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Aspen plus simulation of biomass gasification in a steam blown dual fluidised bed

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The efficient utilisation of biomass resources is of utmost importance. Biomass gasification offers much higher efficiencies than combustion. Gasification is a process in which a fuel is converted to a combustible gas (syngas). A dual fluidised bed gasifier known as the fast internally circulating fluidised bed (FICFB) was selected. It has been demonstrated at industrial scale and data is readily available for model validation. An Aspen Plus model was developed to simulate the FICFB gasifier. The model is based on Gibbs free energy minimisation and the restricted equilibrium method was used to calibrate it. The model has been validated and predicts syngas composition, heating value and cold gas efficiency (*CGE*) in very good agreement with published data. Important operating parameters such as gasification temperature (T_g), biomass moisture, steam to biomass ratio (*STBR*), air-fuel ratio and air and steam temperature were varied. T_g and *STBR* were found to have very strong influence on syngas composition and heating value. Biomass moisture had the most significant impact on *CGE*. The other parameters, although less important, were found to have substantial effect on *CGE*.

Keywords: biomass gasification; dual fluidised bed; aspen plus; modelling; simulation; sensitivity analyses

1. Introduction

The efficient utilisation of biomass resources is of utmost importance if renewable energy is to replace a significant proportion of fossil fuels. Traditional biomass combustion based technologies achieve low electrical efficiencies (20-25%) and therefore cannot compete with fossil fuels. Biomass gasification coupled with advanced power generation systems such as gas turbines or fuel cells offer much higher efficiencies. This technology can help satisfy many EU objectives, including increasing the contribution of renewable energy, improving energy efficiency, increasing security of supply (indigenous resource), raising the level of combined heat and power (CHP) and reduction of greenhouse gas emissions.

Gasification is a thermochemical process in which a carbonaceous fuel is converted to a combustible gas. This combustible gas is known as syngas (from synthetic or synthesis gas) and consists of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), water vapour (H_2O), nitrogen (N_2), higher hydrocarbons and impurities such as tars, ammonia (NH_3), hydrogen sulphide (H_2S) and hydrogen chloride (HCl). The process occurs when a controlled amount of oxidant (pure oxygen, air, steam) is reacted at high temperatures with available carbon in the fuel within a gasifier. Steam gasification of biomass can be represented by the chemical reactions Eq. (1)-(5) in Table 1. Equations (1)-(5) are regarded as the main gasification reactions and hence are the ones considered in this work [1-4]. In addition to the reactions in Table 1, combustion reactions will occur, but these are omitted as Aspen Plus can generate them automatically and they depend on the composition of the fuel. The gasification process may be split into steps: drying (at 100-200 °C), pyrolysis (at 200-500 °C), gasification and combustion. These steps are frequently modelled in series but there is no sharp boundary dividing them and they often overlap [5]. Combustion is necessary to supply the heat required for the endothermic gasification reactions. The pyrolysis step produces char, H_2 , CO, CH_4 , CO_2 , H_2O , tars and hydrocarbons. Pyrolysis is difficult to model and is a source of high uncertainty [1].

The three main types of gasifier include: moving/fixed bed, fluidised bed and entrained flow. Updraft fixed bed gasifiers produce syngas with very high tar content and downdraft fixed beds although attractive for biomass conversion are only suitable for small scale. Entrained flow gasifiers require a pulverised feed making them unsuitable for biomass gasification without extensive pre-treatment of the fuel, such as torrefaction or pyrolysis. Fluidised bed gasifiers are well suited to biomass conversion due to their high fuel flexibility and scale (low MW to 100 MW). A subcategory is the steam blown dual fluidised bed (DFB) gasifier. DFB gasifiers produce high quality syngas (high heating value and N_2 free) and a number of different designs are in development. The fast internally circulating fluidised bed (FICFB) gasifier was selected for this study [6]. It has been successfully demonstrated at industrial scale (8 MW fuel input) and performance data is readily available for model validation.

The aim of this work was to develop a model of the FICFB gasifier, to validate it against actual plant data and utilise it to examine the influence of the main operating parameters on gasifier performance. Building on previous research [7, 8], an Aspen Plus model was developed to simulate the FICFB gasifier. The model is based on Gibbs free energy minimisation and the restricted equilibrium method was used to calibrate it against published data. This was achieved by specifying the temperature approach for a number of the gasification reactions.

Table 1 Gasification reactions specified in model.

