare arrangement. The gasification process inside the gasifier was divided into four distinct zones, *i.e.*, drying bunker, pyrolysis, oxidation and reduction zone. The details of the process can be found in references [11,17].

The simulation was done for syngas composition, such as, H_2, CO, CO_2, CH_4 and N_2 using the experimental condition for both MSWs and food wastes. The model and experimental results are shown in Table 3. It is observed from Table 3 that the model results are in good agreement with the experimental results. More specifically, the model results over-predict MSWs and food wastes by 3.61% and 1.25%, respectively. However, the maximum relative difference of syngas compositions was found to be within 20% for both feedstocks. The conversion levels of biomass fuel to syngas were found to be 47.3% and 43.5% for MSWs and food wastes, respectively. The performance analyses were then extended for a number of other feedstocks (wood, coffee bean husks and green wastes) to identify the optimized operating conditions for each feedstock.

Table 3. Experimental and simulation results for gasification.

Feedstock	Measurement	H_2	CO	CO_2	CH_4	N_2	Others
MSWs	Experimental (%)	4.58	14.89	8.4	1.54	67.34	3.3
	Model (%)	5.2	18.5	7.75	1.32	62.38	2.7
	Difference	+0.62	+3.61	−0.65	−0.22	−5.0	−0.6
	Relative difference (%)	13.53	24.24	7.73	14.28	7.42	18.18
Food wastes	Experimental (%)	5.13	11.29	10.13	2.56	67.01	3.88
	Model (%)	4.89	12.09	11.38	3.2	65.72	2.72
	Difference	−0.24	+0.8	+1.25	−0.64	−1.29	1.16
	Relative difference (%)	4.67	7.08	12.33	25.0	1.92	29.89

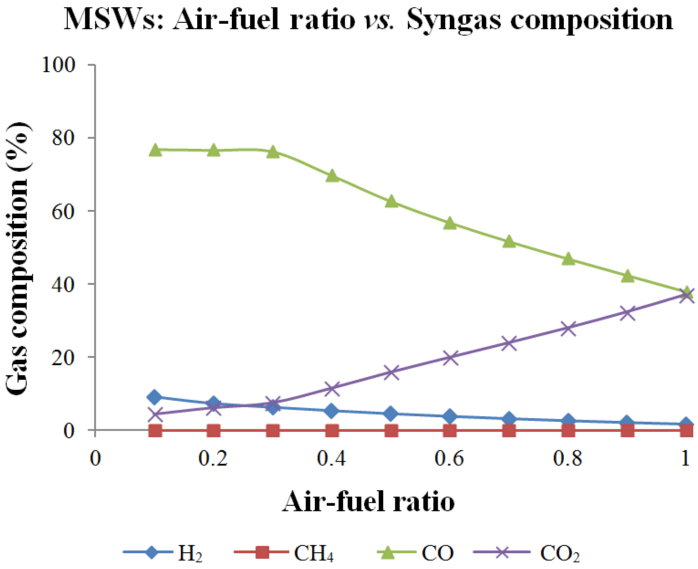
Using the validated model, the effect of air-fuel ratio and gasification temperature on gasification performance was studied for MSWs, wood wastes, green wastes and coffee bean husks. The conversion level of different feedstocks (wood wastes, green wastes and coffee bean husks) to syngas varies within 40% to 64%. Remaining unconverted biomass produces majority char (18%–24%), and the rest are O_2, steam and ash with negligible amounts of argon, sulphur, hydrogen sulphide and ammonia. Figures 3–10 show the concentration of syngas composition (H_2, CO, CO_2 and CH_4) for varying air-fuel ratios and gasification temperatures.

