PAPER • OPEN ACCESS

Co-gasification of coal and empty fruit bunch in an entrained flow gasifier: A process simulation study

To cite this article: M R Deraman *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **702** 012005

View the article online for updates and enhancements.

Co-gasification of coal and empty fruit bunch in an entrained flow gasifier: A process simulation study

M R Deraman, R Abdul Rasid*, M R Othman and L N M Suli

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

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

Abstract. Co-gasification of coal and biomass is a proven method to improve gasification performance and a platform towards being independent of fossil fuel in power generation. Thus, this research was conducted to assess the feasibility of coal and EFB as fuels in co-gasification using Aspen HYSYS. A sequential model of an EFG was developed to predict the syngas composition and the optimum operating condition of the gasifier. The process was modelled with a set of five reactors to simulate various reaction zones of EFG in accordance with its hydrodynamics. The model considers devolatilization, char and volatile combustion, char gasification and water-gas shift reactions. The model prediction has exhibited excellent agreement with the experimental results. Three parameters of BR, Top and S/F were considered to account for their impacts on syngas composition in the process. The CE, CGE, PE and HHV were adopted as the indicators of process performance. The optimal values of BR, Top and S/F were 50%, 950°C and 0.75, respectively. While the value of CE reached above 90% and the maximum value of CGE, PE and HHV was obtained. This finding should be helpful in designing, operating, optimizing and controlling any co-gasification process especially in the entrained flow system.
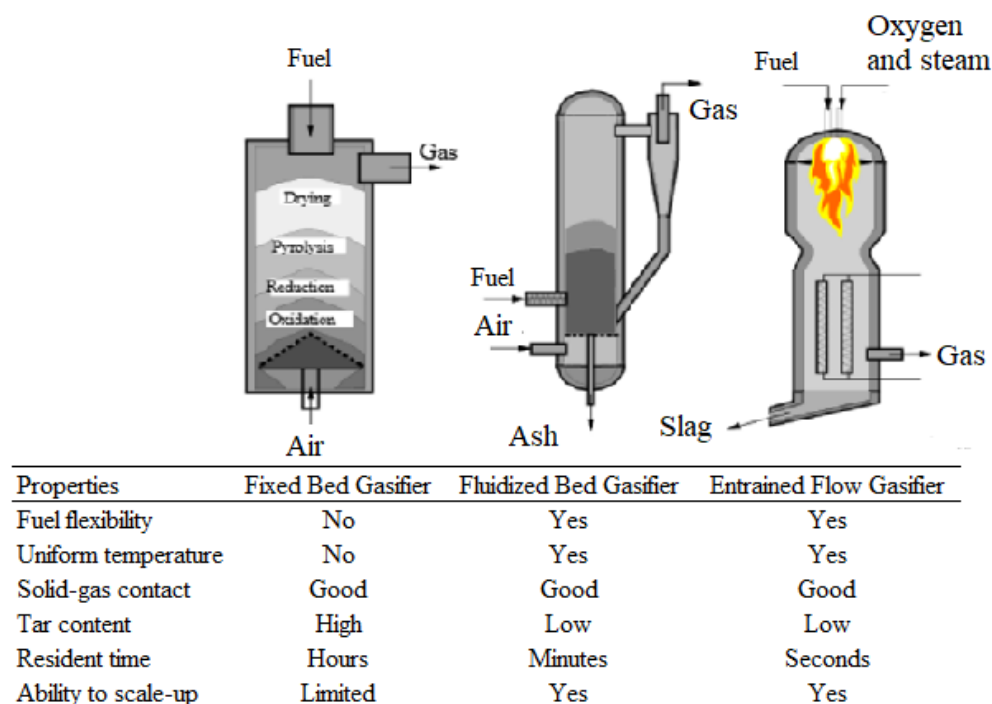
1. Introduction

The use of coal as energy source for electricity has been practiced in centuries [1]. As recorded in 2017 alone, the prevalence of coal utilization is greater than renewable sources in total, owing to the fact that it produces higher magnitude of combustion energy [2]. Unfortunately, not only that burning coal as fuel will contribute to greenhouse gas emission and global warming, a far more important concern is that coal supply is depleting rapidly [3]. The International Energy Agency (IEA) came out with an estimated of 860 billion tons of coal available for a 100-years supply of energy before its resources finally drained [4]. In light of the issue, key players worldwide have been researching and starting a massive shift towards alternative long-lasting energy sources for heat and power generation [5].

Ever since biomass waste becomes a hassle to countries that depends on agriculture as the main economical source, institutions begin to engineer a proper beneficial way to utilize these left-overs as a new source of energy. For agricultural waste such as the palm oil empty fruit bunch (EFB), gasification is appropriate to convert the carbonaceous materials into fuel gas with sufficient thermochemical properties [6]. Gasification enables production of product gases that mainly consist of CO and H_2 from carbon solid fuels in a very efficient way that is both low-cost and safer for the environment [7]. Being heterogeneous, burning biomass directly could increase ash content and cause fouling [8]. Concerning the syngas quality, co-gasification of biomass and coal could improve product quality, ensure higher

efficiency conversion, optimize logistics, and also economically feasible [9]. Using coal to supplement EFB gasification enhances the reactivity of the biowaste material and produce cleaner syngas [10]. Coal-biomass blending is also attractive because the extra hydrogen in the biomass increase H_2 production, while the additional oxygen content lowers activation energy that improves the rate of reaction [11]. Coal deficiency could be delayed, and the seasonal shortage of biomass supply could also be prevented [12]. Most importantly, co-gasification makes utilization of EFB possible, and solves the issue of excessive landfills in agricultural countries, as well as adjourning fossil fuel depletion [13]. Generally, there are three types of gasification reactors that are commercially available including fixed bed gasifiers, fluidized bed gasifier and entrain flow gasifier (EFG) [14-15]. The pros and cons of each type of gasifiers are illustrated in detail in figure 1. Meanwhile, co-gasification is effectively performed using a gasifier which enables conversion of coal and biomass into syngas to be carried out at high temperature [16]. The EFG is often considered favorable for co-gasification of coal and biomass at 1500°C [17]. The EFG enables high heating rate, as well as extreme operating conditions [18]. In terms of large-scale operations, EFG could ensure generation of high quality syngas and efficiency [19]. Interaction between coal and the biomass is a concern, either it may or may not create synergism which will benefit the process or, otherwise [20]. Therefore, the compatibility of blended fuels with respect to their gasification performance must be properly evaluated.

