

Modeling of a Small-scale Biomass Updraft Gasifier

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Biomass can be efficiently transformed into valuable gas products via gasification. Gasification converts biomass through partial oxidation into a gaseous mixture, small quantities of char and condensable compounds. In this work, an updraft gasifier is regarded because the updraft gasifier is suitable for wet fuels such as agricultural residues. Moreover, it is the most simple and can be used as a basis for the design and operation of small-scale gasifier. However, due to the high tar content of the gas produced, updraft gasifiers may not effectively be used without comprehensive gas cleaning. To improve an insight on the gasification process, appropriate mathematical models are required. Further, models are useful for gasifier design and operation such as prediction of operation behavior during normal operation, startup, and shutdown. This article presents a one-dimensional mathematical model for the simulation of a small-scale fixed-bed updraft gasifier of rice straw. The model is based on a set of differential equations describing the entire gasification process. The governing equations include conservation of mass and energy, complemented by boundary conditions, constitutive relationships. The main features of the model include homogeneous and heterogeneous combustion and gasification reactions, pyrolysis kinetics and drying, heat and mass transfer in the solid and gas phases as well as between phases. The simulation results were compared with experimental data, and showed good agreement. The model constructed was then used to predict the effects of varying moisture content and air feed temperature. Fuel with higher moisture content of fuel feed lowered the performance of the gasification process. But, higher temperature of air feed resulted in higher performance with lower tar content and more environmentally preferable.

1. Introduction

Renewable energy plays an important role in reducing greenhouse gas emissions resulting from burning fossil fuels. Biomass refers to any organic materials derived from plants or animals. Biomass is one of the renewable energy sources with a great potential to produce energy, in addition to being carbon neutral. It can be converted to gaseous or liquid fuels by thermo-chemical or biochemical processes (Wetterlund et al., 2010).

Biomass gasification is one of few technologies that can potentially generate carbon neutral energy with pollution-free power and also turn agricultural waste into energy (Moghadam et al., 2013). Biomass gasification is a thermo-chemical process that generates producer gas or synthesis gas by partial oxidation of biomass feedstock in fuel-rich conditions in the presence of air, steam, or oxygen.

The advantage of gasification lies on the fact that using the syngas is potentially more efficient than direct combustion of the original fuel because it can be combusted at higher temperature, so that it shifts the thermodynamic upper limit to the efficiency.

Thermo-chemical gasification can be classified on the basis of the gasifying agent, which could be air, steam, or oxygen. Air blown gasification processes usually yield a low heating value gas. Oxygen and steam blown gasification usually yield a higher heating value gas. However, the disadvantage with the oxygen blown or steam injection systems is the high cost for the oxygen or steam production equipment.

Three types of gasifier including fixed or moving bed, fluidized bed, and entrained flow are generally used. For large-scale applications, the most preferred and reliable system is the circulating fluidized bed. In contrast, fixed bed systems are more appropriate for small-scale systems.

The fixed-bed designs are basically updraft or downdraft. In downdraft gasifiers, the fuel and gasification agent flow in the same direction and the gas leaves the reactor near the hottest zone, which makes the tar concentration much lower than in updraft gasifiers. In the other hand, the fuel bed moves downwards and the gasification agent flows from the bottom upwards in updraft gasifiers. As the gas leaves the reactor near the pyrolysis zone, the gas generated in updraft gasifiers has a high content of organic components (tar). The solid carbon in the fuel is almost completely converted into gas and tar. However, updraft gasifiers can be used for wet fuels and are relatively intensive to the fuel size. Updraft gasifiers generally operate with high overall carbon conversion, high thermal efficiency, high residence time of solids, low gas velocity and low ash carry-over. The updraft gasifiers are suitable for small-scale systems. The maximum size of these units is limited to a few MW fuel power because of the problem of maintaining a regular conversion front in a wide fixed bed.

