Original Research Article

Performance Comparison on Biomass Gasification Reactor using Cocoa Pod Husk Waste for Hydrogen Production

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Abstract: Biomass is gaining recognition as a valuable renewable energy source due to its plentiful supply and relatively cheaper cost than other energy sources. One significant advantage of biomass is its ability to produce minimal carbon dioxide emissions during gasification. Gasification, which typically employs either downdraft fixed bed or bubbling fluidised bed gasifiers, is favoured for producing hydrogen gas, an essential element for energy production. This process can be represented using the Aspen Plus simulator, which is used for process simulation studies. Nevertheless, simulation research's predominant focus has been exclusively on coal gasification, with comparatively less attention given to biomass gasification. This study uses Aspen Plus software to examine the gasification processes of downdraft fixed-bed and bubbling fluidised bed reactors. Utilising cocoa pod husk as feedstock, both processes were analysed under the same operating conditions. The fluidised bed gasification process produced more hydrogen gas (7.62%) than the fixed-bed reactor (5.84%). A sensitivity analysis evaluated the influence of gasifier temperature and air-to-biomass ratio. It was found that the fixed-bed reactor produced more hydrogen (6.33%) at 760 °C, while the fluidised bed reactor yielded more hydrogen (8.43%) at 740 °C with an air-to-biomass ratio of 0.01. The study further discovered that a steam-to-biomass ratio of 0.15 in the fluidised bed reactor demonstrated the highest hydrogen yield, suggesting this as the optimal operating condition. The study offers vital knowledge on how to optimise biomass gasification operations to enhance the production of hydrogen.

Keywords: Biomass Waste; Cocoa Pod Husk; Gasification; Fluidized Bed; Fixed Bed; AspenPlus

1. Introduction

Biomass gasification is a process that involves the partial burning of biomass, resulting in the production of synthesis gas. This gas consists of a combination of carbon monoxide (CO), carbon dioxide (CO2), hydrogen (H2), and a small quantity of methane (CH4). The synthesis gas, also called syngas, can be utilised as either a gaseous fuel or a raw material for fuel cells, simultaneously producing heat and electricity. There are two primary types of gasifiers used in this process: fixed bed and fluidised bed. According to Kiang (2018), fixed-bed gasification can be categorised into downdraft (co-current) gasifiers and updraft (counter-current) gasifiers. Both gasifiers are classified according to the flow direction of the gasifying agent. In a downdraft fixed bed gasifier, the gasifying agent and the biomass feedstock flow downwards together.

In contrast, in an updraft fixed bed gasifier, the biomass goes downwards through the bed while the gasifying agent flows in the opposite, upward direction (Zhang, 2010). This gasifier has the benefit of producing syngas with minimal tar content, thus eliminating the need for extensive cleanup compared to updraft gasifiers. Comprehensive cleaning is necessary for updraft gasifiers to remove a significant amount of tar before their use in synthesis applications.

The gasification process utilises two main types of fluidised bed reactors: bubbling fluidised bed reactors and circulating fluidised bed reactors. The reactors generally operate within a temperature range of 700 °C. In bubbling fluidised gasifiers, the gasification agent is injected at the bottom of the reactor at a velocity that matches the lowest fluidisation velocity. This promotes extensive blending of the hot bed material. Circulating fluidised bed gasifiers function similarly to bubbling fluidised bed gasifiers. However, the key difference is that the speed of the gasification agent in circulating fluidised bed gasifiers usually exceeds the minimum fluidisation point (Rosendahl, 2013). Because of this elevated speed, particles become entrained in the resulting gas. A cyclone separates the particles at the reactor's outlet, and the material from the bed is recycled back into the reactor. (Basu, 2006). Nevertheless, circulating fluidised bed gasifiers have a lower heat exchange capacity than bubbling fluidised bed gasifiers, rendering them inappropriate for various biomass particle sizes. Producing syngas with an air-based bubbling fluidised bed gasifier is relatively straightforward.

