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Chapter

Combating Greenhouse Effects through Biomass Gasification: A Focus on Kinetic Modeling of Combustion and Gasification Zones

Sunday J. Ojolo and Musbau G. Sobamowo

Abstract

The prevalent challenges of global warming, food security, food production, crop production systems, environment control called for consideration and better utilization of green energy system such as biomass. The advanced thermo-chemical conversion of the renewable energy source which is aimed at production of optimal yield of energy has not been well understood. In order to have better physical insights into the detailed structure of the biomass burning process inside a solid bed, the kinetics of the biomass combustion and gasification must be properly analyzed. Consequently, improved kinetic models of the combustion and gasification zones in the thermochemical conversion system are very required. Therefore, the present study focuses on the development of improved kinetic modeling of the combustion and gasification zones in the biomass gasification system. The performance of the biomass gasifier system is evaluated through the equivalence ratio, the syngas composition, cold gas efficiency and lower heating value. Also, the effects of the equivalent ratio on gas compositions, the gasifier performance and the low heating value of the biomass are analyzed. From the analysis, it is established that the concentration of CO, H_2 and CH_4 in the gasifier decrease as the equivalence ratio increases. However, CO_2 concentration increases with an increase in the equivalence ratio. The cold efficiency and LHV decreases as the equivalence ratio increases while the gas yield increases with an increase in the equivalence ratio. The quantity of gas produced increases as the amount of oxygen consumed increases. Also, the ratio of CO/CO_2 decreases as the temperature of the reduction zone increases. Such analysis as presented in this work, is very useful as a time-saving and cost-effective tool for designing and optimizing the biomass gasifier. Therefore, it is evident that this work will play a significant role in the system design including analysis of the distribution of products and ash deposit in the downdraft gasifiers.

Keywords: Kinetic models, Combustion Zone, Gasification Zone, Downdraft Biomass Gasifier

1. Introduction

In the past few decades, the increasing concerns of global warming and fuel prices have aroused the development of new technologies in alternative energy. However, meeting the future demands for electricity, heat, cooling, fuels, and materials with highly limited and fluctuating resources, requires careful planning and allocation of the available resources with highly flexible systems. One of the few renewable resources that is capable of supplying the needs is biomass energy. Biomass as a source of renewable energy and as an organic material from plants and animals can be biochemically and thermochemically converted to produce heat, electricity and fuels. Among all the biomass conversion processes, gasification is one of the most promising [1]. Biomass gasification allows an environmentally friendly energy production. In such a thermochemical conversion process of solid fuel, the most important properties relating to the thermal and biological conversions are moisture content, ash content, volatile matter, and energy density. Therefore, an assessment of the use of biomass as a fuel requires a basic understanding of their composition, characteristics, and performance. The performance of the renewable energy sources in the combustion and gasification systems is ultimate determined by it specific properties [2]. Since biomass materials exhibit a wide range of moisture contents which affect their low and high heating values as a fuel source, it is very important to establish the moisture content of the biomass materials. High or excessive moisture content could defeat the main purpose of the biomass gasification process [3]. Also, the amount of the inorganic component (ash content) in biomass is very important to be determined especially for temperature gasification as melted ash may cause problems in the reactor [2]. The effects of moisture and ash contents on the low heating value (LHV) of some types of biomass are shown in **Table 1**.

The thermal conversion process which involves incomplete combustion of biomass due to insufficient amounts of oxygen from the available supply of air, produces synthetic gases (syngas). Although, the actual biomass syngas composition depends on the gasification process, the feedstock composition and the gasifying agent, a typical syngas by weight from gasification of wood contains approximately 15–21% hydrogen (H_2), 10–20% carbon monoxide (CO), 11–13% carbon dioxide, and 1–5% of methane which are combustible gases. The nitrogen gas (N_2) involved in the gasification process is not combustible but it dilutes the syngas as it enters and burns in an engine. Compared to biomass combustion, biomass gasification has a lower environmental impact due to less greenhouse gas emission. Therefore, biomass gasification has been beneficial in decreasing greenhouse gases emissions. The reduction of fossil fuels dependence for energy supply, the decrease of land use and soil contamination for waste disposal, the higher efficiency and reliability of a

Biomass type (%)	Moisture content (%)	Ash content (dry) (kJ/kg)	Lower heat value
Wood	10–60	0.25–1.70	8,400-17,000
Bagasse	40–60	1.70–3.80	7,700-8,000
Stalk	10–20	0.10	16,000
Rice husks	9	19.00	14.000
Gin trash	9	12.00	14,000

Source: Quaak et al. *[2].*

Table 1.
Effects of moisture and ash contents on LHV of some types of biomass.

grid-connected power net, and, on a larger scale, contribution to air pollution control and global warming reduction are the reasons for the increasing utilization of the biomass gasification technologies.

Indisputably, the optimal yield of synthetic gases from gasifiers has been the main focus of the thermochemical conversion technologies. Based on the method of air introduction, solid fuel usage in the gasification zone and the direction of the syngas leaving the gasifier, there are four types of gasifiers, namely, updraft or countercurrent gasifiers; downdraft or co-current gasifiers; crossdraft gasifiers; and fluidized-bed gasifiers. These four types of gasifiers can be broadly classified as fixed and fluidized bed gasifiers. Yang et al. [4] reported that fixed bed gasification is the most common technology for the energy use of biomass and solid municipal wastes. They are relatively easy to design and operate but have limited capacity. Therefore, fixed bed gasifiers are preferred for small to medium scale applications with thermal requirements up to 1 MW [5, 6]. Fixed bed gasifiers include updraft and downdraft gasifiers The updraft gasifier comes with simple design,, high charcoal burn-out and internal heat exchange. Such reactor has low gas exit temperatures and. However, in such reactor, there is possibility of "channeling" in the equipment, which can lead to oxygen break-through and explosion. The requirement of installing automatic moving grates coupled with the problems associated with the disposal of the tar-containing condensates that result from the gas cleaning operations are also some of the major setbacks in the wide applications of the type of gasifier. **Table 2** shows the Typical Characteristics of Fixed-Bed and Fluidized-Bed Gasifiers.

