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Thermodynamic Modeling of Allothermal Steam Gasification in a Downdraft Fixed-bed Gasifier

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Abstract. A process of converting a solid carbonaceous fuel into a gaseous energy carrier in presence of a gasifying medium at high temperature is called gasification. The resulting gaseous energy carrier, known as producer gas, is more versatile in its use than the original solid fuel. Gasification is widely considered as a more efficient and less polluting initial thermochemical upstream process of converting biomass to electricity. The objective of this study was to investigate the process of allothermal steam gasification in a fixed-bed downdraft gasifier for improved quality (HHV, high hydrogen content) of the producer gas generated. The study involved thermodynamic equilibrium modeling based on equilibrium approach in which the concentrations of the gaseous components in the producer gas at equilibrium temperature are determined based on balancing the moles in the overall gasification equation. The results obtained suggest that the maximum equilibrium yield of producer gas with high energy density is attained at a gasification temperature of around 820°C and a steam/biomass ratio of 0.825 mol/mol. The equilibrium yield was richer in hydrogen at 52.23%vol, and with a higher heating value of 11.6 MJ/Nm^3. Preliminary validation of the model results using experimental data from literature shows a close relationship. The study has further shown the advantage of using steam as a gasifying medium towards the improved quality of the producer gas generated.

1. Introduction

Gasification as a thermo-chemical process for converting solid fuel such as biomass into a combustible gas containing H_2, CH_4, CO, CO_2 and others in presence of a gasifying medium has been known for a while. Factors governing the performance of a biomass gasification process in terms of the component distribution in the producer gas include fuel type, reactor configuration, gas–solid residence time, reaction temperature, pressure, gasifying agent and catalyst. Among these factors, the type of reactor and gasifying medium influence the producer gas composition to a large extent [1]. Previous studies have shown that when steam is used as a gasifying medium, producer gas of a medium heating value (10 – 16 MJ/Nm^3) is obtained, which is higher than that from air gasification (4 – 6 MJ/Nm^3), and less costly than oxygen gasification (10 – 18 MJ/Nm^3) [2-6]. The addition of steam as a gasifying agent together with a catalyst in a gasification process makes it possible to obtain high-grade and nearly N_2-free producer gas [1,7]. In addition, steam gasification can generate a hydrogen-rich gas which offers cleaner combustion [8-10].

Although gasification is widely considered as a more efficient and less polluting initial thermochemical upstream process of converting biomass to electricity than direct solid fuel combustion processes, the performance of the gasification process is highly unpredictable especially small-scale biomass gasification which is targeted for developing country environment. The major culprits are unpredictable fuel behavior and unreliable operating conditions partly due to the inhomogeneous nature of biomass feedstock and the complex phenomena of a gasification process, whose effects are more pronounced in small-scale gasification systems. Gasification process modeling has been suggested as a way to handle the prediction of operation behavior during normal gasification [10]. Furthermore, modeling can guide the preparation and optimization of experiments to be undertaken in a real system. This paper presents the results of a study to establish the influence of key biomass feedstock properties (moisture content, heating value, ultimate and proximate analysis) and gasifier operating conditions (gasifying agent, reactor temperature, steam/biomass ratio) on the amount, composition and heating value of producer gas, and process efficiency. The results are meant to provide insights for the actual gasification process as a crucial step in the formulation of experimental work for validation purposes, to be carried out in a subsequent study.

Nomenclature

P	Operating pressure in the reactor (N/m^2)	$\frac{\dot{S}}{B}$	Mole flow rate of steam per mole of feedstock
p	Partial pressure of component (N/m^2)	$\dot{n}_i$	Mole flow rate of component in the producer gas
y	Mole fraction of component		
ΔG	Standard Gibbs Function of Reaction (kJ/kmol)	$\dot{w}$	mole flow rate of moisture per mole of feedstock
ΔH	Enthalpy change (kJ/kmol)	*Greek letters*	
ΔS	Entropy change (kJ/kmol.K)	η	Efficiency
R	Universal gas constant (kJ/kmol.K)	*Subscripts*	
T	Reaction Temperature (K)	HB	Hydrogen to carbon ratio in biomass feedstock
HHV	Higher Heating Value (MJ/Nm^3).	OB	Oxygen to carbon ratio in biomass feedstock
K_{equil}	Equilibrium constant	NB	Nitrogen to carbon ratio in biomass feedstock
CHP	Combined Heat and Power	SB	Sulfur to carbon ration in biomass feedstock
Ri	Reaction type in the reactor	G	Gasification parameter