Properties	Fixed Bed Gasifier	Fluidized Bed Gasifier	Entrained Flow Gasifier
Fuel flexibility	No	Yes	Yes
Uniform temperature	No	Yes	Yes
Solid-gas contact	Good	Good	Good
Tar content	High	Low	Low
Resident time	Hours	Minutes	Seconds
Ability to scale-up	Limited	Yes	Yes

Figure 1. Pros and cons of different types of gasification technology (adopted from [14, 21]).

Process simulation and modelling is the most sensible way of testing and validating the compatibility of fuels and to study the thermodynamics of reactions without exhausting time and cost for trial and error in the real system [22]. The accuracy and precision of simulation is very reliable, of which engineers use to predict the direction of a process while maintaining the current operation in the plant and avoid unscheduled disturbances [23-24]. The key element of simulation is the mathematical model that is the representation of the actual process and is used to analyze effects of various operating parameters on process behavior based on the conservation laws of mass, energy and momentum [22, 25]. The complexity of models can range from complex three-dimensional models that take fluid dynamics (CFD

models) and chemical reactions into consideration to simpler models where mass and energy balances are considered over the entire gasifier to predict the syngas composition [9].

Simulation of co-gasification that comprises multiple reactions in an entrained flow gasifier usually uses Gibbs free energy minimization method [26-27]. This approach is independent of reactor dimension and suitable to study the influence of operating parameters on syngas composition as it reflects the equilibrium model which is suitable for EFG reactors. Although, the model may deviate from the actual data at lower process temperatures, where CO and H_2 are typically overestimated while CO_2, CH_4, char and tar are underestimated [28]. Previously, Kong and her co-workers utilized Aspen Plus to develop a three-stage equilibrium model for coal gasification in the Texaco entrained flow gasifier by taking into account the pyrolysis and combustion reaction, solid-gas reaction, and gas-gas reaction [26]. Meanwhile, Adeyemi and Janajreh [23] approves the competency of Aspen Plus for simulation of coal and biomass co-gasification, including drying, de-volatilization, volatiles combustion and char gasification in the mathematical model [23]. The model considered the fluid dynamic of an entrained flow reactor which uses the kinetic approach in simulating the processes where different experimental data is required. Aspen HYSYS was used by Bassyouni et al. [24] to simulate biomass gasification with the equilibrium approach [24]. The limitation of it model is that the drying process was neglected by considering the biomass as dry-ash-free (daf)'s fuel, thereby only applicable for a downdraft gasification only. Considering all of the three approaches taken by these authors, it is necessary to developed an equilibrium model which simulates co-gasification of coal and biomass in an entrained flow gasifier that includes all process reaction stages and the hydrodynamic of the reactor.

In this work, Aspen HYSYS was used to model and simulate co-gasification of Illinois #6 coal and EFB in an entrained flow gasifier. The co-gasification process was modeled with a set of five reactors to simulate various reaction zones (including de-volatilization, combustion and gasification) of the entrained flow gasifier in accordance with its hydrodynamics. The effects of fuel blending (B/F), operating temperature (T_{op}) and steam-to-fuel ratio (S/F) on syngas composition was studied. The process performance was analyzed using the carbon gasification efficiency (CE), cold gas efficiency (CGE), syngas product efficiency (PE) and the heating value of syngas product (HHV) values.

2. Methodology

2.1. Model assumptions
A multi-zonal steady state model has been developed to simulate co-gasification of coal and biomass using Aspen HYSYS. The unit operations were arranged in accordance with hydrodynamics of entrained flow gasifier. The assumptions made in the present model are summarized in the following [23, 24, 29]:
1) Steady state isothermal process.
2) Feedstock is assumed to contain only carbon, hydrogen and oxygen.
3) Dry-ash-free feedstock are used, so the drying process is assumed to be instantaneous.
4) Uniformly sized particle with sphericity equal to one and did not affect the reaction.
5) Model eliminates NH_3 and H_2S formation and ignores tar formation to simplify the process.

The following figure 2 shows the schematic diagram of Texaco entrained flow coal-gasifier adopted from literature [30].
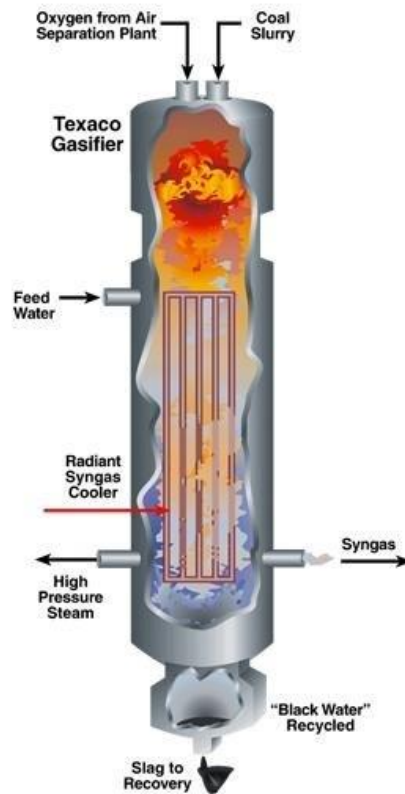
Figure 2. Schematic of Texaco entrained flow coal-gasifier
(adopted from [30]).