Downdraft gasification is a comparatively cheap method of gasification that can yield producer gas with very low tar content. The downdraft gasifier has a simple and stable design, making it effective for small and modular applications if it is well designed. However, downdraft gasifiers cannot be used in some unprocessed fuels. Such gasifier produces higher ash content fuels (slagging) than updraft gasifiers. Also, fluffy, low-density materials give rise to flow problems and excessive pressure drop, and the solid fuel must be pelletized or briquetted before use. As compared to updraft gasifier, downdraft gasifier has lower efficiency due to the lack of internal heat exchange and the lower heating value of the gas. Also, it can only be used in a power range of less than 1 MW due to the necessity of maintaining uniform high temperatures over a given cross-sectional area. The operation of the fixed bed

Characteristics	Fixed-bed downdraft	Fluidized-bed gasifier
Fuel size(mm)	10–200	0–20
Ash content (%wt)	< 6	< 25
Moisture content	> 10, < 25	> 30
Operating temperature (°C)	800–1400	750–950
Control	Simple	Average
Turndown ratio	4	3
Capacity (MW)	< 2.5	< 1–50
Hot gas efficiency (full load %)	85–90	—
Cold gas efficiency (full load %)	65–75	—
Tar content (g/Nm^3)	< 0.5	< 1.5
Low Heating Value (kJ/Nm^3)	4.5–5.0	1.0

Table 2.
Typical characteristics of fixed-bed and fluidized-bed gasifiers.

gasifiers is influenced by the morphological, physical and chemical properties of the fuel. In such reactors, there are technical problems such as lack of bunker flow, slagging and extreme pressure drop over the gasifier.

In order to combat these problems, a fluidized bed gasifier was developed. The fluidized-bed gasifiers are able to handle a wide range of biomass with high throughput. However, the fluidized bed design presents several flaws such as particle fracture due to collision with the walls of the vessel, propeller blades, and adjacent particles that render the packing ineffective and useless. Maintenance costs associated with the moving parts increase the overhead needed to repair the damage. These flaws make the immobilized packed design (fixed bed design) a more attractive and practical alternative since it eliminates the moving parts and their inherent problems, and also, allows for packing or media to be simply regenerated once it becomes saturated with contaminants. Instability of the reaction bed, feeding problems and fly-ash sintering in the gas channels can occur in fluidized bed. Additionally, the fluidized bed gasifier produces high tar content of the product gas (up to 500 mg/m^3 gas) with incomplete carbon burn-out, and poor response to load changes. A solution to the problem of tar entrainment in the gas stream is provided by the utilizations of downdraft gasifiers. In fact, the downdraft gasifiers have the possibility of producing a tar-free gas suitable for engine applications. Because of the lower level of organic components in the condensate, downdraft gasifiers suffer less from environmental objections than updraft and fluidized gasifiers.

The understanding of the interactions between chemical and physical mechanisms occurring in the gasifier is of fundamental importance for the optimal design of the reactor. This therefore, provokes the simulations of the thermochemical processes in the gasifiers. The increased computer efficacy and advanced numerical techniques as possessed in various numerical simulation techniques such as CFD tools have offered an effective means of simulating the physical and chemical processes in the biomass thermo-chemical reactors (such as fluidized beds, fixed beds, combustion furnaces, firing boilers, rotating cones and rotary kilns) under various operating conditions in different virtual environments. The CFD simulates the fluid flow behavior, heat and mass transfer, chemical reactions, phase changes and mechanical movement. CFD model results are capable of predicting both qualitative and quantitative information. The results of accurate simulations with the aid of CFD tools can help to optimize the system design and operations and understand the dynamic processes inside the reactors. Also, the use of CFD software for the flow visualization in a fixed bed gasifier has resulted in saving stresses and time engages in using other modeling and simulation methods. Additionally, the predictions made by the use of CFD software can help in the design of the fixed bed gasifier. Consequently, Fletcher et al. [7] simulated the flow and reaction in an entrained flow biomass gasifier using the CFX package. With the aid of CFD model, Gerun et al. [8] presented a two-dimensional heat and mass transfer for the oxidation zone in a two-stage downdraft gasifier. Meanwhile, Zhou et al. [9] adopted a CFD model to simulate the optimal conditions for the production of hydrogen-rich gas in a fluidized bed biomass gasifier. A further study was presented by Papadikis and Gu [10]. The authors presented CFD modeling of the fast pyrolysis of biomass in fluidized bed reactors. In the same year, Wang and Yan [11] carried out an overview of different CFD studies on thermo-chemical biomass conversions such as gasification and combustion processes in fixed beds, furnaces, and fluidized beds.

In some specific studies, Yimlaz, et al. [12] and Cornejo and Farias [13] adopted the multiphase model in FLUENT while Paes [14], Watanabe and Otaka [15], Huang and Ramaswamy [16] and with the aid of mathematical user-defined functions, Cuoci, et al. [17] presented the mathematical model of the thermochemical processes. Focusing on using oil-palm fronds, Atnaw and Sulaiman [18] submitted a
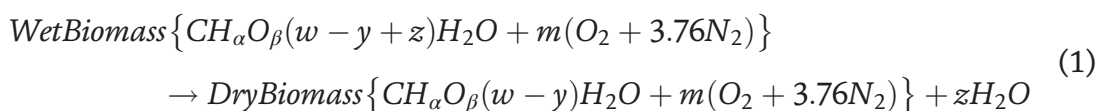
modeling and simulation study of downdraft gasifier. With the aid of computational fluid dynamics techniques, Hamzehei et al. [19] adopted multi-fluid Eulerian modeling while incorporating the kinetic theory for solid particles to simulate the unsteady-state behavior of two-dimensional non-reactive gas–solid fluidized bed reactor. The CFD tool was utilized by Tingwen et al. [20] to present detailed high-resolution simulations of coal injection in a gasifier applying. In the following year, the hydrodynamic behaviors of an internally interconnected fluidized beds (IIFB) which is a novel, self-heating biomass fast pyrolysis reactor was studied by Zhang et al. [21] using the computational tool. The hydrodynamic behavior in a circulating fluidized bed (CFB) riser was studied by Peng et al. [22] with the help of the CFD model. Chen et al. [23] analyzed a three-dimensional simulation of gas–solid flow in biomass circulating fluidized bed gasifier's riser. Considering the conditions of highly preheated air and steam, Wu et al. [24] showed the a two-dimensional CFD simulation of biomass gasification in a downdraft fixed-bed gasifier. Luo [25] and Liu et al. [26] submitted a three-dimensional CFD model to simulate the full-loop of a dual fluidized-bed biomass gasification system consisting of a gasifier, a combustor, a cyclone separator, and a loop-seal. In the recent year, Lu et al. [27] used CFD model to analyze an updraft gasifier that uses carbonized woody briquette as fuel while in the same year, Kumar et al. [28] investigated the thermochemical conversion of biomass in a downdraft gasifier with a volatile break-up approach. Yang et al. [4] carried out a Eulerian–Lagrangian simulation of air–steam biomass gasification in a three-dimensional bubbling fluidized gasifier.

