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BIOMASS GASIFICATION IN A PILOT-SCALE SYSTEM

by
Yunye Shi

A thesis submitted in partial fulfillment
of the requirements for the Doctor of
Philosophy degree in Mechanical Engineering
in the Graduate College of
The University of Iowa

May 2016

Thesis Supervisor: Associate Professor Albert Ratner

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Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

Yunye Shi

has been approved by the Examining Committee
for the thesis requirement for the Doctor of Philosophy
degree in Mechanical Engineering at the May 2016 graduation.

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ABSTRACT

Biomass is a renewable, carbon-neutral resource that produces minimal pollution when used to generate electricity, fuel vehicles, and provide heat for industry. Every year in Iowa, millions of bushels of treated seed corn go unused, and are wasted (sent to the landfill). Old treated seed corn goes unplanted because of low germination rates, but it goes unused because of the toxicity associated with the pesticides and fungicides applied to it. If the toxic additives could be destroyed through gasification with a long, high-temperature residence time, the producer gas from treated seed corn could then be used as a fuel source in regular power plants. The temperature and reactivity required to destroy these chemicals is best achieved in a reactive bed, like one formed by carbon char. This makes a char producing combustion system an ideal candidate for this type of fuel.

In this work, a char-producing downdraft gasification system is used to examine system behavior for seed corn fuel. The system is pilot-scale and the producer gas is of primary interest for power production. Both experiments and numerical simulations are carried out and a range of parameters are examined, including the thermal profile, equivalence ratio, bed depth, and producer gas composition. A second downdraft gasifier, with two-stage gasification, is also studied to compare the systems' behaviors. From these results, a 1-d hybrid model was developed and utilized to predict optimal gas production in these systems. Results show that above the minimal char bed level, higher equivalence ratio (ER) value results in a higher combustion zone temperature and a higher gas yield while leading to a lower CO concentration in the producer gas. Bed height consumes more heat in the combustion zone which brings about a lower combustion zone temperature. In general, ER plays a more dominating role in determining gas yield and combustion zone

temperature. The two-stage system, which expands the combustion zone, effectively increases carbon conversion rate and hence generates a producer gas with high cold gas efficiency, although this makes maintaining sufficient char depth difficult.

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Biomass is a renewable, carbon-neutral resource that produces minimal pollution when used to generate electricity, fuel vehicles, and provide heat for industry. Every year in Iowa, millions of bushels of treated seed corn go unused, and are wasted (sent to the landfill). Old treated seed corn goes unplanted because of low germination rates, but it goes unused because of the toxicity associated with the pesticides and fungicides applied to it. If the toxic additives could be destroyed through gasification with a long, high-temperature residence time, the producer gas from treated seed corn could then be used as a fuel source in regular power plants. The temperature and reactivity required to destroy these chemicals is best achieved in a reactive bed, like one formed by carbon char. This makes a char producing combustion system an ideal candidate for this type of fuel.

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Energy use continues to increase as the world population grows and more countries industrialize. Unfortunately, the development of renewable and minimally disruptive energy sources has not kept pace with the expanding demand. The major energy sources for most countries are still conventional fossil fuels: oil, coal, and natural gas. These engender two significant problems: future depletion of these fuels and deterioration of the global environment. Therefore, there is great interest in alternative energy resources which are cost effective, renewable, and environmentally friendly. Biomass is both renewable and produces minimal pollution when used to generate electricity, fuel vehicles, and provide heat for industry.

One of the primary ways in which biomass is used is through gasification. Gasification typically involves first partially combusting the biomass to create heat and then to use this heat in the absence of oxygen to vaporize most of the remaining solid material. This process results in the production of combustible gases consisting of carbon monoxide (CO), hydrogen (H₂) and small amounts of methane (CH₄), and traces of other gases. This mixture of gases is called producer gas and can be cleaned and directly used in internal combustion engines and boilers (Tinaut, V., 2010; Tinaut, 2006; Serrano, C., 2008; Singh, R., 2007). It can also be converted to various types of biofuels (Martínez, J., 2012). The byproducts of biomass gasification include bio-char and tar. Bio-char can be also utilized in different ways including burning for its BTU energy, applied to fields as a soil amendment, or even used as a chemical adsorbent. In 2013, the first U.S. commercial

cellulosic ethanol plant was at the testing state using gasification and anaerobic fermentation and in 2014 the plant was officially operated (Ineos Bio, 2013).

In the current research, seed corn is selected as the primary biomass material for gasification. Corn is locally abundant most places in Iowa and every year millions of bushels of treated seed corn goes unused, and is wasted (sent to the landfill). This waste is considered toxic and is required by law to be stored 18 inches under the soil in an isolated area far from water supplies. The corn's toxicity is associated with the pesticides and fungicides applied to the corn before it is planted. If the toxic additives could be destroyed through gasification with a long, high-temperature residence time, the producer gas from treated seed corn could then be used as a fuel source in regular power plants. However, the insecticides used in commonly treated seed corn are known to produce toxic gases if exposed to moderately high temperatures and allowed to decompose. Therefore, the difficulty lies in finding a series of temperatures and conditions that eliminate the toxic components while producing the highest energy value producer gas and without generating problems like ash fusion or excessive tar formation. As the temperature range and conditions for breaking down the toxic material and ash fusion are well known, the work here focuses on the gasification process for seed corn and the quality of the producer gas. For ease of use, this research is performed using untreated seed corn.

Since 2003, the University of Iowa (UI) has been using oat hulls as a source of biofuel. The energy produced from oat hull combustion replaces the energy that would have been generated by burning coal. By doing this, UI has replaced 168,915 tons of coal and avoided 376,141 tons of CO₂ over the last 10 years. The success of biomass utilization at the UI power plant highlights the benefits of biomass use and motivates further biomass

research. The Green Power Initiative Award from the US Department of Energy provided UI with support to install a pilot-scale research biomass gasifier at the Oakdale power plant. Building on that effort, a more recent National Science Foundation award, Iowa EPSCoR, provided support for research utilizing the gasifier and with enhanced analytical tools.

1.2 Objectives, Scope, and Outline

While substantial prior work has been done on biomass energy conversion, especially pyrolysis and gasification, many questions remain about the behavior of downdraft gasification systems. Extensive research has been focused on lab-scale systems. Conversely, information about system performance at pilot and industrial scale are still lacking. Also, research using seed corn as feedstock is very rare. Therefore, the current work is aiming to provide useful information about the design, operation, and system performance of a pilot-scale one-stage air-blown system. Also, this work compares the current one-stage system with a moderately different two-stage system to elucidate potential improvements for the current design and operation. In addition, a 1-d hybrid model was developed for the system to provide parametric predictions.

This thesis examines the system design, operation, and performance evaluation. In gasification, as discussed in the previous section, the products include producer gas, bio-char, and unwanted byproduct bio-tar. The current work focuses on the system performance evaluation, specifically on the production and efficiency of bio-producer gas. It compares experimental data on producer gas obtained from the current system with a two-stage downdraft system. Also, the theoretical gas output is predicted using a mathematical model.

Chapter 2 presents a literature review of the related technologies on biomass gasification and current research facilities in other universities and institutions. Chapter 3 demonstrates the original and the modified design of the overall system, operation, and experimental procedures. Chapter 4 evaluates the performance of the system, specifically on the thermal profile of the reactor and producer gas at the exit of the unit. Chapter 5 illustrates a double-stage air-blown downdraft system which has the same reactor zone dimensions with the Oakdale system. System evaluation is also performed. In addition, the comparison between the two systems is taken to draw a conclusion on the potential design improvement of the Oakdale system. Chapter 6 represents a mathematical model of the downdraft gasifier. The model is validated using experimental data from the two-stage air-blown system and employed to predict the optimal producer gas output for the Oakdale system.

CHAPTER 2

BIOMASS GASIFICATION: STATE OF ART

2.1 Renewable Energy Resources in the U.S.

The US with consumes 19.2% of the world's energy (Energy & Environment, 2012). The country also ranks seventh in energy consumption per-capita after Canada and some small countries by 2011 (United States Census Bureau, 2012). According to IEA energy statistics, fossil fuels are still the majority of total energy consumption (80% share in 2011). Renewable energy had a share of 9%. Over the last decade, the US consumption has decreased fossil fuel consumption by 4% (84% in 2000) and increased renewable energy share by 1% (8% in 2000) (The President's Energy Initiatives, 2013).

The outlook for global renewable energy is vigorous. According to International Energy Agency (IEA) Executive Director's speech at the 10th Annual Renewable Energy Finance Forum, total renewable generation capacity is expected to grow to nearly one-quarter of the global electricity generation capacity by 2018. According to the U.S. Energy Information Administration (EIA) International Energy Outlook 2011, "the amount of global hydroelectric and other renewable electric generation capacity will rise 2.7% per year through 2035, more than any other electricity generating source" (The President's Energy Initiatives, 2013).

According to EIA data, the biomass power has experienced significant growth in the recent years in all regions of the country. In the year 2013, the completion of some large-scale systems added more than 750 megawatts (MW) which would be able to power hundreds of thousands of homes and businesses. Thermal conversion of biomass into energy, generated from combusting or gasifying organic matter for heating or cooling is of

significant interest in regions of the U.S. where there are (1) abundant reliable biomass resources (2) high-priced fossil fuels (3) prolonged heating energy demand. Areas meet these conditions are typically located in the Northwest, Midwest, Mountain West, Northeast, and Mid-Atlantic.

2.2 Conversion Technologies

McKendry, P. (2002) in the review of energy production from biomass conversion technologies compared bio-energy process options. The two main routes presently used to convert biomass into energy are thermo-chemical and bio-chemical. The choice of conversion processes depends on many factors: the availability of biomass feedstocks; energy end-use requirement; environmental and economic conditions. There are mainly three types of products through different routes: power generation; heat generation; and transportation fuels (Figure 2.1). For producing gas, only pyrolysis/gasification and anaerobic digestion are currently cost-effective, while pyrolysis is more suited to producing fuel oils which are usually used in diesel engines and gas turbines. For gasification, to produce power/heat, the technology has yet to become consolidated as a mature technology, the main issue being the gasifier design, operation, treatment, and adaption of the gas generated (Ruiz, J., 2013). Basu, P. (2010) thoroughly reviewed biomass gasification technology including feedstocks, system design, and theory.

2.3 Types of Gasifier

There are mainly two types of gasifier: fixed bed and fluidized bed, with variations in each type. A third type, the entrained flow bed, has been developed for pulverized coal gasification with requirement for fine particles. This makes it unsuited for most biomass materials. Besides, material size pretreatment add extra cost which is undesirable.

2.3.1 Fixed Bed Gasification

The fixed bed gasifier has been the traditional category because of easy operation and comparatively low cost. The operating is around 1000°C. Depending on the direction of airflow, the gasifier is classified as updraft, downdraft, and cross-draft.

2.3.1.1 Updraft Gasification

In a traditional updraft gasifier, the materials are fed from the top and the air at the bottom of the unit via a grate (Figure 2.2) (Mckendry, P., 2002). Biomasses are immediately dried introduced from top and then devolatilized falling down with higher surrounding temperatures. Lower down the chamber, the products from devolatilisation experienced reduction zone, in which rich CO and CH₄ are formed. Above the grate, the solid char are formed and combusted. Ash falls through the grate at the bottom and the hot gasses pass upwards and exit. In the pyrolysis (devolatilisation zone), volatile compounds are released and at the same time, considerable amount of tar are formed. However, low temperature caused some of the tar to condense. Condensed tar partly left with the producer gas. Due to low gas temperature, the overall efficiency of updraft systems is high but also is the tar concentration of the gas.

Broad work has been done to improve the performance of updraft systems and decrease tar production. Duleeka and Andreas (2014) gasified bio-coal pellets in an updraft high-temperature agent gasification (HTAG) with preheated air at 900°C. This preheated air provided additional heat to the gasification process, with which CO/CO₂ ratio was near 5 for the highest Equivalence Ratio (ER), and the gas purity was maximized when ER was at minimum. The Low Heating Value (LHV) and cold gas efficiency were also maximized. Gunarathne, D. et al. (2006) also did experiments on an updraft with

HTAG technique. The agent gases employed were mixtures of air and steam preheated to 1400°C.

The producer gas was characterized with respect to composition, including a detailed tar analysis. The results suggested a much higher LHV and total gas yields. It was also found that tar had been extensively cracked due to the high temperature of outgoing gas. Pedroso, D. et al. (2013) modified the conventional updraft gasifier with adding a secondary air to decrease tar concentration in the producer gas (Figure 2.3). The new design has two agent gas entrances. One is still at the bottom same with the conventional design and a secondary one formed by four nozzles are in the middle of the gasifier. In this way, a combustion zone is established to increase the producer gas temperature and thus decrease tar composition.

2.3.1.2 Downdraft Gasification

A conventional downdraft gasifier is shown in Figure 2.4. The biomasses and air move in the same direction. The producer gases leave the system after passing through the high-temperature zone (oxidization zone), enabling the partial cracking of the condensable tars and providing producer gas with low tar content. Since the gases leaving the system at a higher temperature 700-1000°C, the overall thermal efficiency of a downdraft gasifier is lower due to considerable quantities of heat carried over by the hot gas. However, the main advantage is lower tar concentration in the gases, which enable its application in internal combustion engines (ICE) and extend the durability of ICE. It is reported that tar yields range from 10 to 100 g m⁻³ of gas for updraft gasifier (Bhattacharya, S., 2009; Kinoshita, C.,1994; Narváez, I., 1997) and 50-500 mg m⁻³ of gas for downdraft gasifier (Bhattacharya, S., 2009; Sami, M., 2001).

Downdraft gasifiers depending on different top designs are categorized as open top and closed top, respectively. The open top design configuration is shown in Figure 2.5. Biomasses and air forced to move downwards homogeneously throughout the gasifier. The design efficiently prevented hot spot formation and the possibilities of the formation of preferential channels and internal bridges.

The closed top design has two different types, namely one with a conventional downdraft with a strait cylindrical reactor shown in Fig 2.4 and one with a throat in the core of the reactor shown in Fig 2.6. The throat design has air intake just above the throat which enhance material mixing and even temperature and thus decrease tar concentration in the gas (Sami, M., 2001).

A modified design of downdraft gasifier shown in Fig 2.7 had been favored to further reduce tar concentration in the product gas (Bhattacharya, S., 2003; Henriksen, U., 2003). Similar to the modified updraft system with a secondary air inlet, this design is also known as a two-stage gasifier with first stage air introduced from top and second stage of air feeding at the core of the gasifier. This way, a combustion zone is formed to crack down tars after which a gasification zone functions as a filtration bed, enabling high char conversion and lower ash and tar content. According to Hughes, W. et al. (1998), a greater reactor length may increase operational efficiency. Also, the two-stage design requires greater vertical diameter. Thus, the modified design is more suitable for a scaled-up system.

2.3.1.3 Crossdraft Gasification

In a cross-flow gasifier, biomass materials are fed from top and move downwards. Air is introduced from the side, the gases being withdrawn from the opposite side. A hot

combustion/oxidization zone is formed at the entrance of the air and a drying and devolatilization zone being formed higher up in the chamber. The cross-draft design is not seen very often for several reasons. First, due to the comparatively short residence time, it cannot handle fuel that has high-tar content. Second, it usually operates in small scale. Third, it causes hot spot which can leads to local material problems.

2.3.2 Fluidized Bed Gasification

Fluidized Bed (FB) gasification has been extensively used in coal combustion and coal gasification industry with the advantages of uniform temperature distribution achieved in the reaction zone. Air is introduced with a bed of fine-grained material. The fluidizing bed material ensures intimate mixing of the hot bed material, the hot producer gas, and the biomass feed. A FB gasifier consisting of a vessel with a grate at the bottom through which introducing air is known as Bubbling bed FB gasifier. By controlling air/biomass ratio, the bed temperature can be regulated to 700-900°C. Circulation FB (CFB) gasifier is another well-known category. The bed materials are circulated between the reaction chamber and a cyclone separator, in which ash is removed and bed materials and char returned back to the chamber in a CFB.

2.4 Basic Chemistry

Gasification is a thermochemical partial oxidation process in which carbonaceous substances (biomass, coal, and plastics) are converted into gas in the presence of a gasifying agent (air, steam, oxygen, CO₂ or a mixture of these). The gas generated, commonly referred to as syngas (synthesis gas), consists mainly of H₂, CO, CO₂, N₂, small particles of char (solid carbonaceous residue), ashes, and tar (Ruiz, J., 2013). Gasification

process adds value to the original feedstock which has low or negative value by converting it into marketable products and fuels.

The chemistry of biomass gasification is complex. Generally speaking, the overall process can be broken down into the following four stages: drying, devolatilization, oxidation, and reduction.

Drying.

The moisture content of biomass typically ranges from 5%-35%. Drying occurs at about 100-200°C. After this stage, the moisture content can be reduced to about 5%.

Devolatilization (pyrolysis).

In this stage, solid fuel is heated to up to 400°C. Thermal decomposition occurs and the volatile matters release in the absence of oxygen air. This results in the formation of hydrocarbon gases from biomass, which condenses at a sufficiently low temperature to generate liquid tar. The residual is solid charcoal. Devolatilization is a combined physical and chemical process.

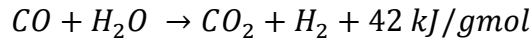
Oxidation:

With existence of air, oxygen or steam, solid charcoal can be oxidized, resulting in formation of CO₂. Hydrogen present in biomass is also oxidized to generate water. A large amount of heat is released during this stage which sustains the energy needed for the following stage.

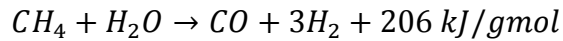
Reduction (gasification):

In the absence of oxygen, several reduction reactions occur in the temperature range of 800-1000°C. These reactions mostly are endothermic and oxidation provide some of the heat needed. The main reactions occurring in this stage are as follows:

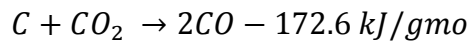
Shift reaction (2.1)



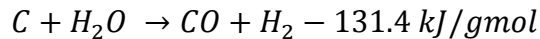
Methane reforming reaction (2.2)



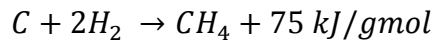
Bounded reaction (2.3)



Water-gas reaction (2.4)



Methane reaction (2.5)



Equations 2.3-2.5 involve heterogeneous reactions of solid carbon and gaseous products to produce CO, H₂, and CH₄ which are the main combustible gases in the syngas.

2.5 Effects of Gasification Operating Conditions

2.5.1 Materials

Researchers categorize biomasses in various ways but one simple way it to characterize them in four types, namely woody biomass, herbaceous plants/grasses, aquatic plant and manures. Herbaceous depending on the moisture content percentage can be subdivided into two categories. High moisture content biomass, including the herbaceous plant sugarcane, usually be converted in a 'wet/aqueous' process, involving

biologically mediated reactions such as fermentation. However, low-moisture content biomass including woody biomass and some other herbaceous plants is more suited to thermal conversion such as pyrolysis, gasification, and combustion. Pre-moisture treatment is used when the energy required would not be inordinately large compared to the energy content of product formed.

Another method of categorizing biomasses depends on the contents of varying amount of cellulose, hemicellulose, lignin and a small amount of other extractives. By definition (McKendry, P., 2002), cellulose is a glucose polymer, consisting of linear chains of (1, 4)-D-glucopyranose units, in which the units are linked 1–4 in the β -configuration, with an average molecular weight of around 100,000. Hemicellulose is a mixture of polysaccharides, composed almost entirely of sugars such as glucose, mannose, xylose and arabinose and methyl glucuronic and galacturonic acids, with an average molecular weight of <30,000. Lignin can be regarded as a group of amorphous, high-molecular-weight, chemically related compounds. Generally speaking, biomasses contain 40%-50% cellulose and 20%-40% hemicellulose by weight. Yang, H. et al. (2007) characterized hemicellulose, cellulose and lignin pyrolysis using TGA-DSC and packed bed coupled respectively with FTIR and Micro-GC as online-gas monitors. Considerable differences of the pyrolysis behavior were found. According to Yang, H. (2007), hemicellulose is the easiest among three to degrade, pyrolysis starts at a temperature range of 220-315°C and then followed by cellulose whose pyrolysis focuses at 315-400°C while lignin pyrolysis covers a whole temperature range 150-900°C. Another major observation was that the pyrolysis of hemicellulose and lignin involved exothermic reactions while those of cellulose were endothermic at lower temperatures (<500°C). However, at higher

temperatures (>500°C) the results were just the inverse. Cellulose/lignin ratio plays a vital role in biochemical conversion processes. A higher cellulose/lignin ratio leads to a higher overall conversion.

In addition, the following material properties are of interest regarding biomass as an energy source in thermal conversion processes.