2.2. Simulation basis manager

Simulation basis manager (SBM) is an interface provided in Aspen HYSYS to assists users in defining and choosing pure components, appointing a property package to execute flash and physical properties calculations, and specifying reactions which can be fixed into any unit operations during simulation process [24]. Aspen HYSYS does not have Illinois #6 coal and EFB as library component, thus they were modelled as hypothetical components using the feedstock's analysis in table 1. Peng-Robinson equation of state (EOS) was preferred as property package to estimate the physical properties of components, and has been reported to well estimate the physical properties in an IGCC power plant simulation [24, 29, 31, 32].

2.3. Model descriptions

The co-gasification of coal and biomass in an entrained flow gasifier was simulated in three zones that include devolatilization process, combustion process (char and volatiles), and gasification process (char). The feedstock used were Illinois #6 coal and EFB, and their proximate and ultimate analysis are shown in table 1. The gasifying agents were oxygen and steam. The operational condition of reactor is as follows: 0.5 of biomass ratio; 0.3 of equivalent ratio; 0.75 steam/fuel ratio; 950°C; and 24 atm. The simulation was carried out using Aspen HYSYS, and the process flow diagram of the simulation, as well as a detailed description of main unit operation models is shown in figure 3.

Table 1. Ultimate and proximate analysis of empty fruit bunch and American coal, Illinois #6.

Feedstock Analysis	Empty Fruit Bunch	Illinois #6 Coal
Proximate Analysis (wt.%)		
Moisture (wet basis)	55.600	-
Moisture (dry basis)	5.180	-
Volatile matter	82.580	24.460
Fixed carbon	8.970	60.010
Ash	3.450	15.500
Ultimate Analysis (wt.% dry basis)		
C	46.620	74.100
H	6.450	6.210
N	1.210	1.100
O	45.660	1.320
S	0.035	1.770
Molecular Formula	$CH_{1.649}N_{0.022}O_{0.735}S_{0.000}$	$CH_{0.999}N_{0.013}O_{0.013}S_{0.009}$

The model was based on the following global steam-oxygen co-gasification reaction [33]:

$$C_xH_yO_z + aH_2O + bO_2 \rightarrow \alpha_1H_2 + \alpha_2CO + \alpha_3H_2O + \alpha_4CO_2 + \alpha_5CH_4 \tag{1}$$
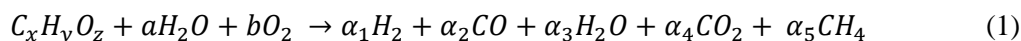
where x, y and z are the molar fraction of carbon, hydrogen and oxygen in the dry-ash-free (daf)'s fuel, which were determined from the ultimate analysis data (table 1), a and b are the molar flow rate of steam and oxygen fed to the reactor per mole of processed dry fuel. On the right-hand side of equation 1, α_i coefficients are the unknown moles of gaseous species leaving the gasifier (i.e., i = H_2, CO, CO_2, CH_4 and H_2O) for mole of processed coal/biomass.
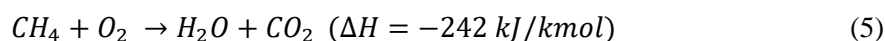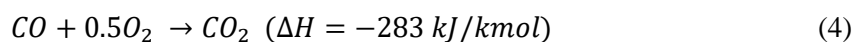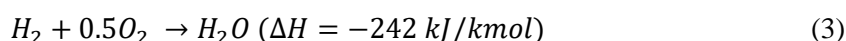
2.3.1. Devolatilization. As moisture has been removed from the fuel mass, subsequent heating may create volatiles from a process known as devolatilization [23, 34]. Devolatilization is a rather rapid process [35] when initiated at 400°C to 600°C in a reactor without the presence of oxygen or air [18]. In general, the dried fuel is converted into a denser solid known as char, along with CO, CO_2, H_2, H_2O and CH_4 [36]. Thus, for entrained flow gasifier that usually uses temperatures higher than 1000°C, devolatilization is expected to be spontaneous [18, 23] and was modelled with Conversion reactor in Aspen HYSYS. The devolatilization process of Illinois #6 and EFB is represented by the following equation [18].
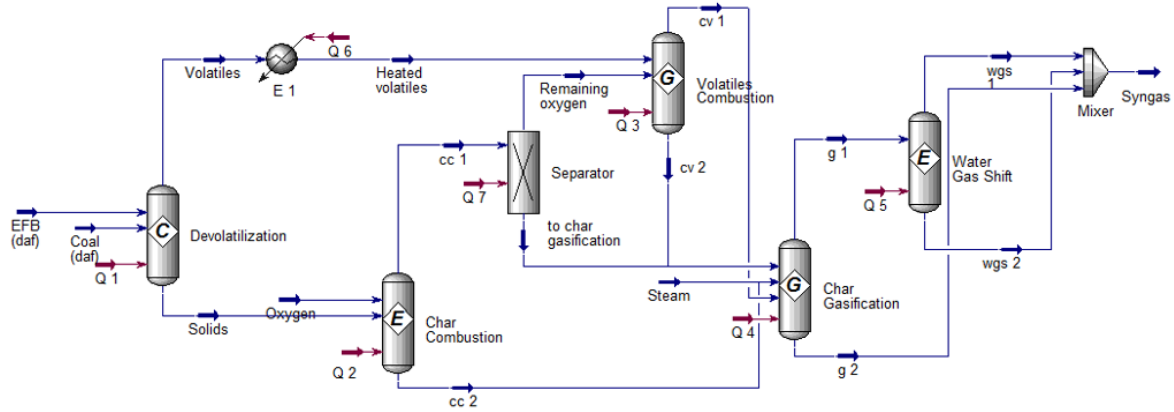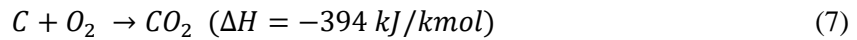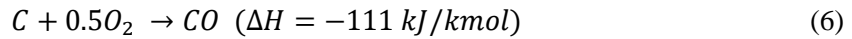
$$C_xH_yO_z \rightarrow \alpha_1 Char + \alpha_2CH_4 + \alpha_3H_2 + \alpha_4CO + \alpha_5CO_2 \tag{2}$$
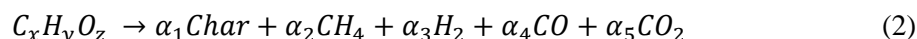
where x, y and z are the molar fraction of carbon, hydrogen and oxygen, while α_n is the number of moles of the species involved in the reaction.