The predictions of the temperature and pressure distributions and histories of a biomass particle in a downdraft gasifier are major determinants of a detailed characterization study of thermochemical conversions of biomass. Such predictions are heavily dependent on the kinetic modeling of the reaction process in the biomass gasification system [29, 30]. Consequently, improved kinetic models in the combustion and gasification zones in the thermochemical system are very needed. Therefore, the present study focuses on the developing improved kinetic models of the combustion and gasification zones in the biomass gasification system [31, 32]. The performance of the biomass gasifier system is evaluated through the equivalence ratio, the syngas composition, cold gas efficiency and lower heating value (LHV). Also, the effects of the equivalent ratio on gas compositions, the gasifier performance and the low heating value of the biomass are analyzed and presented.
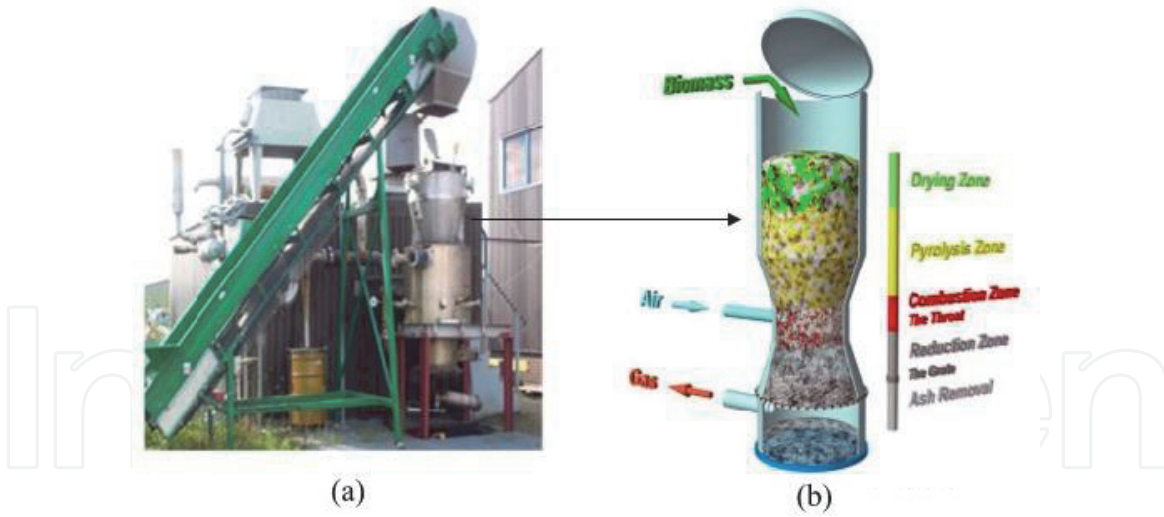
2. The description of downdraft biomass gasifier

Downdraft gasifier has four distinct zones which are drying, pyrolysis, oxidation/combustion, and reduction/gasification zones from top to bottom of the gasifier, respectively. In this type of gasifier, air or oxygen is usually admitted or drawn to the fuel bed in the drying zone through intake nozzles from the throat attached to the combustion zone of the gasifier as shown in **Figure 1a**.

In the **drying zone**, biomass fuel descends into the gasifier and its moisture is removed by evaporation using heat generated in the zones below. The reaction model is shown in Eq. (1) and **Figure 2**.

$$WetBiomass\{CH_\alpha O_\beta(w-y+z)H_2O + m(O_2 + 3.76N_2)\}$$
$$\rightarrow DryBiomass\{CH_\alpha O_\beta(w-y)H_2O + m(O_2 + 3.76N_2)\} + zH_2O \tag{1}$$

After the evaporation of free surface water from the biomass as shown in Eq. (1), the dried biomass fuel descends to the pyrolysis **zone** where irreversible
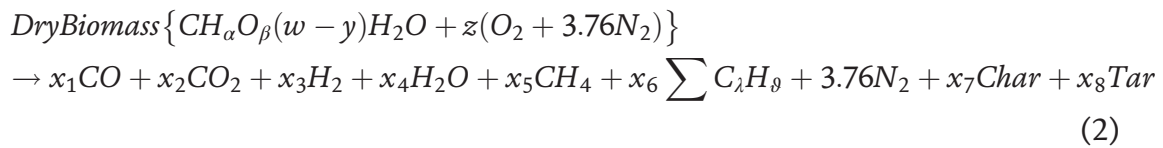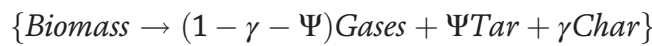
Figure 1.
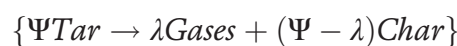*(a) Downdraft biomass gasification plant. (b) Downdraft biomass gasifier.*
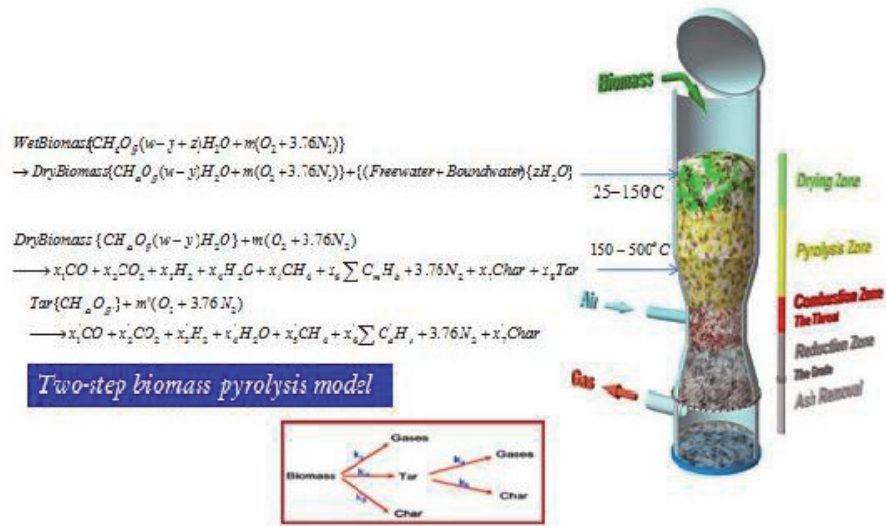
Figure 2.
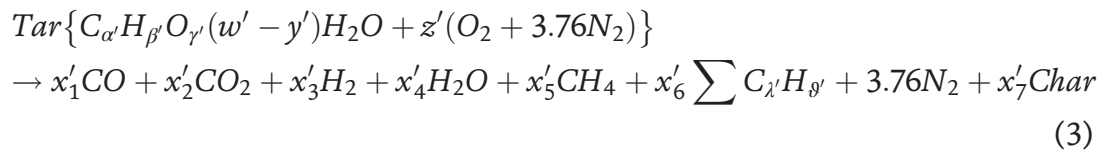*Reactions at the drying and pyrolysis zones in the downdraft biomass gasifier.*