Equilibrium modeling and experimental work on fixed-bed gasification has been reported by a number of researchers such as Umeki et al. [8], Adam et al. [11], Schuster et al. [4], Sheth and Babu [12], Zainal et al. [3], Sharma [13], Puig-Arnavat et al. [14], Jarungthammachote and Dutta [15], but not as widely reported as the research published on fluidized bed gasification. The thermodynamic modeling and experimental work on the performance of steam gasification in fixed-bed downdraft gasifier is still needed in order to generate more reliable information that can aid the optimal design of commercial small-scale gasifiers. This study has contributed to the thermodynamic modeling of steam gasification process, with an overall goal of improving the characteristic properties of the producer gas for better compatibility and higher efficiency in the downstream CHP system integration.

2. Gasification as an Energy Conversion Process

2.1 Materials

In the modeling study, Eucalyptus grandis wood physical and chemical properties given in Table 1 were applied. The physical and chemical properties were determined by authors using standard methods. The characteristic properties form part of the data necessary for modeling the steam gasification phenomena.

Table 1**:** Characteristic properties of the feedstock (Ugandan Eucalyptus grandis).

Property		Value
Moisture [wt%, w.b.]		10.9
Proximate Analysis [wt%, d.b.]	Volatile	88.4
	Fixed C	11.5
	Ash	0.1
Ultimate Analysis [wt%, d.b.]	C	48.45
	H	7.52
	O	43.86
	N	0.11
	S	0.06
HHV [MJ/kg, d.b.]		19.2
Ash Melting Temp. [^{o}C]	Sintering	1334

Steam, which is chosen as a gasifying medium is envisaged to be generated from a heat recovery steam generator unit of a small scale CHP plant based on an indirectly fired micro gas turbine process integration that utilizes the producer gas generated from the process. The steam is delivered to the reactor at a temperature of 500^{o}C and at atmospheric pressure. The steam flow into the gasification zone is in excess of the stoichiometric requirements for char gasification in order to provide favourable conditions for complete gasification of char, since sufficient interactions of the medium with both the char's external surfaces and internal pore reaction surfaces needs to be realized. Also the presence of steam in excess may favour the water-gas shift reaction. However too much steam may lower the reactor temperature and thus a good balance is needed. Experimental results involving steam gasification of wood in a fixed bed gasifier revealed that a steam to biomass ratio within the range 0.5 -0. 9 kg steam/kg dry biomass is appropriate [8].

2.2 The Gasification Process in a Downdraft Gasifier

During gasification, sequences of conversion processes take place; initially drying and pyrolysis, subsequently oxidation of volatiles and char and finally char gasification by carbon dioxide and steam. In a downdraft gasifier, feedstock (biomass) is fed from the top and moves down through the reactor. The gasifying agent (air, oxygen, steam, or a mixture of these) is fed from a certain height above the bottom of the reactor (Fig. 1). The heat required to sustain the endothermic pyrolysis process is either supplied from an external source or through partial oxidation of the feedstock. When air or oxygen is fed into the reactor, it meets the pyrolyzed char particles and combustible pyrolysis gases resulting in combustion (oxidation). The combustion products, noncondensable pyrolysis gases (CO, H_2, CH_4, CO_2, H_2O) and tars move down to the reduction zone where they are gasified in presence of char at high temperature. When steam is used as a gasifying agent and energy carrier, the process follows different reaction steps resulting in producer gas with more hydrogen per unit of carbon, with process intermediate products like H_2 reacting with char in the reduction zone. The producer gas exits the reactor near the hottest zone and thus providing an environment for tar cracking.