Heterogeneous reactions	Eq.	Homogeneous reactions	Eq.	NH ₃ , H ₂ S and HCl formation reactions	Eq.
$C + 2H_2 \leftrightarrow CH_4$	(1)	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	(4)	$0.5N_2 + 1.5H_2 \leftrightarrow NH_3$	(6)
$C + H_2O \leftrightarrow CO + H_2$	(2)	$CO + H_2O \leftrightarrow CO_2 + H_2$	(5)	$H_2 + S \leftrightarrow H_2S$	(7)
$C + CO_2 \leftrightarrow 2CO$	(3)			$Cl_2 + H_2 \leftrightarrow 2HCl$	(8)

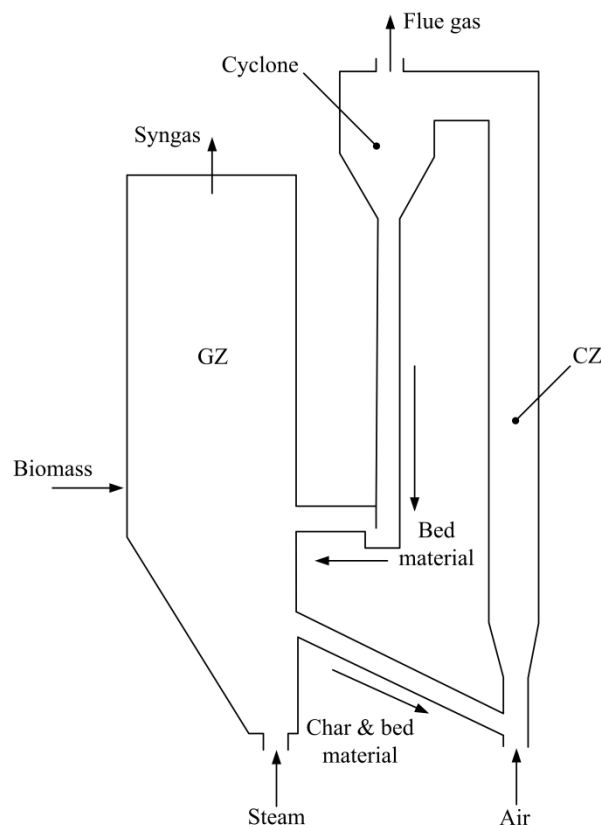
2. Technology description and DFB simulation literature review

2.1 Technology description

A DFB gasifier is based on the principle that separation of the gasification and combustion zones (GZ and CZ) will avoid N₂ dilution of the syngas (due to combustion of fuel with air) and thus a high quality gas will be produced without the need for an expensive air separation unit, which would be required for O₂ blown gasification. Examples of these gasifiers include: the Pyrox DFB, Silvagas DFB, MILENA and FICFB (selected for this study). The reader is referred to Corella et al. [9] and Göransson et al. [10] for a detailed review of the various DFB gasifier technologies.

The FICFB technology has been under development since the early 1990s at TU Wien and has been successfully demonstrated at industrial scale (8 MW fuel input) in Güssing (Austria) since 2002 [6]. For a detailed description of the Güssing plant see Doherty et al. [11]. The fundamental idea of this gasification system is to physically separate the gasification and combustion reactions in order to gain a largely N₂ free syngas [12]. With reference to Fig. 1, the biomass fuel enters a bubbling fluidised bed reactor (GZ) where it is dried, pyrolysed and gasified with steam [13]. Residual char leaves the GZ with bed material through an inclined chute and enters a circulating fluidised bed riser (CZ) where it is combusted with air. After separation from the flue gas in a cyclone, the heated bed material flows back to the GZ via a loop seal [13]. This bed material provides the heat required to drive the endothermic steam gasification reactions which produce the syngas. The FICFB gasifier operates at atmospheric pressure. The syngas is of high quality and is characterised by low N₂ content, high H₂ content, low tar levels and high heating value. These favourable characteristics make the syngas suitable for many applications, including CHP using gas engines, gas turbines or fuel cells, as an intermediate product for chemical synthesis or for synthetic natural gas production [14].

In Oberwart (Austria) the second CHP plant based on the FICFB gasification technology was realised and has been operational since 2008 [2]. In addition, two more FICFB based facilities began operating recently (one located in Villach, Austria and another in Ulm, Germany) [15].

**Fig. 1** FICFB gasifier schematic diagram.

2.2 DFB simulation literature review

No Aspen Plus models of the FICFB gasifier have been found in the literature. A small number of FICFB models using other computer simulation software have been published. Computer simulation models of other DFB gasifier designs have also been developed.

Kaushal et al. developed a complex one-dimensional model of the FICFB gasifier [1]. Both reaction kinetics and bed hydrodynamics were considered. The model predicted the syngas composition profile (i.e. variation in composition in the axial direction) and the results indicated that most of the biomass conversion takes place in the bottom zone of the gasifier with little change in syngas composition in the freeboard. This finding proves that zero-dimensional models, like the one developed in this work, are sufficient to simulate the FICFB process. Gassner and Maréchal presented a Belsim model of the FICFB gasifier [16]. They also applied the temperature approach method to adjust the predicted syngas composition. They investigated ways to improve the efficiency of the process and predict a ~10% increase in cold gas efficiency (*CGE*) if the biomass is pyrolysed before feeding to the FICFB reactor. Pröll et al. reported work on an IPSEpro model of the FICFB gasifier [13, 14]. It is described as a black box model with functional equations for parametric modelling [14]. Reaction kinetics were not considered and some empirical equations were used in the model calculations. A pure equilibrium FICFB model was developed by Schuster et al. using IPSEpro [3]. It is clear from the results of this simulation that the real FICFB process is far from equilibrium as the predicted H_2 and CO contents are well above real FICFB gasifier values and CH_4 and CO_2 contents are well below actual levels. Two ChemCAD FICFB models have been published by an Italian research group [4, 17]. The models are based on the 500 kW FICFB pilot plant operating at the ENEA Trisaia Research Centre. The results for both models do not show good agreement with the reported syngas composition for the FICFB pilot plant.