thermal degradation takes place (Eq. (2)). The drying process is achieved by using the released heat energy released from the partial oxidation of the pyrolysis products. When the producer gas flows downwards through the reactor, it enables the pyrolysis gases to pass through hot bed of char which is around 1100°C. Thus, it will crack most of the tars into light chain hydrocarbon and water vapors as shown in Eq. (3) and **Figure 2**.
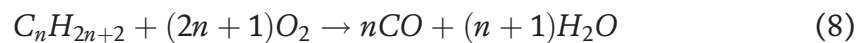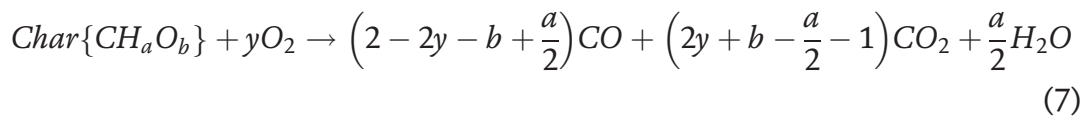
Primary Pyrolysis

$$\{Biomass \rightarrow (1 - \gamma - \Psi)Gases + \Psi Tar + \gamma Char\}$$

$$DryBiomass\{CH_\alpha O_\beta(w - y)H_2O + z(O_2 + 3.76N_2)\}$$
$$\rightarrow x_1CO + x_2CO_2 + x_3H_2 + x_4H_2O + x_5CH_4 + x_6 \sum C_\lambda H_\vartheta + 3.76N_2 + x_7Char + x_8Tar$$

$$(2)$$

Secondary Pyrolysis

$$\{\Psi Tar \rightarrow \lambda Gases + (\Psi - \lambda)Char\}$$

$$Tar\{C_{\alpha'}H_{\beta'}O_{\gamma'}(w' - y')H_2O + z'(O_2 + 3.76N_2)\}$$
$$\rightarrow x_1'CO + x_2'CO_2 + x_3'H_2 + x_4'H_2O + x_5'CH_4 + x_6'\sum C_{\lambda'}H_{\vartheta'} + 3.76N_2 + x_7'Char \tag{3}$$
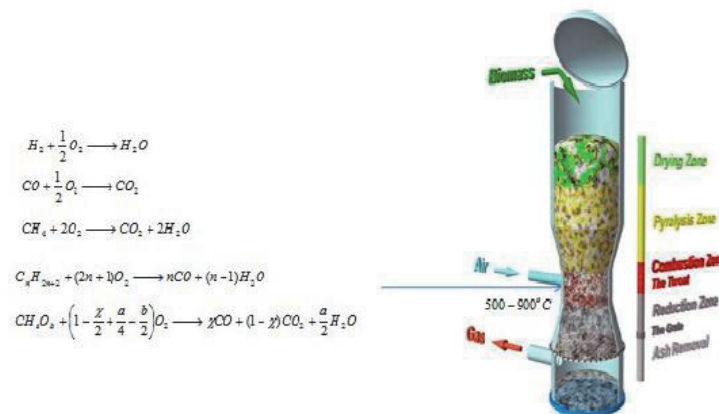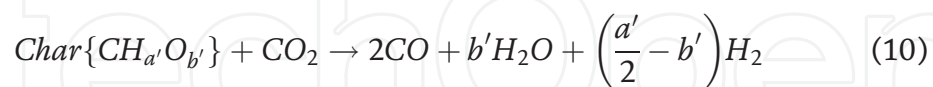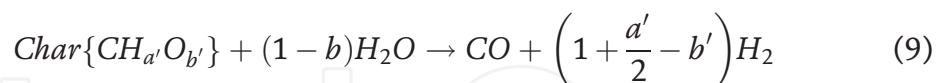
The Tar is given as $C_{6.407}H_{11.454}O_{3.482}$ while the Char is $CH_{0.2526}O_{0.0237}$.

In the **oxidation/combustion zone**, the volatile products and the char produced during pyrolysis are partially oxidized (Eqs. (4)–(8)) in the exothermic reactions resulting in a rapid rise of temperature up to 1200°C in the throat region. The heat generated is used to drive the gasification reactions.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{4}$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \tag{5}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{6}$$

$$Char\{CH_aO_b\} + yO_2 \rightarrow \left(2 - 2y - b + \frac{a}{2}\right)CO + \left(2y + b - \frac{a}{2} - 1\right)CO_2 + \frac{a}{2}H_2O \tag{7}$$

$$C_nH_{2n+2} + (2n + 1)O_2 \rightarrow nCO + (n + 1)H_2O \tag{8}$$
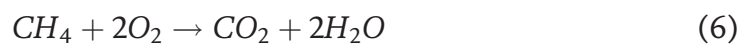
It should be stated that the combustion zone determines the temperatures in the gasifier and the reactions in the other zones and is therefore pivotal in the gasification process. **Figure 3** depicts the combustion reactions in the downdraft gasifier.