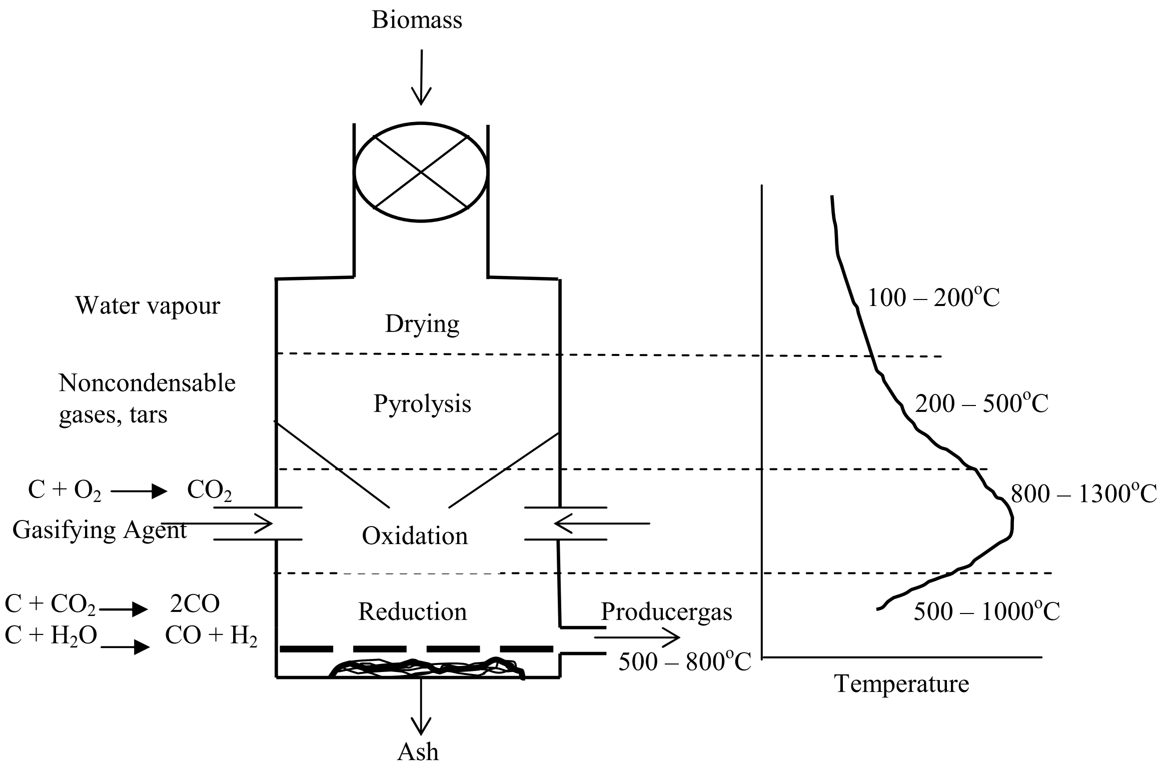

Fig. 1. Gasification reactions in a typical downdraft gasifier.

2.2.1 Chemical reactions during gasification

Understanding the chemistry of reactions in a gasifier is crucial in optimizing the desirable properties of the producer gas. The dominant heterogeneous (gas-solid) reactions are the Devolatilization (reaction R1 in Table 2) and char-gas (mainly O_2, CO_2 and H_2O) reactions (reactions R2 – R6). The dominant homogeneous (gas-gas) reactions are the oxidation of volatiles (reactions R7 – R9), the water-gas shift reaction (reaction R10) and the Methanation and methane reforming reactions (reactions R11 – R14) [6]. The rate of gasification of char depends on its reactivity and reaction potential in the gasifying medium. Oxygen for example is the most active (R5), followed by steam (R3) and carbon dioxide (R2). The carbon-hydrogen reaction is the slowest during char gasification. The gasification of char in steam, known as the water-gas reaction is perhaps the most important gasification reaction [10].

$$C + H_2O \rightarrow CO + H_2 \quad \text{(R3 in Table 2)}$$

The first step involves the dissociation of H_2O on a free active site of carbon (C_{fas}), releasing hydrogen and forming a surface oxide complex of carbon, C(O). In the second and third steps, the surface oxide complex produces a new free active site and a molecule of CO. The shift reaction (R10) is an important gas-phase reaction. It increases the hydrogen content of the producer gas at the expense of CO. The shift reaction is slightly exothermic and its equilibrium yield decreases slowly with increase in temperature. However, the shift reaction is independent of pressure. Table 2 shows the main reactions taking place during a typical gasification process, in agreement with several authors such as Basu [10], Barea and Leckner [6], Higman and Burgt [16].

Table 2: Main reactions in a biomass gasification process.