The Aspen Plus process simulator has emerged as a prominent tool in simulation studies. Its application is particularly notable in representing the desired gasification processes. This widespread usage is due to the simulator's comprehensive and accurate modelling capabilities, which allow researchers to simulate and forecast process performance

without complex calculations (Muslim *et al.*, 2017). Nikoo and Mahinpey (2008) employed Aspen Plus software to model the gasification process of pine sawdust in a fluidised bed reactor. Simultaneously, Figueroa *et al.* (2013) investigated the steam gasification of sugarcane bagasse in a fixed-bed reactor. Mansaray *et al.* (2000) also used Aspen Plus to model rice husk gasification, basing their simulation on material and energy balances and chemical equilibrium relations. Despite these studies, previous research has predominantly focused on a single type of gasifier, neglecting to investigate and compare the performance of different gasifier types. Comparing the performance of varying gasifier types is crucial for advancing the field of biomass gasification, as it can provide valuable insights into the advantages, limitations, and tradeoffs of various gasification technologies, enabling researchers and engineers to make more informed decisions and drive further improvements (Inayat *et al.*, 2019). Henceforward, this study aims to compare the performance of bubbling fluidised bed gasifiers and downdraft fixed bed gasifiers, using cocoa pod husk as biomass input for hydrogen production. Cocoa pod husk is an underutilised biomass resource that, despite its abundance as a waste product in cocoa production, has been less studied and applied in gasification reactors, presenting a unique opportunity to explore its potential for sustainable energy generation and waste management.

Aspen Plus is used to generate process design flowsheets for both types of gasifiers. Their performances are then evaluated based on total syngas production. Additionally, a sensitivity analysis is performed to investigate the impact of operating variables, such as the steam to biomass ratio and gasifier temperature, on syngas production.
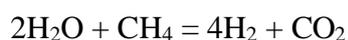
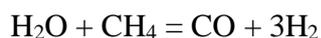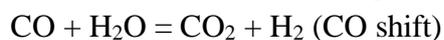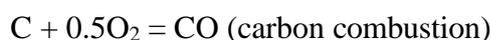## 2. Gasification Model Development

In this section, a detailed presentation of the modelling approach is provided. This includes (i) the different process assumptions used to simplify the physical problem, (ii) the main features of the model, and (iii) the process modelling is conducted using the Aspen Plus simulator. Aspen Plus is a comprehensive software that numerous professional researchers utilise to simulate models and forecast process performance without complex calculations.

2.1. Gasification Process Properties Assumptions

The gasification process model was built on several key assumptions. Firstly, it was assumed that the entire process operates under steady-state conditions, keeping a consistent level of operation. Secondly, factors such as pressure drops and potential heat loss from the reactor were considered negligible and thus ignored. Certain assumptions, such as neglecting pressure drops and heat losses, were likely made in the gasification process model to simplify

the simulation and reduce computational complexity, but these assumptions can impact the accuracy of the results by failing to account for real-world phenomena that can influence the gasification performance (Xue *et al.*, 2016); however, such simplifications are often necessary in modeling to balance accuracy and feasibility, and the significance of the impact depends on the specific application and the sensitivity of the process to those factors.

Additionally, it was assumed that the biomass undergoes instantaneous devolatilization, leading to the production of primary gases like Hydrogen (H2), Carbon Monoxide (CO), Carbon Dioxide (CO2), and Methane (CH4). It was also hypothesised that all gasification reactions reach equilibrium, ensuring a stable balance of reactants and products. The model considered the composition of the char, which was presumed to consist only of carbon and ash (Moretti *et al.*, 2022). Ash was viewed as an inactive component that does not participate in the reaction. As such, the small amounts of sulphur, chlorine, and nitrogen were deemed negligible and thus disregarded. All gasification reactions were based on these assumptions.