Abdelouahed et al. simulated the Silvagas and TNEE DFB gasification processes [18]. The model is a semi-kinetic Aspen Plus simulation that incorporates Fortran subroutines. A pyrolysis correlation was implemented and both tar and char were considered. Bed hydrodynamics were neglected. Jie et al. presented an Aspen Plus model of a 150 kW DFB gasifier (called the MIUN gasifier by the authors) [19]. They applied the Gibbs free energy minimisation with temperature approach method and empirical equations were used to predict the products of pyrolysis including char and tar. De Kam et al. developed a process simulation model of the Silvagas DFB gasifier using Aspen Plus [20]. The Gibbs free energy minimisation with temperature approach method was also applied by these authors. An Aspen Plus heat stream was used to simulate the transfer of heat from the gasifier CZ to the GZ via bed material. The amount of char directed to the CZ was set at 19.7%; this constraint reduces the model prediction capability. An Aspen Plus model of the Silvagas process was published by Cohce et al. [21]. The model uses National Renewable Energy Laboratory correlations to adjust the syngas composition from an Aspen Plus RGibbs reactor. From the article it is not clear if the model was validated.

3. Modelling

3.1 Model description

The Aspen Plus flowsheet of the FICFB gasifier is depicted in Fig. 2. The model is based on the following main assumptions: isothermal and steady state operation; zero-dimensional; operation at atmospheric pressure (~1 bar); ideal gases; pressure drops are neglected; char is 100% carbon (C); all fuel bound N_2 is converted to NH_3 [2, 3, 20, 22]; all fuel bound sulphur (S) is converted to H_2S [2, 3, 20]; all fuel bound chlorine (Cl_2) is converted to HCl [20]; drying and pyrolysis are instantaneous [5]; tar formation is not considered [3, 4]; a heat stream is used to simulate the heat transferred by the circulation of bed material between the gasifier CZ and GZ [19-21]; heat loss from the gasifier is neglected [18].

The Peng-Robinson equation of state with Boston-Mathias modifications was selected as the property method for the model. With reference to Fig. 2, the stream 'BIOMASS' was specified as a non-conventional stream and the ultimate and proximate analyses, given in Table 2, were entered. The biomass lower heating value (*LHV*) was also specified with the HCOALGEN and DCOALIGT property models chosen to estimate the biomass enthalpy of formation, specific heat capacity and density based on the ultimate and proximate analyses. Finally, the stream thermodynamic condition (1 bar and 25 °C) and mass flow rate were inputted. The reader should note that the pressure of all feed streams and unit operation blocks were set to 1 bar (i.e. no pressure drop in the system). The mass yields of the RYield reactor 'BRKDOWN', which converts the non-conventional biomass into conventional components, are determined and set using a calculator block.

The outlet stream 'ELEMENTS' is fed to a separator block 'CHARSEP' whose purpose is to separate out a portion of the char (assumed 100% C) and all of the ash. The char split fraction is set using a design specification; the block split fraction is varied until the gasification temperature (T_g) of 850 °C is achieved [16, 23]. The char and ash are directed to the gasifier CZ, simulated by an RStoic reactor titled 'COMB'.