Stoichiometry	**Heat of reaction [kJ/mol]**	**Name**
Biomass $\longrightarrow$ char + tar + H_2O + light gas ($CO + CO_2 + H_2 + CH_4 + C_2 + N_2 + \dots$)	≥ 0	Devolatilization (R1)
Char-gas reactions		
$C + CO_2 \longrightarrow 2CO$	+173	Boudouard (R2)
$C + H_2O \longrightarrow CO + H_2$	+131	Steam gasification (R3)
$C + 2H_2 \longrightarrow CH_4$	-75	Hydrogasification (R4)
$C + 1/2O_2 \longrightarrow CO$	-111	Partial combustion (R5)
$C + O_2 \longrightarrow CO_2$	-394	Complete combustion(R6)
Homogeneous volatile oxidation		
$CO + 1/2O_2 \longrightarrow CO_2$	-283	Carbonmonoxide oxidation (R7)
$H_2 + 1/2O_2 \longrightarrow H_2O$	-242	Hydrogen oxidation (R8)
$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$	-803	Methane oxidation (R9)
Shift reaction		
$CO + H_2O \longleftrightarrow CO_2 + H_2$	-41	Water-gas shift (R10)
Methanation reactions		
$2CO + 2H_2 \longrightarrow CH_4 + CO_2$	-247	(R11)
$CO + 3H_2 \longleftrightarrow CH_4 + H_2O$	-206	(R12)
Steam reforming reaction		
$CH_4 + H_2O \longleftrightarrow CO + 3H_2$	+206	(R13)
$CH_4 + 1/2O_2 \longrightarrow CO + 2H_2$	-36	(R14)

2.2.2 Allothermal Steam Gasification

The concept of allothermal steam gasification is depicted in Fig. 2. When using steam as a gasifying medium in the allothermal mode, energy is required for heating the fuel to the reactor temperature and for sustaining the endothermic reactions. This was considered to be provided by heat transfer from the combustion of a re-circulated portion of the producer gas in the outer shell of the gasifier. The steam used for gasification was considered generated from a heat recovery process in the downstream CHP system, and supplied to the gasification zone at a temperature of $500^{o}C$ and at atmospheric pressure.

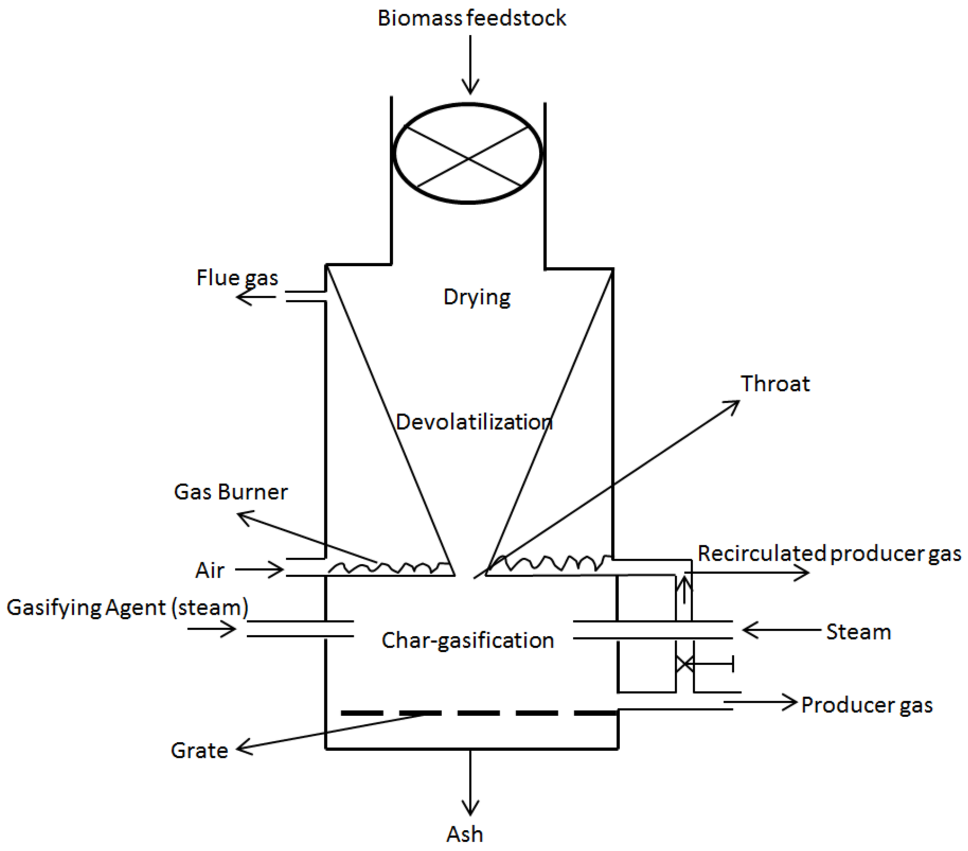

Fig. 2. Allothermal gasification in a downdraft gasifier based on internal gas recirculation.