$C + O_2 = CO_2$ (carbon combustion)
$C + 0.5O_2 = CO$ (carbon combustion)
$C + CO_2 = 2CO$ (Boudouard reaction)
$C + H_2O = CO + H_2$ (water-gas)
$CO + H_2O = CO_2 + H_2$ (CO shift)
$C + 2H_2 = CH_4$ (methanation)
$H_2 + 0.5O_2 = H_2O$ (H2 combustion)
$H_2O + CH_4 = CO + 3H_2$
$2H_2O + CH_4 = 4H_2 + CO_2$

2.2. Physical Property Method

Both gasification processes use the Redlich-Kwong-Soave (RKS) cubic equation of state with the Boston-Mathias alpha function (RKS-BM). This method has been employed by Begum *et al.* (2008) for calculating the physical properties of conventional components and has demonstrated significant effectiveness across various applications. The RKS-BM approach is recommended for gas-processing, refinery, and petrochemical sectors, including gas plants, crude towers, and ethylene facilities. It is primarily utilised for nonpolar or mildly polar mixtures, such as hydrocarbons and light gases like CO_2, hydrogen sulfide, and H2. Using RKS-BM, reliable results can be anticipated across all temperature and pressure conditions, and the method remains consistent in critical regions. Overall, the RKS-BM property method is valuable in studying and understanding gasification processes.

2.3. Gasification Modelling

The gasification process is built in the Aspen Plus process simulator employing downdraft fixed bed and bubbling fluidised bed gasifiers. Both gasification models utilise identical working circumstances, with a feed flow rate of 10 kg/hr, an air flow rate of 10 kg/hr at a temperature of 700°C, and a pressure of 1 bar. The details of the flow process for each gasification model are explained in the subsection below. Meanwhile, cocoa pod husk is used as a feed for both gasification processes. In this research, the chosen models for feed and ash's enthalpy and density are unconventional components. The feed in this study is categorised as unconventional components, based on their distinct ultimate and proximate analysis as shown in Table 1.

Table-1. Characteristic of Cocoa Pod Husk

Moisture content (wt. %)	14.43
Proximate analysis (wt.% dry basis)	
Volatile Matter	58.75
Fixed Carbon	19.83
Ash	6.99
Ultimate analysis (wt.% dry basis)	
C	48.82
H	7.89
O	39.85
N	1.95
S	1.49

Source: Akinola *et al.* (2018)

2.3.1. Fixed bed gasification model

The gasification process in a fixed bed reactor involves four main stages: feed drying, feed decomposition, char gasification, combustion, and process separation. In the first stage, the feed dries, simulating the evaporation of the air mixture within. The decrease in moisture content is vital as the downdraft fixed bed necessitates biomass input with a moisture level below 20% to compensate for the gas stream's low thermal efficiency and high exit temperatures (900-1000°C). RGIBBS, RYIELD, and RSTOIC are three different reactor models which were used in this gasification model, where Gibbs Free Energy Minimisation (RGIBBS) calculates equilibrium compositions, Yield Reactor (RYIELD) specifies reaction yields, and Stoichiometric Reactor (RSTOIC) models reactions based on stoichiometric coefficients. Firstly, the RSTOIC reactor simulates feed decomposition. Using a FORTRAN

statement that specifies the reaction's extent, a portion of the inlet feed transforms into water. FORTRAN in AspenPlus is a high-level, compiled programming language for creating custom user-defined models, subroutines, and advanced calculations that extend the software's native capabilities for complex thermodynamic, chemical engineering, and process simulation tasks.