3.2. Effect of Air-Fuel Ratio

The air-fuel ratio is defined as the ratio of the amount of air required for a unit amount of fuel to complete combustion. This ratio has a strong effect on syngas production. In this study, the air-fuel ratio was varied from 0.1 to 1.0 for each feedstock while the gasifier temperature was 700 °C. The effects of air-fuel ratio on syngas composition are shown in Figures 3–6 for MSWs, wood wastes, green wastes and coffee bean husks, respectively. These are discussed below:

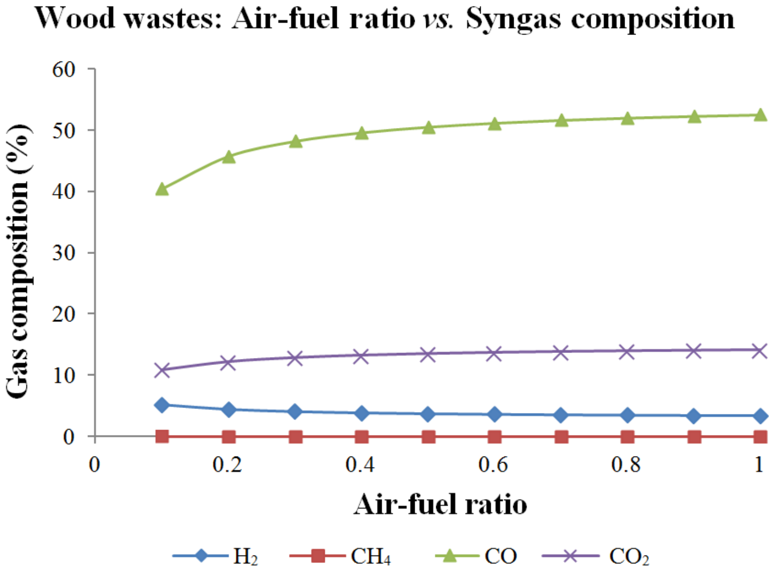
MSWs: the composition of syngas produced from MSW gasification is shown in Figure 3. It can be seen from Figure 3 that the concentration of CO_2 increases (10% to 40%) with increasing air-fuel ratio and that of CO decreases (75% to 40%) after the air-fuel ratio increases from 0.3 to 1.0. It can also be seen that the concentration of H_2 decreases (10% to 2%), whereas CH_4 does not vary with air-fuel ratio.

Figure 3. Effect of air-fuel ratio for municipal solid wastes (MSWs) (gasifier temperature: 700 °C).



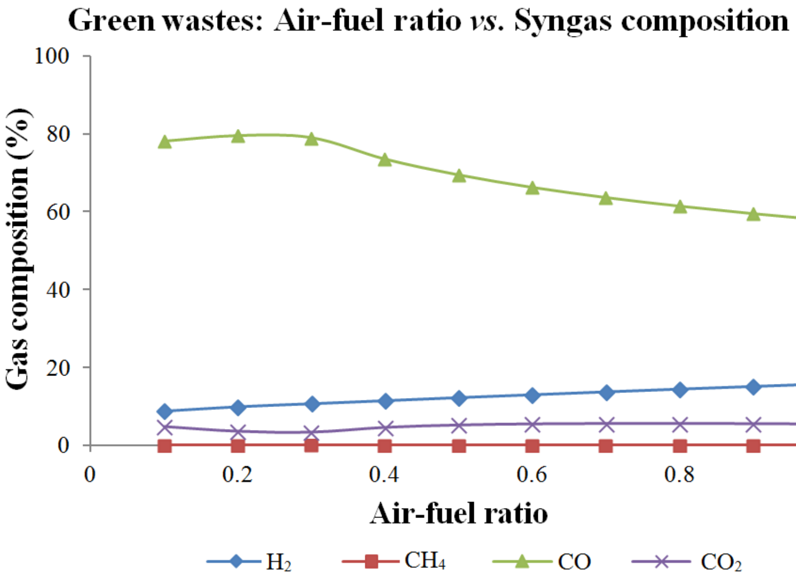
Wood wastes: syngas composition for wood waste is shown in Figure 4. It is clearly shown that CO and CO_2 concentration increases (CO: 40% to 52% and CO_2: 10% to 13%) with an increase of air-fuel ratio from 0.1 to 1, whereas H_2 decreases slightly (5% to 3%). CH_4 follows the same trend as for MSWs.