Moisture content

There are two forms of moisture content in biomass: intrinsic moisture and extrinsic moisture. Intrinsic moisture content is the portion which is not influenced by weather. On the contrary, extrinsic moisture reflects the prevailing weather during harvest. In practical, the extrinsic moisture is more of concern since intrinsic moisture usually is achieved only under laboratory conditions. Hughes, W. et al. (1998) studied the effect of fuel moisture on Biomass-IGCC performance and found that for a fixed moisture content into the gasifier, efficiency, and power output are unaffected by the moisture content of the raw biomass into the dryer when this moisture level is 30 percent or less and higher levels significantly reduces cycle efficiency. Thermal conversion processes favor lower moisture level biomass but bio-conversion can utilize high moisture content. Woody and low moisture content herbaceous plants are the most efficient biomass resources for thermal conversion to power and liquid fuels, such as methanol (Kaewluan, S., 2011; Deng, J., 2009). Kaewluan, S. et al. (2011) investigated various moisture content levels' influence on the performance of co-gasification of woodchip with rubber waste in a bubbling fluidized bed. The results showed that increased moisture reduced both bed temperature and freeboard temperature, and thus have a negative effect on carbon conversion efficiency and overall gasification efficiency. Bhattacharya, s. et al. (2009)

found that increase in moisture content resulted in the increase in concentration of CO₂ and H₂ while that of CO decreased. Due to the fact that increased moisture favors the formation of H₂, some attentions were focused on directly gasifying wet biomass to produce H₂ (Domínguez, A., 2006). The scheme aimed to utilize steam automatically generated from wet biomass moisture as a reactant to react with intermediate products to produce additional hydrogen. Hu, W. et al. (2008) also studied the fuel gas production by gasification of wet biomass. His conclusion was that using it is a promising method to generate H₂ on a cost of low CO and CO₂ formation.

Calorific value

Calorific value (CV) of a material is an expression of the energy content released when burnt in air. The CV is usually measured in terms of the energy content per unit mass with the units such as MJ/kg for solid biomass. The CV further can be expressed in two forms including high heating value (HHV) and lower heating value (LHV). HHV is the total energy released when the fuel is burnt in air, including the latent heat contained in the water vapor and thus expresses the maximum energy potentially can be recovered from a given fuel. LHV exclude the latent heat contained in the water vapor since it usually cannot be used effectively. Therefore, LHV is the appropriate value to use for the energy potential for subsequent thermal conversion.

Proportions of fixed carbon and volatiles

Fuel analysis has been developed based on solid fuels, which consists of the chemical energy stored in two forms, fixed carbon and volatiles:

Volatile matter (VM) is measured by the gaseous product released when heating the material to 950°C for 7 minutes. The fixed carbon content (FC) is the mass remaining

after the release of volatile matter, excluding the ash and moisture contents. The importance of the VM and FC content in biomass is that it reveals the feasibility biomasses can be ignited and subsequently gasified, or oxidized. Compared to lignite or bituminous coal, biomass materials typically have higher CM content and lower FC content. Therefore, a scheme that co-firing biomass and coal was developed (Munir, S., 2010). Sami, M. (2001) strongly advocated co-firing of biomass with higher quality coal since the balance of CM and FC content would improve flame stability and also make the coal ignition easier.

Ash/ residue content

The chemical breakdown of biomass materials, either by thermo-chemical processes or bio-chemical processes, produces a solid residue, which is called ash. The ash content of biomass materials highly affects material handling, processing cost, and overall energy conversion cost. Through thermo-chemical conversion process, the composition of as can present significant operation problems.

Alkali metal content

The alkali metal content of biomass including Na, K, Mg, P and Ca, is critical to thermo-chemical conversion. The reaction of alkali metals with silica present in the ash results in a sticky, mobile liquid phase, which can block the airways of furnace or boiler (Salo, K., 1998; Gil, J.,1997).

2.5.2 Gasifying Medium

Gasifying medium (or gasifying agent) include, but not limited to air, steam, oxygen, CO₂ or combination of them. The selection of gasifying mediums highly depends

on the desired composition of the product gas and the utilization of it since gasifying medium has direct influence on the product gas composition distribution and gas heating value.

Steam gasification starts to gain attention due to the possibility of producing more H₂ gas from hydrogen molecules in steam. However, steam gasification is highly endothermic that it needs external heat supply or circulation system in order to achieve auto thermal process which is cost inefficient. The use of pure oxygen has a positive effect on carbon conversion efficiency and increases the heating value of the product gas but the production of pure oxygen is very expensive. CO₂ gasification originated from the innovation of high concentration CO₂ capture and storage. Pure CO₂ as gasifying medium requires an indirect or external heat supply for the endothermic gasification reaction. Compared to the other methods, this method is novel and still in the research phase. Air gasification is the simplest and direct method. The disadvantage is the dilution effect of nitrogen in air. But due to its low cost, it is still the most common way so far. There are also many researchers working on mixture of different gasifying agent, such as air-steam mixture, air-CO₂ and oxygen-steam mixture (Gil, J., 1997; Lv, P., 2004; Campoy, M., 2009).

2.5.3 Operating Temperature

Gasification temperature is one of the most critical factors influencing the product gas composition and gas yield. Increasing gasification temperature is typically beneficial to carbon conversion efficiency since it increases the gas-solid reactions. Gasification temperatures in different zones are usually tested using thermocouples located in different locations. Thermocouples can be arranged either horizontally through the side of the

reactor or vertically from the top (Martinez, J., 2011; Balu, E., 2012; Biagini, E., 2014). Thermocouples placed through the side horizontally are usually projected up to the internal reactor wall to avoid possible solid fuel flow problems. However, for a small scale system, this type of design might bring in errors due to the radiation heat loss from the wall. The vertical design is more beneficial since it is placed near the center of the reactor. Typically, a holding structure is used to install a series of thermocouples along the depth of the reactor.

2.5.4 Effect of Equivalence Ratio

The equivalence ratio (ER) is defined as the ratio of the actual air supply to the stoichiometric air required for complete combustion on a dry ash free basis. ER value is usually determined by measuring the actual air flow rate and solid biomass consumption rate. ER indicates the oxygen feed in the gasification and it is critical because it highly affects the overall performance of the gasification process. ER can be adjusted by both the air feeding rate and the fuel feeding rate.

2.5.5 Effect of Fuel Feeding Rate

Fuel feeding rate is usually controlled by metering and hence can be measured during experiment. For a specific gasifier, accelerating fuel feeding rate enhances the production capacity which is beneficial. However, excessively high feeding rate is unwanted because it will result in a shorter gas residence time. Low gas residence time leads to insufficient contact between gas and solid and the condensed tar has very low chance to be broken down which causes high tar (hydrocarbons produced through gasification that can be condensed) yield in the producer gas.

2.6 Downstream Utilization

2.6.1 Syngas Cleaning

To achieve further utilization, syngas needs to be cleaned to remove sulfur compounds, tar, and particles, among which tar is of the most concern. The reason involves: tar is difficult to be broken down under low temperatures which is inefficient when burning with syngas; tar condensed into a liquid at low temperatures, easily combined with water, carbon, etc., which causes clogging in airways and is corrosive to metal; it is also harmful to health after burning. Therefore, syngas cleaning before subsequent utilization is very important.

All the methods available for tar removal can be categorized into two types depending on the location where tar is removed; either in the gasifier itself (known as primary method) or outside the gasifier (known as secondary method). The primary method can be defined as to prevent or convert tar formed in the gasifier, shown in Fig 2.8. To achieve best-quality exit gas, the gasifier performance needs to be optimized, including a proper overall design, the appropriate operating conditions, and proper use of bed additives or catalysts

Downdraft design is known as having the lowest tar yield among the various types which is 0.01-6 g/Nm³. The operating conditions also play very important role in all respects during gasification, especially in tar formation and tar reduction. For example, a homogeneous bed temperature profile is of utmost importance to avoid cool spots and thus avoid tar formation. Also, to achieve a high carbon conversion with low tar formation, temperature above 800°C is favored. Kinoshita, C. (1994) found that the total number of detectable tar species decrease with the temperature increase during sawdust gasification

in a bench-scale fluidized bed gasifier. Knight, H. et al. (2000) investigated vessel pressure up to 21.4 bar and found that the total amount of tar decreased, phenols were even eliminated, but the fraction of polycyclic aromatic hydrocarbons (PAH) increased. Gil, J., (1997) studied influence of the ER and found that the tar content decreases sharply with the ER increase and it strongly affect the gasification product. In addition, many researchers have been looking for the appropriate catalysts for tar removal and Sutton, D. et al. (2001) had done an extensive report on it. Among all discovered, only a few catalysts have been tried as bed additive inside the gasifier. There is a great potential of in-bed catalysts in terms of tar reduction and thus avoiding downstream tar removal.

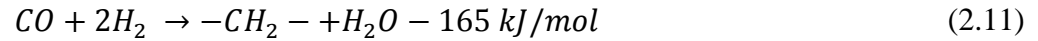
The secondary methods, shown in Fig 2.9, are generally used as treatments to the exit gas from the gasifier, including physical and chemical approaches. The chemical methods usually refer to tar cracking downstream either thermally or employing catalysts and the physical way includes use of baffle filter, cyclone, fabric filter, ceramic filter, rotating particle separator, electrostatic filter, and scrubber.

Although, the downstream processing methods are proved to be very effective, in many cases they are not economically acceptable. Narvaez, I. et al. (1997) investigated a three-step method that could achieve very low tar concentration in the gas.

2.6.2 Conversion of Syngas to Bio-power, Biofuels, and Bio-products

During gasification, most of the biomass is converted to syngas and part of it is converted to char and tar. Depending on the quality, syngas can be used as a fuel for internal combustion engineering, gas turbines for heat and power generation, or as a feedstock for synthesis of transportation fuels and chemicals. The main application paths are shown as Figure 2.10.

High-quality syngas with almost no tar or dust and with high heating value can be fed to gas engines directly or turbines for power generation. Besides, by steam reforming with catalysts, it can achieve H₂ production. In addition, a gas mixture of CO and H₂ can be employed to produce hydrocarbons of variable chain length via the Fischer–Tropsch (FT) reaction:



The $-CH_2 -$ is precursor for long-chain hydrocarbons. By FT reaction, hydrocarbons of different lengths can be made, including alternative to conventional diesel, gasoline, kerosene, etc.

2.7 Gasification Modeling

Biomass gasification is a complex process due to the anisotropic nature of biomass and the heterogeneous chemistry of biomass gasification. Mathematical models are helpful for system design, prediction of system operation, emissions, change of operational parameters which is beneficial to improve the development of the technology. There are mainly four types of models available for downdraft gasifiers: thermodynamic equilibrium, kinetics, Computational fluid dynamics (CFD), and Artificial Neural Networks (ANNs) (Patra, T., 2015; Basu, P., 2010). Each model has its advantage and disadvantage and is hence suitable for different applications.

The thermodynamic equilibrium model assumes the achievement of thermodynamic equilibrium or chemical equilibrium in the reactor to calculate the theoretical maximum yield that can be obtained. It is independent of the reactor design and dimensions. In reality, it is impossible to achieve equilibrium within the gasifier. However, at high temperature, the model provides reasonable predictions. It is commonly used at

reactor temperature higher than 1200C. Extensive work can be found on thermodynamic equilibrium modeling (Chern, S. et al., 1991; Zainal, Z. et al., 2001; Melgar, A. et al., 2007).

If reactants are left to react for an infinite time, equilibrium can be achieved. However, in practice, only finite time is available for reactions in the gasifier. Therefore, equilibrium models are only able to provide an ideal yield and kinetic models are needed to predict the products from a gasifier that only provides certain time for reaction. A kinetic model sometimes involves parameters such as reaction rate, residence time, superficial velocity, diffusion rate, and length of the reactor. Thus, kinetics models can usually provide a wide range of investigations on the behavior of a gasifier (Blasi, C., 2000; Blasi, C., 1997). They are more accurate but still computationally intensive.

CFD has an important role in the modeling of fluidized-bed gasifiers. A CFD-based model usually solves the equations of conservation of mass, momentum, species, and energy over a specified domain. The approach can be achieved with commercial software such as ANSYS Fluent. Comprehensive work using CFD modeling for biomass gasification is still lacking due to the complexity of the problem. However, some simplified CFD models have been developed (Fletcher, D., 2000; Yu, L. et al., 2007; Janajreh, I. et al., 2013).

ANNs modeling is inspired computer modeling designed to simulate the way in which human brain processes information. ANNs gather information by detecting the patterns and relationships in data and “learn” through “experience. The method does not provide an analytical solution, it brings numerical results. It has been widely used in

fluidized bed with reasonable success to predict gas yield (Bing, G. et al., 1997; Xiao, G. et al., 2009).

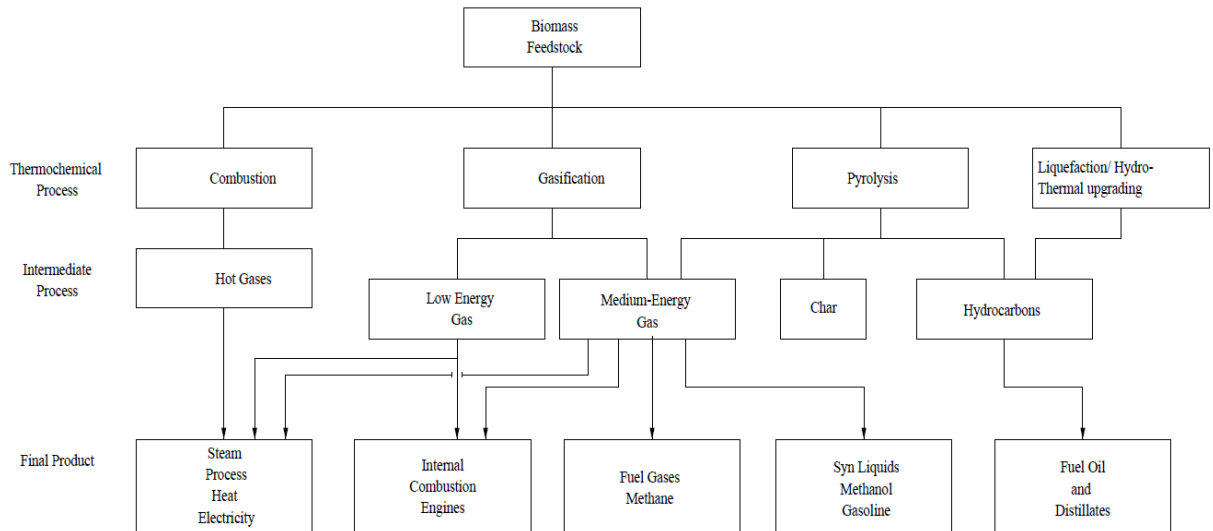


Figure 2.1 Main processes, intermediate energy carriers and final energy products from the thermo-chemical conversion of biomass. (Source: McKendry, P., 2002)

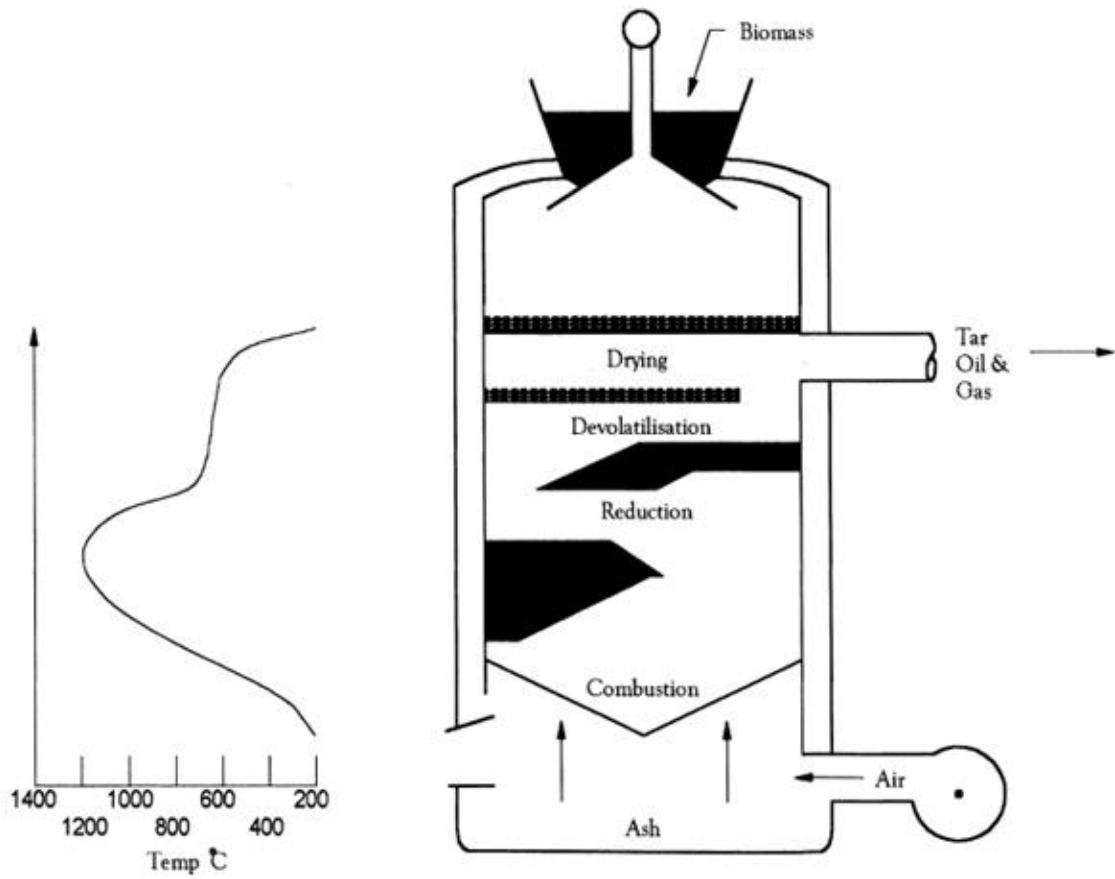


Figure 2.2 Schematic of updraft gasifier. (Source: McKendry, P., 2002)

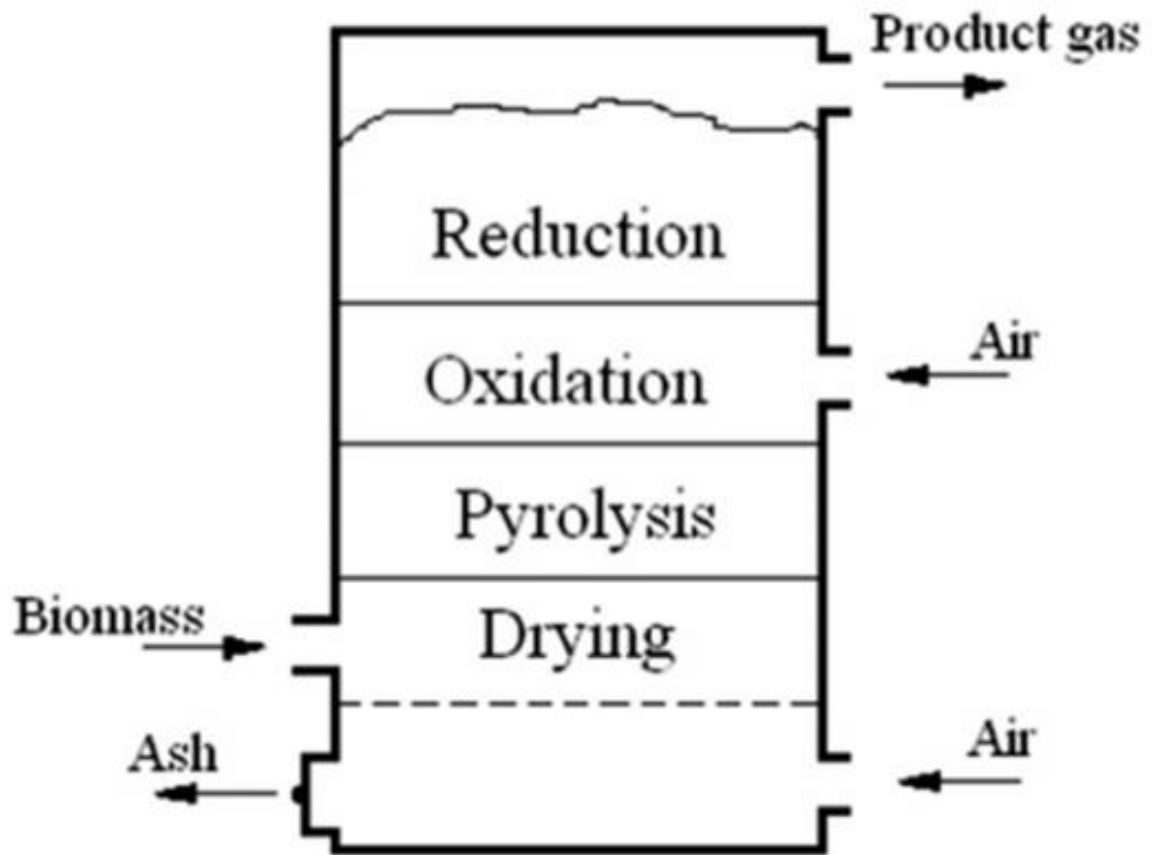


Figure 2.3 Modified updraft gasifier design. (Source: McKendry, P., 2002)