After drying, the feed is introduced into the RYIELD reactor, where it undergoes breakdown into its constituent atomic elements: carbon, hydrogen, oxygen, sulphur, nitrogen, and ash. A FORTRAN statement in a calculator block facilitates the conversion of the feed into specific yields for each syngas type. The RGIBBS reactor then performs the gasification and combustion processes. Since the biomass's Gibbs free energy can't be calculated directly due to its non-conventional nature, the biomass must first be decomposed into its elements (C, H, O, N, and S) using the RYIELD reactor. These decomposed elements and air are then sent to the RGIBBS reactor for combustion and gasification reactions. Finally, the resulting syngas is collected at the end of the process stream.
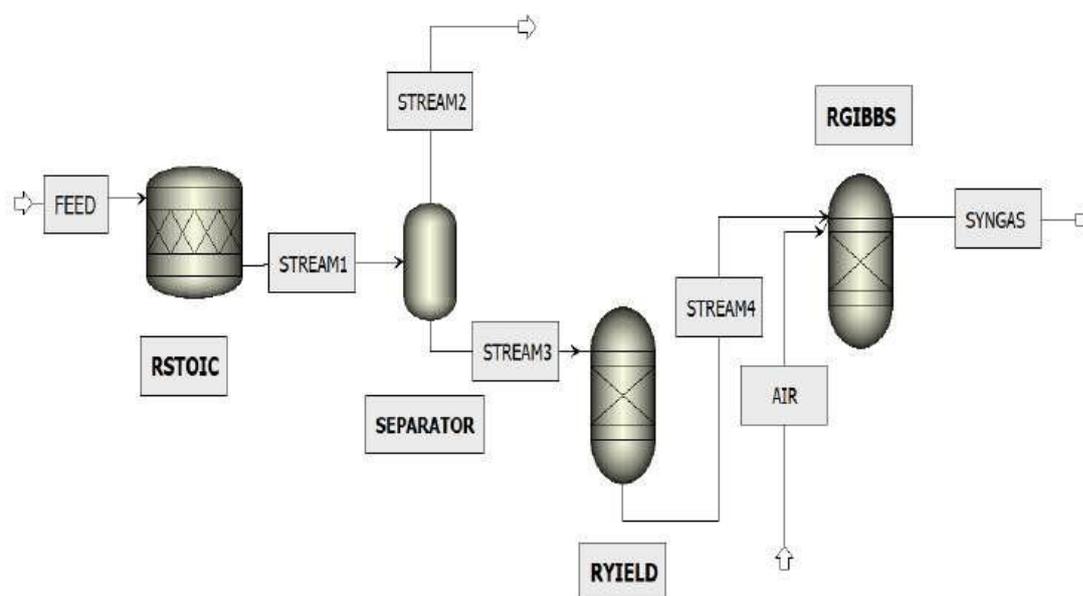

Figure 1. The fixed-bed Gasification model flowsheet

2.3.2. Fluidised bed gasification model

The gasification process in a fluidised bed may be categorised into four main stages: feed degradation, volatile reactions, char gasification, and gas-solid separation. Figure 2 illustrates the Aspen Plus flow sheet for this operation. In the first stage, represented by the RYIELD, the biomass is decomposed into its components using a FORTRAN statement. The

carbon (C), hydrogen (H), oxygen (O), sulphur (S), nitrogen (N), and ash elements in the cocoa pod husk are turned into their corresponding yields for each syngas, depending on the yield distribution obtained from the ultimate analysis. The SEPARATOR and RGIBBS are the two components involved in the volatile reactions stage. The products of the yield reactor are separated into volatile materials and solids by the SEPARATOR. Aspen Plus specifies the quantity of volatile matter based on data from the biomass database from earlier research conducted by Muslim *et al.* (2015). This sorted volatile matter is then put into the (RGIBBS), where it burns in a way that is thought to follow the Gibbs equilibrium. The following step involves the gasification process repeated in the RGIBBS as the steam and air combine with the syngas in the MIXER. The Gibbs reactor also performs char gasification by specifying the gasification reactions. The final stage is collecting the syngas product at the end of the stream flow.
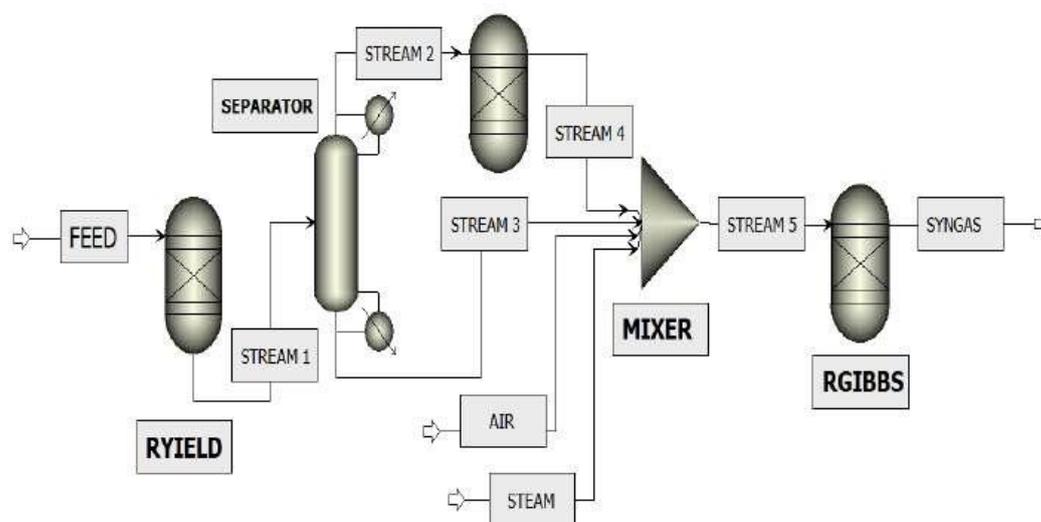