Figure 4. Effect of air-fuel ratio for wood wastes (gasifier temperature: 700 °C).



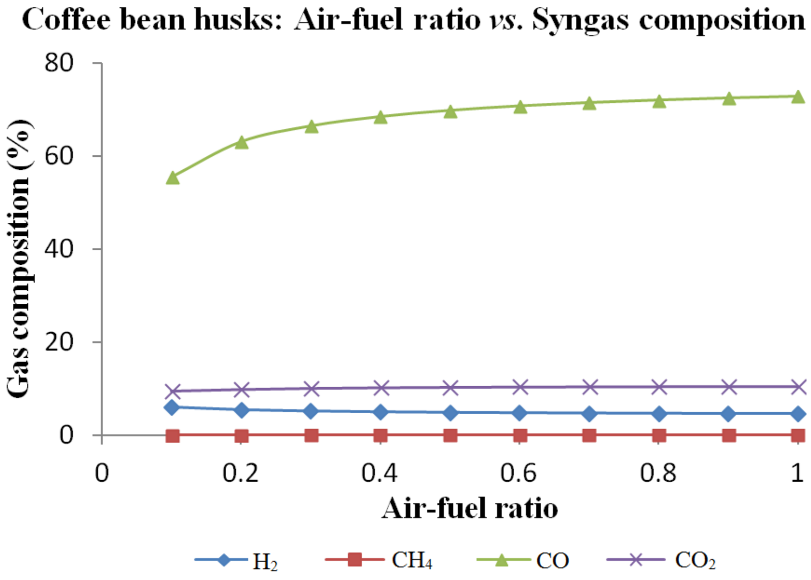
Green wastes: concentration of CO decreases (80% to 65%) after an air-fuel ratio increases from 0.3 to 1.0 as shown in Figure 5. It can also be seen that the concentration of H_2 increases from 10% to 20% with an air-fuel ratio increase from 0.1 to 1. However the concentration of CO_2 and CH_4 remains almost constant.

Figure 5. Effect of air-fuel ratio for green wastes (gasifier temperature: 700 °C).



Coffee bean husks: concentration of H_2, CO_2 and CH_4 varies slightly with air-fuel ratio whereas CO increases (55% to 75%) with an air-fuel ration increase from 0.1 to 1.0 as shown in Figure 6.

Figure 6. Effect of air-fuel ratio for coffee bean husks (gasifier temperature: 700 °C).



Figures 3 and 5 indicate that as expected CO decreases (approx. 75% to 40%) with increasing air-fuel ratio for MSWs and green wastes which could be attributed to their high moisture content. Conversely, the concentration of CO increases with increasing air-fuel ratio for wood wastes and coffee bean husks (Figures 4 and 6) up to air-fuel ratio of 0.3, then remains almost constant. The concentration of H_2 varies only slightly with increasing air-fuel ratio. It should be noted that for wood wastes and coffee bean husks, the concentration of as unexpected CO increases and/or is constant with air-fuel ratio which could be attributed to their significantly lower moisture content than MSWs and green wastes. In the cases of MSWs, green wastes and coffee bean husks, H_2 decreases with increasing air-fuel ratio whereas it increases for wood wastes. A significant increase of CO_2 is observed for MSWs. In the cases of wood wastes, green wastes and coffee bean husks, the production of CO_2 varies only slightly. The concentration of CH_4 is very low for each feedstock. Moisture content of original biomass affects the composition of syngas through the water-gas reaction in Equation (4) and CO shift reaction in Equation (5). In the water-gas reaction, C reacts with steam and produces the syngas components: CO and H_2. Sequentially, the CO shift reaction produces CO_2 and H_2 reacting with steam and CO. Based on Figures 3–6, it is seen that 0.3 is the most suitable air-fuel ratio to perform fixed bed gasification of all feedstocks studied, *i.e.*, for MSWs, wood wastes, green wastes and coffee bean husks, because trend changes start at an air-fuel ratio of 0.3.