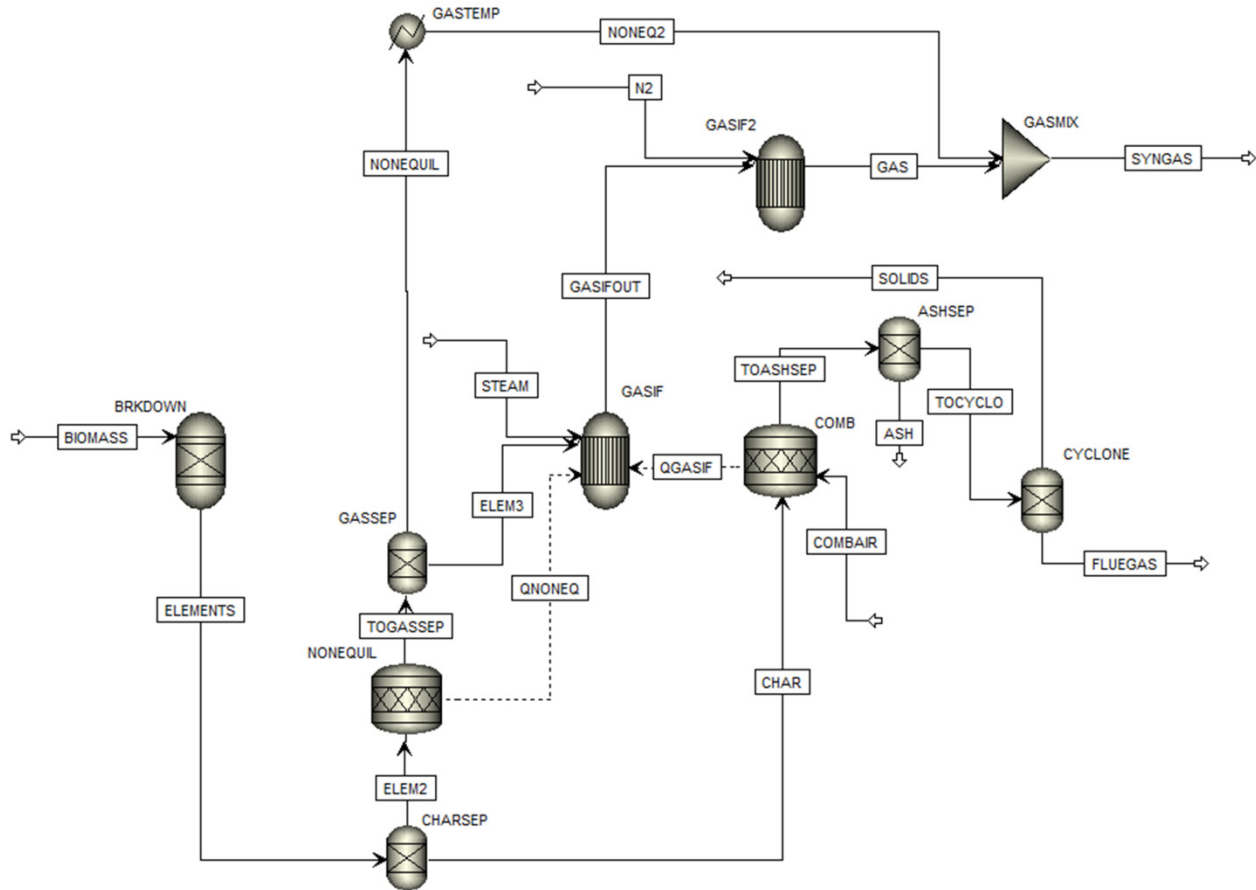


Fig. 2 FICFB gasifier aspen plus flowsheet.

The air stream 'COMBAIR' is also fed to this block. The mole fraction of the air was specified as 0.79 N_2 and 0.21 O_2 and its temperature (T_a) was set to 450 °C [24]. The air mass flow rate is computed and set using a calculator block; air mass flow rate equals biomass mass flow rate multiplied by an assumed air-fuel ratio of 1.12 [24]. The air and char react to produce the heat required for gasification, represented by the heat stream 'QGASIF' connecting the block 'COMB' to 'GASIF'. No chemical reactions were specified; the generate combustion reactions option was selected. The combustion temperature (T_{comb}) is set by a calculator block; T_{comb} was assumed to be 55 °C above T_g [13]. The chosen air-fuel ratio ensures complete combustion of the char; therefore, the stream 'TOASHSEP' contains only CO_2 , O_2 , N_2 and ash.

The separator 'ASHSEP' simulates ash removal from the gasifier. The stream 'TOCYCLO' made up of CO_2 , O_2 and N_2 enters a separator titled 'CYCLONE' where any un-reacted char is separated out and recycled to the gasifier. The block split fraction was specified as 0.85 (typical cyclone separation efficiency). In a real FICFB gasifier entrained bed material and fly ash would also be separated from the exhaust gas and recycled but this has not been modelled. As mentioned above, at normal conditions combustion is complete; therefore, the 'SOLIDS' stream has zero mass flow rate. 'FLUEGAS' represents the final exhaust from the gasifier CZ.

The material stream 'ELEM2' is directed to the RStoic reactor 'NONEQUIL' where 100% of the fuel bound N_2 , S and Cl_2 are converted to NH_3 , H_2S and HCl respectively via Eq. (6)-(8). The enthalpy change due to this process is accounted for by the heat stream 'QNONEQ' fed to 'GASIF'. The NH_3 , H_2S and HCl are removed from the main fuel stream using the separator 'GASSEP'.

The main fuel stream 'ELEM3' is fed to the gasifier GZ simulated using an RGibbs reactor named 'GASIF'. The other feed stream is the steam needed to gasify the biomass and fluidise the bed. The steam temperature (T_{steam}) was set to 450 °C and its mass flow rate depends on the gasifier steam to biomass ratio ($STBR$). $STBR$ is defined as the mass flow rate of biomass moisture plus the injected steam divided by the dry biomass mass flow rate. The injected steam mass flow rate is set by a design specification block employing the wet biomass mass flow rate, the specified moisture content and a $STBR$ of 0.75 in its calculations [23]. In the block 'GASIF' the gasification reactions Eq. (1)-(5) were specified with zero temperature approach for each reaction (i.e. the chemical equilibrium constant for each reaction is calculated at the reactor temperature; so the block outputs the equilibrium gas composition).

Table 2 Biomass (wood chip) composition, heating value and flow rate.