Figure 2. The fluidised bed gasification model flowsheet

3. Results and Discussions

3.1. Performance Analysis

The results of the syngas from both gasification models are analysed in terms of the percentage values of mass flow rate (kg/hr). Hydrogen gas production is higher in the fluidised bed reactor (7.62%) compared to the fixed bed reactor (5.84%), as shown in Table 2. Steam flow in fluidised bed gasification is responsible for promoting hydrogen generation.

The biomass solid fuel particles are exposed to restricted oxygen in a fluidised bed that lacks sufficient oxygen or air. This causes fast drying and pyrolysis by heating the fuel particles to the bed temperature (Basu, 2006). In addition, compared to fixed bed reactors, fluidised bed reactors provide better biomass mixing. This characteristic enhances the gasification process, leading to a higher heating value. It also improves mass and heat transfer from the biomass, increasing hydrogen production (Muslim *et al.*, 2017).

Table 2. Comparison of the syngas (%) amount between the two gasifier models.

Components	Fixed Bed	Fluidized Bed
	% of Mass Flowrate	% of Mass Flowrate
CO	28.24	37.40
CO_2	63.63	52.83
H_2	5.84	7.62
CH_4	2.29	2.14

3.2. Sensitivity Analysis

The sensitivity analysis is implemented to study the effects of gasifier temperature and air-to-biomass ratio on hydrogen production for both gasifiers. In addition, the impact of the biomass ratio is only investigated on the fluidised bed gasifier. The steam-to-biomass ratio is primarily analysed for the fluidised bed reactor due to its more significant effect on heat transfer, reaction kinetics, and overall process efficiency compared to fixed-bed reactors, where factors like bed height and particle size play a more critical role in determining reactor performance (Jiang *et al.*, 2020).

3.1.1. Effect of gasifier temperature

The temperature regulates the chemical reactions' equilibrium throughout the gasification process. Regarding each model, the temperature of the gasifier varies between 700°C and 900°C. The effect of the gasification temperature on syngas production for both models at an air-to-biomass ratio of 0.09 is shown in Figure 3. Figure 3 shows that a higher amount of hydrogen will be produced at 760 °C for the fixed bed reactor and 740 °C for the fluidised bed reactor. Both models result in a slightly increasing amount of hydrogen gas as the temperature rises until a specific temperature. This is due to the water-gas shift reaction (C + H2O = CO + H2) and Boudouard reaction (C + CO2 = 2CO), causing the increasing amount of hydrogen and carbon monoxide. At the beginning of the reactions, the carbon (C) inside the biomass is not fully utilised. Still, when the temperature occurs, the C will oxidise completely, increasing syngas production (Begum *et al.,* 2008). However, at 900°C, the

amount of hydrogen gas is decreasing due to the endothermic Boudouard reaction being too dominant, resulting in increased CO and decreased CO2. More hydrogen will convert into methane, which will undergo an endothermic reaction to produce more CO and CO2. The findings align with Abdulrasheed *et al.* (2020), who observed that at temperatures between 700-1000°C, multiple simultaneous reactions occur, including methane cracking, reverse water gas shift, Boudouard, and carbon gasification. The increased favorability of methane cracking is primarily driven by the concurrent consumption of CO2 and H2, which facilitates these complex thermochemical interactions and promotes the transformation of hydrocarbon and gasification products under high-temperature conditions.