2.3.2. Combustion reactions. The char and volatiles then reacts with oxygen that forms H_2O, CO_2, and CO as the product [23]. However, only CO, H_2 and CH_4 are involved in the volatiles combustion [23], [26]. The char and volatiles undergo a separate combustion reaction, but oxygen is fully utilized to generate sufficient heat from the exothermic reaction in each of the combustion chambers [26]. These char and volatiles combustion reactions were modeled in Aspen HYSYS using Equilibrium and Gibbs reactors, labeled as Char Combustion and Volatiles Combustion, respectively.

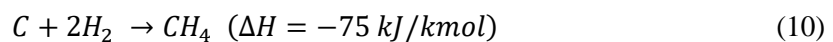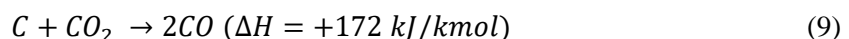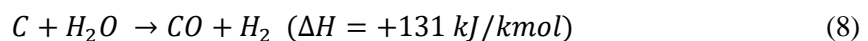　　Volatiles combustion reactions:

$$H_2 + 0.5O_2 \rightarrow H_2O \ (\Delta H = -242 \ kJ/kmol) \tag{3}$$

$$CO + 0.5O_2 \rightarrow CO_2 \ (\Delta H = -283 \ kJ/kmol) \tag{4}$$

$$CH_4 + O_2 \rightarrow H_2O + CO_2 \ (\Delta H = -242 \ kJ/kmol) \tag{5}$$

Char combustion reactions:

$$C + 0.5O_2 \rightarrow CO \ (\Delta H = -111 \ kJ/kmol) \tag{6}$$

$$C + O_2 \rightarrow CO_2 \ (\Delta H = -394 \ kJ/kmol) \tag{7}$$

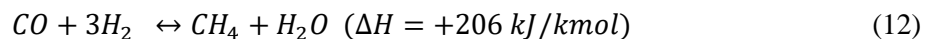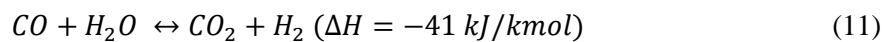| No.	Reaction Zones	HYSYS Reactor/Block ID	Model Description
1	Devolatilization	Conversion/Devolatilization Process	Models the thermochemical conversion of solid fuels into volatiles and char.
2	Combustion	Gibbs/Volatiles Combustion	Models the combustion of volatiles using Gibbs free energy minimization approach.
		Equilibrium/Char Combustion	Models the combustion reaction of char using equilibrium data.
3	Gasification	Gibbs/Char Gasification	Models the main gasification reactions using Gibb free energy minimization approach.
		Equilibrium/Water Gas Shift Reactor	Models water-gas shift and steam-methane reactions using equilibrium data.

Figure 3. Aspen HYSYS flowsheet used for modelling and simulation of co-gasification of coal and biomass in an entrained flow gasifier and its details description of main unit operation models.

2.3.3. Gasification reactions. Carbon (in the form of graphite) from coal/EFB involves in multiple solid-gas reactions that include the carbon-steam, Boudouard, and carbon hydrogenation reactions [26]. Despite the complexity of mixed reactions occurring simultaneously during gasification, the system may reach the state of equilibrium [26, 37]. The char gasification is mainly consisting of reactions with H_2O, CO_2, and H_2 to produce syngas that consists mainly of CO and H_2 [38].
Char gasification reactions:

$$C + H_2O \rightarrow CO + H_2 \ (\Delta H = +131 \ kJ/kmol) \tag{8}$$

$$C + CO_2 \rightarrow 2CO \ (\Delta H = +172 \ kJ/kmol) \tag{9}$$

$$C + 2H_2 \rightarrow CH_4 \ (\Delta H = -75 \ kJ/kmol) \tag{10}$$

Water-gas shift and steam-methane reforming:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \ (\Delta H = -41 \ kJ/kmol) \tag{11}$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \ (\Delta H = +206 \ kJ/kmol) \tag{12}$$

This stage of the co-gasification process was modeled in Aspen HYSYS using coupled Gibbs and Equilibrium reactors. A Gibbs reactor simulates multi-phase reactions including Boudouard, water-gas and methanation reactions using Gibbs free energy minimization method in equilibrium. Meanwhile, Equilibrium reactor simulates water-gas shift and steam-methane reforming reactions, which completes the gasification process.