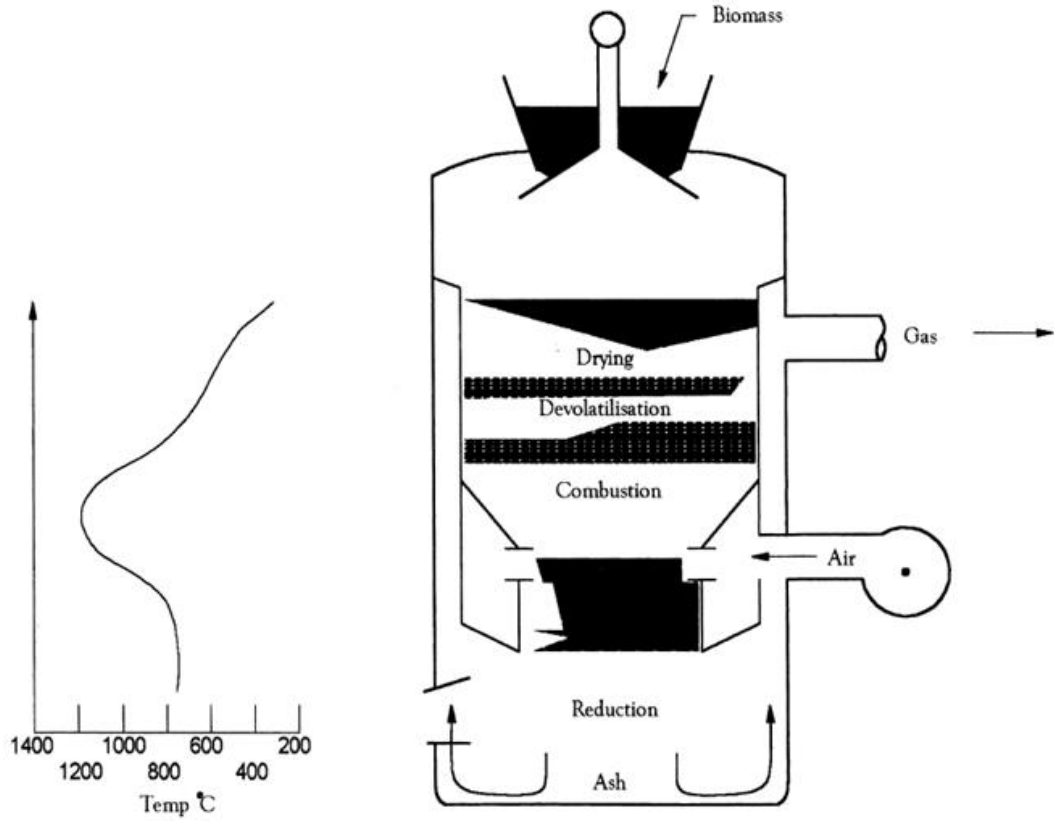


Figure 2.4 Schematic of downdraft gasifier. (Source: McKendry, P., 2002)

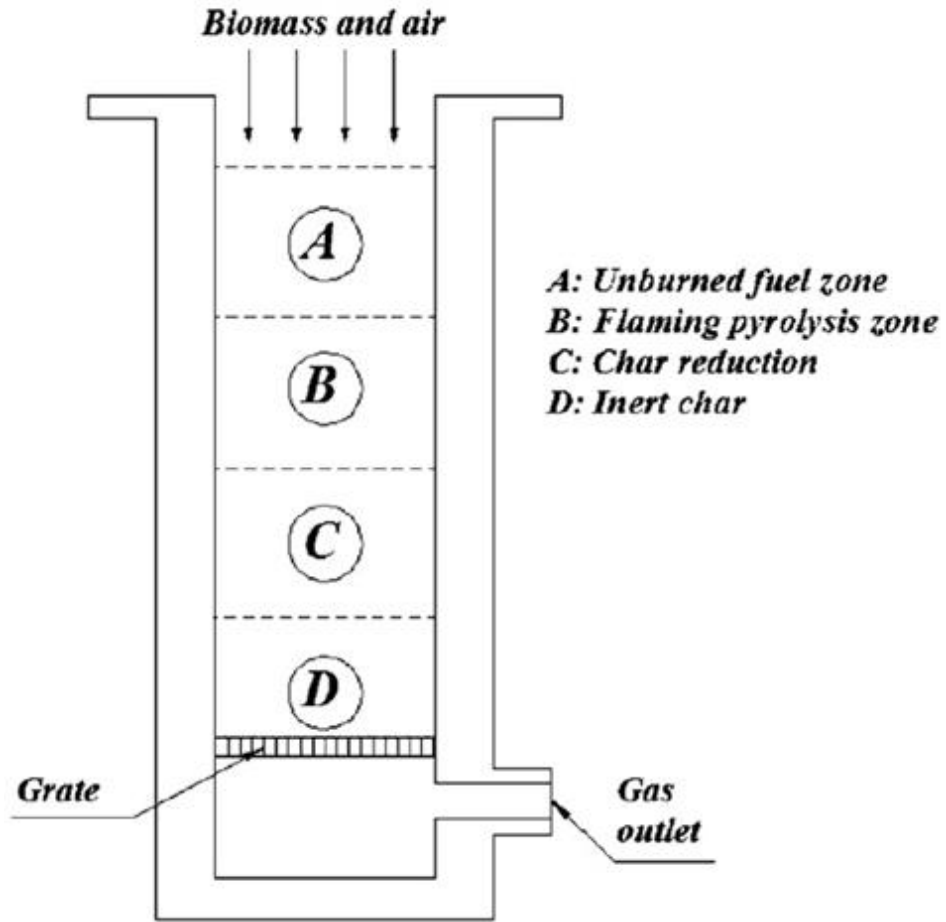


Figure 2.5. Gasifier with open top. (Source: Beenackers, A., 2009)

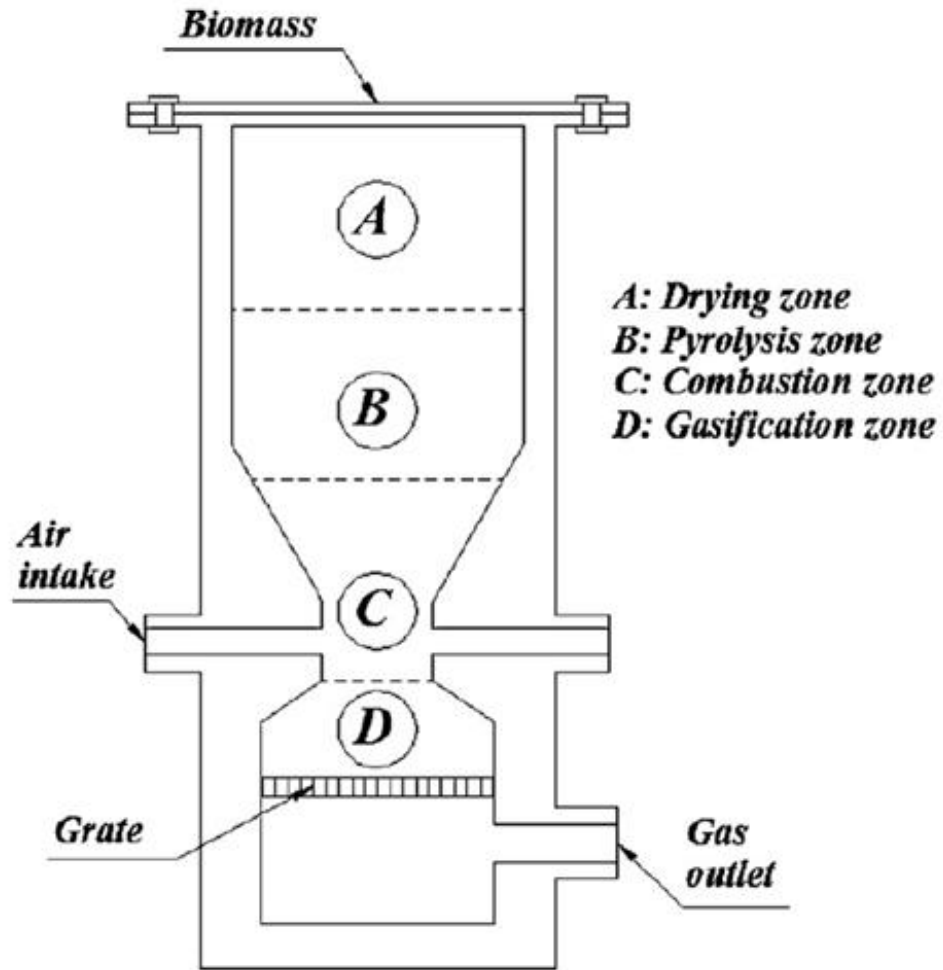


Figure 2.6 Downdraft gasifier with a throat. (Source: Beenackers, A., 2009)

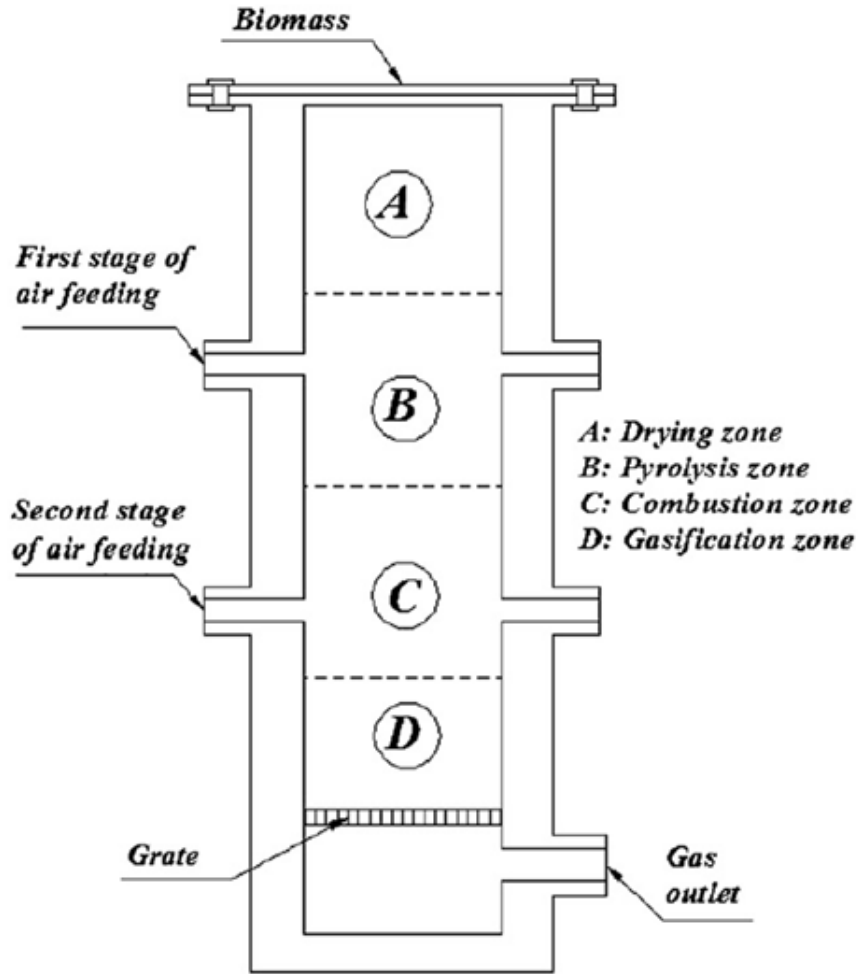


Figure 2.7 Downdraft gasifier with double stage air supply. (Source: Beenackers, A., 2009)

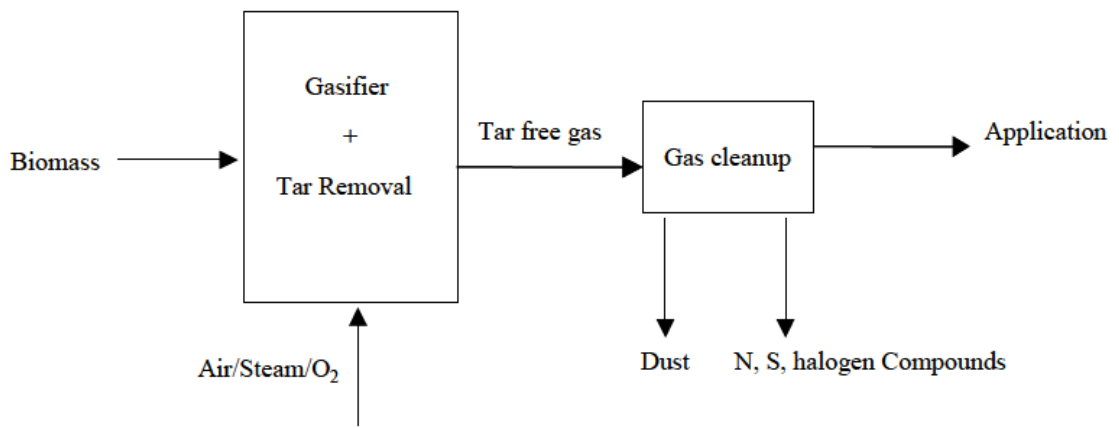


Figure 2.8 Tar reduction concept by primary method (Source: Ponzio, A, 2006)

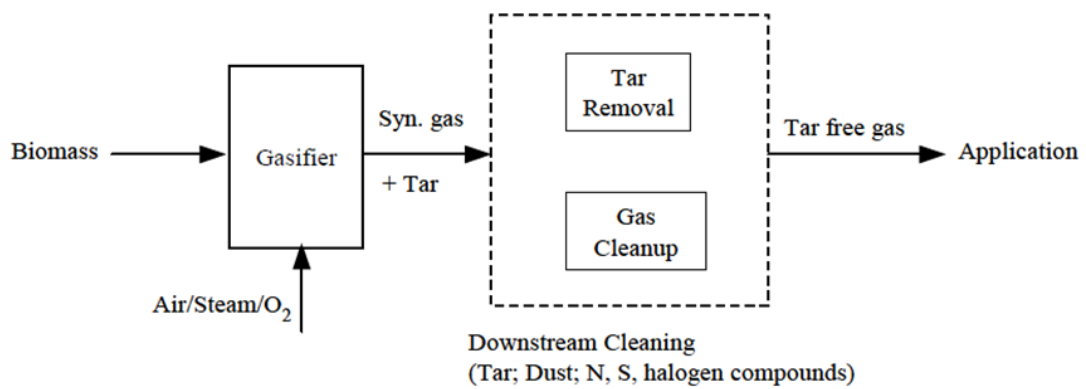


Figure 2.9 Tar reduction concept by secondary method. (Source: Ponzio, A, 2006)

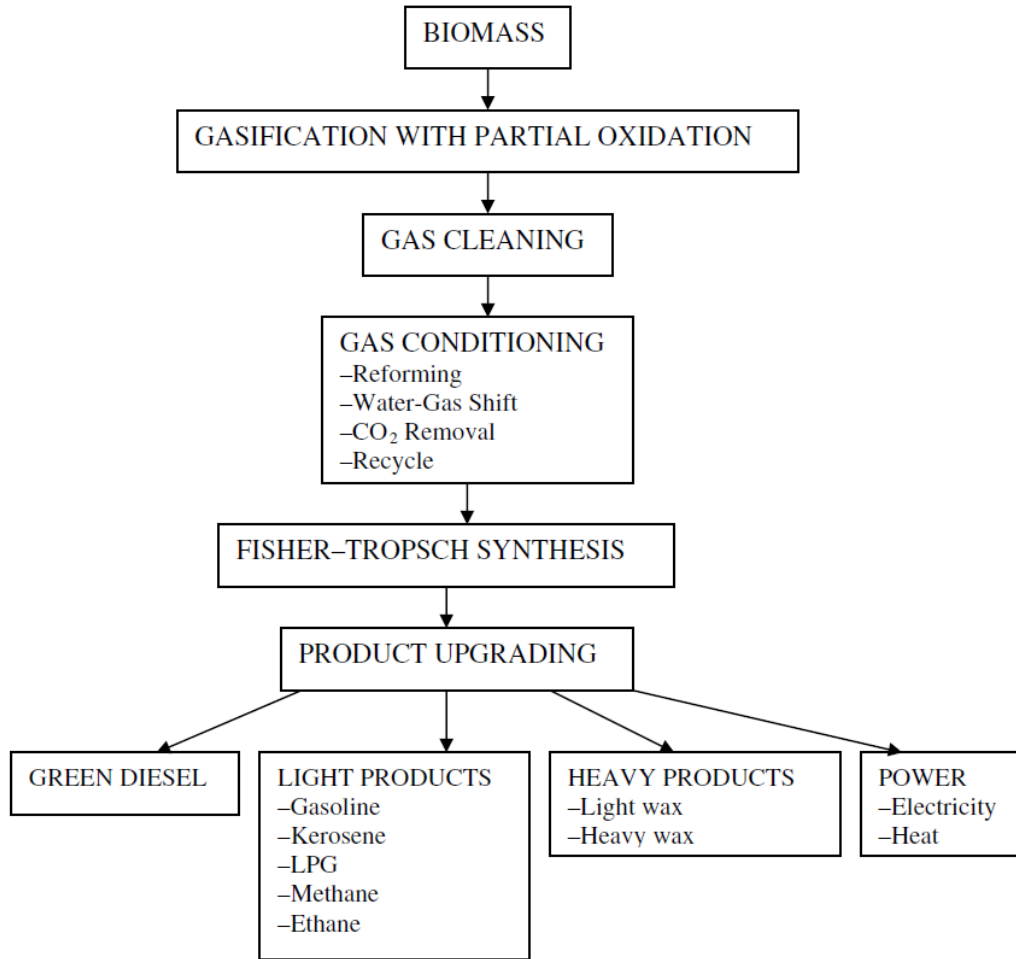


Figure 2.10 Syngas application paths. (Source: Ponzio, A., 2006)

CHAPTER 3
PILOT- SCALE GASIFIERS DESIGN, OPERATION, AND
EXPERIMENTAL PROCEDURES

3.1 Pilot-Scale System

3.1.1 System Introduction

The University of Iowa Biomass Gasification System is located in the University of Iowa Oakdale Power Plant and the system is designed and established for research only (Fig 3.1). The syngas produced from the system is sent into a boiler (Hurst Boiler) for heat co-production.

The pilot-scale gasification system includes the following main components (in the order of material and gas flow): raw material handling system, air intake system, downdraft gasifier, ignition system, syngas outlet, and solid products handling system. The system flow diagram is shown in Fig 3.2. The gasifier was originally designed by Ag Bio – Power Inc., Tama, Iowa and the solid material handling system was designed by Scott Salsbery from the University of Iowa. The system was first installed in Jun 2012 by Ag Bio – Power and the initial tests and following tests were done using seed corn as the primary fuel by the author of the thesis. 20 commissioning tests (including trial test) were done to operate the system at steady state regime. During the tests, several component designs and installation deficiencies were identified including air injection, char/ash delivery, temperature detection, and char bed-level detection. These problems were not related to the gasification reactor itself. However, abnormal and unstable operation severely influences the performance of the overall system. Therefore, a new air damper with better insulation was replaced. Several more thermocouples were added, and new

bed-height detection equipment was purchased. Also, char/ash chute and part of the char/ash screw auger were redesigned and reinstalled.

3.1.2 Gasifier Design

The design of the downdraft gasifier is shown in Fig 3.3. The gasifier is a downdraft open-top unit (both fuel and air intake are from top of the reactor) with a firetube where gasification reactions occur. The refractory material is used for the fire tube with an overall dimension of 62 cm (ID) – 72 cm (OD) * 120 cm (tall). There are four fingers mounted to the firetube 25 cm above the bottom of it. Below the firetube, there is a turntable with four agitation fingers installed in center. The turntable turns at a speed of 0.25rpm. The two sets of agitation fingers at different fuel levels enable better fuel mixing and reaction. These unique features enable better solid–solid and gas–solid mixing. Air and biomass materials both enter the gasifier from the top and go through the gasifier in the same direction. The height of the turntable can be adjusted to indirectly adjust the solid residence time. Raw materials entering the firetube (reaction chamber) go through four different zones: drying, pyrolysis, combustion, and reduction. Bio-char is formed after this process and exit through the edge of the turntable. Product gases going through different reaction zones are removed from the syngas outlet which is near top of the gasifier on the side. Some photos show the inside design of the gasifier shown in Fig 3.4. The holes open on top are for ignition gas, air intake, and thermal couples respectively.

3.1.3 Fuel Storage and Solid Delivery System Design

The fuel storage and handling system is composed of primary fuel storage, secondary fuel storage, temporary fuel storage, and auger delivering system (Fig 3.5). The primary fuel is stored in a bin outside of the power plant on the west side. Materials in

primary and secondary storages are delivered through augers to the fuel bins on top of the gasifier respectively for temporary storage. Both the primary and secondary temporary storage bins have motor control for fuel feeding speed adjustment. Also applying different feeding speeds to different biomass materials can achieve material mixing at various percentages. Storage capacity for the primary, the secondary, and the temporary bins are about 30 tons, 10 tons, and 300 lbs respectively. The bin designs are shown in Fig 3.4.

The solid material handling system delivers solid biomass from storage bin into the gasifier and also delivers solid char produced from the gasifier. Therefore, it is essential to the operation of the gasification system. For UI gasification project design, special considerations were taken into account to meter different types of solid fuels and facilitate co-gasification. Controlling of the material handling system, both fuel input, and char/ash output is accomplished by the gasifier's control system. The fuel input system include two fuel storage bins both of which use auger conveyor to deliver the fuels to the temporary storage bins which are located above the gasifier. Two temporary metering bins each can store about 150kg solid fuels can be controlled to achieve accurate solid fuel feeding rate. The storage bin is designed to fit solids only smaller than 2 in by 2 in to ensure flow in the system. Char/ash output system includes a vertical bin, one side of which is connected to the bottom of the gasifier and the other side is connected to another auger conveyor that delivers the waste outside the power plant. The photos for the trash bin and the auger are shown in Fig 3.6.