Ultimate analysis (dry basis)			Source
Carbon	wt. %	51.19	[24]
Hydrogen	wt. %	6.08	[24]
Oxygen	wt. %	41.3	[24]
Nitrogen	wt. %	0.2	[24]
Sulphur	wt. %	0.02	[24]
Chlorine	wt. %	0.05	[24]
Ash	wt. %	1.16	[24]
Proximate analysis (dry basis)			
Volatile matter	wt. %	80	[3]
Fixed carbon	wt. %	18.84	Calculated by difference
Ash	wt. %	1.16	[24]
Moisture	wt. %	20	[14, 23]
<i>LHV</i> (dry basis)	MJ/kg	19.09	[24]
Thermal power input	MW	8	[13, 14]
Mass flow rate	kg/h	1508.64	Calculated

The function of the next block ‘GASIF2’, which is another RGibbs reactor, is to adjust the gas composition to match data reported in the literature. The block temperature is set to the ‘GASIF’ block temperature by means of a calculator block. Two reactions Eq. (4) and (5) were entered and equilibrium was restricted by inputting temperature approach values (-265 °C and -90 °C respectively). These temperature approach values ensure that the model outputs a realistic syngas composition (see Table 3). This block is also used to inject a small amount of N₂, which is present in the syngas produced by FICFB gasifiers because it is utilised as purge gas in the fuel feeding system [2].

The final block ‘GASMIX’ (an Aspen Plus Mixer) simply mixes back in the NH₃, H₂S and HCl, separated prior to the RGibbs reactors. However before this can be done, these impurities must be brought up to the same temperature as the ‘GAS’ stream (i.e. T_g). This is accomplished by means of the heater block ‘GASTEMP’ and a calculator block is used to set the temperature to T_g . The exit stream from ‘GASMIX’ represents the final output syngas from the gasifier.

3.2 Model validation

The FICFB model was validated against published data for the FICFB gasifier operating at the 8 MW Güssing CHP plant and pilot FICFB plants. The model inputs were the same as those presented in Table 2 and described in section 3.1. These model inputs will be referred to as the base case values for the remainder of this chapter.

As seen in Table 3, the model results are in very good agreement with actual plant data. The percentage error for the syngas composition is 9.26% for CH₄, 4.75% for CO₂ and 0% for H₂, CO and N₂. The model *LHV* value is 2.75% higher than the reported syngas *LHV* value. The model prediction for the gasifier *CGE* is within the range reported in the literature for the FICFB gasifier.

CGE is a means of indicating the gasifier performance and is defined as: $CGE = \dot{m}_{gas} \cdot LHV_{gas} / \dot{m}_{fuel} \cdot LHV_{fuel}$. Where \dot{m}_{gas} and \dot{m}_{fuel} are the mass flow rate in kg/s of syngas and biomass respectively and LHV_{gas} and LHV_{fuel} are the lower heating value in kJ/kg of the syngas and biomass respectively.

In addition, the level of syngas impurities NH₃, H₂S and HCl on a volumetric part per million basis (ppmv) are predicted quite accurately. Finally, the amount of char directed to the gasifier CZ is within the published range for the FICFB gasifier.

Table 3 Model results compared to literature.

	Literature	Source	Model results
Syngas composition (vol. % dry and NH ₃ , H ₂ S, HCl free)	H ₂ 45.8, CO 21.6, CH ₄ 10, CO ₂ 21.2, N ₂ 1.4	[23]	H ₂ 45.8, CO 21.59, CH ₄ 11.02, CO ₂ 20.19, N ₂ 1.4
Syngas <i>LHV</i> (dry at 0 °C and 1 atm)	11.3 MJ/m ³	[23]	11.6 MJ/m ³
<i>CGE</i> (<i>LHV</i> and mass basis)	71.5-78.4%	[14, 16]	76.7%
Impurities (ppmv dry)	NH ₃ 1100-1700, H ₂ S 21.5-170, HCl 100	[2, 17, 24]	NH ₃ 1514, H ₂ S 66.12, HCl 149.5
Char combusted (mass basis)	10-15%	[3, 23]	12.93%