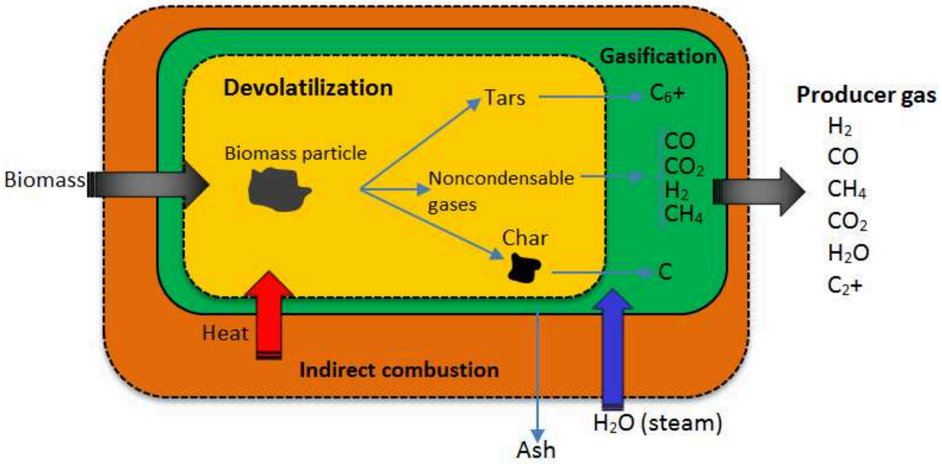

Fig. 3. Biomass particle gasification in a downdraft gasifier under allothermal conditions.

At particle level (Fig. 3), the biomass fed into the reactor becomes a source of noncondensable volatile gases, tar and char. When the particle is heated in an oxygen free environment, it rapidly releases volatile gases and it shrinks in its size due to loss of its hemicellulose and cellulose structure. As the devolatilized particle (char) consisting of mainly carbon descends down the reactor, meeting the gasifying agent (steam), the gasification reactions take place. The reaction of steam and char takes place on the surface of the char particle if the kinetic rate is higher than the diffusion rate of the gasifying medium; otherwise the gasifying medium can react with both outer and inner layers of the particle simultaneously depending on the porosity of the particle. Biomass char is highly porous and this results in a high rate of gasification due to vast interactions of the gasifying medium with outer and inner pore wall surfaces.

2.3 Modeling of the gasification process

The main approaches available for modeling of a gasifier are thermodynamic equilibrium modeling, kinetic modeling and computational fluid dynamics (CFD) [10]. The thermodynamic equilibrium modeling aims at predicting the equilibrium yield of the desired species in a reacting system and is independent of the reactor geometry [6, 10]. Kinetic modeling predicts the time dependent progress of reactions in the reactor, giving the product compositions at different positions along the gasifier. It can take into account the reactor`s geometry as well as its hydrodynamics. CFD models solve a set of simultaneous equations for conservation of mass, momentum, energy and elements over a discrete region of the gasifier. Thus they give distribution of temperature, concentration and other parameters within the reactor [10].

The choice of a modeling technique depends on the objectives of the study. A thermodynamic equilibrium model, for example, is independent of the gasifier design (zero-dimension) and is therefore convenient for studying the influence of feedstock properties and gasifier process parameters. The chemical equilibrium is achieved either by equilibrium constants computations or minimization of Gibbs free energy. Several authors have presented related techniques for equilibrium modeling of the gasification process which give reasonable prediction of the actual gasification phenomena [3,6,10,17,18]. Through such studies, an assessment of the effect of the reactor type has been made to validate equilibrium modeling applied to real biomass gasification units. Their conclusion is that chemical equilibrium is a good approach when simulating entrained-flow and down-draft fixed-bed gasifiers as long as high enough temperature and long enough gas residence time are achieved in the gasifier throat [6].

3. Model Execution, Results and Discussion

3.1 Model Formulation

The basic assumption in equilibrium modeling is that equilibrium is attained in the outlet streams. A reacting system is assumed to achieve its stable composition at chemical equilibrium. In line with these, the following assumptions apply at equilibrium of the gasification process:

- The Gibbs free energy of the system is at minimum i.e. the entropy of the system is at maximum
- There is no further change in the concentration of the reactants and products i.e. the residence time for reacting species is sufficiently high
- Ideal gas behavior for producer gas components
- The gas phase is assumed to be a system made up of five main species: H_2, CO, CO_2, CH_4 and H_2O

Though the processes taking place during steam gasification (drying, pyrolysis and char gasification) are frequently modeled in series, there is no sharp boundary between them, and they often overlap. In consideration of the above, the concentrations of species can be estimated from a single reaction lumping up the processes taking place in the reactor.