3.1.4 Air Intake and Ignition System

Air input and syngas output are basic functions of a gasifier, and they are critical component to accomplishing gasification. Typically, blower are used and placed on the

output (syngas) side of the gasifier to suck the syngas from the reaction zone. For this reason, syngas or production gas is sometimes called suction gas. It is worth noting however that gasification can be accomplished using the blower on the input (air) side of the gasifier, generating positive pressure to move the gas out of the gasifier. There are both advantages and disadvantages, different in either case. An advantage of using vacuum/suction is safety, as the gas cannot accumulate under pressure to pose an explosion hazard. The exit of UI gasifier is connected directly to a boiler which co-combust natural gas and syngas. Therefore, negative pressure is formed inside the gasifier.

Gasification usually needs external heating sources to initiate the reactions. In UI Oakdale system, a natural gas burner is mounted vertically on the top of the gasifier, aimed downward into the fuel bed to ignite the fuel.

3.1.5 Gas Cleaning, Cooling, and Sampling

Producer gas is sampled at the exit of the gasifier and a sampling and cleaning system is designed (Figure 3.7). Producer gas was cleaned in a series of impinger bottles with isopropanol solution based on CEN/TC143 Particle and Tar Analysis Guide (Kamp, W., 2005). After cleaning, the producer gas may then be tested in a flow indicator and sent into GC for gas analysis. Agilent MicrGC490 is employed for producer gas testing. The micro GC is a two channel system both with TCDs. Channel one is a MS5 molsieve column which detects the following permanent gases: He, H₂, O₂, N₂, CH₄, and CO. Channel one runs Argon as a carrier gas. Channel two is a Pora PLOT U (PPU) column which measure CO₂. Channel two runs Helium (He) as carrier gas. A three-point GC calibration was performed using a certified standard gas prior to each test. Producer gas

detection method is shown in Table 3.3. Retention times for each gas in Column MS 5 Channel are tabulated in Table 3.4.

3.2 Pilot-scale Operation

The Oakdale system can be started, operated at steady-state, and shutdown from the PANEL VIEW monitor located on the control cabinet. Four working conditions are defined including shutdown, startup, run, and burndown. When steady running, operator can choose AUTO or MANUAL mode to run the system. Detailed information is provided in Appendix A.

3.3 Pilot-scale Experimental Procedures

3.3.1 Preparation and Characterization of Biomass Materials

All the biomass materials were sent to a lab for ultimate analysis and proximate analysis before the test. The proximate analysis gives moisture content, volatile content (when heated to 950°C and kept for 7 minutes), the fixed carbon remaining at that point, the ash (minerals) in the sample and the high heating value (HHV) based on the complete combustion of the sample to carbon dioxide and liquid water. In addition, the low heating value, LHV, gives the heat released when the hydrogen is burned to gaseous water, corresponding to most heating applications and can be calculated from the HHV and H₂ fraction. The ultimate analysis gives the composition of the biomass in wt% of carbon, hydrogen and oxygen (the major components) as well as sulfur and nitrogen (if any). Table 3.1 and Table 3.2 show the ultimate analysis and proximate analysis for corn which are used as biomass fuel in the research. For HHV value, as a check on the accuracy of the determination, it was also calculated by the IGT equation (Reed, 1981) using Equation 3.3.

$$\text{HHV (kJ/kg)} = 2.326 [146.58 C + 568.78 H - 29.45 - 6.58 A - 51.53 (O + N)] \quad (3.1)$$

Where, C = Carbon % weight

H = Hydrogen % weight

A = Ash % weight

O = Oxygen % weight

N = Nitrogen % weight

3.3.2 Other Determinations

Temperature Measurements and Thermocouple Locations

The temperature in the system was measured by means of thermocouples. The thermocouple used was type K Cr/Al series. All the thermocouples were calibrated using three point method before the test. The measuring range is between 50 and 1350°C. The locations of the thermocouples are listed below Fig 3.8 shows a schematic of all the thermocouples.

T1 = Temperature of product gas leaving the gasifier to Hurst Boiler

T2 = Temperature of external metal on the south side

T3 = Temperature of external metal on the north side

T4 = Temperature of drying zone

T5 = Temperature of solid fuel 1 inch above the bottom of the fuel bed

T6 = Temperature of solid fuel 2 inch above the bottom of the fuel bed

T7 = Temperature of solid fuel 3 inch above the bottom of the fuel bed

Pressure Measurements

The pressure at the exit of gasifier was measured. The pressure indicates vacuum pressure of the Hurst Boiler which acts as the induced draft for the gasifier.

Tar, condensate, char and ash determination

During gasification, substantial tar, char and ash are produced. Each of these components was collected in different locations in the system. The weight of char and ash were measured for mass and energy balance analysis.

Due to the nature of downdraft gasification, most of the tar and condensate were reabsorbed by the char in the reaction and converted to producer gas in the reduction zone. The amount of leftover tar and condensate reabsorbed by the char and ash could be easily determined by examining the char composition. Besides, tar and concentrate were collected in the washing and cooling impinger system. Since it is trace amount in the mass balance, it was not measured.

Char and ash produced during gasification were delivered out of the gasifier through an auger to a barrel outside the power plant. These char samples were measured for weight for further mass closure calculation.

Average Biomass Flow Rate

Before the start of the gasifier, a predetermined weight of biomass materials was added into the storage bin on top of the reaction. During the operation, biomass was added in the reaction by controlling the motor. The speed of the motor is adjustable so that the fuel feeding rate is determined. The amount of solid fuel added during the run is the fuel consumption for that particular run. The average fuel feed rate is calculated by dividing the total biomass added by the total operation time of the gasifier.

Average Air and Gas Flow Rate

The average air velocity was measured by a velocity meter mounted 10 inches above the air damper. Thus, the average air flow rate can be calculated using the air velocity measured at the center and the duct sectional area. The velocity meter was able to read up to 1000 fpm. The equipment was calibrated before installation. Although using center velocity to calculate average air flow rate has brought in systematic errors, it is acceptable in this test because of the small size of the pipe (diameter – 6 inches). Product gas flow rate was calculated based on the assumption that N_2 is balanced during the gasification process.

Chemical Composition of the Gas

The composition of the product gas from the gasifier is an important parameter to be recorded for the preparation of the mass and energy balances and for the calculating the heating value of the gas. The chemical composition of the product gas was measured by Agilent MicroGC-490. The gas samples can be drawn from either exit or different depth inside the gasifier.

Agilent MicroGC490 is employed for producer gas testing. The micro GC is a two channel system both with TCDs. Channel one is a MS5 molsieve column which detects the following gases: He, H_2 , O_2 , N_2 , CH_4 , and CO. Channel one runs Argon as a carrier gas. Channel two is a Pora PLOT U (PPU) column which measure CO_2 . Channel two runs Helium (He) as carrier gas. Producer gas detection method is shown in Table 3.4. Retention times for each gas in column one are tabulated in Table 3.4. A three-point GC calibration was performed using a certified standard gas prior to each test (Appendix B).

The calibration gases are manufactured by Praxair Specialty Gas & Equipment located in Cedar Rapids, Iowa. Figure 3.8 shows an example of calibration curves.

Table 3.1 Ultimate analysis for corn from Iowa

	Corn (Dry Ash Free Basis)
Carbon	44.68%
Hydrogen	6.28%
Nitrogen	1.46%
Chlorine	0.05%
Sulfur	0.11%
Oxygen	47.42%
Total	100.00%

Table 3.2 Proximate analysis for corn from Iowa

	Corn
Moisture	12.91%
Volatile Matter	74.42%
Fixed Carbon	7.46%
Ash	5.21%
Total	100.00%
HV[MJ/kg]	20.72

Table 3.3 GC detection method

	MS 5 Channel	PPU Channel
Column Temperature	100°C	60 °C
Injection Temperature	110 °C	110 °C
Pressure	22 psi	17 psi
Carrier Gas	Argon	Helium
Injection Time	40ms	80 ms
Run Time	150 sec	150 sec
Invert Signal	Yes	No
Stabilization Time	10 sec	10 sec
Sampling Time	30 sec	30 sec
Sample Line Temperature	110 °C	110 °C

Table 3.4 GC retention time

Compound	Retention Time (min)
H ₂	0.58
O ₂	0.76
N ₂	0.95
CH ₄	1.34
CO	1.92
CO ₂	0.65



Figure 3.1 Oakdale power plant

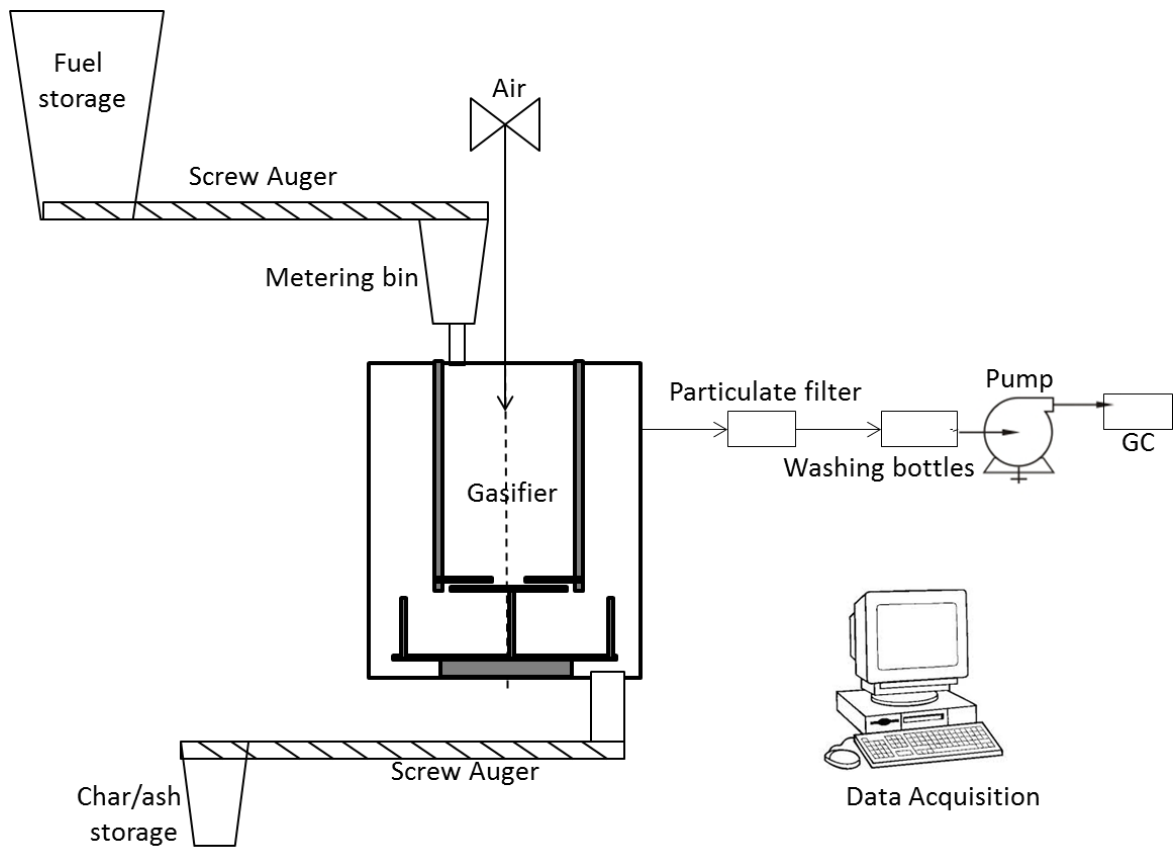


Figure 3.2 Gasification system flow diagram

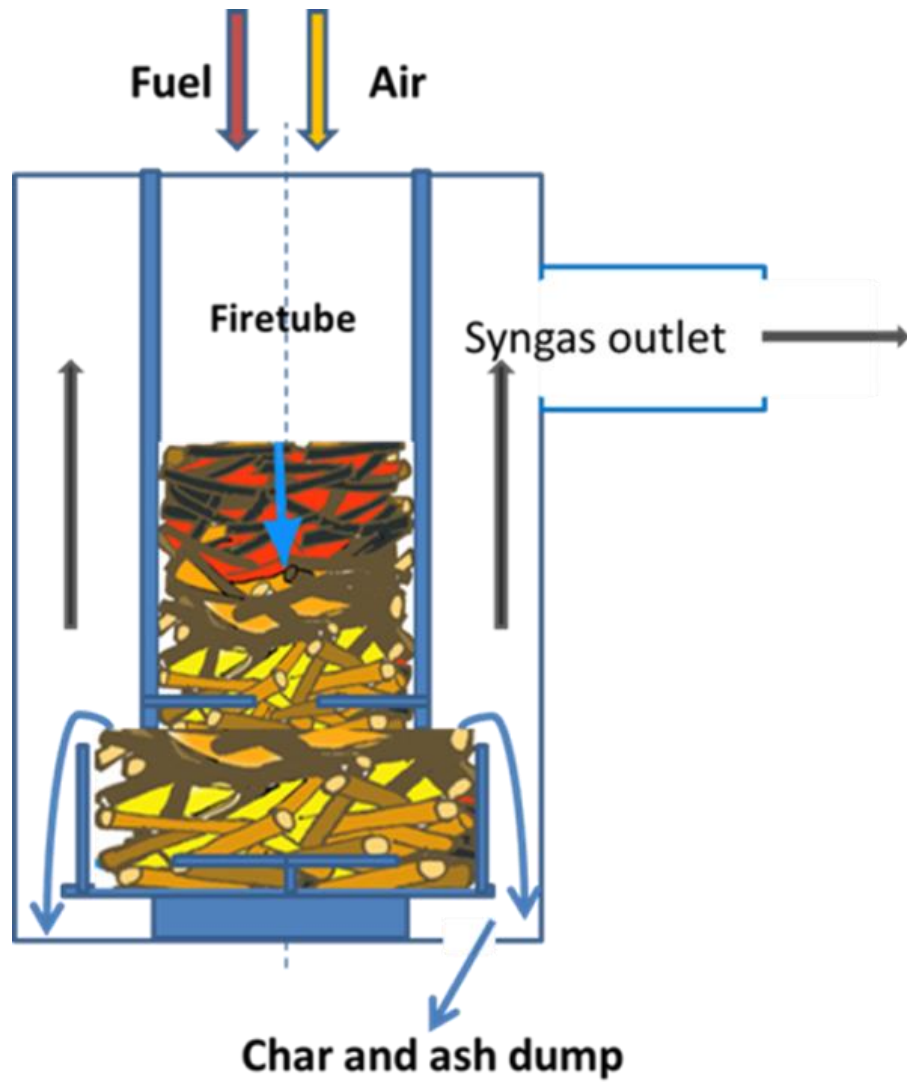


Figure 3.3 Schematic of downdraft gasifier

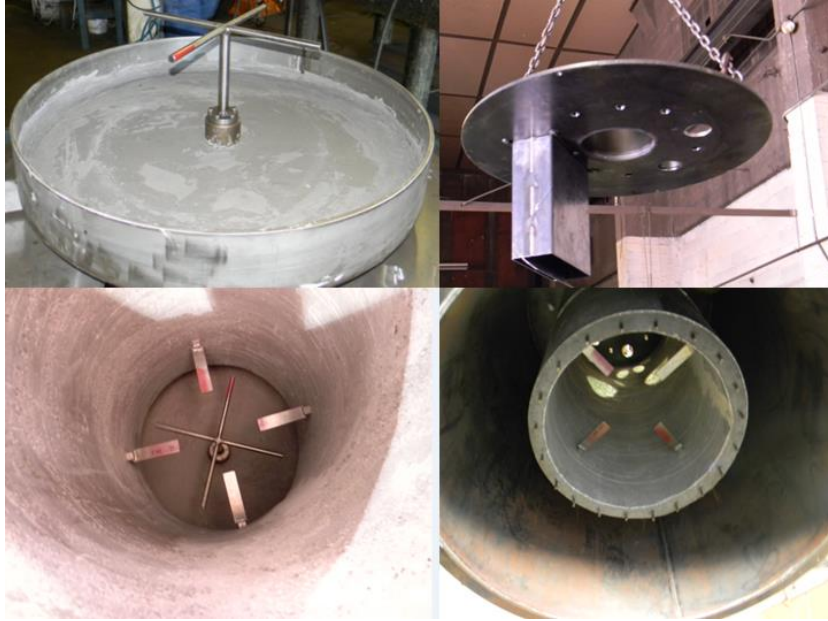


Figure 3.4 Photo of the inside view of the gasifier

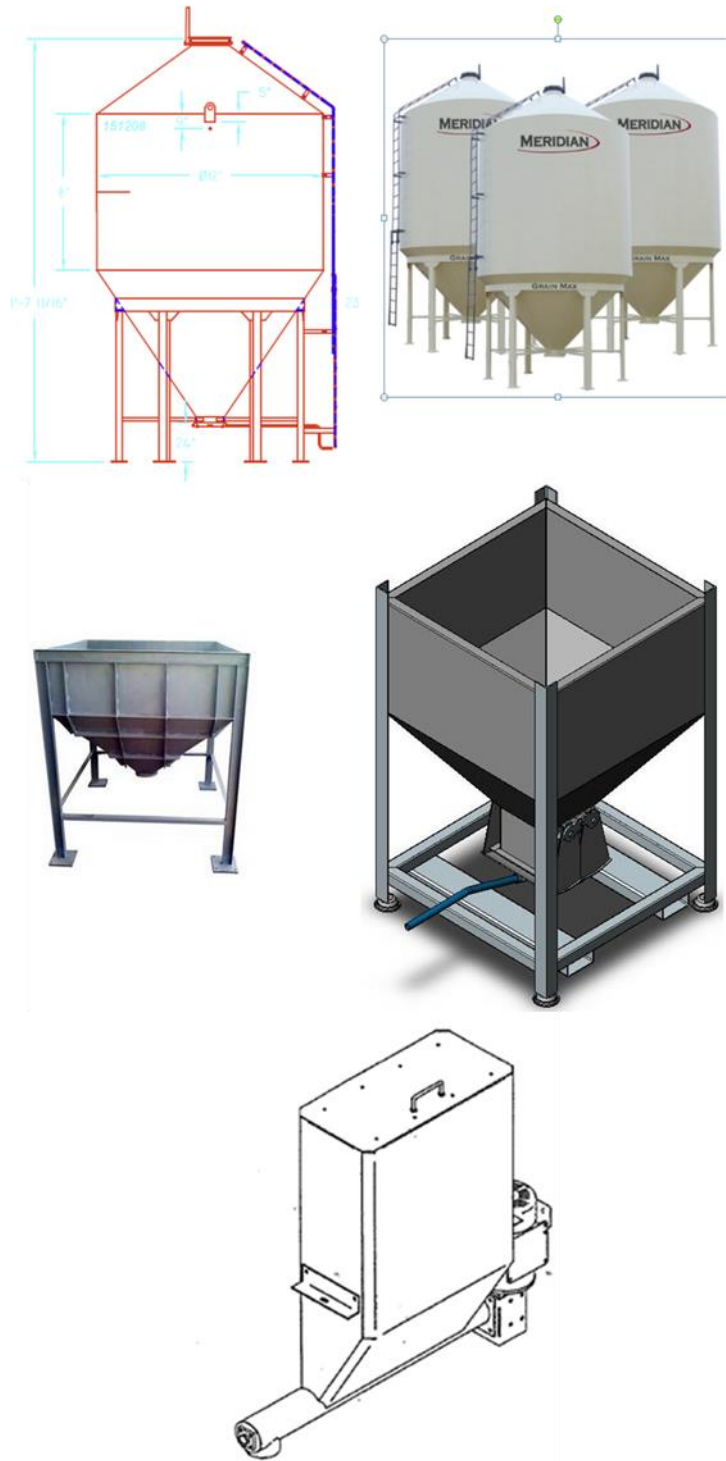


Figure 3.5 Primary (upper), secondary (middle), and temporary metering bin (lower)