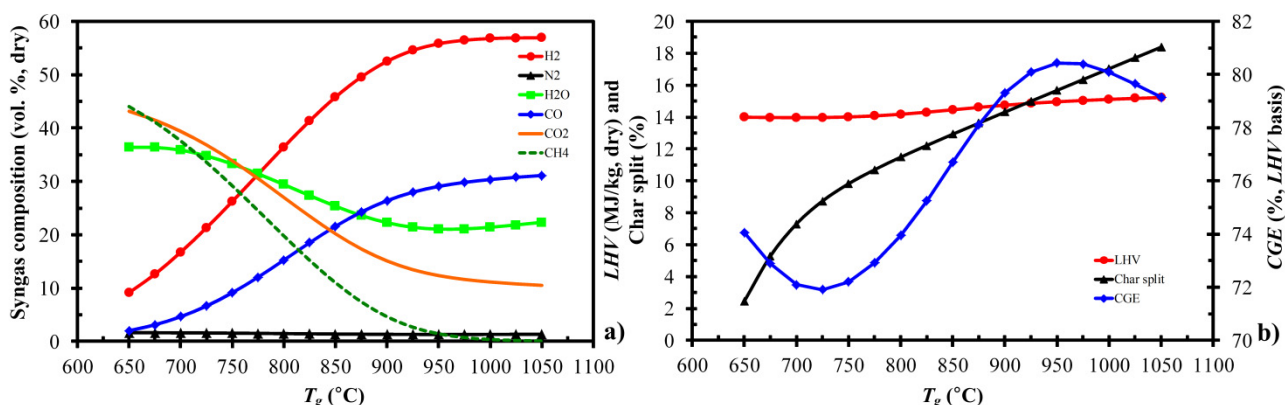


Fig. 3 Effect of gasification temperature on a) syngas composition and b) syngas LHV, gasifier CGE and char split fraction.

4. Results and discussion

The validated model was employed to perform sensitivity analyses of the main operating variables with respect to gasifier performance. Important parameters including T_g , biomass moisture content, $STBR$, air-fuel ratio, T_{steam} and T_a were varied over a wide range. During the sensitivity analyses the input data was kept the same as for model validation (see section 3) with a single parameter being varied at any given time.

4.1 Sensitivity analysis: gasification temperature

The influence of T_g on syngas composition is shown in Fig. 3 a). All gas components are plotted on a volume % dry basis except for H₂O. The gas components H₂S, NH₃ and HCl are omitted due to their very low content and the fact that they would be removed by downstream syngas cleaning equipment. T_g is varied from 650-1050 °C and Fig. 3 a) shows that it has a very strong influence on syngas composition. Fluidised bed biomass gasifiers should operate below 1000 °C to ensure that ash melting does not occur, which would cause agglomeration and defluidisation. Over the T_g range 650-950 °C H₂ increases 46.65 percentage points (9.15-55.8%) and CO rises 27.04 percentage points (2.03-29.07%). Both CH₄ and CO₂ decrease; CH₄ drops from 44.03-1.45% and CO₂ from 43.15-12.35%. A reduction in the level of H₂O in the syngas is seen (36.39-21.06%). T_g has little impact above 950 °C; H₂O reverses its trend and increases slightly. This is most likely due to the decline in CH₄, i.e. the other reactant required for steam-methane reforming Eq. (4). The variation in syngas composition with T_g can be understood by considering that rising temperature favours the products of endothermic gasification reactions Eq. (2)-(4) and simultaneously the reactants of exothermic reactions Eq. (1) and (5). From these results it is concluded that T_g is the most important parameter with respect to syngas composition and it is recommended to operate the FICFB gasifier in the temperature range 850-950 °C in order to maximise H₂ and CO and to minimise CO₂ and H₂O.

Figure 3 b) displays how T_g affects the LHV of the syngas, gasifier CGE and the char split fraction (i.e. the percentage of char sent to the CZ of the gasifier). The heating value, CGE and char split are all on a mass basis. The LHV is calculated from the dry gas composition and the CGE is determined using LHV values for both syngas and biomass input (see section 3.2). It is shown in Fig. 3 b) that T_g has significant influence on all three of the performance indicators. LHV increases from 13.99-15.23 MJ/kg over the T_g range. As expected, the char split fraction climbs from 2.45-18.39% (the higher the T_g the greater the amount of char combusted to achieve the desired T_g). Gasifier CGE rises and falls over the T_g range; with a maximum at 950 °C and a minimum at 725 °C (80.44% and 71.9%). These results reiterate what was stated above; the gasifier should be operated in the T_g range 850-950 °C in order to maximise CGE and produce a high heating value syngas with high H₂ and CO content.

4.2 Sensitivity analysis: biomass moisture content

Biomass moisture content (mass basis) was found to have little impact on syngas composition, e.g. the H₂ content increased only 3.27 percentage points from 44.76-48.03% over the moisture range 5-40% and this was the second highest change (H₂O content increased by 3.73 percentage points). The $STBR$ was held constant at the base case value of 0.75 during this sensitivity analysis; e.g. for a moisture content of 5% steam must be fed to the gasifier at a rate of 999.5 kg/h, whereas for a moisture content of 40% only 75.4 kg/h of steam is required. This explains the seemingly greater influence on gas composition displayed by $STBR$ (see section 4.3) even though both are chemically equivalent. A much greater mass flow rate of H₂O is fed to the gasifier during the $STBR$ sensitivity analysis, which results in a greater impact on gas composition compared to biomass moisture content.