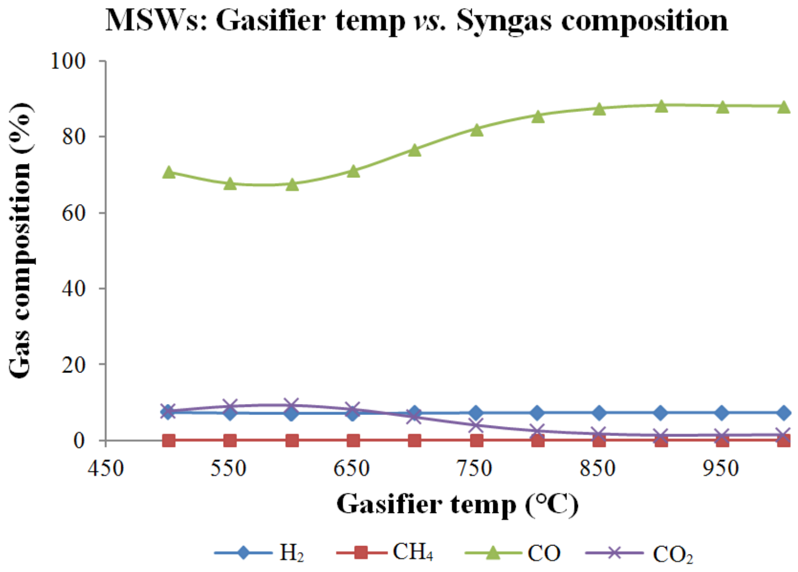
With increasing amounts of air (O_2), the C conversion in the feedstock increases until a certain level. However, an excess amount of O_2 oxidizes the feedstock completely and the production of syngas declines. Initially, the amounts of CO and H_2 increase due to the higher conversion rate of the feedstock, but after a certain limit (0.3) the production of syngas decreases due to complete combustion of the feedstock.

3.3. Effect of Gasifier Temperature

The gasification temperature controls the equilibrium of the chemical reactions [18]. The effects of gasification temperature on syngas production at an air-fuel ratio of 0.3 (*i.e.*, the optimum air-fuel ratio) are shown in Figures 7–10 for MSWs, wood wastes, green wastes and coffee bean husks, respectively. The gasifier temperature was varied from 500 °C to 1000 °C. These figures are explained below:

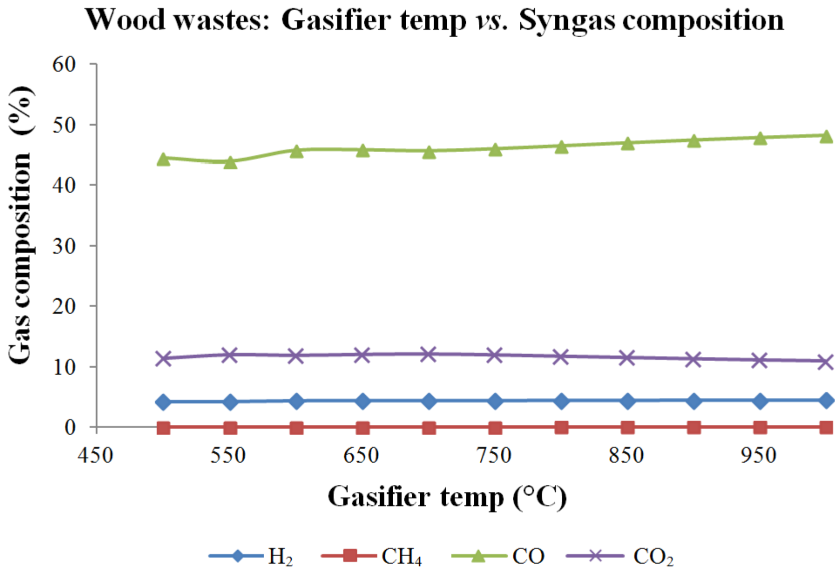
MSWs: concentration of CO increases (75% to 90%) with increasing gasifier temperature, particularly after 650 °C; conversely, CO_2 decreases as shown in Figure 7. H_2 and CH_4 both vary slightly with increasing temperature.