Figure 3.6 Solid product shute and delivering auger

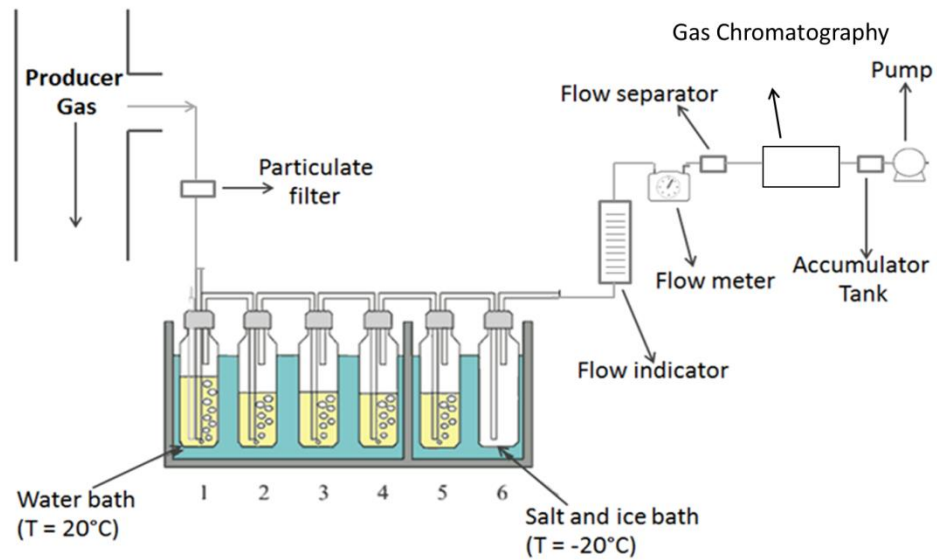


Figure 3.7 Product gas sampling line

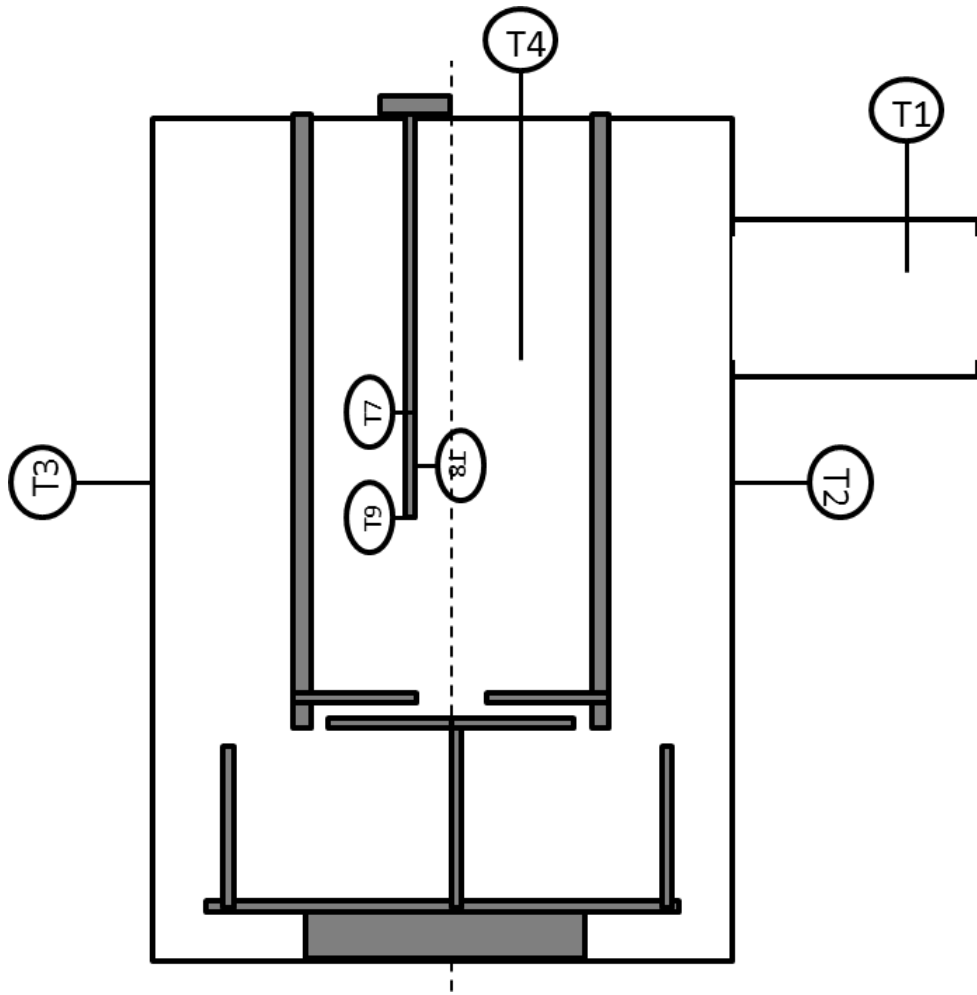


Figure 3.8 Thermocouple locations

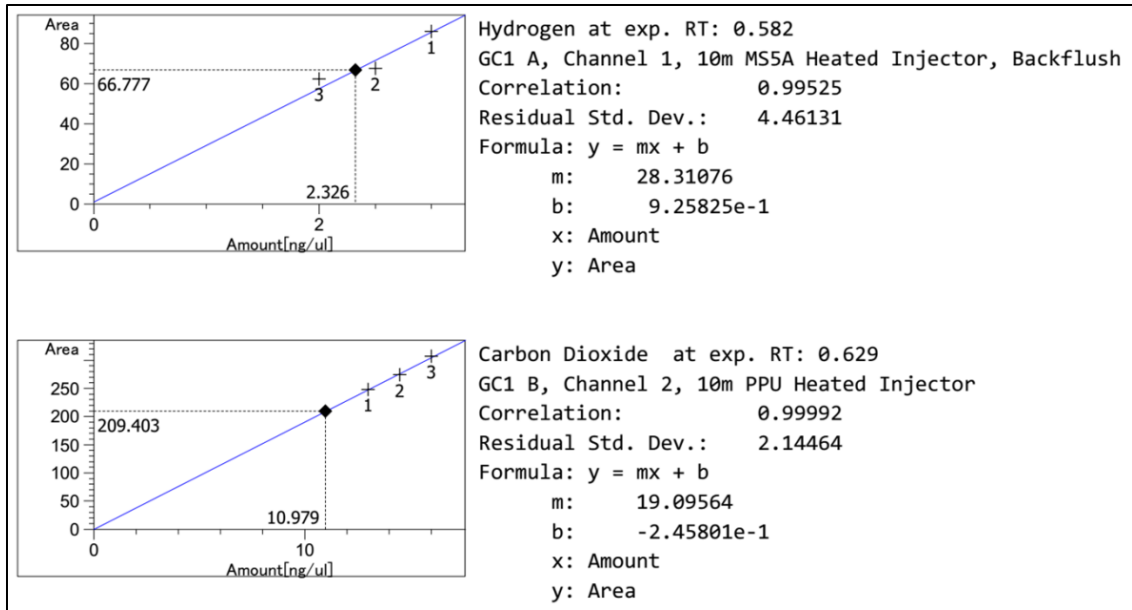


Figure 3.9 Examples of GC calibration curves

CHAPTER 4

PILOT SYSTEM PERFORMANCE EVALUATION

4.1 Experiment Runs and Experimental Planning

4.1.1 Experiment Runs

Over 300 hours of tests were accomplished in total to achieve repeatable steady-state operation. During the tests, several disadvantages of the component design had been discovered and the modified design successfully solved the problems. A primary one was the redesign of the ash bin and screw auger which had been remade to avoid a narrow path causing char clogging problem. Another one was adding two thermocouples on the gasifier outside metal which was to provide more information to the operator to prevent problems such as overheating.

A 2*3 factorial experimental planning was designed with two factors – air flow rate and fuel bed level. Air flow rate was tested at two different levels, and fuel bed level was tested with three different levels (Table 4.1). Without full replication, a total of 6 tests conditions were performed. The reason for not having full replication of the tests is that it was only possible to carry out one test per day. After the tests were done, screenings of the obtained data were performed. The test trials with non-logical or out of tendency values, related to literature data, were repeated.

4.1.2 Start-up Operation to Steady-state Operation

Thermal cracking temperature range for corn kernels is from 350-400°C. Therefore, a well-controlled thermal cracking process is very important. Figure 4.1 is a schematic of operation regarding fuel loading action. There are typically three phases: materials ignition, start-up operation, and steady-state operation. In the first phase,

methane burner was operated for more than 20 min to ignite the biomass materials and to provide enough heat for material self-ignition. The second phase was start-up operation. This is a transition period from spontaneous ignition to steady-state operation. The combustion of methane in the first phase provided a small portion of heat for gasification. In this period, by adjusting air flow and fuel feeding rate, air/fuel ratio can be controlled. Start-up operation usually begins with complete combustion with a high air/fuel ratio. Since combustion reactions are mostly exothermic, the heat release gradually provides more heat to sustain. At the same time, char produced from complete and incomplete combustion started to build up from the bottom of the turntable. When air supply and material supply are kept at a certain rate, the temperatures monitored including drying zone temperature and producer gas temperature tend to stop fluctuation, it is known as steady-state operation. Data were collected after steady-state operation was achieved for 30 minutes. Figure 4.3 shows a typical operation diagram. It can be observed that steady state was usually reached around one hour from the beginning of the run. T_1 - T_4 shows the temperatures at the different locations of the system. T_2 and T_3 were installed to monitor the metal temperature for safety reasons. Equivalence Ratio (ER) (0.25-0.33 in this test) during the run was calculated to determine whether the gasifier was running under the expecting conditions. According to Reed (1998), ER is crucial to gasification shown in Figure 4.2. It can be found that in the start-up period, the gasifier was running under combustion conditions in which ER is approaching 1. In steady state, ER is in the range of 0.25-0.35.

4.2 Thermal Profile and Gasification Zones

When steady-state was achieved and kept for 30 minutes, temperature at different height inside the gasifier was tested using the K-type thermocouples. A thermocouple holding structure was designed and it can hold 3 thermocouples at the same time. When collecting data, the turntable was stopped for about 10 minutes for temperature measurement. The thermocouple holding structure was lifted up 5 cm per time manually to get a temperature profile until the thermocouple was removed from the fuel bed. At each location, the temperature was averaged to minimize the error.

Figure 4.4 shows a temperature profile at steady-state with two different ER at the same bed level (0.55m). X-axis indicates temperature in °C and Y-axis indicates the distance from the bottom of the char bed. The thermocouple moved up 5 cm per time. It was found that along the gasifier longitudinal direction temperature experienced an increase followed by a stable zone and then decreased sharply. From the top, the reaction zones are recognized drying and preheating zone, flaming pyrolysis and combustion zone, and reduction zone respectively. When fuel fed from the top of the gasifier, firstly it went through the drying and preheating zone in which temperature range is 80-400°C. Materials were dried and moisture in the materials was evaporated, and at the same time, biomass was preheated. The zone followed by the drying zone is called flaming-pyrolysis and combustion zone which has a temperature range of 900-1300°C. After drying, the fuel was heated up to around 400°C which is sufficient for pyrolysis to occur. Pyrolysis happening in an air-rich environment results in product gas combustion. Combustion thus ignited top-layer fuel and a thin layer of fuel were burning on top of the fuel bed. The reactions happening in combustion zone include carbon oxidation reactions and pyrolysis product

gas oxidation reactions, mostly of which are exothermic, and thus supplying heat to gasification happening below. The reaction zone under combustion is reduction zone which has a temperature range around 600-1000°C. The most important reactions result in the production of CO, CH₄, and H₂ took place in this zone (Equation 4.1 – 4.5). Reduction largely depends on combustion happening before it because most of the reactions are endothermic. Thus, combustion provides sufficient heat for the reactions in reduction zone to occur and at the same time produce the preliminary gases.



Phenomenon observed spatially corresponds to reactions in the lab-scale on a time base (Ulstad, J., 2011). In a lab-scale gasifier, reaction starts with a temperature decrease and followed by an increase. Temperature decrease can be caused by the preheating and pyrolysis and then char oxidization experiences a higher temperature which then supplies heat for reduction reaction.

The current design of the gasifier with fuel and air both flowing from the top makes it unique that pyrolysis and oxidation zone are combined on the top layer and leaves reduction zone a thick depth which is about 50-70% of the whole fuel bed. Comparing ER at 0.25 and 0.33 at the same bed depth, it is evident that a higher in ER (i.e. higher oxygen concentration) increases the combustion zone depth and thus decreases

the deduction zone depth. At the same temperature, an increased ER results in the increase of combustion zone temperature, and even the overall reactor temperature.

Comparisons have been also made to investigate the difference between the current design with updraft gasifier and downdraft with a throat at the core shown in figure 4.5. Updraft gasifier has contrary flow and solid flow directions. The highest temperature (1200°C) occurs in the combustion zone which is just above the grate and the gas leaving the gasifier has a temperature around 200°C. Low product gas temperature enables updraft gasifier to have a higher efficiency but with higher tar concentration. Throat design downdraft gasifier has the highest temperature in combustion zone (1200°C) followed by the reduction zone in which the gas temperature decrease to 700°C. The design has much lower tar concentration in the syngas but with lower gasifier efficiency.

4.3 Mass Balance

4.3.1 Mass Components

The mass balance is one way of validating data reliability. In theory, the total mass input should be equal to the total mass output. However, experimental errors are inevitable which cause discrepancies in mass balance calculation. Therefore, the usual method to quantify the discrepancies is to define the ratio of the total mass output to that of total mass input. Input and output mass components are listed as follows:

Total mass input

1. Corn (ash-free, dry basis), moisture, and ash
2. Air containing of O₂, N₂, and water

Total mass output

1. Product gas containing of CO, CO₂, CH₄, H₂, O₂, N₂, and moisture in gas
2. Tar (The mass is negligible.)
3. Char
4. Ash

Mass balance closure

$$\text{Mass balance closure} = 100\% * \frac{\text{total mass output}}{\text{total mass input}}$$

4.3.2 Total Mass Input

Corn input

The molecular formula derived for corn is CH_{1.69}O_{0.8} having a molecular weight of 23.29 kg/kmol (daf). Corn input mass is weighted at the temporary metering bin.

Air intake

Air intake volume flow rate is measured at the inlet using a volume flow meter. The mass flow rate of air at the inlet of the gasifier can be treated as ideal gas with the inlet condition of 25°C and 1atm.

$$\dot{m}_{\text{air}} = \frac{Q_{\text{air}} * P * MW_{\text{air}}}{R * T} \quad (4.6)$$

4.3.3 Total Mass Output

Product gas output

The mass flow rate of product gas at the outlet of the gasifier can be treated as ideal gas at the outlet condition. It is calculated from the nitrogen balance by assuming

that the nitrogen in the product gas does not take part in the gasification process and that the mass of nitrogen in the product gas is equal to the mass of the nitrogen in the air fed into the gasifier. Thus,

$$\dot{m}_{N2,air} = \dot{m}_{N2,gas}$$

$$\dot{m}_{N2,air} = \dot{m}_{air} * x_{N2,air} * MW_{N2} / MW_{air}$$

$$\dot{m}_{N2,gas} = \dot{m}_{gas} * x_{N2,gas} * MW_{N2} / MW_{gas}$$

$$\dot{m}_{gas} = \frac{Q_g * P * MW_{gas}}{R * T} \quad (4.7)$$

where,

$x_{N2,air}$ = volume fraction of N2 in dry air

$x_{N2,gas}$ = volume fraction of N2 in dry gas

\dot{m}_{air} = mass flow of dry air

\dot{m}_{gas} = mass flow of dry gas

Q_g = the volume flow rate of the product gas

P = pressure of the product gas

MW_{gas} = the molecular weight of the product gas

MW_{air} = the molecular weight of the air

T = temperature of the product gas

R = gas constant (0.08205 J atm/ mole*K)

Char and ash output

The total mass of char and ash output are weighted after each test trial.

4.4 Carbon Conversion Rate

Carbon conversion rate (CCR) is calculated by

$$\text{CCR} = \frac{\text{mass of carbon in product gas}}{\text{mass of carbon in corn}}$$

The carbon balance can be evaluated in terms of carbon conversion rate - the carbon content in each compound entering or leaving with the producer gas. Carbon input comes from carbon in corn only. Carbon output is composed of carbon in syngas including CO, CO₂, and CH₄, carbon in char, and carbon in tar. The mass of tar in product gas is very little so that the carbon mass in tar is ignored in the calculation. The carbon content in char is not of interest. Therefore, only carbon in product gas is evaluated.

4.4.1 Carbon Input

Since only corn contains carbon, the dry corn carbon input mass flow, $\dot{m}_{C(\text{input})}$, can be calculated as below:

$$\dot{m}_{C(\text{input})} = \dot{m}_{C(\text{corn})} = \dot{m}_{\text{corn}} * y_{C(\text{corn})} \quad (4.8)$$

where,

\dot{m}_{corn} = mass flow of dry corn

$y_{C(\text{corn})}$ = wt% carbon in corn

4.4.2 Carbon in Product Gas

The total carbon output in product gas contains carbon in CO, CO₂, and CH₄. The dry mass flow rate of carbon output is:

$$\dot{m}_{C(\text{product gas})} = \dot{m}_{C(\text{CO})} + \dot{m}_{C(\text{CO}_2)} + \dot{m}_{C(\text{CH}_4)} \quad (4.9)$$

where,

$\dot{m}_{C(\text{CO})}$ = dry mass flow rate of carbon in CO

$\dot{m}_{C(\text{CO}_2)}$ = dry mass flow rate of carbon in CO₂

$\dot{m}_{C(CH_4)}$ = dry mass flow rate of carbon in CH₄

4.5 Hydrogen Conversion Rate

Hydrogen conversion rate (HCR) is calculated by

$$\text{HCR} = \frac{\text{mass of hydrogen in product gas}}{\text{mass of hydrogen in inputs}}$$

The hydrogen balance can be evaluated in terms of hydrogen conversion rate - the hydrogen content in each compound entering or leaving with the producer gas. Hydrogen input comes from hydrogen in corn, hydrogen in moisture in corn, and hydrogen in moisture in air. Hydrogen output is composed of hydrogen in syngas including H₂ and CH₄, hydrogen in moisture in syngas, hydrogen in char, and hydrogen in tar. Only hydrogen in syngas gas is evaluated to calculate HCR.

4.5 Hydrogen Conversion Rate

4.5.1 Hydrogen Input

Since hydrogen input comes from hydrogen in corn, hydrogen in moisture in corn, and hydrogen in moisture in air, the hydrogen input mass flow, $\dot{m}_{H(\text{input})}$, can be calculated as below:

$$\dot{m}_{C(\text{input})} = \dot{m}_{H(\text{corn})} + \dot{m}_{H(\text{water in corn})} + \dot{m}_{H(\text{water in air})} \quad (4.10)$$

where,

$\dot{m}_{H(\text{corn})}$ = mass flow rate of hydrogen in corn

$\dot{m}_{H(\text{water in corn})}$ = mass flow rate of hydrogen in water in corn

$\dot{m}_{H(\text{water in air})}$ = mass flow rate of hydrogen in water in air

4.5.2 Hydrogen in Product Gas

The total hydrogen output in product gas contains hydrogen in H₂ and CH₄. The mass flow rate of hydrogen output in product is:

$$\dot{m}_{\text{H(product gas)}} = \dot{m}_{\text{H(H}_2)} + \dot{m}_{\text{H(CH}_4)} \quad (4.11)$$

where,

$$\dot{m}_{\text{H(H}_2)} = \text{mass flow rate of hydrogen in H}_2$$

$$\dot{m}_{\text{H(CH}_4)} = \text{mass flow rate of hydrogen in CH}_4$$

4.6 Other Indicator for Gasifier

There are several important indicators for gasifier evaluation listed as follows:

Equivalence Ratio

Equivalence ratio (ER) is defined as:

$$\text{ER} = \left(\frac{\text{mass of actual oxidant}}{\text{mass of dry ash free corn}} \right) / \left(\frac{\text{mass of stoichiometric oxidant}}{\text{mass of dry ash free corn}} \right) \quad (4.12)$$

Superficial velocity

Superficial velocity (SV) is defined as:

$$\text{SV} = \frac{\text{total dry volumetric gas flow}}{\text{cross sectional area of gasifier}} \quad (4.13)$$

Cold gas efficiency

Cold gas efficiency η_{cold} is defined as

$$\eta_{\text{cold}} = \frac{\text{energy of cold gas}}{\text{chemical energy in corn}} = \frac{\text{chemical energy of dry gas}}{\text{chemical energy in corn}} \quad (4.14)$$

Producer gas yield rate

Producer gas yield rate (Y_{gas}) is defined as

$$Y_{\text{gas}} = \frac{\text{volumetric flow rate of product gas}}{\text{mass of corn input}} \quad (4.15)$$

4.7 Uncertainty Analysis

The experimental measurements always have associated parameters that influence the uncertainty results. Because of this, the uncertainty of the measured parameter was assessed. The main sources of uncertainty in Oakdale biomass gasification are: the temperature measurements, the determination of gas composition, and the measurement of air flow.

The uncertainty analysis for each parameter was performed by the following procedures (Figliola, R., 2011):

- Identify the elemental errors in the measurement.
- Estimate the magnitude of systematic and random error in each of the elemental errors.
- Use root-sum-squares (RSS) method to calculate the propagation of elemental random and elemental systematic uncertainties.
- Calculate the uncertainty estimate for the results including random and systematic errors using RSS method.

An uncertainty analysis was carried out under the test condition of the air flow of 75.34 kg/h. The parameters considered were the temperature, the gas composition, and the air flow, whose uncertainties are shown in Table 4.5.

4.8 System Performance Evaluation

System performance is evaluated using indexes such as mass closure, cold gas efficiency, superficial velocity, gas yield. Table 4.2 – Table 4.4 show the parameters for all six test runs at various equivalence ratio (ER) and bed level. ER and bed level are two

main parameters that influence gasification performance in the current system. According to literature, the range of ER between 0.25 and 0.33 are suggested for most systems and a bed level below 70% of its capacity is preferable for safety considerations. Therefore, ER with 0.25 and 0.33, and bed level within 40cm 70cm were selected for producer gas production performances.