2.4. Sensitivity analysis and performance measurement
The optimal value of biomass ratio (BR), operating temperature (T_{op}) and steam-to-fuel ratio (S/F) were determined from the sensitivity analysis of results. The biomass ratio defines the ratio of EFB feed rate to the total feed rate (coal + EFB) on carbon basis [39]–[41].

$$BR = \frac{EFB\ feed\ rate\ (mol_{carbon}/hr)}{Total\ feed\ rate\ (mol_{carbon}/hr)} \tag{13}$$

Steam-to-fuel ratio, denoted by S/F, defines the ratio of the mass flow rate of steam to the total feed rate.

$$S/F = \frac{The\ mass\ flow\ rate\ of\ steam\ (kg/hr)}{The\ mass\ flow\ rate\ of\ fuel\ (kg/hr)} \tag{14}$$

Next, performance indicators that include CGE, CE, PE and HHV values of syngas produced by 1 kg feedstock were assessed to evaluate the process characteristic. The CE refers to the percentage of the moles of carbon in syngas to the moles of carbon in solid fuel [40].

$$CE\ (\%) = \frac{moles\ of\ carbon\ in\ syngas}{moles\ of\ carbon\ in\ fuel}\ X\ 100 \tag{15}$$

The CGE refers to the percentage of the HHV value of syngas to the HHV value of feedstock [42-44].

$$CGE\ (\%) = \frac{HHV_{syngas}}{HHV_{feedstock}}\ X\ 100 \tag{16}$$

The HHV of syngas (MJ/Mm^3) and HHV of feedstock (MJ/kg) could be calculated by using the following correlation proposed by [45, 46].

$$HHV\ of\ syngas\ (MJ/Mm^3) = 12.75H_2 + 12.63CO - 39.82CH_4\ /100 \tag{17}$$

$$HHV\ of\ feedstock\ (MJ/kg) = 0.3419x_C + 1.1783x_H - 0.1034x_O \tag{18}$$

The PE is the percentage of the moles of CO and H_2 in the syngas to the moles of C and H_2 in the feedstock [47].

$$PE\ (\%) = \frac{n_{CO} + n_{H_2}}{n_{i,C} + n_{i,H_2}}\ X\ 100 \tag{19}$$

where n_{CO} and n_{H_2} are the moles of CO and H_2 in the syngas, respectively. While $n_{i,C}$ and n_{i,H_2} are the mole of C and H_2 in the feedstock.

The percentage of combustible gas in the syngas (n) is defined as the percentage of the moles of CO, H_2 and CH_4 in the syngas to the mole of syngas [47].

$$n\ (\%) = \frac{n_{CO} + n_{H_2} + n_{CH_4}}{n_{total}}\ X\ 100 \tag{20}$$

where n_{CO}, n_{H_2} and n_{CH_4} are the moles of CO, H_2 and CH_4 in the syngas, respectively. The n_{total} is the mole of syngas.

3. Results and discussion

3.1. Model validation

To evaluate the co-gasification performance, the model was initially tested for coal gasification using Illinois #6 as presented in table 1. Then, the simulation result was validated with practical data from operating a Texaco entrained flow gasifier obtained in the literature, as shown in table 2. Of the total of 9 recorded experimental runs with varying conditions, the simulation results was compared with one experimental set up of 1227°C and 24 atm, with 316.44 kg/hr coal feed; 0.787 O_2/coal ratio; and 0.268 steam/coal ratio [18, 26]. The predicted results were found to satisfactorily compliment the actual data with minor errors. Referring to the percentage of H_2 and CO (which are crucial components that contribute to the calorific value of fuel), when combined, the predicted value is a total of 97.36% against 98.88% of the experiment with a minimum error of 1.74%. The predicted calorific value of 12.34 MJ/m^3 compares reasonably well with the experimental value of 12.54 MJ/m^3 with 1.59% of error.

Table 2. The comparison of syngas composition between simulation results and experimental data of Texaco entrained flow coal gasification.

Syngas composition	Experimental data	Simulation result
Hydrogen (mol.%)	39.76	34.66
Carbon monoxide (mol.%)	59.12	62.70
Carbon dioxide (mol.%)	1.12	2.64
Calorific value (MJ/m^3)	12.54	12.34

*3.2. Effect of biomass blend on syngas composition*

It is important to understand to what extent the composition of syngas is affected by the amount of EFB used in the biomass/coal blend. Not only that, the results would clarify the intensity of synergy between EFB and Illinois #6 as fuels for co-gasification. The simulation was set to 100 kmol/hr of feedstock at equivalent ratio (ER) of 0.3, S/F of 0.75, operating temperature (T_{op}) of 950°C and operating pressure (P_{op}) of 24 atm. The major chemical reactions occurring in the gasifier are as shown in equations 1 - 11. The results, as illustrated in figure 4 shows that syngas composition was affected in a non-linear manner (especially for H_2) with BR increase. This gives the impression that the properties of EFB compliments that of Illinois #6 which produces a positive synergism as a blend of fuel [41]. Increasing the proportion of EFB in the fuel blend provides higher carbon availability to react with gasifying agents that alleviates product gas yield [41, 48]. However, the production of H_2 started to deplete as BR exceeds 0.5. It appears that beyond 0.5 BR, Boudouard and water-shift reactions are favored, thereby, explains the CO and CH_4 increase and the reduction of H_2/CO ratio in the gas yield. The increase in H_2O could be attributed to higher internal water bond in the EFB [49]. Usually, this can only be achieved from a high temperature reaction at more than 1000°C. However, the simulation analysis suggests that these circumstances are achievable at lower temperature by utilizing co-gasification of coal and EFB. High H_2O in the product gas would not be a matter of concern because water is easily separated and the quality of syngas would not be affected [24]. Other than that, increasing BR did not affect the composition of CO_2 as well as the calorific value of dried syngas. Generally, these results agree with the findings from several literatures that the optimal composition of biomass is 50% of the overall fuel [39, 41].
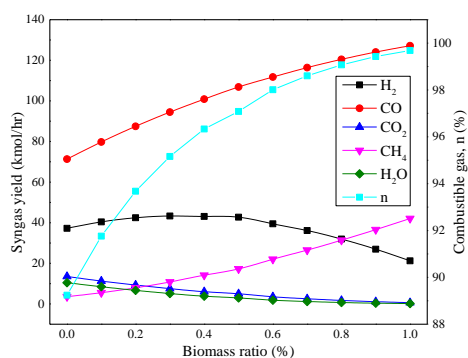
Figure 4. Effect of different biomass ratio on the total product gas yield in co-gasification process.
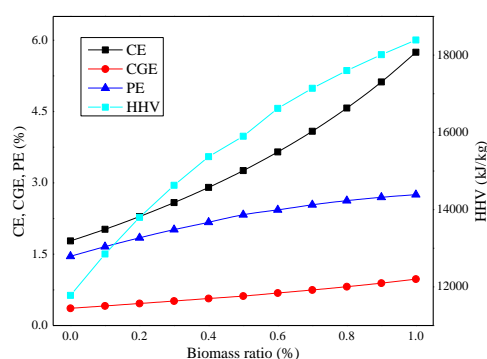
Figure 5. The performance evaluation indexes of the co-gasification of Illinois #6 coal and EFB at different biomass ratio (B/F).
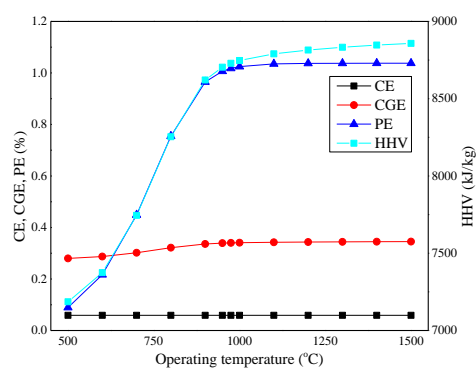
In terms of the performance of the co-gasification of coal and EFB, figure 5 shows remarkable increase of CE, CGE, PE and HHV with the increase of BR (CE: 160% to 580%; CGE: 23.5% to 68.9%; PE: 150% to 170%; and HHV: 12000 kJ/kg to 18250 kJ/kg). Based on figures 2 and 3, it can be concluded that the addition of EFB into coal gasification will improve the performance of gasification. However, considering the BR effect on syngas composition, the optimum value of BR is 0.5. Thus, this finding proves that co-gasification process of coal and biomass is more efficient than gasification of coal alone