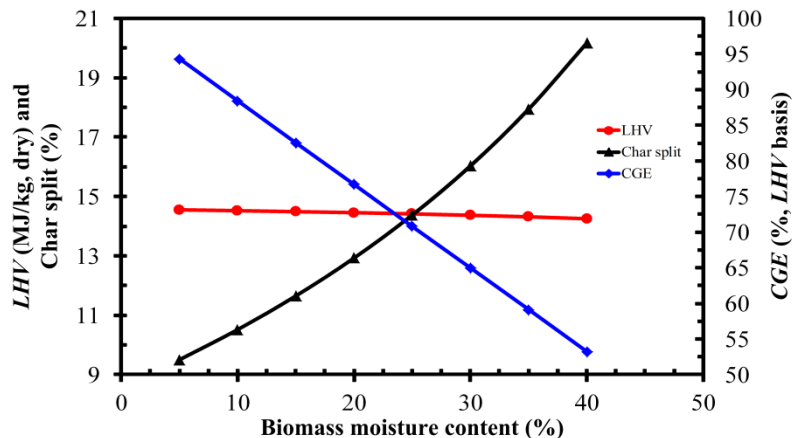


Fig. 4 Effect of biomass moisture content on syngas *LHV*, gasifier *CGE* and char split fraction.

The effect of increasing moisture content on *LHV* of the syngas, gasifier *CGE* and the char split fraction is illustrated in Fig. 4. As expected, moisture content has little effect on syngas *LHV* (the *LHV* depends on the gas composition). However, moisture content was found to have a very strong influence on *CGE* (decreases from 94.28% at 5% moisture to 53.24% at 40% moisture). This influence on *CGE* may be explained by the increase in char split fraction with rising moisture (9.5-20.17% across the moisture range). Greater char split fraction results in less char being gasified, which in turn means less syngas is produced by the gasifier. *CGE* depends on both the syngas *LHV* and mass flow rate; it is the drop in syngas mass flow rate that causes the dramatic reduction in *CGE* for high moisture content. Based on these results the biomass moisture content proved to be the most significant parameter regarding gasifier *CGE* and therefore should be as low as possible, i.e. the biomass fuel should be dried prior to use in the gasifier.

4.3 Sensitivity analysis: steam to biomass ratio

Figure 5 a) depicts the changes in syngas composition in response to variation in *STBR* (mass basis). It has been reported that the practical range for *STBR* is 0.5-1 for the FICFB gasifier [23]. It is evident from Fig. 5 a) that *STBR* has little impact on composition above 1.35. Considering this and the reported practical range, the *STBR* range 0.25-1.35 will now be discussed. Over this *STBR* range H_2 increases by 25.7 percentage points; however, on a wet basis this increase drops to only 7.85 percentage points. It may be more useful to consider the wet gas composition in this analysis as there is such a large increase in H_2O (it rises from 9.26% to 37.6%). CO and CH_4 drop by 17.69 and 15.8 percentage points respectively (dry basis) and CO_2 increases by 7.27 percentage points. From these results it is clear that *STBR* is the second most important parameter in respect of syngas composition.

From Fig. 5 b) it can be seen that *STBR* has the most significant impact on syngas *LHV* in comparison to the other sensitivity analyses; however, it is the least important parameter with respect to *CGE*. Gas *LHV* decreases with *STBR* because the increase in H_2 is outweighed by the drop in both CO and CH_4 . The variation in *CGE* may be explained by the fact that at low *STBR* the *LHV* is high; however, the syngas mass flow rate is low. Conversely, at high *STBR* the *LHV* is low and the syngas mass flow rate is high. These opposing trends result in little change in the *CGE*. In comparison to moisture content, the moisture degrades gasifier *CGE* to a much greater extent. This is due to its low temperature of 25 °C, which leads to higher char combustion than for steam at 450 °C. Considering these findings, it is recommended to operate the gasifier in the range 0.5-1. Operation at higher *STBR* is not advisable considering the detrimental effect on syngas *LHV* and the energy that would be required to generate the steam.

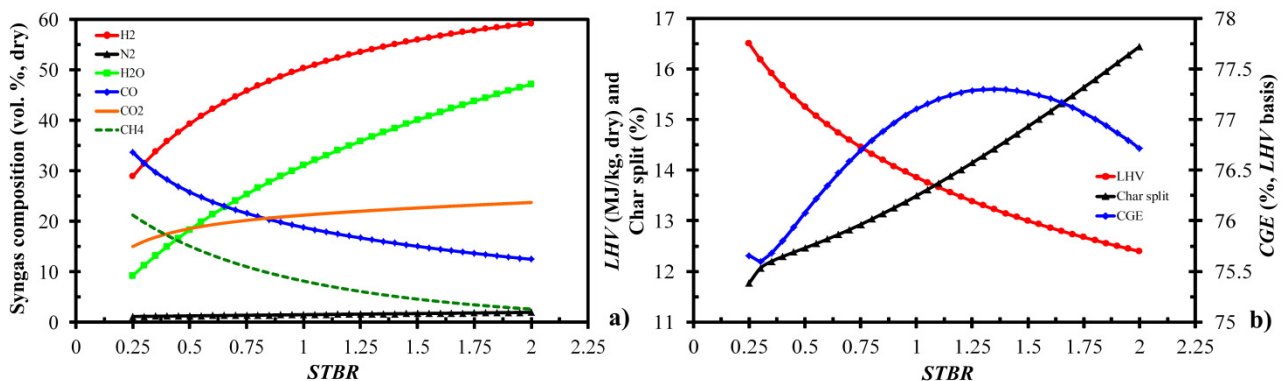


Fig. 5 Effect of steam to biomass ratio on a) syngas composition and b) syngas *LHV*, gasifier *CGE* and char split fraction.