Under these test conditions, it is observed that the concentrations of CO, CO₂, CH₄, H₂, and N₂ in the producer gas vary between 9% - 15%, 10% - 16%, 1% - 2.5%, 2.5% - 4.5%, and 65% - 75% respectively. The system is calculated to have a useful gas power about 60 kW – 85 kW, and a cold gas efficiency of 20% - 30%. The gas yield by unit kilogram of biomass is around 2 Nm³/kg. Carbon conversion rate is around 50%. Compared to literature, the output of the current system is at the lower range in product gas production, gas power output, cold gas efficiency, and carbon conversion rate. The possible reason is that 15% - 25% of the biomass is converted to char which contains calorific energy and carbon content. To achieve a higher system output, the energy and carbon contained in the char bed needs to be used. For mass closure, around 80% mass balance is achieved. The missing mass can be because of several reasons. For one reason, for a pilot-system, some char can be left over at the turntable and conveyor that is not counted. Another reason that 20% of the mass is missing can be because of the moisture in the product which was not counted in the mass output. To check this, a hydrogen conversion rate (HCR) for all the test conditions were calculated and shown in Table 4.4. Results show that with a hydrogen input mass flow rate of about 4 kg/h, 8%-13% of hydrogen is found to be in the producer gas. The leftover hydrogen in the output can be hydrogen in moisture in product gas, hydrogen in other hydrocarbons, hydrogen in tar, and

hydrogen in char. Moisture has a molecular weight 9 times of hydrogen which can also be a critical reason that the 20% of mass missing in mass balance. The experimental results well agree with other studies. Zainal et al. (2002) in studying various materials gasification in downdraft bed obtained mass closure within 80%-95%. Dogru, M. et al. (2002) found mass balance around 90% in gasification of hazelnut shells. Erlich, C. et al. (2011) in the experiments of downdraft gasification of pellets made of various biomasses indicated the difficulty of achieving precise mass balance because of the feedstock will stay in the feeding system.

For two different ER, the results show that a higher ER leads to a higher gas yields per unit solid fuel and combustion zone temperature. For a given solid mass flow rate, ER increases with the increase in the mass flow of air. Therefore, this explains the reason for increasing trend of total gas yields with the increase in ER. Also, the gas yields per unit weight of fuel increases with ER. In the combustion zone, oxygen concentration is critical determining combustion temperature. Therefore, higher ER with higher oxygen percentage leads to higher combustion zone temperature. Zainal, Z. et al. (2002) observed a 20% increase in gas production rate per unit weight fuel with a 10% ER increase. It is also found that CO concentration decreases with an increased ER. Zainal, Z. et al. (2002) investigated the variation of percentage of the components of the producer gas against equivalence ratio. Results show that CO increases with ER up to some peak value and then starts decreasing. And since CO percentage makes the most significant contribution to the calorific value of the producer gas, the calorific value of the gas has similar trend. Dogru, M. et al. (2002) also observed very clear trend that CO decreases with increasing ER when ER is between 0.25 and 0.33.

Bed height determines the height of various reaction zones, especially the reduction zone where all the gasification reactions occur to produce useful combustible gases. At a certain ER, it is found in this experiment that an increased bed level results in a decreased combustion zone temperature. The possible reason is because most of the reduction zone reactions are endothermic and the heat source is from the combustion zone. Theoretically, increased bed height should lead to higher carbon conversion rate and gas yield. However, only a mild increase in gas yield per unit solid is observed. No distinct evidence has been found about the correlation between bed height and carbon conversion rate. Bridgwater, A. (2003) indicated the importance of long residence time and high temperature for gasification. For a certain gas flow rate, long residence time means deep char bed. However, many other influencing factors also play important role in the process. Therefore, to draw further conclusion, more future work are needed.

Comparing the effect of both ER and bed depth on the system performance parameters: a 25% increase in ER value increased superficial velocity (SV) by 22% and increased combustion zone temperature by 15% while decreasing CO concentration by 13%; a higher bed height in the reduction zone requires more heat from the combustion zone to sustain the endothermic reactions which brings about a lower combustion zone temperature; a 43% increase in bed height increased SV by 2-4% while decreasing combustion zone temperature by 4-5%; no correlation between bed height and carbon conversion rate was identified. In sum, it is evident that ER has a dominating effect on gas yields and combustion zone temperature.

Table 4.1 Summary of experimental runs and parameters investigated

Runs	Materials	Parameters investigated
1 - 20	Seed corn and char	Commissioning runs to achieve stable and steady-state operation
21 - 25	Seed corn	Different fuel bed level at air flow rate of 85 m ³ /h
26 - 29	Seed corn	Different fuel bed level at air flow rate of 50 m ³ /h

Table 4.2 Mass flows and energetic flows

	Mass flows (kg h ⁻¹)					Energetic flows (kW)		η_{cold} (%)
	\dot{m}_{air}	\dot{m}_{corn}	\dot{m}_{char}	\dot{m}_{gas}	Closure	E_{corn}	E_{useful}	
Run 21	109.87	50	13	114	79.4%	287.5	72.92	25.36
Run 24	109.87	50	12	120.84	83.09%	287.5	75.17	26.15
Run 25	109.87	50	13	118.47	82.2%	287.5	78.65	27.36
Run 27	75.34	50	13	87.21	80.0%	287.5	62.23	21.64
Run 28	75.34	50	12	86.75	78.8%	287.5	60.63	21.09
Run 29	75.34	50	10	90.97	80.6%	287.5	85.18	29.68

Table 4.3 Producer gas concentration

	CO (V%)	CO ₂ (V%)	CH ₄ (V%)	H ₂ (V%)	N ₂ (V%)
Run 21	9.95	10.54	1.45	2.61	75.45
Run 24	9.93	11.91	1.45	2.37	74.33
Run 25	9.55	12.39	1.61	3.25	73.19
Run 27	11.53	14.70	1.50	3.04	69.22
Run 28	11.15	15.36	1.56	2.87	69.06
Run 29	14.51	14.15	2.05	4.14	65.15

Table 4.4 Performance evaluation

	ER	Bed level (cm)	Superficial velocity (m s^{-1})	Y_{gas} (Nm^3/kg)	Carbon conversion rate (CCR) (%)	Hydrogen conversion rate (HCR) (%)	Combustion zone temperature ($^{\circ}\text{C}$)
Run 21	0.33	40	0.44	2.43	46.43	10.53	1354
Run 24	0.33	55	0.46	2.5	52.25	10.05	1313
Run 25	0.33	70	0.46	2.5	51.79	12.68	1298
Run 27	0.25	40	0.34	1.8	46.02	8.74	1158
Run 28	0.25	55	0.34	1.83	44.75	8.74	1130
Run 29	0.25	70	0.35	1.93	51.84	12.62	1096

Table 4.5 Uncertainty analysis for Oakdale experiment

Parameter	Units	Uncertainty
Air flow rate	m ³ /h	8.14
Temperature T ₁ -T ₄	⁰ C	9.17
Temperature T ₅ -T ₇	⁰ C	6.02
H ₂	V%	0.5772
CO	V%	0.7234
CO ₂	V%	0.3277
CH ₄	V%	0.2311
N ₂	V%	1.6603

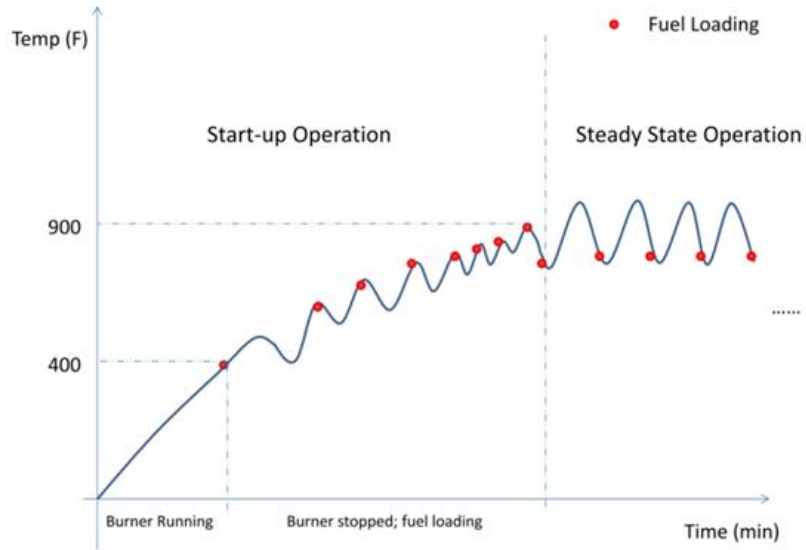


Figure 4.1 Start-up and steady-state fuel loading

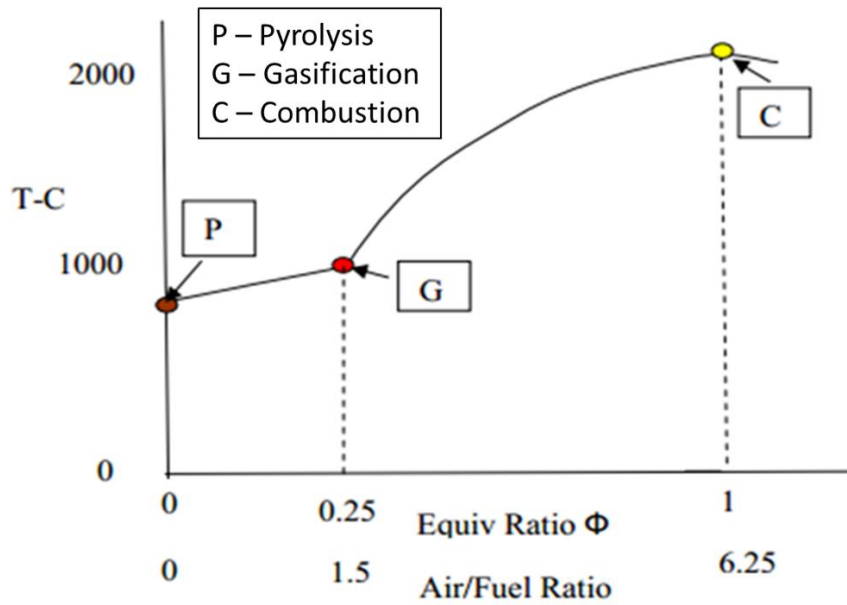


Figure 4.2 The equivalence ratio and air fuel diagram (Source: DeCristofaro, E., 2009)

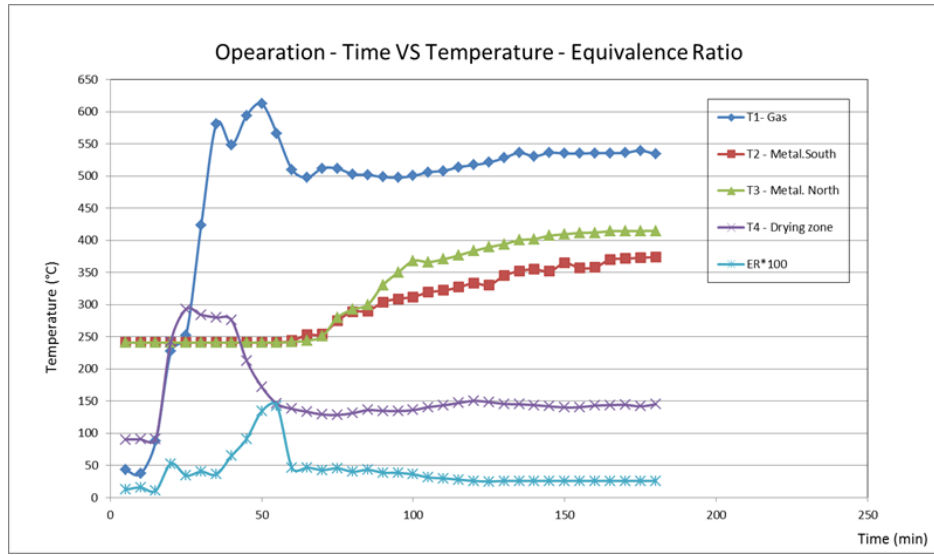


Figure 4.3 Time vs temperature – air/fuel ratio (Run 22)

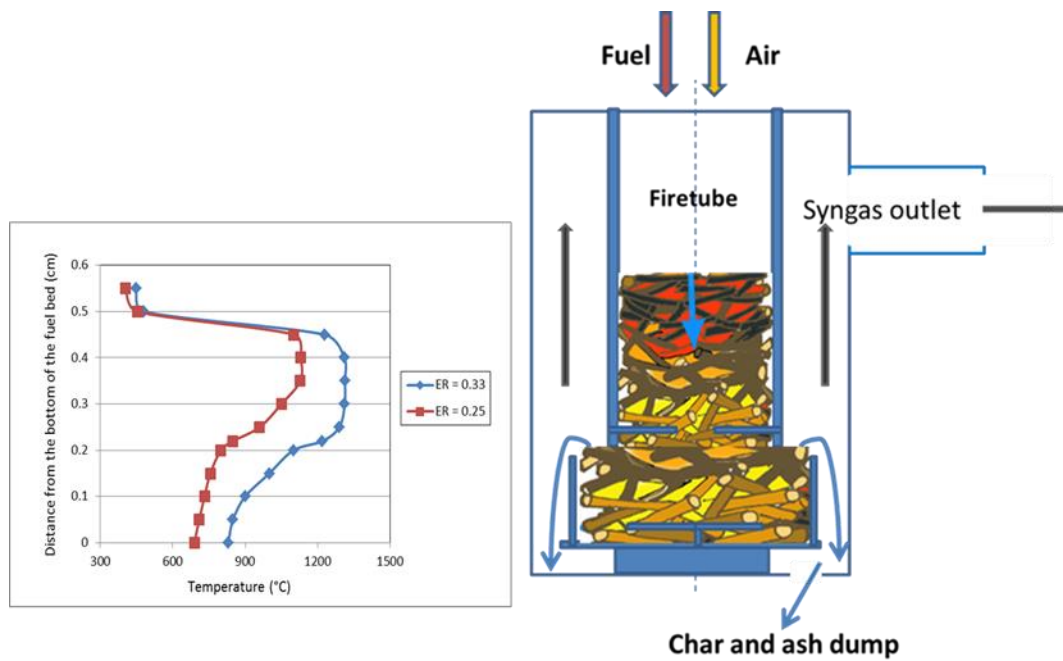


Figure 4.4 Thermal profile and different zones

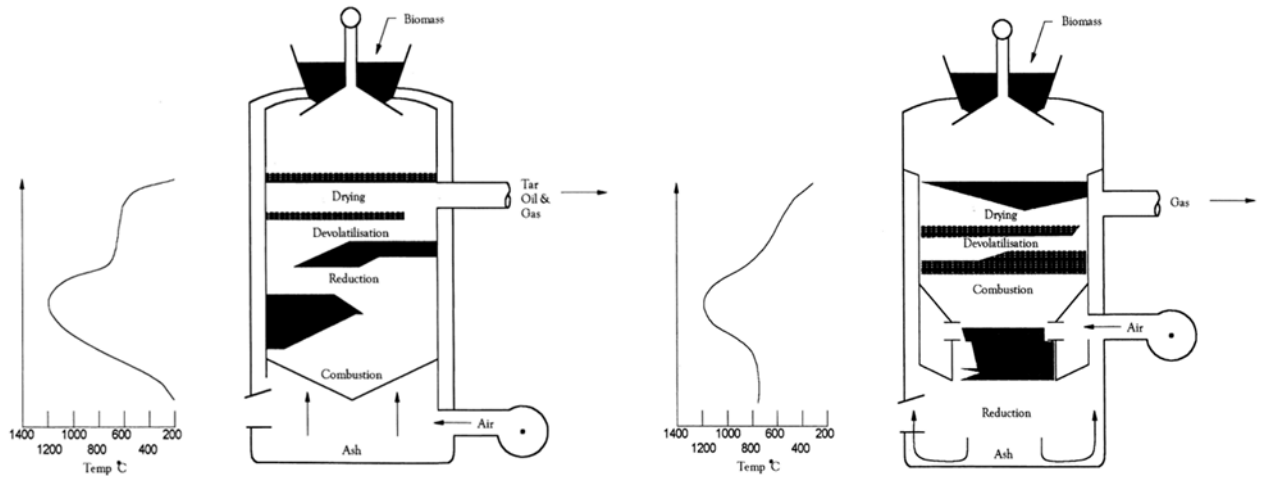


Figure 4.5 Updraft gasifier (left) and throat design downdraft gasifier (right) temperature profile (source: Mckendry, P., 2002)

CHAPTER 5
GASIFICATION OF CORN IN A TWO-STAGE AIR-BLOWN
DOWNDRAFT REACTOR

5.1 Introduction

Due to the limitation of air-blown in downdraft reactors on carbon conversion and product gas quality, two-stage air-blown systems were developed (Galindo, A., 2014; Jaojaruek, K., 2011; Bhattacharya, S., 1999; Martínez, J., 2011; Ma, Z., 2012; Raman, P., 2014). Instead of introducing oxidizer from only one position, a two-stage air-blown system is designed to provide air at two different locations in the gasifier. Some systems (Sridhar, G., 2002) are designed as an open top reactor with air inlet both through the top and in the oxidation zone. Some other systems (Galindo, A., 2014, Martínez, J., 2011) have closed top while having two ports of air supply so that the pyrolysis zone is separated from the reduction zone.

One benefit in which a two-stage gasifier influences the system performance is that it reduces the tar production in producer gas. The Asian Institute of Technology (AIT) (Jaojaruek, K., 2011, Bhattacharya, S., 1999) designed a two-stage air-blown gasifier which produces tar approximately 40 times lower than conventional gasifier. Jaojaruek et al. (2011) also studied the eucalyptus gasification in the system with different air supply regime: single stage (SS), two-stage air supply (AA) and two stage air and air-gas supply (AG). The results show that AA produces the most tar which is approximately ten times the tar production with AA and thirty times with AG.

Another way in which a two-stage gasifier benefits the system performance is that it produces a gas with increased calorific value. Ma., et al. (2012) in the experimental

investigation of a 190 kW biomass fixed bed gasification found that the secondary air supply results in a high temperature in the oxidation zone which significantly improve the quality of the gas produced. By comparing the three different air supply approaches, namely SS, AA, and AG, many other researchers (Jaojaruek, K., 2011) also found that both the total combustible gas concentrations and high calorific value increase with a secondary air supply.

5.2 System Design

The two-stage downdraft gasification system includes a closed-top two-stage downdraft gasifier and a gas sampling and analysis system, as shown in Figure 5.1.

The two-stage downdraft air-blown gasifier was designed and built by the company Termoquip Energia Alternativa Ltda (Campinas, Sao Paulo, Brazil). It has a dimension of an internal diameter of 0.3 m and a height (from the top of the reactor to the grate) of 1.06m. The reactor was designed to produce high-quality gas with low tar and particulate matter.

The material used for building the gasifier is carbon steel with an internal coating of refractory material. Along the reactor, there are six K-type thermocouples installed to monitor the temperature profile at different heights. Thermocouples are located at the inner reactor wall, in order to minimize its influence on the solid material flow. Therefore, it does not read the center temperatures. However, it avoids a significant problem in fixed bed – channeling and bridging. Another way in which the system built to avoid flow problem is that it has two vibrator devices (one is at the top and another one is at the bottom) coupled with a timer which greatly improve the uniform distribution of solid biomass. Of the six thermocouples, two are used to measure the temperature of the inlet

air; another one is used to measure the temperature of the exit gas. The air supply uses a blower for both air channels. The gas produced in the system leaves through the lower section, after passing the reduction zone, the grate, and the cyclone where big particles are removed.

Usually, gasification is initiated with preheating the bed by means of an external fuel and an external burner. When the temperature at the combustion zone achieves 250 °C, air starts to feed into the system. By adjusting air flow rate, combustion zone temperature achieves approximately 800 °C and stabilizes. This is obtained through flow measurement by an orifice plate and a control valve at each stage. Steady state is reached when there are no significant variations in temperature or gas concentrations.

5.3 System Performance

1. Experimental details

Dried seed corn produced from Minas Gerais state was used for the experiment to compare with the system in Iowa. The ultimate and proximate analysis including ash, volatile, fixed carbon content, elemental analysis (carbon, hydrogen, nitrogen, oxygen, and sulfur), and the lower heating value of the biomass were performed in the NEST/UNIFEI laboratories (Table 5.1). For the two stage air blown gasifier, the total air flow and the air ratio (AR) between the primary and secondary stage were controlled in this experiment. Parameters regarding the system performance are shown in Table 5.2.

2. CO, CH₄, and H₂ concentrations, temperature, and lower heating value

The temperatures in different zones from the beginning of the start-up process to steady state condition were monitored. The start-up process takes about 1-2h and at the same time producer gas concentration is also monitored. The temperature profile and the

concentration of producer gas at different locations in the steady state of the process are more of interest and thus are shown in Figure 5.2 and 2.3. The temperatures measured include the temperatures at drying zone, pyrolysis zone, oxidation zone, and gasification (reduction) zone. The producer gas concentrations shown in the figure involve the useful producer gas CO, H₂, and CH₄. It is observed that under the test condition, steady state lasts about 3.5 hours.

The average temperature values for drying zone, pyrolysis zone, combustion zone, and reduction (gasification) zone are 196.70 °C, 715.34 °C, 801.78 °C, and 584.60 °C with a standard deviation of 15 °C, 50.88 °C, 24.22 °C, and 8.61 °C respectively. The gas composition (CO, CH₄, H₂) was used to calculate the lower heating value (LHV) of the gas to be 4.14 MJ/Nm³.

The results agree with data reported in the literature for biomass gasification in downdraft systems. Garcia-Bacaicoa et al.(2008), in a throat-type downdraft reactor and using wood as fuel, found concentrations of 22.1 %v CO, 2.9 %v CH₄ and 13.4 %v H₂ for a lower heating value around 5590 kJ/Nm³. Bui et al. (1994), studying a multistage throatless downdraft gasifier, obtained a higher heating value of 3720 kJ/m³ with CO, CO₂, H₂ and CH₄ compositions of 17.6, 13.6, 10.7 and 1.2 %v, respectively. Jain & Goss [14], with rice husk and a stratified type downdraft reactor, obtained a producer gas with a lower heating value of 4000 kJ/Nm³. Dogru et al. [15], in gasification experiments of hazelnut shells also in an imbert gasifier (throat-type downdraft reactor), obtained a fuel gas with a higher heating value of 4550 kJ/Nm³ with CO, CH₄ and H₂ concentrations of 16.8; 1.7 and 14.12 %v, respectively. In a throat-type downdraft gasifier, Pathak et al. (2008) with a wood consumption rate of 55 kg/ h found a calorific value of 4240 kJ/Nm³.