The last zone in the downdraft gasifier is the **reduction zone** often refers to as the gasification zone as shown in **Figure 4**. In this zone, the char produced during pyrolysis is converted to the producer gas by reacting with the hot gases from the upper zones. The gases are reduced to form a greater proportion of H_2, CO and CH_4. While leaving the gasifier at the temperature between 200°C and 300°C, the produced gases carry over some dust, pyrolytic products (tar), and water vapor and these are removed by scrubber and electrostatic precipitator.
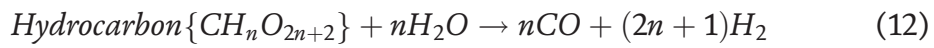
$$Char\{CH_{a'}O_{b'}\} + (1 - b)H_2O \rightarrow CO + \left(1 + \frac{a'}{2} - b'\right)H_2 \tag{9}$$

$$Char\{CH_{a'}O_{b'}\} + CO_2 \rightarrow 2CO + b'H_2O + \left(\frac{a'}{2} - b'\right)H_2 \tag{10}$$
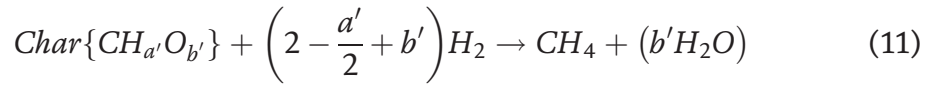

Figure 3.
Reactions at the combustion zone in the downdraft biomass gasifier [33].
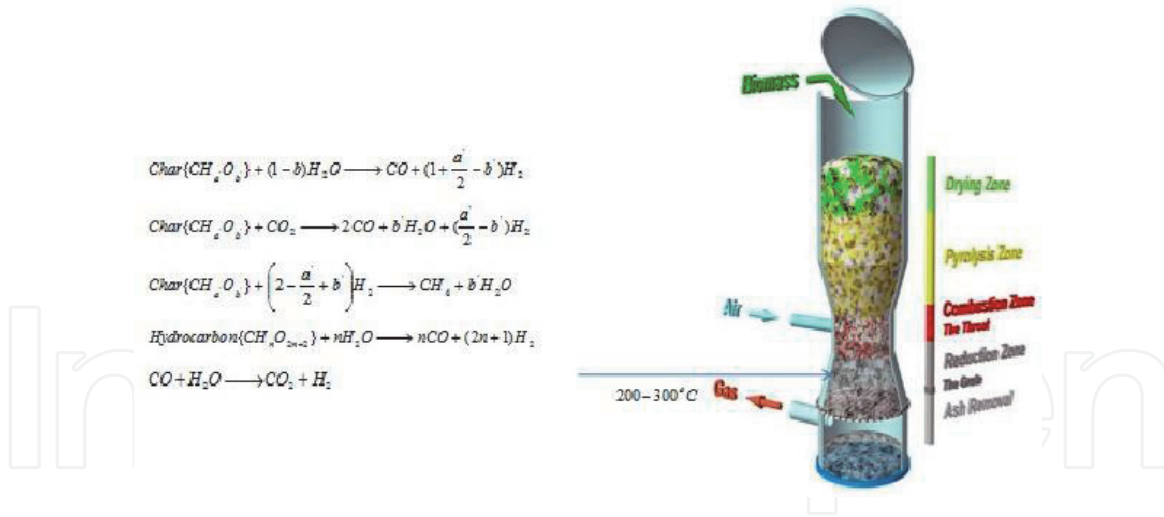
Figure 4.
Reactions at the reduction zone in the downdraft gasifier.

$$Char\{CH_{a'}O_{b'}\} + \left(2 - \frac{a'}{2} + b'\right)H_2 \to CH_4 + (b'H_2O) \tag{11}$$

$$Hydrocarbon\{CH_nO_{2n+2}\} + nH_2O \to nCO + (2n + 1)H_2 \tag{12}$$

$$CO + H_2O \to CO_2 + H_2 \tag{13}$$

where a = 0.2526 and b = 0.0237.

3. Kinetic reactions models for the combustion and the gasification processes

The combustion of CO_2, CO, H_2, CH4 and Hydrocarbon as well as the char combustion and gasification chemical-reactions are determined through improved chemical models. The models involve both homogeneous and heterogeneous reactions. The heterogeneous reaction-rates were determined by combining an Arrhenius kinetic-rate and a diffusion rate using the kinetics/diffusion surface reaction model. Homogeneous reaction-rates were described by a turbulent mixing rate using the eddy dissipation model.

The kinetic reaction rates in the gas phase and of the char are given as.

3.1 Hydrogen combustion

$$r_{H_2-O_2} = \min\left(\left\{2\varepsilon_{H_2} A_{H_2} T_e^{-1.5}. \exp\left(\frac{-E_{H_2}}{RT_e}\right)C_{H_2}^{1.5}C_{O_2}\right\}, C_{mix}\rho_{H_2}\left[\frac{150D_{H_2}(1-\varepsilon_{H_2})^{2/3}}{l_p^2\varepsilon_{H_2}} + \frac{1.75u_{H_2}(1-\varepsilon_{H_2})^{1/3}}{l_p\varepsilon_{H_2}}\right]\min\left[\frac{C_{fuel}}{S_{fuel}}, \frac{C_{O_2}}{S_{O_2}}\right]\right) \tag{14}$$

3.2 Carbon monoxide combustion

$$r_{CO-O_2} = \min\left(\left\{\varepsilon_{CO} A_{CO} \exp\left(\frac{-E_{H_2}}{RT_e}\right)C_{CO}C_{O2}^{0.25}C_{H_2O}^{0.5}\right\}, C_{mix}\rho_{CO}\left[\frac{150D_{CO}(1-\varepsilon_{CO})^{2/3}}{l_p^2\varepsilon_{CO}} + \frac{1.75u_{CO}(1-\varepsilon_{CO})^{1/3}}{l_p\varepsilon_{CO}}\right]\min\left[\frac{C_{fuel}}{S_{fuel}}, \frac{C_{O_2}}{S_{O_2}}\right]\right) \tag{15}$$