The simplified overall steam gasification equation can be of the form:

$$CH_{HB}O_{OB}N_{NB}S_{SB} + \left(\dot{w}+\frac{\dot{S}}{B}\right)H_2O \rightarrow \dot{n}_{CO}\,CO+\dot{n}_{CO_2}\,CO_2+\dot{n}_{H_2}\,H_2+\dot{n}_{H_2O}\,H_2O+\dot{n}_{CH_4}\,CH_4+\dot{n}_{N_2}\,N_2+\dot{n}_{SO_2}\,SO_2+\dot{n}_C\,C \cdot \qquad (1)$$

Where $CH_{HB}O_{OB}N_{NB}S_{SB}$ denotes the chemical formula of the dry biomass feedstock, $\dot{w}$ denotes the mole flow rate of moisture per mole of feedstock, $\frac{\dot{S}}{B}$ denotes the mole flow rate of steam per mole of dry biomass (molar steam-biomass ratio) and $\dot{n}_i$ denotes the mole flow of each specie in the producer gas per mole of dry biomass. The subscripts (HB, OB, NB, SB) in the chemical formula of biomass represent the mole ratio of the elements to carbon (H/C, O/C, N/C, S/C) for hydrogen, oxygen, nitrogen and sulfur respectively, known from the ultimate analysis. Char (carbon) is estimated from the proximate analysis. The gas composition was estimated from the molar balances for C, O and H.

The dominant reactions taking place in the reactor during steam gasification are:

R2 (Boudouard): $C + CO_2 \leftrightarrow 2CO$
R3 (Steam gasification): $C + H_2O \leftrightarrow CO + H_2$
R4 (Hydrogasification): $C + 2H_2 \leftrightarrow CH_4$
R10 (Water-gas shift): $CO + H_2O \leftrightarrow CO_2 + H_2$
R13 (Steam reforming): $CH_4 + H_2O \leftrightarrow CO + 3H_2$

The equilibrium constants for these equations can be expressed as:

$$K_{equil,\ R2} = \frac{C_{CO}^{\ 2}}{C_{CO_2}} = \frac{p_{CO}^{\ 2}}{p_{CO_2}} = \frac{y_{CO}^{\ 2}P}{y_{CO_2}} = \exp\left(-\frac{\Delta G}{RT}\right)$$

$$K_{equil,\ R3} = \frac{C_{CO}C_{H_2}}{C_{H_2O}} = \frac{p_{CO}p_{H_2}}{p_{H_20}} = \frac{y_{CO}y_{H_2}P}{y_{H_2O}} = \exp\left(-\frac{\Delta G}{RT}\right)$$

$$K_{equil,\ R4} = \frac{C_{CH_4}}{C_{H_2}^{\ 2}} = \frac{p_{CH_4}}{p_{H_2}^{\ 2}} = \frac{y_{CH_4}}{y_{H_2}^{\ 2}P} = \exp\left(-\frac{\Delta G}{RT}\right)$$

$$K_{equil,\ R10} = \frac{C_{CO_2}C_{H_2}}{C_{CO}C_{H_2O}} = \frac{p_{CO_2}p_{H_2}}{p_{CO}p_{H_2O}} = \frac{y_{CO_2}y_{H_2}}{y_{CO}y_{H_2O}} = \exp\left(-\frac{\Delta G}{RT}\right)$$

$$K_{equil,\ R13} = \frac{C_{CO}C_{H_2}^{\ 3}}{C_{CH_4}C_{H_2O}} = \frac{p_{CO}p_{H_2}^{\ 3}}{p_{CH_4}p_{H_2O}} = \frac{y_{CO}y_{H_2}^{\ 3}P^2}{y_{CH_4}y_{H_2O}} = \exp\left(-\frac{\Delta G}{RT}\right)$$

$$\Delta G = \Delta H - T\Delta S$$

The values of the enthalpy change and entropy of reaction in the temperature range of interest were calculated using JANAF thermochemical property data appended in Applied Combustion textbook by Keating [19].