3.3. Effect of operating temperature

Gasification of solid fuel to produce syngas involves a few reactions that occur on the same time which makes it rather complicated. Despite the challenge, manipulation of operating temperature could promote a certain type of reaction and decreases the intensity of others. Using the same operating condition (ER, 0.3; S/F, 1.5; P, 24 atm), the temperature was varied from 500°C to 1500°C to study the effect of heat on co-gasification performance and characteristics. figure 6 exhibits the pattern of yield gas that was generated in response to temperature rise. Initially, a notable increase of H_2 denotes that a high temperature is advantageous for high H_2 yield [47]. It is also expected that H_2 increase was also contributed by the primary water gas reaction (PWG) and the methane reforming [47]. Looking at the pattern for CO_2, the gas was high at the lowest temperature setting because PWG and water-gas reaction (WGS) reactions were favored [47]. The amount of CO_2 continued to drop as the temperature was increased, by which BD, reverse WGS and MRF reactions dominated the extreme temperature where CO_2 and H_2 were consumed to produce CO [47, 50]. On the same time, it seems that MRF and the reverse methane formation (rMF) coincided which decreased the production of CH_4 [47]. Thus, it is clear that the percentage of combustible gas in the syngas has a positive effect with increased temperature, and it was above 80% when the temperature was higher than 950°C.
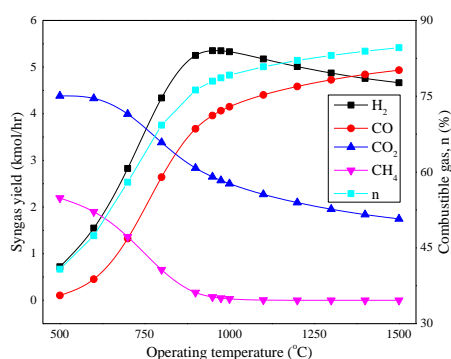
Figure 6. Effect of different operating temperature on syngas composition in co-gasification process.
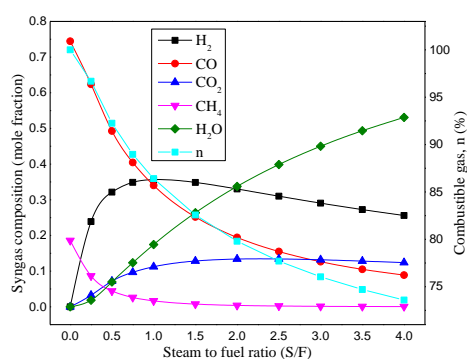

Figure 7. The performance evaluation indexes of the co-gasification at different operating temperature.

Figure 7 exhibits the results of the performance indexes in response to temperature increase. First, CE was found to be constant, which suggest that carbon conversion from coal/EFB was independent of temperature change. CGE increased slightly before it went into constant value of 36% as the temperature reached 950°C. PE increased significantly, also until 950°C when it started to remain constant at 110% as the temperature was raised higher. It is believed that the reason CGE and PE were not affected by temperature beyond 950°C was because of high availability of H_2 and CO [47]. HHV increased in a similar manner as PE where it reached the highest value of 8700 kJ/kg at 950°C. Instead of becoming constant like PE, HHV increased as much as 200 kJ/kg from 950°C to 1500°C which might be related to the value of combustible gas, n in figure 4. It is thus, demonstrated that the most optimum temperature for co-gasification of coal and EFB is 950°C.