Biomass gasifiers are complex facilities, which makes it difficult to investigate their various operating conditions. The characteristics of biomass greatly influence the performance of a biomass gasifier. A proper understanding of the physical and the chemical properties of biomass feedstock is essential for the design and operation of a biomass gasifier to be reliable. Numerous models for biomass gasifier have been developed. These models can be categorized into two groups: (1) thermodynamic equilibrium models and (2) kinetic models. The thermodynamic equilibrium models, also known as zero-dimensional (0D) models, are widely used among researchers to predict the composition of the produced syngas and the equilibrium temperature by assuming that the chemical reactions reach equilibrium. However, these models cannot provide highly accurate results and also cannot provide the concentration or temperature profiles inside the reactor. Because this approach is independent of the gasifier design, kinetic models, which take into account the reaction kinetics and the transfer phenomena among the phases, one-dimensional (1D) biomass gasification models have been developed. These models simulated the variations in the physical and chemical properties along the reactor height by considering the vertical movements. A 1D unsteady mathematical model of updraft wood gasifier was developed and used to simulate the structure of the reaction fronts and the gasification behavior of a laboratory-scale plant (Blasi, 2004). Blasi and Branca (2013) developed a mathematical model of an open-core downdraft gasifier with dual air entry. The reaction front structure varies with percentage and position of secondary air. Thus, char and tar conversion can be improved. Two-dimensional (2D) models have been developed to improve an insight on the effects of the reactor geometry. Wu et al. (2013) developed a 2D computational fluid dynamics (CFD) model for downdraft gasifier with preheated air and steam in order to investigate various operating conditions. Zhang et al. (2011) used 2D CFD model for and updraft gasifier to perform a simulation of municipal solid waste gasification.

In this study, we developed a 1D mathematical model of small-scale updraft biomass gasifier. Rice straw was used as fuel feed. The model developed was validated with experimental data. The mathematical model constructed was then used to investigate the effects of varying moisture content and air feed temperature. The paper is organized as follows. In section 2, principles of biomass gasification are presented. In section 3, experimental setup used to validate the model developed is presented. In section 4, the model development and validation are presented. In sections 5, the effects of various parameters are discussed. In the last section, we conclude the paper.

2. Principles of biomass gasification

Gasification is partial thermal oxidation resulting in a high proportion of gaseous products, small quantities of char, ash and condensable compounds. Steam, air or oxygen is supplied to the reaction as a gasifying agent. The chemistry of biomass gasification is complex and consists of the following stages:

2.1 Drying

In this stage, the moisture content of the biomass is reduced. The typical moisture content of biomass ranges from 5 to 60%. Most gasification systems use dry biomass with moisture content of 10 to 20%. The final drying takes place at about 400 - 500 K after the feed enters the gasifier, where it receives heat from the hot zone downward. This heat dries the feed, which releases water. As the temperature rises, the low-molecular-weight extractives start volatilizing. This process continues until a temperature of approximately 500 K is reached.

2.2 Thermal decomposition

In pyrolysis no external agent is added. The oxygen is largely diminished. The volatile matter in the biomass is reduced. Consequently, hydrocarbon gases are released from the biomass, and the biomass is reduced to solid charcoal. The hydrocarbon gases can condense at a sufficiently low temperature to generate liquid tars.

2.3 Gasification

The gasification step involves chemical reactions among the hydrocarbons in fuel, steam, carbon dioxide, oxygen, and hydrogen in the reactor, as well as chemical reactions among the evolved gases. Char gasification is the most important. The char produced through pyrolysis of biomass is not necessarily pure carbon. It contains a certain amount of hydrocarbon comprising hydrogen and oxygen. Gasification of biomass char involves several reactions between the char and the gasifying mediums. In the absence of oxygen, several reduction reactions occur in the 1100 - 1300 K temperature range. These reactions are mostly endothermic.

2.4 Combustion

Most gasification reactions are endothermic. To provide the required heat of reaction as well as that required for heating, drying, and pyrolysis, a certain amount of exothermic combustion reaction is allowed in a gasifier. Combustion is a reaction between solid carbonized biomass and oxygen in the air, resulting in formation of carbon dioxide. Hydrogen present in the biomass is also oxidized to generate water. A large amount of heat is released with the oxidation of carbon and hydrogen. Combustion reactions are generally faster than gasification reactions under similar conditions.

3. Experimental setup

A small-scale updraft biomass gasifier has been devised. Figure 1 shows a schematic diagram of the updraft gasifier used in this work. The reactor is a vertically cylindrical chamber with 0.15 m diameter and 0.6 m height. The fuel feed, rice straw, was introduced from the top of a chamber using a continuous screw feeding system. Gasifying medium (air) was preheated to 313.5 K by an external heater to maintain a stable operation, and fed to the chamber through a grid at the bottom of the chamber. The gas then rose through a bed of descending fuel or ash in the gasifier chamber. The grate stopped biomass/char particles, resulting in a charcoal bed. The temperature of 1500 K was the highest temperature being close to the grate, where oxygen met and burned the char. Hot gas produced by combustion traveled up, providing heat to the endothermic gasification reactions at 1000 to 1200 K, and met pyrolyzing biomass at a lower temperature of 500 to 800 K. Primary tar was produced in this temperature range. The temperatures were measured using thermocouple probes located at the centerline along the height of the reactor in various different reaction zones. The product gas, which was sampled at the outlet, left from the top while solids left from the bottom. The feedstock used for this study was rice straw, 0.01 m in diameter, with an average length/diameter ratio of 1 to 2.5. The bulk density of rice straw was 150 kg/m³. The properties of the feedstock are shown in Table 1.