Figure 7. Effect of gasifier temperature for MSWs (air-fuel ratio: 0.2).



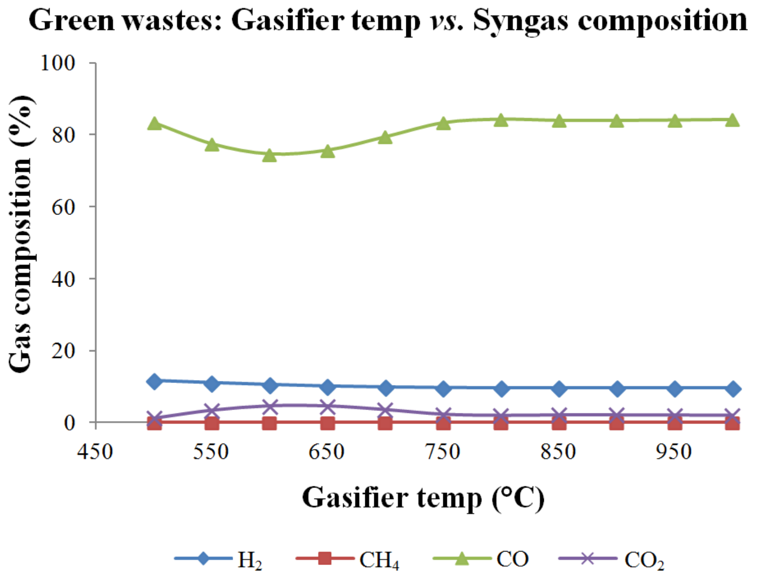
Wood wastes: as shown in Figure 8, the concentration of CO slightly increases with increase of gasifier temperature, whereas H_2, CO_2 and CH_4 maintain almost constant levels.

Figure 8. Effect of gasifier temperature for wood wastes (air-fuel ratio: 0.2).



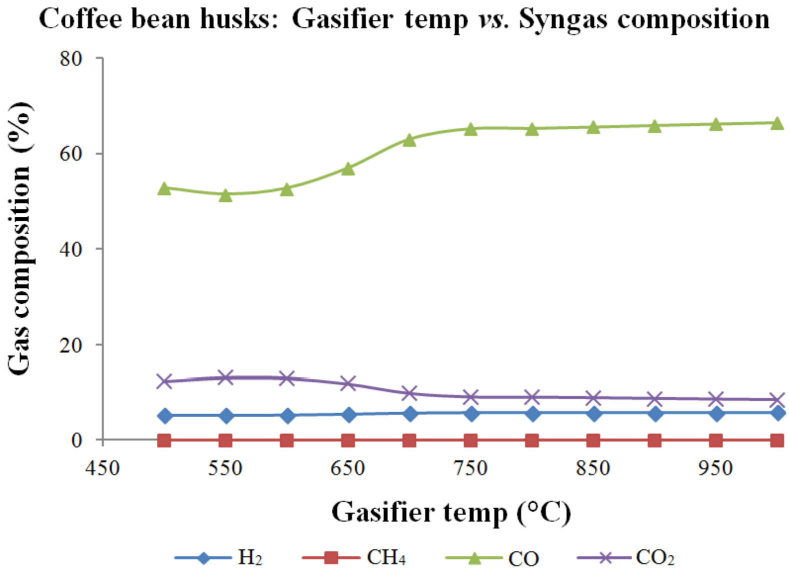
Green wastes: it can be seen from Figure 9 that the concentration of CO slightly decreases with gasifier temperature increase up to a temperature of 650 °C. Then there is a slight increase between temperatures of 650 °C and 750 °C, after which it remains almost constant. The concentration of CO_2 decreases with increasing gasifier temperature, while that of H_2 remains almost the same.