3.1.2. Effect on air-to-biomass ratio (ABR)

The air-to-biomass ratio is the amount of biomass compared to the air fed into the gasifier. As the ABR goes up, more oxygen is delivered to the gasifier because more carbon is being converted (Wahid *et al.*, 2015) The ratio has a strong effect on both gasification models. This study's ratios varied from 0.01 to 0.15, while the gasifier temperature was 700°C. The air-to-biomass (ABR) ratios of 0.01 to 0.15 were systematically selected to explore the complex relationship between oxygen supply and gasification performance, balancing carbon conversion, syngas quality, and energy efficiency across different combustion regimes from fuel-rich to near-stoichiometric conditions. The results of the effect of air-biomass ratio on the percentage amount of syngas produced are shown in Figure 4. Both gasification models show that a high amount of hydrogen will be produced at an air-to-biomass ratio of 0.01. This is in total agreement with the study by Lv *et al.*, (2004) for hydrogen gas composition, which decreases with air-biomass because it is being consumed in reaction. Besides, when operating at a higher equivalence ratio, the partial combustion is more favourable, resulting in a loss of the solid carbon and reducing the hydrogen (H_2) production while increasing the equivalence ratio. Additionally, the ratio of air to biomass influences the temperature of the gasification process, causing more oxidation reactions to occur at higher temperatures, leading to an increased composition of CO (Begum *et al.*, 2008). A portion of the CO2 is transformed into CO, increasing CO composition (Sheth & Babu, 2010).
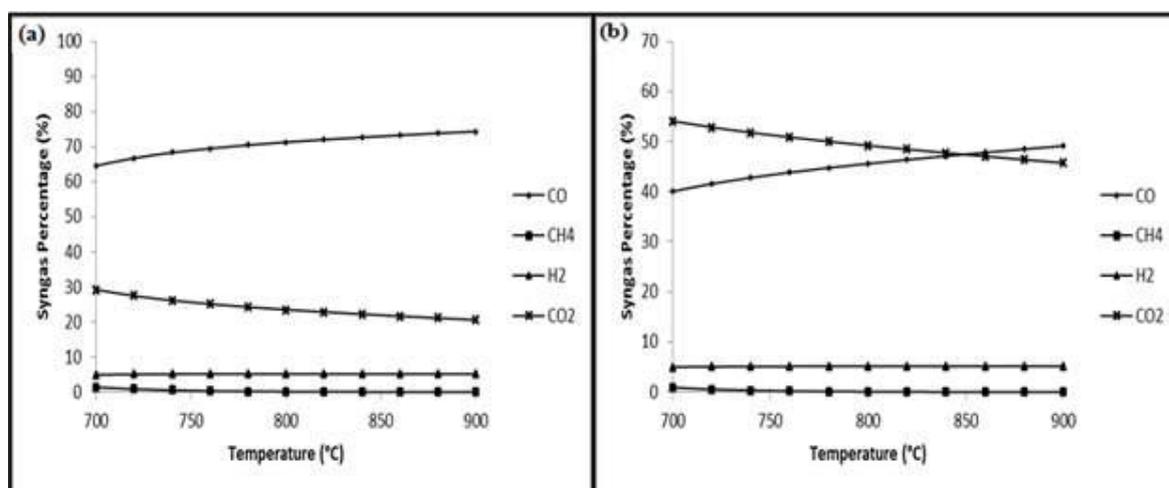
Figure 3. Effect on gasifier temperature: (**a**) Fixed bed; (**b**) Fluidised bed
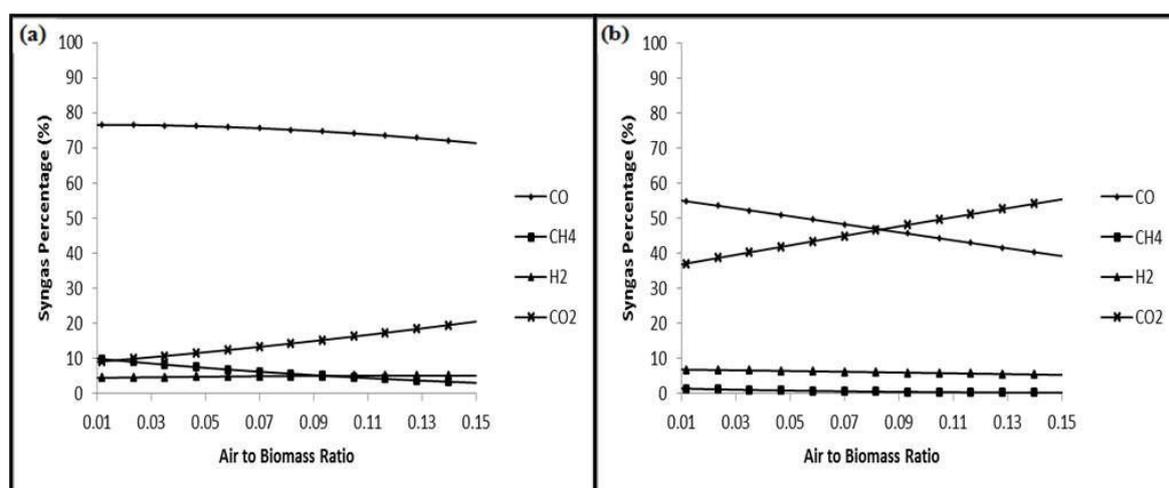