Table 1: Characterization of the feedstock, rice straw.

Proximate analysis		Ultimate analysis	
Total moisture (%)	12.00	C (%)	37.48
Ash (% , dry basis)	12.65	H (%)	4.41
Volatile matter (% , dry basis)	56.46	O (%)	33.27
Fixed carbon (% , dry basis)	18.88	N (%)	0.17
		S (%)	0.04

4. Model development and validation

Updraft gasifier was modeled by means of the equations of conservation of mass and energy for the solid and gas phases. The model was derived as an unsteady system for a one-dimensional along reactor axis. Fuel was assumed to be the same size and shape with constant porosity, and without intraparticle gradients of temperature. Turbulence in chamber was taken in to account through the correlations for the heat/mass transfer coefficients. In addition, constant pressure along the axis of chamber was considered. The main processes modeled included: (1) moisture evaporation/condensation, (2) finite-rate kinetics of biomass devolatilization to gaseous species, primary tar, and char, (3) primary tar degradation to gaseous species and refractory tar, (4) heterogeneous gasification and combustion of char, (5) combustion of volatile species, (6) steam reforming of methane and refractory tar, (7) finite-rate gas-phase water-gas shift, (8) extra-particle mass transfer resistances, (9) heat and mass transfer across the bed resulting from macroscopic (convection) and molecular (diffusion and conduction) exchanges, (10) absence of thermal equilibrium, (11) solid- and gas-phase heat transfer with the reactor walls, (12) radiative heat transfer through the porous bed, and (13) variable solid and gas flow rates.

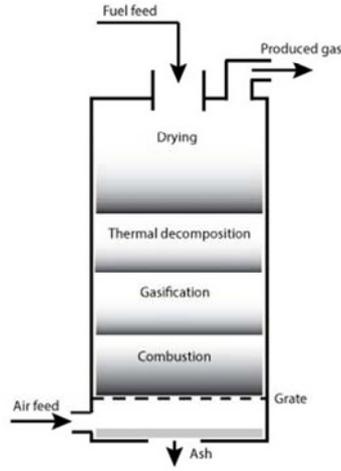


Figure 1: Diagram of an updraft gasifier.

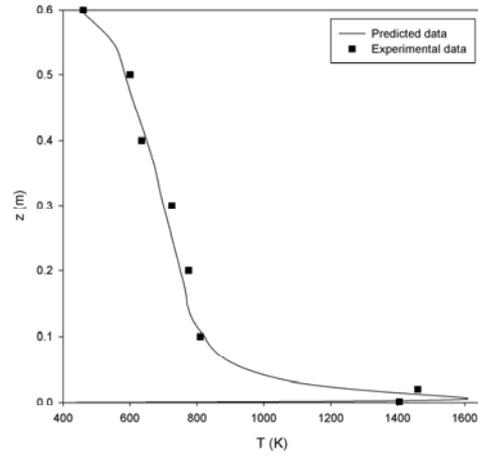


Figure 2: Experimental and predicted temperatures.

The conservation equations are governed based on the work by Blasi (2004) as following equations.

Biomass:

$$\frac{\partial}{\partial t} \rho_{\text{biomass}} + \frac{\partial}{\partial z} U_g \rho_{\text{biomass}} = -r_{p1} \quad (1)$$

Moisture:

$$\frac{\partial}{\partial t} \rho_{\text{moisture}} + \frac{\partial}{\partial z} U_g \rho_{\text{moisture}} = -m_{\text{moisture}} \quad (2)$$

Gas-phase species:

$$\varepsilon \frac{\partial}{\partial t} \rho_i + \frac{\partial}{\partial z} U_g \rho_i = \frac{\partial}{\partial z} (\varepsilon D_i \rho_g \frac{\partial}{\partial z} Y_i) + M_i \sum_j v_{ij} r_j + v_i r_{p1} + v_i^* r_{p2} \quad (3)$$

Where $i = \text{O}_2, \text{H}_2, \text{CO}, \text{CO}_2, \text{CH}_4$, $j = \text{c}_1\text{-c}_6, \text{g}_1\text{-g}_3, \text{wg}, \text{sr}_1, \text{sr}_2$