3.3 Methane combustion

$$r_{CH_4-O_2} = \min\left(\left\{\varepsilon_{CH_4}A_{CH_4}\,T_e^{-1}.\,\exp\left(\frac{-E_{CH_4}}{RT_e}\right)C_{CH_4}C_{O_2}\right\},\ C_{mix}\rho_{CH_4}\left[\frac{150D_{CH_4}(1-\varepsilon_{CH_4})^{2/3}}{l_p^2\varepsilon_{CH_4}} + \frac{1.75u_{CH_4}(1-\varepsilon_{CH_4})^{1/3}}{l_p\varepsilon_{CH_4}}\min\left[\frac{C_{fuel}}{S_{fuel}},\frac{C_{O_2}}{S_{O_2}}\right]\right]\right)$$

(16)

3.4 Char combustion

$$r_{char-O_2} = \frac{(A/V)_{char}\varepsilon_{O_2}C_{O_2}\left[\frac{M_{char}}{\left(1-\frac{\chi}{2}+\frac{a}{2}-\frac{b}{2}\right)M_{O_2}}\right]}{\frac{1}{k_d}+\frac{1}{k_k}}$$

(17)

where

$$k_k = A_{char}\exp\left(\frac{-E_{char}}{RT_s}\right)$$

(18)

3.5 Hydrocarbon combustion

$$r_{C_nH_{2n+2}-O_2} = \min\left(\begin{array}{l}\left\{\varepsilon_{C_nH_{2n+2}}A_{C_nH_{2n+2}}T_eP_{C_nH_{2n+2}}^{0.3}\exp\left(\frac{-E_{H_2}}{RT_e}\right)C_{C_nH_{2n+2}}^{0.5}C_{O_2}\right\},\\[2ex] C_{mix}\rho_{C_nH_{2n+2}}\left[\frac{150D_{C_nH_{2n+2}}(1-\varepsilon_{C_nH_{n+12}})^{2/3}}{l_p^2\varepsilon_{C_nH_{2n+2}}} + \frac{1.75u_{C_nH_{2n+2}}(1-\varepsilon_{C_nH_{2n+2}})^{1/3}}{l_p\varepsilon_{C_2H_{2n+2}}}\min\left[\frac{C_{fuel}}{S_{fuel}},\frac{C_{O_2}}{S_{O_2}}\right]\right]\end{array}\right)$$

(19)

where

$$\begin{aligned}T_e &= \Omega T_g + (1-\Omega)T_s && T_g \leq T_s\\ T_e &= T_g && T_g \leq T_s\end{aligned}$$

(19a)

Ω *is a weighing factor*

3.6 Char reaction with water vapor

$$R_{char-H_2O} = \frac{(A/V)_{char}\varepsilon_{H_2O}C_{H_2O}\left[\frac{M_{Char}}{(1-b)M_{H_2O}}\right]}{\frac{1}{k_d}+\frac{1}{k_r}}$$

(20)

where

$$k_k = A_{H_2O}T_{char}\exp\left(\frac{-E_{char}}{RT_{char}}\right)$$

(21)

3.7 Char reaction with carbon dioxide

$$R_{char-CO_2} = \frac{(A/V)_{char}C_{CO_2}\left[\frac{M_{Char}}{M_{CO_2}}\right]}{\frac{1}{k_d}+\frac{1}{k_r}}$$

(22)

where

$$k_k = A_{CO_2}T_{char}\exp\left(\frac{-E_{char}}{RT_{char}}\right)$$

(23)

3.8 Char reaction with hydrogen gas

$$R_{char-H_2} = \frac{(A/V)_{char} C_{H_2} \left[\frac{M_{Char}}{(2+b-\frac{a}{2})M_{H_2}} \right]}{\frac{1}{k_d} + \frac{1}{k_r}} \tag{24}$$

where

$$k_k = A_{H_2} \exp\left(\frac{-E_{char}}{RT_{char}}\right) \tag{25}$$

3.9 Water-gas shift

$$R_{CO-H_2O} = \varepsilon_{CO} k_{WGS} \left(C_{CO} C_{H_2O} - \frac{C_{CO_2} C_{H_2}}{k_E} \right) \tag{26}$$

where

$$k_{WGS} = A_{WGS} \exp\left(\frac{-E_{WGS}}{RT_{CO}}\right), k_E = A_E \exp\left(\frac{-E_E}{RT_{CO}}\right) \tag{27}$$

3.10 Steam reforming of hydrocarbon

$$R_{CH_nO_{2n+2}} = A_{sr} T^{b+1} \exp\left(\frac{-E_{sr}}{RT}\right) C_{CH_nO_{2n+2}} C_{H_2O} \tag{28}$$

where

$$k_d = \begin{pmatrix} \dfrac{D_g\left(0.644\,\mathrm{Re}^{0.5} Sc^{0.433}\right)}{d_p}, & Rectangular - shaped\ particles \\[2em] \dfrac{D_g\left(2 + 1.1\,\mathrm{Re}^{0.6} Sc^{1/3}\right)}{d_p} & Cylindrical - shaped\ particles \\[2em] \dfrac{D_g\left(1.05 + 0.6\,\mathrm{Re}^{0.6} Sc^{1/3}\right)}{d_p} & Spherical - shaped\ particles \end{pmatrix} \tag{29}$$