Figure 9. Effect of gasifier temperature for green wastes (air-fuel ratio: 0.2).



Coffee bean husks: in case of coffee bean husks, the concentration of CO_2 decreases at a gasifier temperature of 700 °C, whereas it increases for CO as shown in Figure 10. H_2 shows a constant concentration with increasing temperature and CH_4 is very minimal.

Figure 10. Effect of gasifier temperature for coffee bean husks (air-fuel ratio: 0.2).



It can be seen from Figures 7–10 that, for each feedstock, CO concentration increases with increase in gasification temperature while CO_2 concentration follows an opposite trend. H_2 concentration increases slightly with the increase in gasifier temperature. The concentration of CH_4 varies only very slightly with the increase in gasifier temperature. Based on the developed model, it is observed that a gasifier temperature of 700 °C provides an ideal condition for MSWs, wood wastes, green wastes and coffee bean husks.

For each feedstock, at low temperatures (less than 600 °C), both unburnt C and CH_4 are present in the syngas composition, and C in the feedstock is not fully utilized, resulting in a sub-optimal syngas production rate, but with increasing temperature, the C is oxidized completely and this increases the syngas production rate. According to gasifier chemistry and the Boudouard reaction in Equation (3), with increasing operating temperature C is converted to CO. CH_4 is converted into H_2 by the reverse of the methanation reaction in Equation (6). The water gas reaction in Equation (4) implies that a high temperature increases the production of both CO and H_2. The increase of H_2 concentration could be explained by the endothermic reactions in Equations (4), (8) and (9), and CO concentration would increase because endothermic reactions in Equations (3), (4) and (8) are more dominant than the exothermic reaction in Equation (2). Although endothermic reaction in Equation (9) releases CO_2 (and the CO_2 concentration should increase), the CO_2 concentration decreased as the temperature increased. This is because endothermic reaction in Equation (3) was more dominant, placing the reaction toward the right, and resulting in the increase of CO and decrease of CO_2 as the temperature increased [10,19]. Similar trend has been observed in literature [9,10]. In the cases of MSWs and green wastes, production of CO_2 concentration is slightly less than for wood wastes and coffee bean husks.

4. Conclusions

An integrated fixed bed gasifier model has been developed for four different biomass feedstocks, namely MSWs, green wastes, wood wastes and coffee bean husks, using Aspen Plus. The predicted model data were compared with the experimental data of Naveed *et al.* [10] to establish the model. Simulated data were found to be in fair agreement with the experimental data which indicates the developed model is capable of predicting gasifier performance accurately over a wide range of operating conditions. Further performance analyses were done for MSWs, wood wastes, green wastes and coffee bean husks. The effects of air-fuel ratio and gasifier temperature on gasification performance is analyzed, discussed and compared to identify the most suitable operating conditions with MSWs, green wastes, coffee bean husks and wood wastes. The following results were identified: (1) gasifier temperature of 650 °C and air-fuel ratio of 0.3 is a good combination of operating conditions for all four feedstocks; (2) concentration of CO of 60%–75% can be achieved at gasifier temperatures of 650 °C to 800 °C; (3) an air-fuel ratio of more than 0.3 provides decreasing CO concentration for MSWs and green wastes, whereas the concentration of CO increases with an increase in air-fuel ratio for food wastes and coffee bean husks; and (4) concentration of H_2 decreases until gasification temperature reaches 700 °C, then increases with the increase in temperature. The developed model can be useful for other biomass feedstocks to predict the syngas composition.

Conflicts of Interest

The authors declare no conflict of interest.

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