Steam:

$$\varepsilon \frac{\partial}{\partial t} \rho_{\text{water}} + \frac{\partial}{\partial z} U_g \rho_{\text{water}} = \frac{\partial}{\partial z} (\varepsilon D_{\text{water}} \rho_g \frac{\partial}{\partial z} Y_{\text{water}}) + M_{\text{water}} \sum_j v_{\text{water},j} r_j + v_{\text{water}} r_{p1} + v_{\text{water}}^* r_{p2} + m_{\text{moisture}} \quad (4)$$

Where $j = \text{c}_1\text{-c}_5, \text{g}_1\text{-g}_3, \text{wg}, \text{sr}_1, \text{sr}_2$

Vapor-phase primary tar:

$$\varepsilon \frac{\partial \rho_{\text{tar}_1}}{\partial t} + \frac{\partial (U_g \rho_{\text{tar}_1})}{\partial z} = \frac{\partial}{\partial z} (\varepsilon D_{\text{tar}_1} \rho_g \frac{\partial}{\partial z} Y_{\text{tar}_1}) + v_{\text{tar}_1} r_{p1} - r_{p2} - M_{\text{tar}_1} r_{c1} \quad (5)$$

Vapor-phase refractory tar:

$$\varepsilon \frac{\partial \rho_{\text{tar}_2}}{\partial t} + \frac{\partial (U_g \rho_{\text{tar}_2})}{\partial z} = \frac{\partial}{\partial z} (\varepsilon D_{\text{tar}_2} \rho_g \frac{\partial}{\partial z} Y_{\text{tar}_2}) + v_{\text{tar}_2} r_{p2} - M_{\text{tar}_2} r_{c5} - M_{\text{tar}_2} r_{\text{sr}_1} \quad (6)$$

Nitrogen:

$$\rho_{\text{N}_2} = \rho_g - \sum_{i \neq \text{N}_2} \rho_i \quad (7)$$

Total gas continuity:

$$\varepsilon \frac{\partial}{\partial t} \rho_g + \frac{\partial}{\partial z} U_g \rho_g = \sum_i \sum_j v_{ij} M_i r_j + m_{\text{moisture}} + (1 - v_{\text{char}}) r_{p1} \quad (8)$$

Where $i = \text{O}_2, \text{H}_2, \text{CO}, \text{CO}_2, \text{CH}_4, \text{N}_2, \text{H}_2\text{O}$, $j = \text{c}_6, \text{g}_1\text{-g}_3$

Solid-phase enthalpy:

$$\frac{\partial}{\partial t}(\sum_i \rho_i c_{gs}(T_s - T_0)) = \frac{\partial}{\partial z}(\lambda_s^* \frac{\partial T_s}{\partial z}) + \frac{\partial}{\partial z}(U_s \sum_i \rho_i c_{gs}(T_s - T_0)) - \sum_j r_j \Delta H_j - h_{sg} A_p v_p (T_s - T_g) + \frac{4h_{sw}}{d}(T_w - T_s) - m_{\text{moisture}} \Lambda \quad (9)$$

Where i = biomass, char, moisture, j = c₅, g₁-g₃, p₁.

Gas-phase enthalpy:

$$\frac{\partial}{\partial t}(\sum_i \rho_i c_{gi}(T_g - T_0)) = \frac{\partial}{\partial z}(\lambda_g^* \frac{\partial T_g}{\partial z}) + \frac{\partial}{\partial z}(U_g \sum_i \rho_i c_{gi}(T_g - T_0)) - \sum_j r_j \Delta H_j - h_{sg} A_p v_p (T_s - T_g) + \frac{4h_{gw}}{d}(T_w - T_g) \quad (10)$$

Where i = N₂, O₂, H₂, CO, CO₂, CH₄, water, tar₁, tar₂, j = c₁-c₅, wg, p₂, sr₁, sr₂.

Ideal gas law:

$$P = \frac{\rho_g R T_g}{\sum_i M_i Y_i} \quad (11)$$

Where i = N₂, O₂, H₂, CO, CO₂, CH₄, water, tar₁, tar₂.

T denotes temperature. U denotes velocity. Y represents mass fraction. D stands for diffusion coefficient. d represents reactor diameter. A_p is particle surface area. m is evaporation rate. M is molecular weight. ρ is gas phase mass concentration. ϵ is porosity. Λ is moisture enthalpy. h_{sg} and h_{sw} are solid-gas and solid-wall heat transfer coefficients. The subscripts s , g , and w stand for solid, gas and wall, respectively. The reactions p₁ is related to thermal decomposition where the fractions of gas, primary tar and char generated. Primary tar undergoes secondary cracking to produce gases and refractory tar in reaction p₂. The reaction of steam reforming of refractory tar and methane were taken into account through reactions sr₁ and sr₂. Combustion of volatile products including the reactions for primary and refractory tars, methane, carbon monoxide, and hydrogen were modeled in reactions c₁ to c₅. Heterogeneous reactions of char were modeled as reaction c₆, g₁, g₂ and g₃. The reaction wg is related to water-gas shift. These reactions with corresponding kinetic parameters, as well as moisture evaporation rate and heat and mass transfer coefficients were modeled the same way as in Blasi and Branca (2013), but omitted here for brevity.