Where at a low Reynold number

$$k_d = \frac{D_{H_2}\left\{ W_0(\mathrm{Re}) Sc^{0.33} + W_1(\mathrm{Re}) \right\}}{d_p} \tag{30}$$

$$W_o = \begin{bmatrix} 0.4627 \exp\left(1.01633\left(\log_{10}(\mathrm{Re})\right) + 0.05121\left(\log_{10}(\mathrm{Re})^2\right.\right. & 10^{-2} \leq \mathrm{Re} \leq 3.14 \\[1em] 0.597\left(\dfrac{\mathrm{Re}}{In\left(\frac{1}{\mathrm{Re}}\right)^{\frac{1}{3}}}\right) & \mathrm{Re} < 10^{-2} \end{bmatrix} \tag{31}$$

$$W_1 = \begin{bmatrix} \begin{bmatrix} 0.10666 \exp\left(0.41285\left(\log_{10}(\mathrm{Re})\right) + 0.43847\left(\log_{10}(\mathrm{Re})\right)^2 + 0.1915\left(\log_{10}(\mathrm{Re})\right)^3 \right. \\ \left. +0.01802\left(\log_{10}(\mathrm{Re})\right)^4 - 0.005225\left(\log_{10}(\mathrm{Re})\right)^5 \right] \end{bmatrix} & 10^{-2} \leq \mathrm{Re} \leq 3.14 \\[1em] 0.0917 & \mathrm{Re} < 10^{-2} \end{bmatrix} \tag{32}$$

4. Results and discussion

The developed models are solved numerically and parametric studies are carried out. The variations of gas compositions with equivalence ratio in the gasification zone are shown in **Figure 5**. The result depicts a slight decrease in the percentage composition of CH_4 with an increase in the equivalence ratio. The decrease is simply attributed to increased moles of air intake into the gasifier. It could be observed that the variation of H_2 concentration as the equivalence ratio increases follows an inverse trend. This is because higher availability of O_2 first consumes H_2, which is also reflected in an increasing concentration of H_2O. The same trend was also observed in the variation of CO with the equivalence ratio. The decrease in CO concentration as the equivalent ratio increases is due to oxidation of CO at higher equivalence ratio, which is further validated by the increasing trend of CO_2 concentration with equivalence ratio. It could therefore be stated that the compositions and distributions of CO, H_2 and CH_4 in the gasifier decrease as the equivalence ratio increases. However, the temperature distribution in the reactor increases with an increase in the equivalence ratio.

In this work, the performance of the biomass gasifier system is evaluated through the equivalence ratio, the syngas composition, cold gas efficiency and lower heating value (LHV). **Figure 6** presents the variation of gasifier performance parameters i.e., cold gas efficiency, gas yield and LHV of gas with equivalence ratio. As it could be seen in the figure that the cold efficiency and LHV decrease as the equivalence ratio increases while the gas yield increases with an increase in the equivalence ratio. The increased gas yield is due to higher air intake as the equivalence ratio increases while the decrease in cold gas efficiency and LHV of gas may be attributed to the consumption of combustible gas due to more availability of air as the equivalence ratio increases.

Figure 7 shows the impact of oxygen consumed on gas produced while **Figure 8** depicts the influence of gasification zone temperature on the CO/CO_2 ratio in the gasification zone. From the **Figure 7**, it is shown that the quantity of gas produced
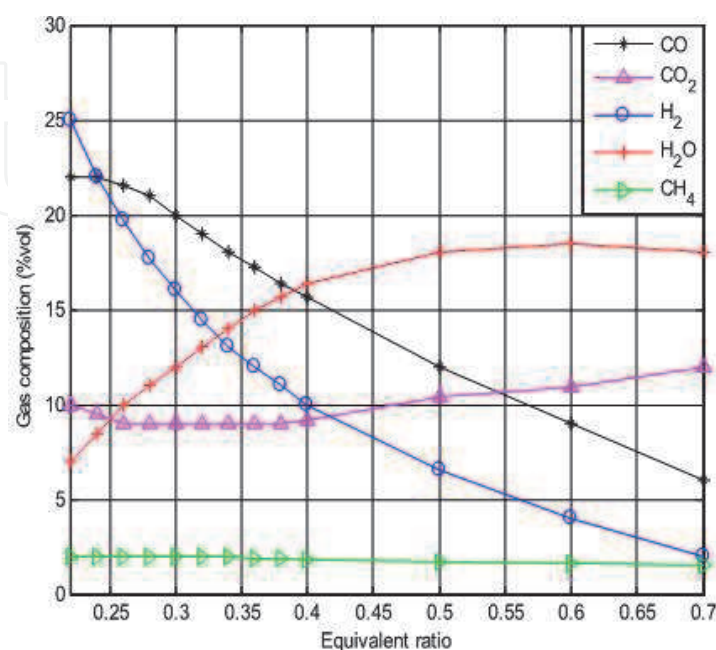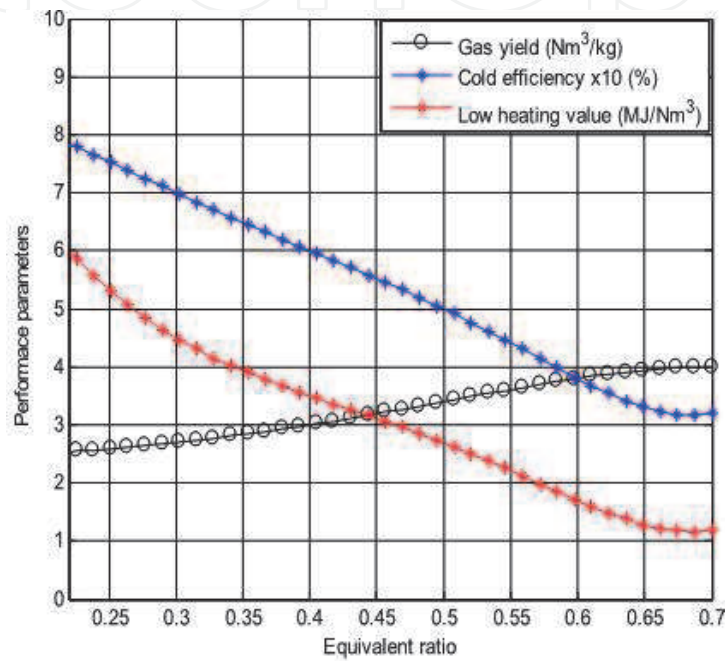

Figure 5.
*Effects of equivalent ratio on the percentage gas composition.*

increases as the amount of oxygen consumed increases. This is due to increasing in the rate of combustion of the products of pyrolysis as more oxygen is consumed in the combustion process or oxidation reactions, more gases are produced from the reactor. It is also shown in **Figure 8** that the ratio of CO/CO_2 decreases as the temperature of the reduction zone increases.