Figure 4. Effect on air-to-biomass ratio: (**a**) Fixed bed; (**b**) Fluidised bed

3.1.3. Effect on steam to biomass ratio (SBR)

The effect of steam flow on the fluidised bed gasification process is shown in Figure 5. The range of steam-to-biomass ratio that has been applied is between 0.01 and 0.15. The amount of hydrogen gas will increase the amount of steam flow. This is due to the presence of hydrogen molecules inside the water that also will trigger hydrogen production for the fluidised bed gasification process (Dong *et al.*, 2017). Figure 5 shows that increasing the steam-to-biomass ratio will increase the hydrogen produced. As shown below, hydrogen will be produced at a steam-to-biomass ratio of 0.15. The steam-to-biomass ratio is primarily examined in the context of fluidised bed reactors because it has a more pronounced effect on heat transfer, reaction kinetics, and overall process efficiency. In contrast, bed height and

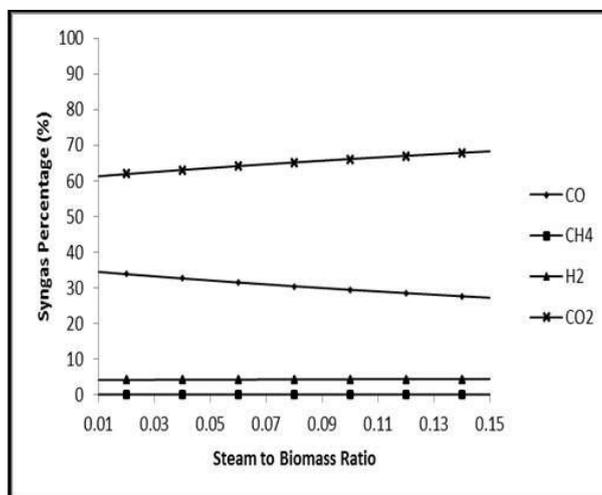particle size are more influenced by fixed-bed reactors, which are critical in determining their performance.

Figure 5. The effect or output on the biomass ratio for the fluidised bed model gasification

4. Conclusions

Aspen Plus was used to design models for both downdraft fixed-bed and bubbling fluidised bed gasification processes, which were successfully executed. The bubbling fluidised bed process produced more hydrogen gas (7.62%) than the downdraft fixed-bed reactor (5.84%) under the same operating conditions. A sensitivity analysis was performed to evaluate the influence of gasifier temperature and air-to-biomass ratio. Findings revealed that the downdraft fixed-bed reactor produced more hydrogen (6.33%) at a temperature of 760°C. Meanwhile, the bubbling fluidised bed reactor produced approximately 8.43% of hydrogen gas at a temperature of 740°C and an air-to-biomass ratio of 0.01. Additionally, the ideal steam-to-biomass ratio for the bubbling fluidised bed to attain a higher level of hydrogen production was determined to be 0.15. Future research should focus on investigating cocoa waste-derived biomass as a potential feedstock for hydrogen production, exploring innovative gasification technologies such as catalytic steam gasification or plasma-assisted gasification to optimise hydrogen yield and assessing the economic and environmental sustainability of utilising agro-industrial residues like cocoa shell, pod husk, and pulp waste.

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