3. Tar content

Tar produced during gasification process were collected and tested for its weight and it is found that the tar concentration under the test condition is 8.27 mg/Nm^3 . As reported [9], the maximum limit of tar concentration in syngas varies depending upon its end use. The tolerable limit of tar concentration in syngas is 500 mg/Nm^3 , 100 mg/Nm^3 , 0.5 mg/Nm^3 , and 5 mg/Nm^3 for compressors, internal combustion engines, methanol synthesis, and gas turbine, respectively. Downdraft gasifier, because of the producer flow direction, which goes through the high-temperature zones such as combustion zone and gasification zone, produce much lower tar than in both updraft and fluidized-bed gasifiers.

In a two-stage air blown downdraft gasifier, there is an “additional” combustion zone which helps break down the potential tar-forming big molecules from pyrolysis zone. The amount of tar produced reaches a maximum at temperature of $500 \text{ }^\circ\text{C}$ in pyrolysis zone (Devi, L. et al., 2003; Reed, T., 1988; Fagbemi, L., 2001). Galindo, A. (2014) found that using wood in this two-stage downdraft gasifier, the tar yield decreases with the increase of the total air flow and AR. Both results agree with data reported in current study. Although the biomass is different, seed corn is used in current study. However, the results reveal intuitive results that because of the high temperature in all four different zones, the tar yield is low. Also by comparing the temperature in different zone with the results from Galindo, A. (2014), it can be observed that the pyrolysis temperature is higher at the same ER and AR ratio. This temperature increase in the pyrolysis zone, which is approaching the combustion zone temperature, suggests a reduction in the amount of tar formed during the pyrolysis process to be possible as it should promote the cracking of tar in the combustion zone.

4. Mass, carbon, hydrogen balance, and performance parameters

The mass balance was calculated to be 97.3%. Carbon conversion rate (CCR) and hydrogen conversion rate (HCR) were calculated to be 96.95% and 50% respectively of the total input. Besides existing in producer gas, hydrogen also exists in water in producer gas, hydrocarbons in producer gas, tar, and char. This allows the determination of performance variables such as power related to useful energy of the producer gas (E_{useful} , kW), gas yield (Y_{gas} , $\text{Nm}^3\text{kg}^{-1}$), superficial gas velocity (SV, m s^{-1}), equivalence ratio (ER), and cold gas efficiency (η_c). The data is listed in 5.2.

Superficial velocity, as an important parameter influencing the performance of gasification including gas yield, the gas energy content, the fuel consumption rate, the power output, and char and tar production rate, has been studied by many researchers. Reed et al. [18] found that lower SV results in a relative slow pyrolysis conditions mainly favoring the formation of high tar content. On the contrary, the higher SV causes faster pyrolysis conditions favoring char production and thus decreasing tar production. The data from current study agree with these results. By comparing the data with Juan et al.'s work [7], it is found that under the same ER and AR ratios, SV is doubled in the current study which also shows a decrease in tar content.

5. Uncertainty analysis

The experimental measurements always have associated parameters that influence the uncertainty results. Because of this, the uncertainty of the measured parameter was assessed. The main sources of uncertainty in the two-stage biomass gasification are: the temperature measurements, the determination of gas composition, the determination of tar,

and the measurement of air flow. In this case, ISO 5167-1 (ISO 5167-1, 2003) and 5167-2 (ISO 5167-2, 2003) were used in the air flow measurements uncertainty analysis.

Generally, the calculation of uncertainty needs the definition of components that affect it, the determination of standard and combined uncertainty to finally obtain the expanded uncertainty of the process variables, according to Equation 5.1 – 5.3.

u_A is the Standard Uncertainty, so u_c is the Combined Uncertainty. The u_{xi} values ($i = 1, 2, \dots, n$) represent the individual uncertainty in the measurement of each variable, directly measured. And the partial derivative of y with respect to u_{xi} is the sensitivity coefficient. The Expanded Uncertainty u_p depends on the confidence level k_p .

$$u_A = \frac{\sigma_{n-1}}{\sqrt{n}} \quad (5.1)$$

$$u_c = \sqrt{\left(\frac{\partial y}{\partial x_1} * u_{x1}\right)^2 + \left(\frac{\partial y}{\partial x_2} * u_{x2}\right)^2 + \dots + \left(\frac{\partial y}{\partial x_N} * u_{xN}\right)^2} \quad (5.2)$$

$$u_p = u_c(y) * k_p \quad (5.3)$$

An uncertainty analysis was carried out for the test condition. The parameters considered were the temperature, the tar, the gas composition, and the air flow whose uncertainties are shown in Table 5.3. The uncertainty values for all parameters show that the obtained data have a high level of confidence.

5.4 Oakdale Gasification System and NEST Two-stage Gasification System Performance

Comparison

Comparing the design of the two gasification systems, the dimensions of the reaction zones are both 0.3 m (ID)* 1 m (height - rounded). The only difference is air intake approach. In NEST system, air is blown into the reaction zone from two different

locations at the core of the bed which is believed to make the difference on producer gas production and system efficiency. With the same ER value of 0.33 and bed level 70 cm, NEST double stage system shows similar trend in gas yield with Oakdale system, which is about 2.5 Nm³-gas/kg-biomass. However, the two-stage system indicates a 46% increase in carbon conversion, 80% increase in hydrogen conversion and a higher concentration of CO and H₂. Since CO and H₂ are the main source of the useful energy, the cold gas efficiency also doubled in the two-stage system. In addition, an 80% increase in HCR indicates that more hydrogen exist in the form of moisture in the producer gas in Oakdale system which is less efficiency. Therefore, to have a higher producer gas energy output, the energy in the char bed needs to be converted into useful gas energy. An additional source of air in the reduction zone effectively reinforces carbon conversion.

Table 5.1 Proximate and ultimate analysis of corn from Brazil

Proximate analysis		Ultimate analysis	
Moisture	13.17 %	Carbon	43.98 %
Volatile Matter	71.28 %	Hydrogen	5.99 %
Fixed Carbon	13.91%	Nitrogen	1.53 %
Ash	1.64 %	Sulfur	0.21%
Total	100.00%	Oxygen	48.29 %
HV[MJ/kg]	15.85	Total	100%

Table 5.2 System performance

CO (V%)	16.24	Mass flows	\dot{m}_{air} (kg h ⁻¹)	32.33
CO ₂ (V%)	14.00		\dot{m}_{corn} (kg h ⁻¹)	15
CH ₄ (V%)	1.02		\dot{m}_{char} (kg h ⁻¹)	0.45
H ₂ (V%)	13.27		\dot{m}_{gas} (kg h ⁻¹)	46.05
N ₂ (V%)	55.47		Closure (%)	97.3
ER	0.33	Energetic flows	E _{corn} (kW)	66.04
Bed level (cm)	70		E _{useful} (kW)	44.59
SV (m s ⁻¹)	0.15		E _{sensible} (kW)	3.23
Y _{gas} (Nm ³ /kg)	2.58		η_{cold} (%)	67.52
CCR (%)	96.95	HCR (%)	50.00	

Table 5.3 Uncertainty analysis for NEST experiment

Parameter	Units	Uncertainty
Air flow 1	m ³ /h	0.23
Air flow 2	m ³ /h	0.35
Total air flow	m ³ /h	0.28
Drying temperature	⁰ C	2.25
Pyrolysis temperature	⁰ C	8.83
Gasification temperature	⁰ C	7.56
Combustion temperature	⁰ C	10.02
Air flow 1 temperature	⁰ C	0.89
Air flow 2 temperature	⁰ C	1.05
H ₂	V%	0.113
CO	V%	0.280
CO ₂	V%	0.161
CH ₄	V%	0.055
Tar content	mg/m ³	0.78

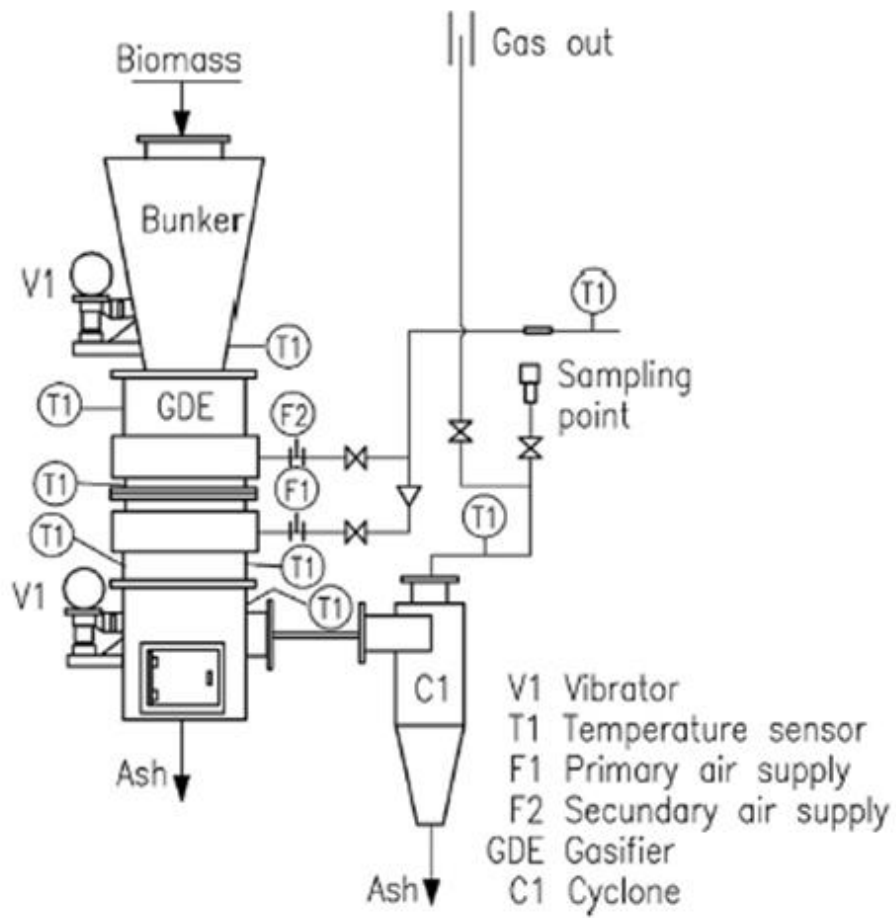


Figure 5.1 – Schematic of the two-stage air blown downdraft gasification system

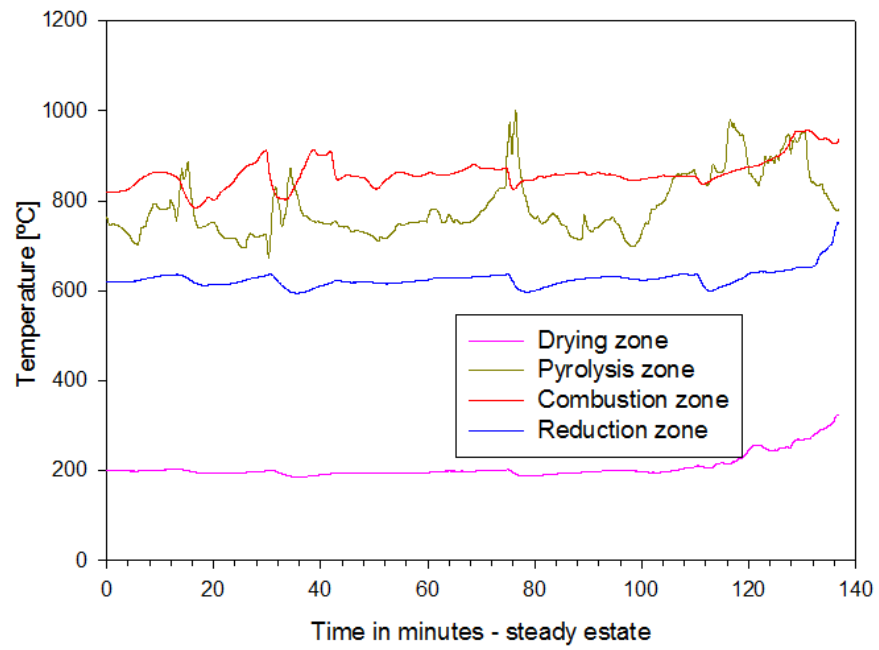


Figure 5.2 Temperature at steady state regime

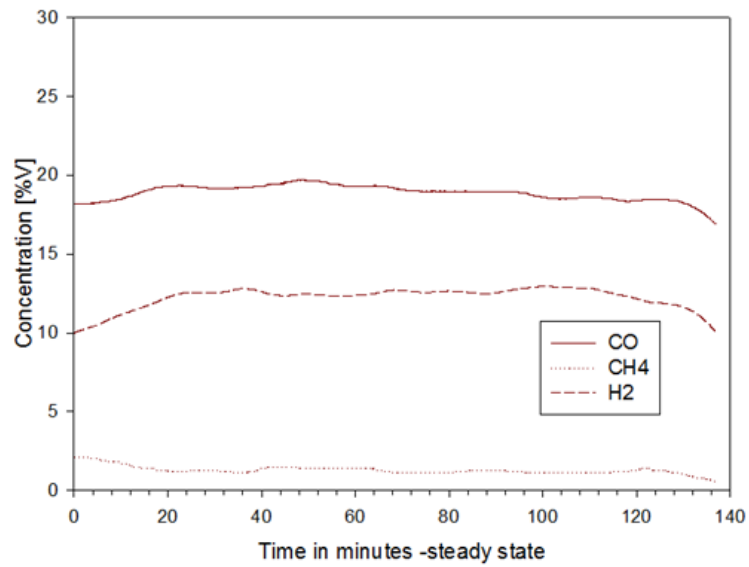


Figure 5.3 Schematic of the gasification system.

CHAPTER 6

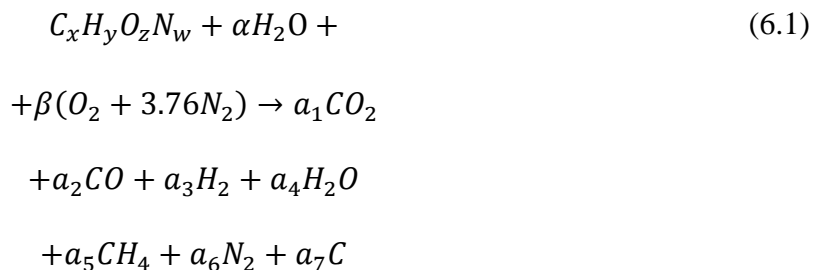
A HYBRID MODEL FOR DOWNDRAFT GASIFICATION

6.1 Model Description

A hybrid model is developed for open-top downdraft gasification to predict temperature variations in the reaction zone and producer gas composition at the exit of the unit. The model divides the reaction zone into two parts: pyrolysis-oxidation where pyrolysis and oxidation reactions take place and reduction zone, where the reduction reactions occur. In pyrolysis-oxidation zone, an equilibrium (stoichiometric) model is used. In the reduction zone, a kinetic model considering finite reaction rate is adopted.

6.1.1 Model of Pyrolysis-oxidation Zone

In this part, the stoichiometric model starts from the global reaction for air gasification in the downdraft gasifier, and can be written as:



Where x , y , z , w , and v are the number of atoms of carbon, hydrogen, oxygen, nitrogen and sulfur in the feedstock, respectively. The molar moisture content of biomass is represented by α . The molar quantity of oxygen is represented by β , and 3.76 represents the molar amount of nitrogen whereas the air is composed primarily of oxygen and nitrogen mixture in the proportion of 79% nitrogen and 21% oxygen. All inputs on the left-hand side of Eq. (6.1) are defined at 25 °C.

From the thermodynamic tables is possible to determine the enthalpy of formation of the components at 298 K as follows:

$$\overline{h}_{f,CO_2}^0 = -393546 \left(\frac{kJ}{kmol} \right) \quad (6.2)$$

$$\overline{h}_{f,CO}^0 = -110541 \left(\frac{kJ}{kmol} \right) \quad (6.3)$$

$$\overline{h}_{f,CH_4}^0 = -74831 \left(\frac{kJ}{kmol} \right) \quad (6.4)$$

$$\overline{h}_{f,H_2O_l}^0 = -285855 \left(\frac{kJ}{kmol} \right) \quad (6.5)$$

$$\overline{h}_{f,H_2O_g}^0 = -241845 \left(\frac{kJ}{kmol} \right) \quad (6.6)$$

$$\overline{h}_{f,N_2}^0 = 0 \quad (6.7)$$

$$\overline{h}_{f,H_2}^0 = 0 \quad (6.8)$$

Making a stoichiometric balance for each element, the following equations are determined:

Carbon:

$$x = a_1 + a_2 + a_5 \quad (6.9)$$

Hydrogen:

$$y + 2\alpha = 2a_3 + 2a_4 + 4a_5 \quad (6.10)$$

Oxygen:

$$z + \alpha + 2\beta = 2a_1 + a_2 + a_4 + 2a_7 \quad (6.11)$$

Nitrogen:

$$w + 7.52\beta = 2a_6 \quad (6.12)$$

And the sum of the molar ratios of products:

$$a_8 = a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 \quad (6.13)$$

Where $a_{i, i=1...7}$ are the number of moles of seven unknown species on the product gas. Seven equations are necessary to solve the system of seven unknowns. In order to complete the set of seven equations, two equilibrium reactions have to be considered.

The equilibrium model assumes that all chemical reactions are in thermodynamic equilibrium and the main reactions involved are described below:



Based on the assumption that all reactions take place at atmospheric pressure and assuming that all gases are ideal, equilibrium constants can be written as a result of minimization of the Gibbs energy. Thus, the equilibrium constant for k_1 and k_2 can be written as follows:

$$k_1 = \frac{a_5}{(a_3)^2} = e^{-(\bar{g}_{T,CH_4} - 2\bar{g}_{T,H_2})/RT} \quad (6.16)$$

$$k_2 = \frac{a_1 a_3}{a_2 a_4} = e^{-(\bar{g}_{T,CO_2} + \bar{g}_{T,H_2} - \bar{g}_{T,CO} - \bar{g}_{T,H_2O})/RT} \quad (6.17)$$

Where $g(t, i)$ is defined as the Gibbs equation:

$$\bar{g}_{T,i} = \bar{h}_T - T\bar{s}_T \left(\frac{kJ}{kmol} \right) \quad (6.18)$$

And the temperature equilibrium of the reactions can be determined by the first law of thermodynamics:

$$\sum_R N_i \bar{h}_{ir} + Q_{loss} - \sum_P N_f \bar{h}_{ip} = 0 \quad (6.19)$$

Where \bar{h}_{ir} is the formation enthalpy (kJ / kmol) of the reagents in the reference state ($T_0 = 298.15$ K and $P_0 = 1$ atm) and \bar{h}_{ip} is the formation enthalpy of products. Q_{loss} is the heat loss rate in this zone which is dependent on the solid biomass feeding rate. The heat Specific heat, enthalpy and, entropy have been calculated as a function of temperature.

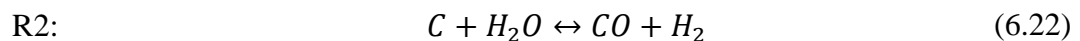
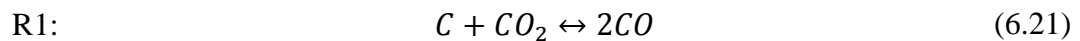
Considering the stoichiometric oxidation of biomass the equivalence ratio (ER), β can be determined. And the molar amount of moisture in the biomass can be defined as a function of molecular weight of the biomass on a wet basis and biomass moisture content:

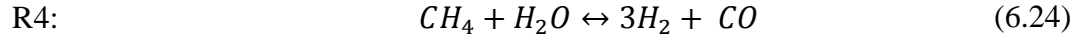
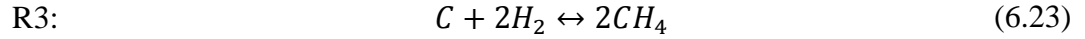
$$\alpha = \frac{MC \cdot M_{bio}}{M_{H_2O}(100 - MC)} \quad (6.20)$$

Equations 6.1-6.20 forms a system of nonlinear equations of 8 equations and 8 unknowns to determine the molar ratios of the products to a_1 to a_8 and thermodynamic equilibrium temperature is generated from the equations of mass balance and equilibrium constants.