The validation of the computational fluid dynamic simulations is very necessary. The comparison of the computational fluid dynamic simulations with the results of the experiment [33, 34] as shown in **Figure 9**. The results showed good agreements with the results of the measurement.
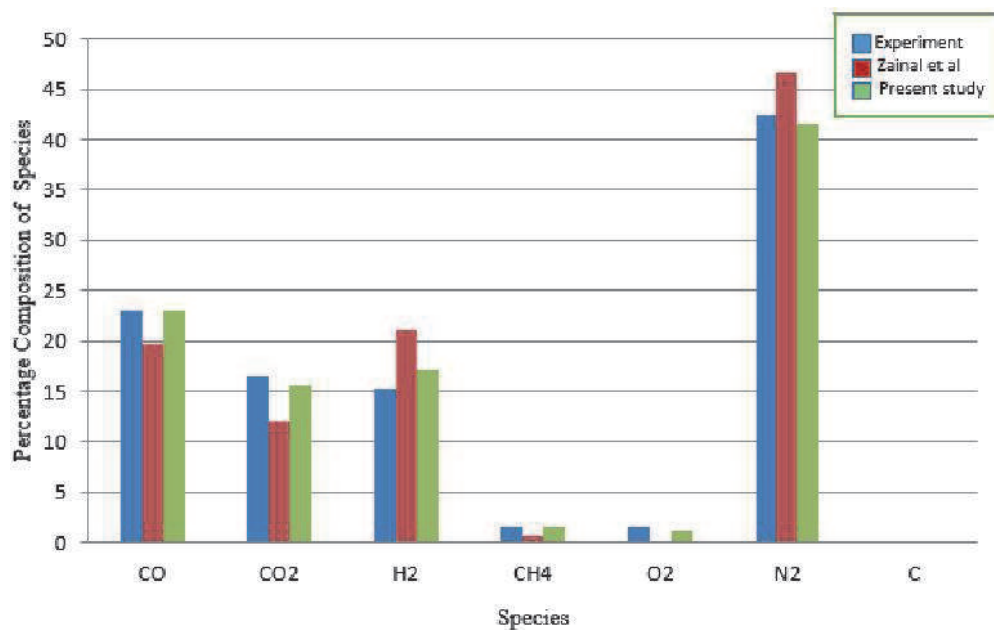

Figure 6.
Effects of char particle diameter on the char combustion rate.
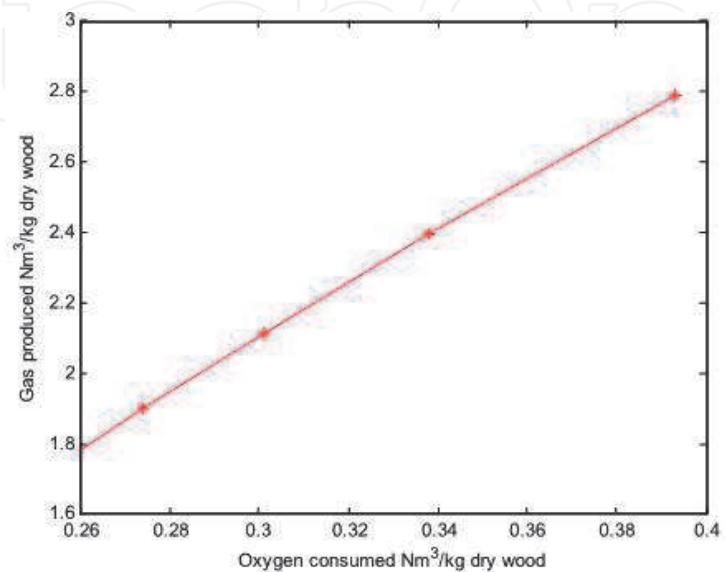
Figure 7.
Effects of oxygen consumed on gas produced.
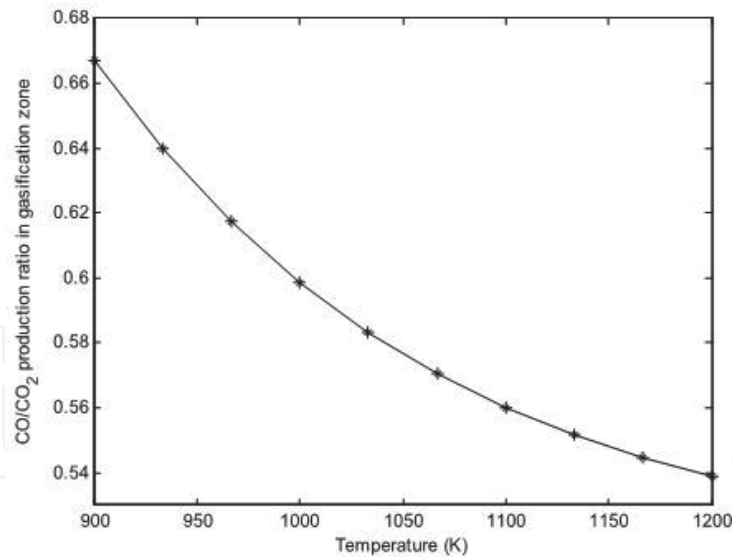
Figure 8.
Effects of temperature on CO/CO$_2$ ratio in the gasification zone.

Figure 9.
Comparison of the results.

5. Conclusion

In this work, improved kinetic models for the combustion and gasification zones in the thermochemical system have been developed. The performance of the biomass gasifier system was evaluated through the equivalence ratio, the syngas composition, cold gas efficiency and lower heating value. Also, the effects of the equivalent ratio on gas compositions, the gasifier performance and the low heating value of the biomass were investigated. From the analysis, it is established that

    i. the concentration of CO, H$_2$ and CH$_4$ in the gasifier decrease as equivalence ratio increases.

    ii. the CO$_2$ concentration increases with increase in the equivalence ratio.

iii. the cold efficiency and LHV decreases as the equivalence ratio increases while the gas yield increases with increase in the equivalence ratio.

iv. the quantity of gas produced increases as the amount of oxygen consumed increases.

v. the ratio of CO/CO_2 decreases as the temperature of the reduction zone increases. The developed model is validated with the experimental results.

The analysis is far less costly and time consuming than the experimental approach. Such analysis is useful as a time saving and cost effective tool for designing and optimizing the biomass gasifier.

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