At the bottom of reactor ($Z = 0$), temperature, velocity, and densities of the feed air were given. The solid was assumed to be at ambient temperature. At the top of the chamber, the fuel feed properties and a convective outflow conditions were assigned. At initial, the gasifier filled with biomass was fed by hot feed air. After a certain time, the feed air temperature was set back to the predefined conditions. The simulation was then performed with selected parameters.

Model validation was performed using experimental data. The moisture content of rice straw used as fuel feed was 12%. The mass flow rate of fuel feed, and feed air were 1.65 and 2.15 kg/h, respectively. Feed air and fuel were preheated to 313.5 K by an external heater to maintain a stable operation. Figure 2 shows the comparison of the predicted and experimental temperature profiles, at the bottom of the reactor, temperature drastically increases from ambient to 1600 K, which is the highest temperature. The temperature predictions were in good agreement with the experimental data. The gas produced at the outlet was about 450 K. Biomass devolatilization occurred at the temperature above 650 K. The rapid rise of the solid temperature approached 1600 K at slightly above the grate resulted from char combustion.

5. Effects of parameters

The performance of the gasification process was evaluated based on efficiency term defined as the ratio of the exergy of the syngas to the exergy of the biomass (Ptasinski, 2008).

5.1 The effects of moisture content in fuel feed

The moisture content of fuel feed was varied from 8 to 20 % while keeping the other parameters constant. The performance of the gasifier was directly influenced by the moisture content of fuel feed. Figure 3 shows the performance of gasifier at different moisture contents of fuel feed. The fuel with higher moisture content lowered the performance of the gasification process. Fuel feed with higher moisture content required longer drying zone resulting in a relative decrease in the biomass resident time. In addition, more energy was used to dry biomass, and the temperature inside the chamber decreased.

5.2 The effects and air feed temperature

Air feed temperature was preheated to varying temperatures ranging from 313.5 to 338.5 K while keeping the other parameters constant. Figure 4 shows the performance of gasifier at different air feed temperatures. The higher temperature of air feed resulted in higher performance with lower tar content.

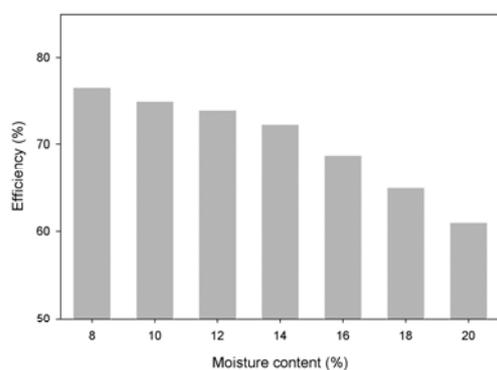


Figure 3: The effect of feed moisture content.

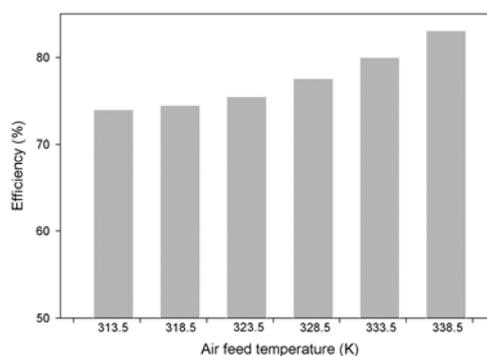


Figure 4: The effect of air feed temperature.

The highest temperature inside the chamber increased as the air feed temperature increased. Because, the hot feed air with higher enthalpy induced an increase of the temperature. The positive impacts of the higher bed temperature were higher chemical reaction rates and enhanced heat transfer. The drying zone was significantly reduced.

6. Conclusions

In this work, a one-dimensional mathematical model for the simulation of a small-scale fixed-bed updraft gasifier has been developed and validated with experimental data of small-scale updraft gasifier of rice straw. Good agreement between the model developed and experimental data has been obtained. The mathematical model constructed was then used to study the effects of varying moisture content and air feed temperature. The fuel with higher moisture content lowered the performance of the gasification process. But, higher temperature of air feed resulted in higher performance with lower tar content and more environmentally preferable.

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