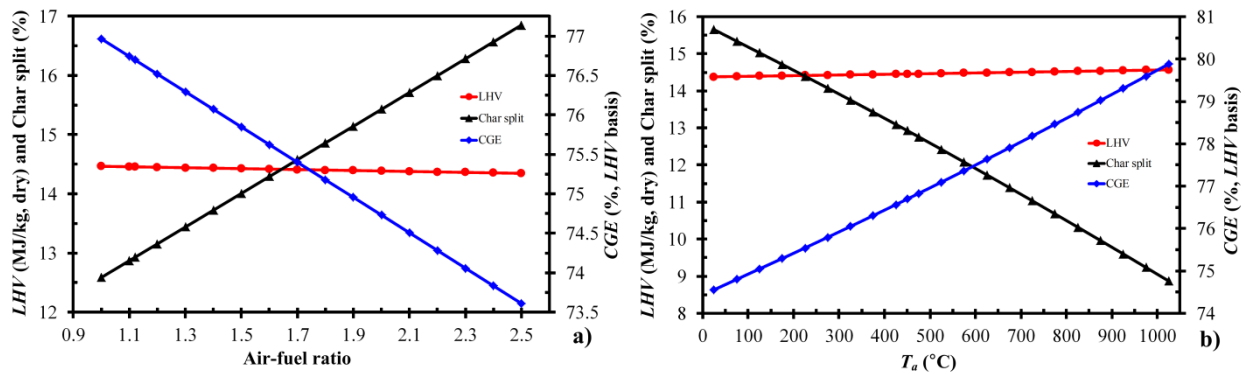


Fig. 6 Effect of a) air-fuel ratio and b) combustion air temperature on syngas LHV , gasifier CGE and char split fraction.

4.4 Sensitivity analysis: air-fuel ratio

Syngas composition was found to have a weak dependence on air-fuel ratio (mass basis). The largest change in the combustible gases was an increase from 45.7-47% for H_2 . Referring to Fig. 6 a), syngas LHV remains fairly constant. There is however a substantial decrease in CGE with increasing air-fuel ratio (CGE drops 3.35 percentage points). The decline in CGE can be attributed to the increase in char sent to the gasifier CZ and the resulting reduction in syngas mass flow rate. As air-fuel ratio increases the excess air lowers the temperature of the CZ, which in turn affects T_g . In order to maintain T_g at the desired temperature more char must be burned. In conclusion, air-fuel ratio should be as low as possible but high enough to ensure complete combustion of the char.

4.5 Sensitivity analysis: steam temperature

Syngas composition and LHV remain somewhat unchanged with a rise in T_{steam} (150-1000 °C). The elevated steam temperature does reduce the amount of char required in the gasifier CZ (14.25-10.16%), which has a positive effect on gasifier performance. The CGE increases from 75.66-78.87% (up 3.21 percentage points). The improvement in performance is only slight; therefore, preheating the steam to high temperature (e.g. 500-1000 °C) is not recommended considering the energy that would be required. Waste heat, where available, should be utilised for preheating purposes.

4.6 Sensitivity analysis: combustion air temperature

Preheating the combustion air from 25-1025 °C causes slight changes in syngas composition. The largest variation in the combustible gases was a drop from 46.64-44.57% for H_2 . This negative trend is offset by small increases in both CO and CH_4 . Figure 6 b) shows how syngas LHV increases due to the change in composition and how the char split fraction drops and CGE increases. The rise in CGE is substantial (5.33 percentage points) and is as a result of the drop in char split fraction. The amount of char required in the gasifier CZ is lowered with increasing T_a because the sensible heat of the air supplies a greater portion of the heat required by the gasifier. Based on these results, air preheating is more attractive than steam preheating and if waste heat is available, it should be used to increase T_a .

5. Conclusions

A computer simulation model of the FICFB gasifier was developed using Aspen Plus. The aim of the research work, which was to develop a model of the FICFB gasifier, to validate it against actual plant data and utilise it to examine the influence of the main operating parameters on gasifier performance, was achieved. The effects of varying T_g , biomass moisture content, $STBR$, air-fuel ratio, T_{steam} and T_a were investigated, the results of which revealed the following: T_g is the most important parameter with respect to syngas composition and has significant influence on LHV and CGE ; the gasifier should be operated in the T_g range 850-950 °C; biomass moisture content is the most significant parameter regarding CGE and should be as low as possible; $STBR$ is the most important parameter in terms of LHV but is the least significant in respect of CGE ; air-fuel ratio should be as low as possible while ensuring complete combustion; air preheating is more attractive than steam preheating.

Future work includes integration of the FICFB gasifier model developed here with an Aspen Plus solid oxide fuel cell model [11, 25].

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