3.4. Effect of changing steam/fuel ratio (S/F) on syngas composition

The relevance of S/F is that it could influence the direction of reactions in co-gasification by means of using steam to increase the amount of H_2 and CO [47]. As steam was readily available as the output from tar cracking, utilizing the steam would favor PWG, MRF and WGS reactions. Thus, it is important to study the effect of steam-to-fuel ratio (S/F) on syngas composition. The simulation was set to ER of 0.3, 24 atm, and 950°C, and S/F was varied from 0.0 to 4.0. Supposedly, setting the temperature to 950°C yields more H_2 and CO, but the simulation results in figure 8 exhibit a clear increase of H_2 and

CO_2 instead. It is obvious that H_2 spiked quite rapidly from S/F=0.0 to S/F=0.5 which denotes the significance of steam injection. Seems that the reaction shifts to the right where PWG and WGS took place and generated more H_2 and CO. However, much of the CO were also utilized in WGS which proliferates the amount of H_2 and CO_2. figure 6 also shows that H_2 depletes after S/F=0.5 and this is consistent with the literature [24, 47]. On the other hand, CH_4 exhibits a decreasing trend, almost reach zero when S/F exceeds 0.5. As discussed previously on the subject of figure 6, operating the procedure at 950°C will inhibited the production of CH_4 [47, 51, 52]. Meanwhile, the percentage of combustible gas, n slightly decreased with the increasing of S/F. This is due to the drastic drop in CO component when S/F was increased.

Figure 8. Effect of different steam to fuel ratio (S/F) on syngas composition in co-gasification process.
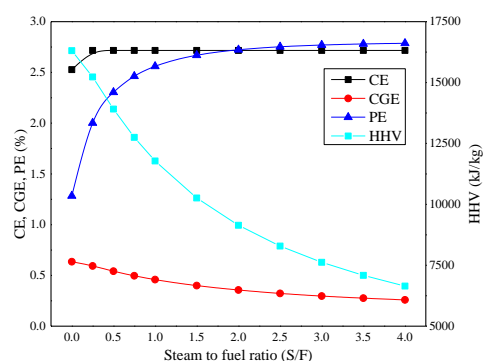
Figure 9. The performance evaluation indexes of the co-gasification process at different steam-to-fuel ratio..

Variation of steam injected into the fuel appears to affect CE and PE in a positive way, but CGE and HHV were affected negatively, as shown in figure 9. The positive trend of CE shows that steam improves carbon conversion, but the increment is minimal. Meanwhile, PE increased steadily until S/F=2.0, then remained constant afterwards. This can be associated to the content of CO and H_2 in the syngas, which means, it depends on the degree of which steam affects carbon conversion of coal/EFB fuel. In accordance to the findings in figure 8, steam injection have increased the interaction of CO and H_2 that caused CO to decrease and H_2 to remain constant when carbon was fully converted, thereby explaining the trend of CE and PE in figure 9 [47]. On the other hand, higher ratio of steam has caused a very apparent reduction of CGE value, which was recorded to decrease from 63.54% to 25.89%. Likewise, HHV also decreased significantly from 17000 kJ/kg to 7000 kJ/kg. The reason may have been caused by the vaporization of extra steam that required additional energy. Generally, these results corroborate the findings of other related studies [23, 24] exhibits the results of the performance indexes in response to temperature increase. First, CE was found to be constant, which suggest that carbon conversion from coal/EFB was independent of temperature change. CGE increased slightly before it went into constant value of 36% as the temperature reached 950 °C. PE increased significantly, also until 950 °C when it started to remain constant at 110% as the temperature was raised higher. It is believed that the reason CGE and PE were not affected by temperature beyond 950 °C was because of high availability of H_2 and CO [47]. HHV increased in a similar manner as PE where it reached the highest value of 8700 kJ/kg at 950 °C. Instead of becoming constant like PE, HHV increased as much as 200 kJ/kg from 950 °C to 1500 °C which might be related to the value of combustible gas, n in figure 6. It is thus, demonstrated that the most optimum temperature for co-gasification of coal and EFB is 950 °C.

Based on the results shown in figures 8 and 9, the highest value of CO and H_2 composition in syngas yield was found at S/F=0.75 which also corresponds to reasonable value of CE, PV, CGE, and HHV. Thus, the optimal S/F value for co-gasification of coal and EFB is 0.75. It is interesting to find that Seo

and his co-worker also recorded S/F=0.7 for co-gasification of coal/biomass blend [41]. The value differs slightly due to different operating condition and reactor set up.

4. Conclusions

This study was intended to simulate the synergy of Illinois #6 coal and EFB in co-gasification by manipulating the biomass ratio (BR), operating temperature (T_{op}), and steam-to-fuel ratio (S/F) and evaluate the composition of syngas produced from the reactions. Taken together all strands of findings from this study, it was proven that coal and EFB would be beneficial for mass production of combustible gas. The maximum H_2 yield was achieved with BR of 50%. From the aspect of CE, PE and CGE, the optimal temperature to simulate co-gasification was 950°C. The best ratio of steam to fuel (S/F) is supposedly S/F=0.75.