The extent of char (carbon) gasification depends on both the concentration and reaction rate of the gasifying medium. The concentration of steam in the reactor is much higher than that of CO_2 and H_2 among the species capable of reacting with char. Also the rate of steam gasification (R3) is about two to five times faster than that of carbondioxide gasification (R3) [20]. The char-hydrogen gasification (R4) is the slowest of all. Equilibrium and kinetic predictions were compared by Dupont et al. [21] and the conclusion was that steam reforming of methane is far from equilibrium under the operating conditions of interest for biomass gasifiers and thus the reaction is kinetically limited. The steam reforming reaction of methane is realized if a catalyst like nickel is inserted in the gasification zone. Taking into consideration the requirements for the dominant reactions above, only two reactions (R3 and R10) are capable of taking place to a large extent. Therefore towards equilibrium, steam gasification and water-gas shift reactions are considered as the main reactions in the reactor. Thus the equilibrium constants of the two reactions were determined over a desired temperature range to establish their influence on the producer gas components.

3.2 Thermodynamic equilibrium in the gasifier

Equilibrium modeling was used in this study to predict the performance of a downdraft steam gasification process in terms of feedstock conversion, gas composition, heating value, and gasification efficiency. The behavior of tars and ash sintering were assumed to have negligible influence on the process and thus were not modeled in this study; the high temperature gasification conditions in the reactor provide an environment for cracking the tars into lighter hydrocarbons, and the ash melting temperature for the feedstock used in this study is far above the gasifier operating temperature. The ash content in the feedstock is also very low in the range of 0.1% as shown in Table 1.

The rate of steam gasification of char increases as the temperature of the gasification zone increases as observed from the equilibrium constant variation with temperature (Table 3). Within the temperature range of interest, the heterogeneous steam gasification of char is far from equilibrium. Therefore high temperature favours the reaction of char with steam resulting in high yield of H_2 and CO.

Table 3: Equilibrium constant of the dominant gasification zone reactions at typical gasifier operating temperatures.

	Equilibrium constant (K_{equil})		
Reaction	**1000 [K]**	**1100 [K]**	**1200 [K]**
R3: Heterogeneous steam gasification reaction, $C + H_2O \leftrightarrow CO + H_2$	2.49	7.20	38.00
R10: Homogeneous water-gas shift reaction, $CO + H_2O \leftrightarrow CO_2 + H_2$	1.13	0.99	0.74

The homogeneous water-gas shift reaction shows a decreasing trend of its equilibrium constant with increase in temperature. This implies that as the temperature increases, the rate of the forward reaction decreases and thus the amount of hydrogen formed is less. This reaction reaches equilibrium within the typical gasification zone temperature. Interpolating between the values, the water-gas shift reaction attains its equilibrium state at 1093 K (820^{o}C). The conclusion is that with steam gasification, a reactor temperature close to 820^{o}C is high enough to generate producer gas with high H_2 and CO contents due to favourable conditions for the most dominant reactions. The shift reaction further converts the CO available to more H_2 as it attains its equilibrium state.

3.3 Description of the gas phase composition

From the ultimate analysis, the woody biomass specie considered has negligible sulfur and nitrogen and thus this eliminates their gaseous constituents in eq. (1) for modeling simplification. The char was assumed to be pure carbon, which was assumed to be fully converted by reaction with steam in the gasification zone, and its amount is estimated from the proximate analysis. The dry woody biomass sample, whose chemical formula ($CH_{1.86}O_{0.68}$) is estimated from the ultimate analysis, is devolatilized and the remaining char is gasified by steam to yield five main gas species namely CO, H_2, CH_4, CO_2 and H_2O. The concentrations of these gas species are predicted at or near the equilibrium temperature for the dominant water-gas shift reaction. A steam-biomass ratio of 0.6 kg steam per kg of dry biomass was used which falls within the range reported from experimental work with fixed-bed gasifiers [8]. The amount of water vapour in the reactor is a summation of the steam flow rate and the evaporated moisture from the biomass. The overall steam gasification equation with evaluated stoichiometric coefficients yielded the solution as shown in eq. (2):

$$CH_{1.86}O_{0.68} + 0.993H_2O \rightarrow 0.3645CO + 0.4375CO_2 + 1.0935H_2 + 0.198CH_4 + 0.4335H_2O\,. \qquad (2)$$

The reaction of steam with char yields more H_2 and CO that adds to that formed during devolatilization. The water-gas shift reaction converts some of the steam to more hydrogen as the reaction approaches equilibrium. This results in high hydrogen concentration in the producer gas and is thus the reason for the high concentration of hydrogen (52.23%) shown in Table 4. There is a significant concentration of CO_2 (20.9%) in the producer gas, arising mainly from the water-gas shift reaction. The heating value of the producer gas is high at 11.6 MJ/Nm^3 with major contribution by hydrogen. Therefore, using steam as a gasifying medium leads to generation of good quality producer gas with high HHV. The high energy density producer gas can then be utilized in a CHP system to generate heat and electricity efficiently. It can be concluded that the maximum equilibrium yield of producer gas with high energy density is attained at a gasification temperature of around 820^{o}C and a steam/biomass ratio of 0.825 mol/mol.