References

[1]   Song Y and Wang N 2019 *J. Energy* **168** 1073
[2]   Gil M V and Rubiera F 2019 *New Trends in Coal Conversion: Combustion, Gasification, Emissions, and Coking* 117
[3]   Singh G K, Rajeev P, Paul D and Gupta T 2018 *Springer* 53
[4]   BP 2018 *British Petroluem Statistical Review of World Energy -Electricity generation* Report in June 30 **67**
[5]   Islas J, Manzini F, Masera O and Vargas V 2018 *Solid Biomass to Heat and Power*
[6]   Vega, F., Alonso-Farinas, B., Baena-Moreno, F.M., Rodríguez, J.A. and Navarrete, B 2019 *New Trend in Coal Conversion: Combustion, Gasification, Emissions and Coking* 141
[7]   Beheshti S M, Ghassemi H and Shasavan M R 2015 *Energy Convers. Manag.* **94** 345
[8]   de Jong W, Nola G D, Venneker B C H, Spliethoff H and Wójtowicz M A 2007 *Fuel* **86 (15)** 2367
[9]   Mikulandrić R, Loncar D, Bohning D and Bohme R 2013 *Biomass gasification process modelling approaches* Proc. of the 13th European Int. Conf. on Polygeneration Strategies Vienna, Austria 1-13
[10]   Haykiri-Acma H and Yaman S 2007 *Fuel* **86 (3)** 373
[11]   Haykiri-Acma H and Yaman S 2008 *Waste Manag.* **28 (11)** 2077
[12]   Yang Z, Wu Y, Zhang Z, Li H, Li X, Egorov R I, Strizhak P A and Gao X 2019 *Renew. Sust. Energ. Rev.* **103** 384
[13]   Goldfarb J L and Liu C 2013 *Bioresour. Technol.* **149** 208
[14]   Farzad S, Mandegari M A and Görgens J F 2016 *Biofuel Res. J. 3***(4)**, 483-495
[15]   Ramos A, Monteiro E, Silva V and Rouboa A 2018 *Renew. Sustain. Energy Rev.* **81** 380
[16]   Biagini E, Bardi A, Pannocchia G and Tognotti L 2009 *Ind. Eng. Chem. Res.* **48 (19)** 9028-9033
[17]   Valero A and Usón S 2006 *Energy*, **31(10-11)**, 1643-1655
[18]   Ali D A, Gadalla M A, Abdelaziz O Y, Hulteberg C P and Ashour F H 2017 *J. Nat. Gas Sci. Eng.* **37** 126
[19]   Vascellari M, Roberts D G, Shwe S, Harris D J and Hasse C 2015 *Fuel* **152** 58-73
[20]   Moon C, Sung Y, Ahn S, Kim T, Choi G and Kim D 2013 *Exp. Therm. Fluid Sci.* **47** 232
[21]   Molino A, Chianese S and Musmarra D 2016 *J. Energy Chem.* 25 (1) 10
[22]   Gòmez-Barea A and Leckner B 2010 *Prog. Energ. Combust. Science* **36(4)**, 444-509
[23]   Adeyemi I and Janajreh I 2014 *Renew. Energy* **82** 77-84.
[24]   Bassyouni M, Hasan S W U, Abdel-Aziz M H, Abdel-hamid S M S, Naveed S, Hussain A and Ani F N 2014 *Energy Convers. Manag.* **88** 693
[25]   Mikulandrić R, Lončar D, Böhning D, Böhme R and Beckmann M 2014 *Energ. convers. manage.* **87** 1210-1223

[26]   Kong X, Zhong W, Du W and Qian F 2013 *Chinese J. Chem. Eng.* **21 (1)** 79

[27]   Kruger M 2014 *Int. J. Thermodyn.* 17(2), 87-95

[28]   Puig-Arnavat M, Bruno J C and Coronas A 2010 *Renew. Sustain. Energy Rev.* **14 (9)** 2841

[29]   Acevedo J C, Posso F R, Durán J M and Arenas E 2018 *J. Phys. Conf. Ser.* **1126 (1)**

[30]   Li S 2010 *Char-SLag Transition During Pulverized Coal Gasification* Thesis University of Utah

[31]   Mansaray K G and Ghaly A E 2002 *Energ. Sources* **21 (5)** 453

[32]   Pérez-Fortes M, Bojaeski B and Nadal F S 2008 *Comput. Aided Chem. Eng.* **25** 793

[33]   Brachi P, Chirone R, Miccio F, Miccio M and Ruoppolo G 2018 *Fuel* **220** 744

[34]   Basu P 2018 *Biomass gasification, pyrolysis and torrefaction: practical design and theory* Academic press United Kingdom **3** 479

[35]   Hla S S, Arris D J and Roberts D G 2008 *Gasification conversion model : PEFR* CCSD Pullenvale

[36]   Svensson H, Tunå P, Hulteberg C and Brandin J 2013 *Fuel* **106** 271

[37]   Nguyen T D B, Lim Y I, Song B H, Kim S M, Joo Y J and Ahn D H 2010 *Fuel* **89 (12)** 3901

[38]   Sharma M, Attanoor S and Dasappa S 2015 *Fuel Process. Technol.* **138** 435

[39]   Kumabe K, Hanaoka T, Fujimoto S, Minowa T and Sakanishi K 2007 *Fuel* **86** 684

[40]   Ma X, Zhao X, Gu J and Shi J 2019 *Renew. Sustain. Energy Rev.* **132** 509

[41]   Seo M W, Goo J H, Kim S D, Lee S H and Choi Y C 2010 *Energ. Fuel.* **24 (5)** 3108

[42]   Ravikiran A, Renganathan T, Pushpavanam S, Voolapalli R K and Cho Y S 2012 *Ind. Eng. Chem. Res.* **51 (4)** 1601

[43]   Shabbar S and Janajreh I 2013 *Energy Convers. Manag.* **65** 755

[44]   Wang Z, Zhou J, Wang Q, Fan J and Cen K 2006 *Int. J. Hydrogen Energy* **31 (7)** 945

[45]   Lide D R 2004 *CRC Handbook of Chemistry and Physics* CRC press **85**

[46]   Channiwala S A and Parikh P P 2002 *Fuel* **81** 1051

[47]   Duan W, Yu Q, Wang K, Qin Q, Hou L, Yao X and Wu T 2015 *Energy Convers. Manag.* 100 30

[48]   Quan C and Gao N 2016 *Biomed Res. Int.* **2016** 1

[49]   Lee H V, Hamid S B A and Zain S K 2014 *Sci. World J.* **2014** 1-20

[50]   Renganathan T, Yadav M B, Pushpavanam S, Voolapalli R K and Cho Y S 2012 *Chem. Eng. Sci.* **83** 159

[51]   Wang X, Wang N, Zhao J and Wang L 2010 *Int. J. Hydrogen Energy* **35 (23)** 12800

[52]   Tursun Y, Liu J, Xu S, Wei L and Zou W 2013 *Fuel* **112** 641