Table 4: Composition of the producer gas at equilibrium at a temperature of 820^{o}C.

	Composition		
Component	Mol flow/mol of dry wood	Mole (%)/mol of dry producer gas	Experimental yield* Mole (%)/mol of producer gas
H_2	1.0935	52.23	48.88
CO	0.3645	17.41	22.7
CH_4	0.1980	9.46	6.22
CO_2	0.4375	20.90	22.2
H_2O	0.4335		

*Data taken from Karmakar and Datta [18]

The comparison of the model results with experimental data shows comparable gas composition. In addition, the optimized steam gasification conditions (temperature and steam flow rate) in this study are in agreement with the experimentally determined values for steam gasification of wood by Franco et al. [9]. Therefore, systematic equilibrium modeling calculations are capable of giving a true picture of the producer gas yield in a physical reactor.

3.4 Gasification Efficiency

Cold gas efficiency was used to reveal the gasification performance. The equilibrium model assumed 100% carbon conversion to gaseous products under favourable reactor temperature and sufficient steam flow. The heat requirements of the process and for maintaining the reactor temperature of 820^{o}C was estimated to be met by re-circulating 30% of the producer gas generated during the entire gasification process. The heat requirements include the energy for drying and devolatilization of the feedstock, energy required to raise the temperature of the devolatilization products, steam and the reactor to the gasification temperature and the energy required for the endothermic reactions in the reduction zone. The calculated heat requirement is increased by a factor of 2 to cater for all unknown reactions in the reactor such as tar cracking as well as the system irreversibility. The cold gas efficiency based on HHV was determined as the ratio of the energy contained in the net producer gas flow to the energy contained in the supply streams into the reactor. The energy in the supply streams include the energy content of the solid wood feedstock and the energy of the steam flowing into the reactor. For the re-circulated producer gas, the burner efficiency was taken to be 80%, with losses in the flue gas and heat transfer inefficiencies accounting for 20%. The thermal power delivered by the producer gas generated is capable of generating 100 kW$_e$ when the producer gas is utilized in a novel small-scale CHP system integration, which in turn provides the steam requirements during gasification. The results of producer gas flow and energy analysis of the reactor are presented in Table 5.

Table 5: Energy flow and gasification efficiency based on the equilibrium model results for a fixed-bed downdraft gasifier.

Property	Value
Wood feed rate	0.02 [kg/s]
Steam flow rate at 500°C, 1 bar	0.012 [kg/s]
Gross producer gas generated	0.04 [Nm^3/s]
Re-circulated producer gas	0.012 [Nm^3/s]
Net producer gas flow from the system	0.028 [Nm^3/s]
HHV of producer gas	11.6 [MJ/Nm^3]
Process heat requirements in the reactor	115 [kW_{th}]
Reactor temperature in the gasification zone	820[°C]
Gas burner efficiency for re-circulated producer gas	80%
Gasification efficiency (η_G)	76.3%

4. Conclusions

The results reveal that the quality of the producer gas as well as the reactor efficiency is greatly improved by allothermal steam gasification, without major modification of the conventional downdraft gasification reactor. With steam gasification, a reactor temperature of 1093 K is high enough to generate a producer gas with high H_2 and CO contents due to favourable conditions for the most dominant reactions and thus resulting in producer gas with high energy density. The shift reaction further converts the steam to more hydrogen as it attains its equilibrium state at 1093K. The results in this study have qualitatively and quantitatively demonstrated the influence the gasifier operating conditions have on the producer gas properties for given feedstock characteristic properties. The producer gas composition obtained in this study is similar to the literature data published on downdraft gasifiers. It is in the interest of the authors that case specific experimental work to validate the results from the thermodynamic equilibrium model will be carried out in further work in order to gain sufficient confidence in applying the results to process optimization and commercial-scale gasifier design.

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