6.1.2 Model of Reduction Zone

The input data to the reduction zone is from the output data from the exit of the pyro-oxidation zone. The reduction reactions considered in the zone are (Sharma, A., 2008):





The specific reaction rates are expressed as kinetic rate equations and the kinetic rate parameters are obtained from Wang, Y. et al. (2003). Therefore, the reaction rate of each chemical reaction can be written as

$$r_{R1} = C_{RF} A_{R1} e^{\left(\frac{-E_{R1}}{R_m T}\right)} (y_{CO_2} - y_{CO}^2 / K_{R1}) \quad (6.25)$$

$$r_{R2} = C_{RF} A_{R2} e^{\left(\frac{-E_{R2}}{R_m T}\right)} (y_{H_2O} - y_{H_2} y_{CO} / K_{R2}) \quad (6.26)$$

$$r_{R3} = C_{RF} A_{R3} e^{\left(\frac{-E_{R3}}{R_m T}\right)} (y_{H_2}^2 - y_{CH_4} / K_{R3}) \quad (6.27)$$

$$r_{R4} = C_{RF} A_{R4} e^{\left(\frac{-E_{R4}}{R_m T}\right)} (y_{H_2O} y_{CH_4} - y_{CO} y_{H_2}^3 / K_{R4}) \quad (6.28)$$

The control volume of the reduction zone is shown in Fig. 6.1. The mass balance for the species i across the control volume k can be expressed as

$$n_i^k = n_i^{k-1} + R_i^k \Delta V_k \quad (6.29)$$

Where n_i^k is the molar flow rate, in mol/s, R_i^k is the net rate of production of species i , in mol/m³s, and ΔV_k is volume of the k th control volume, in m³.

The energy balance can be expressed as

$$\sum_{i=1}^6 n_i^{k-1} H_i^{k-1} + n_7^{k-1} C_{p,c} (T^{k-1} - T_0) + Q_{loss}^{k-1} \quad (6.30)$$

$$= \sum_{i=1}^6 n_i^k H_i^k + n_7^k C_{p,c} (T^k - T_0)$$

Where H_i^k is the enthalpy of species i in k th control volume, in J mol^{-1} , Q_{loss}^{k-1} is heat loss rate in the $k-1$ th control volume.

The equilibrium constants $r_{R1} - r_{R4}$ are calculated at a tentative temperature. R_i^k and n_i^k are calculated by equation (6.30). And then the temperature for the k th control volume is determined by the energy balance equation.

6.2 Model Validation and Results Discussion

The model has been validated against experimental data from the two – stage gasifier using the corresponding biomass properties and operating conditions. Air blown from two different locations is lumped together using ER value. Figure 6.2 (b) shows the temperature variation along the vertical direction of the reduction zone of the gasifier, measured in experiment at different locations and predicted value from the present model. Temperature decreases along the length of the reduction zone because of the endothermic reactions in the reduction zone. The rate of temperature decay depends on the rate of the gasification reactions, calculated by their kinetics. It is observed that the temperature decreases fast over a short distance from the inlet of reduction zone and it hardly drops any further at a distance of 0.4 from the inlet. It is because that the predicted reaction rates are higher at the inlet of the reduction zone, and approaching the grate all the char gets consumed which leads to no significant reduction reactions downstream. Figure 6.2 (a)

compares the composition of dry producer gas obtained from experiment and predicted from the model. The producer gas is presented by mole fractions of different species. H₂ is somewhat underestimated in the model. However, the predictions generally agree very well with experimental data on CO, CO₂, N₂, and CH₄. Data comparison is shown in Table 6.2. Root-mean-square (RMS) error (Equation 6.31) is calculated to be 2.32% and it indicates a good agreement between the model and experimental data.

$$RMS = \left(\frac{1}{n} \sum_{i=1}^n (model_i - observed_i)^2 \right)^{0.5} \quad (6.31)$$

The present model has also been validated as a test case against experimental results from other literature (Jayah, T., 2003). Results also show good agreement on temperature in the reduction zone. In addition, CO, CO₂, N₂, and even CH₄ and H₂ agree very well with the corresponding results. Results indicate the feasibility of using the model for downdraft gasification temperature and syngas composition predictions.

The model is also used to predict producer gas concentrations for Oakdale system. A comparison of the data obtained from the model and experiment in Oakdale system is shown in Table 6.1. The model shows a much higher concentration for H₂ and CO, while CO₂ concentration is close. CO₂, a primary product from combustion zone, can be converted to CO in the reduction zone. Reduction zone is also critical to H₂ production. However, gasification in Oakdale system shows a less efficient conversion rate in converting CO₂ and H₂O to CO and H₂. In the results from the model, temperature profile in reduction zone decreases comparatively slower. This might be able to explain the lower conversion rate in the reduction zone. Since most of the reactions are endothermic and the heat source is mainly from the energy released from combustion zone, insufficient heat in the reduction zone can deactivate some of the reactions and hence result in low CO and H₂

production. In the two-stage air-blown system, an “additional” combustion region effectively solved the problem by providing extra heat.

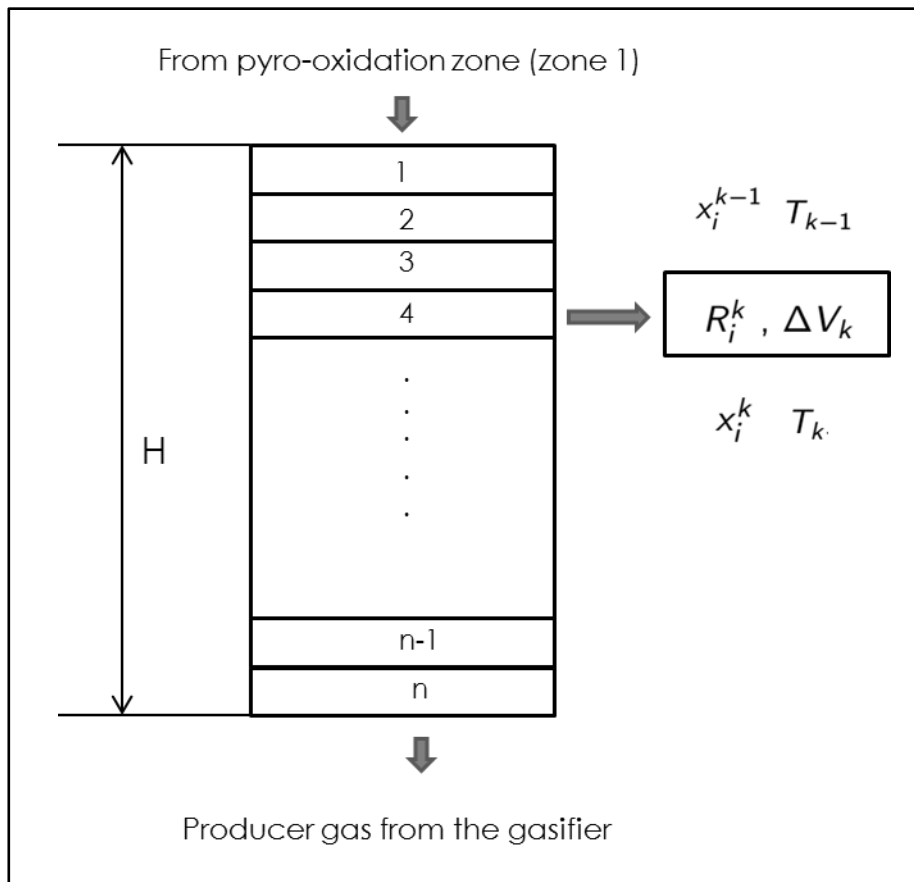
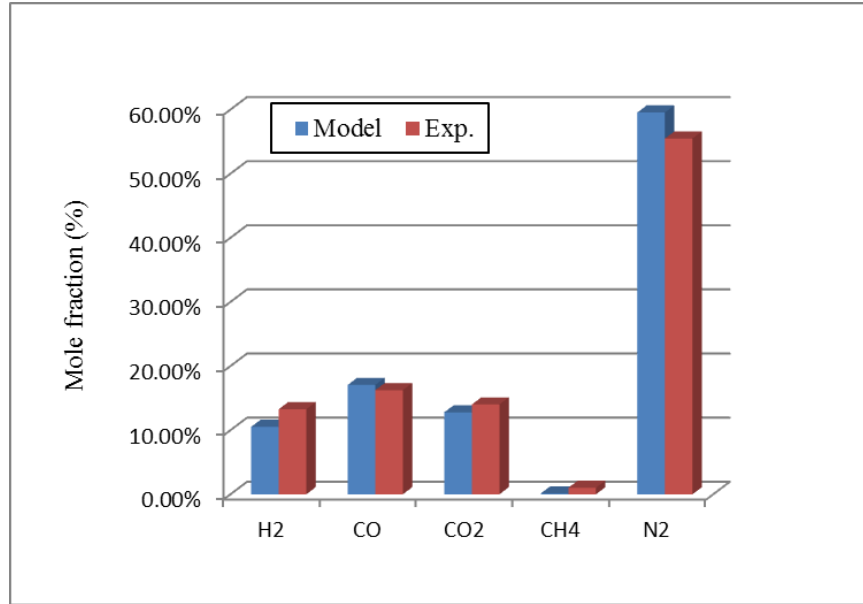
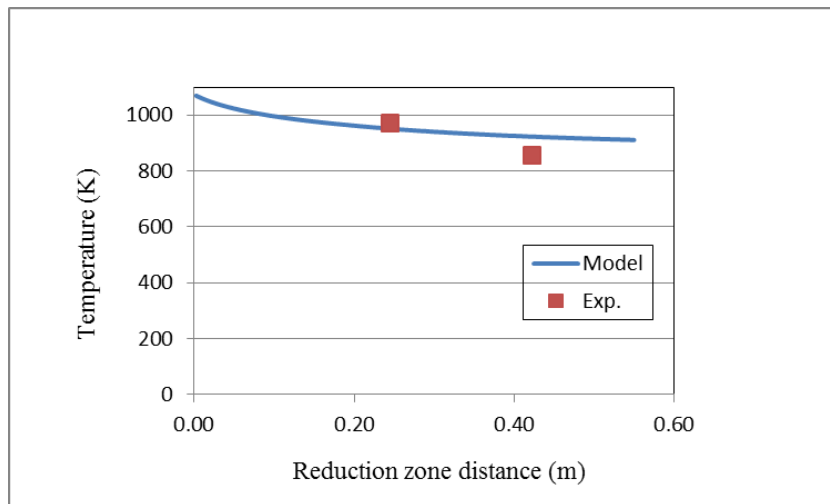


Figure 6.1 Reduction zone model

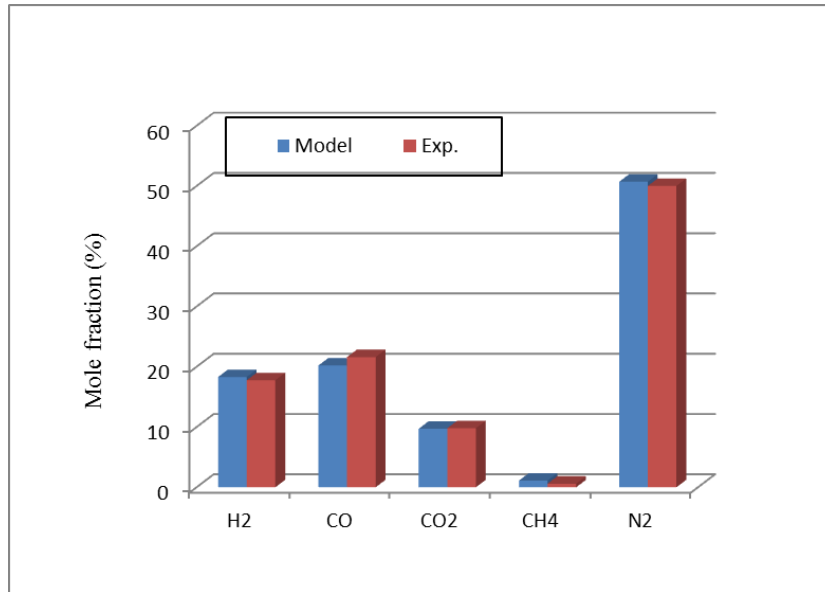


(a) Validation of producer gas concentration

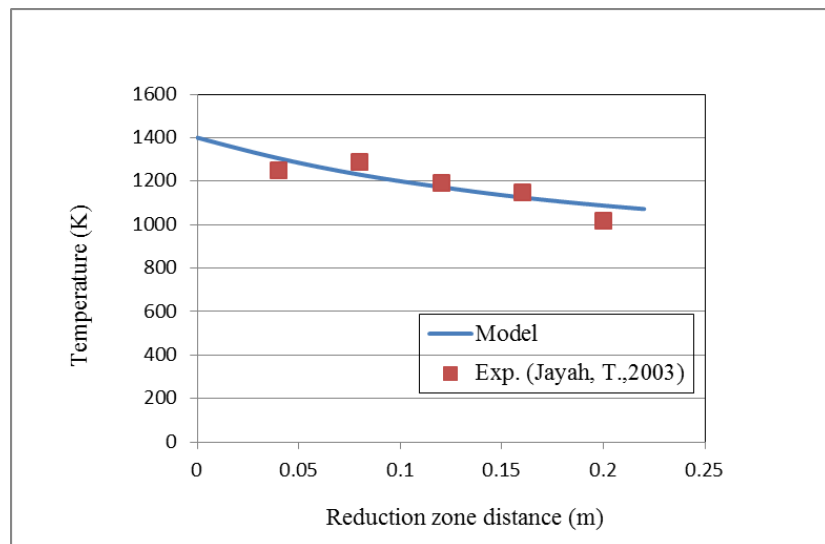


(b) Validation of temperature

Figure 6.2 Model validation against NEST data



(a) Validation of producer gas concentration



(b) Validation of temperature

Figure 6.3 Model validation against literature data

Table 6.1 Comparison of producer gas concentration: Oakdale experiment and model

	H ₂	CO	CO ₂	CH ₄	N ₂
Model	10.89%	16.19%	11.06%	0.34%	50.02%
Oakdale Exp.	3.25%	9.55%	12.39%	1.61%	73.19%

Table 6.2 Comparison of syngas concentration: NEST experiment and model

	H ₂	CO	CO ₂	CH ₄	N ₂
Model	10.52%	17.05%	12.78%	0.14%	59.54%
NETS Exp.	13.27%	16.24%	14.00%	1.02%	55.47%
RMS Error	2.32%				

Table 6.3 Comparison of syngas concentration: literature experiment and model

	H ₂	CO	CO ₂	CH ₄	N ₂
Model	17.76	21.6	9.8	0.6	50.0
Literature Exp.	18.3	20.2	9.7	1.1	50.7
RMS Error	0.78%				

CHAPTER 7

SUMMARY AND CONCLUSION

In this work, the producer gas production in a pilot-scale downdraft gasifier was investigated through experimental tests and numerical simulations. The system was first characterized including assessment of original and modified component design, system operation, and experimental procedures. Evaluations of the performance included measurement of the thermal profile, producer gas composition, operational stability, and system efficiency. After over 300 hours of operation and further testing, components such as air the air damper, char/ash delivery system, and control algorithms were modified to achieve steady-state operation. At the same time, an operational and experimental procedure was developed.

To broaden the applicability of this work, another two-stage pilot-scale downdraft unit having the same reaction zone dimensions was also studied and used to compare the systems' behaviors. With this additional information, a general 1-d hybrid model was then developed and utilized to predict optimal gas production.

The original system was tested at various ER values and fuel bed heights to evaluate the performance of producer gas output. Results show that the concentrations of CO, CO₂, CH₄, H₂, and N₂ in the producer gas vary between 9% - 15%, 10% - 16%, 1% - 2.5%, 2.5% - 4.5%, and 65% - 75.5% respectively with a useful gas power of 60 kW – 85 kW and a cold gas efficiency of 20% - 30%. A 25% increase in ER value increased superficial velocity (SV) by 22% and increased combustion zone temperature by 15% while decreasing CO concentration by 13%. A higher bed height consumes more energy in the combustion zone which brings about a lower combustion zone temperature. A 43%

increase in bed height increased SV by 2-4% while decreasing combustion zone temperature by 4-5%. No distinct evidence has shown any correlation between bed height and carbon conversion rate since many other factors play important roles in determining carbon conversion rate. In sum, ER has a dominating effect on gas yields and combustion zone temperature.

A two-stage air-blown downdraft gasifier with the same reaction zone dimension was employed to compare with the Oakdale system. By analysis, it was found that the two-stage system has a carbon conversion rate of 96.95% which yields a producer gas with the concentration of CO, CO₂, CH₄, H₂, and N₂ 16.24%, 14%, 1.02%, 13.27%, and 55.47% respectively. By comparing the system output at the same ER value, it is evident that an “additional” combustion zone in the two-stage system plays an important role in increasing carbon conversion and cold gas efficiency.

In these systems, there are two distinct reaction zones: a pyro-oxidation zone and a reduction zone. The former one has a temperature of up to 1300 °C and the latter one has a decreasing temperature profile in which the reactions are dominated by reduction reactions. Therefore, a hybrid 1-d model was developed by formulating two reaction zones – one is using equilibrium model and the other one is using kinetics model. The model shows a good agreement with results from the two-stage gasifier. By comparing the data obtained from the model and experimental data from Oakdale system, conclusion was drawn that insufficient heat in the reduction zone can deactivate some of the reduction zone reactions and hence result in low CO and H₂ production from the system. In addition, an “additional” combustion zone in the two-stage system effectively can solve the problem by providing extra heat.

CHAPTER 8

FUTURE WORK

During the research work, a number of possible modifications in the gasifier system were identified to improve the reliability of the gasifier and the feasibility of future research. These recommendations are as follows:

1. The air injection damper control can be replaced with a smaller bypass pipe with valve control. This could increase the control accuracy and also make gasification with various agent gases feasible.
2. The operation of the thermocouple probe can be considerably simplified by the use of a mechanical system such as screw meter control.
3. The strength of the canister material can be further reinforced by adding a ceramic liner. It will also reduce heat loss and improve efficiency.

Based on the results of the current study, the implementation of double-stage air-injection is effective and efficient for improving carbon conversion and gas yield. Therefore, installing a secondary air injection system to the core of the fuel bed is also recommended. In addition, gaseous products and solid char sampling inside the fuel bed are of great interest to understand the chemical mechanism in different zones inside the reactor. Therefore, designing of a sampling probe which can maintain the composition of the samples is suggested.

APPENDIX A OAKDALE SYSTEM OPERATION

The Oakdale system can be started, operated at steady-state, and shutdown from the PANEL VIEW monitor located on the control cabinet. Four working conditions are defined including shutdown, startup, run, and burndown. When steady running, operator can choose AUTO or MANUAL mode to run the system.

Startup Operation

In the startup operation, the operator needs to ignite the system and to achieve steady-state running by adjusting fuel and air balance. All the actions should be done in MANUAL mode. The physical procedures in startup operation are as follows:

- 1) Thoroughly inspect the gasifier and its surroundings for both operability & safety (Turntable is not touching the fingers; char bin shute is closed)
- 2) Ensure that the biomass slide gate is open (large outside shelled corn bin)
- 3) Ensure that the ash/char receptacle is in place
- 4) Request “Hurst Enable” signal from the Boiler Operator, and request pressure at around 0.3 WC
- 5) Pull out E-Stop button (red light goes out)
- 6) Push manual Reset button to left of E-Stop button

Then operate from PANEL VIEW manually as follows:

- 7) Ensure that there is sufficient fuel in the metering bins, and add to 250 lbs if necessary
- 8) Push STARTUP MODE button (virtual) on the PANEL VIEW screen (gasifiers air intake damper begins opening to 100% - gasifier’s ignition burner will not operate until damper is open)

- 9) Start, in order, the Long Auger motor, Airlock motor, Short Auger motor, Turntable motor (from the Motor Controls screen)
- 10) Open Hurst Boiler slide gate
- 11) Monitor air flow through the gasifier (air intake & syngas tube flow should be the same)
- 12) Feed 50 lbs biomass (shelled corn) into the gasifier
- 13) Activate gasifier igniter/burner (preset to 1200 seconds – 20 minutes)
- 14) Monitor syngas temperature and air intake/syngas flow rates. As syngas temperature increases beyond 400 degrees F, begin adding additional fuel (no more than 40 lbs. continuously, then wait four minutes – one turntable revolution – before adding more)
- 15) Once the syngas tube temperature reaches 750 F degrees or higher for a period of five minutes, STARTUP has been achieved, and the igniter Burner can be stopped. The operator should then change from the STARTUP MODE to the RUN MODE. The Air Intake Damper cannot be changed from 100% while in the STARTUP MODE.

Steady-state Operation

Once the PANEL VIEW condition has changed from STARTUP MODE to RUN MODE, the air intake can be adjusted by damper changing from 100% open to 100% closed. The operator takes the following steps until a steady state condition is reached:

- 1) Set air intake damper to 30%

- 2) Continue entering fuel in intervals (not more than 25 lbs each time) until desired fuel level is reached (if syngas temperatures begin to fall during these intervals, stop entering fuel until they again begin to rise)
- 3) Use a combination of airflow/syngas flow and fuel level to reach the optimal syngas temperature – normally 850 degrees F.
- 4) Ensure ash/char flow to the ash/char receptacle outside the building. (If 300 lbs. of fuel has been added to the gasifier, and no ash/char or raw fuel is exiting, use the agitating rod to break the big chunk char)
- 5) It takes about 90-120 minutes to reach steady-state operation. During this period, the operator continues to monitor temperature, pressure, airflow, syngas flow, fuel level, and ash/char removal component operations.
- 6) Steady-state operation is achieved in the RUN MODE once monitored temperatures and pressures barely fluctuate, and the desired fuel level is reached.
- 7) When steady-state operation is achieved, the operator can choose AUTO MODE to run the system with monitoring all the variables.

Shutdown Operation

In the shutdown operation, the operator needs to burn down the residual materials and cool the system down. Besides the standard shutdown, emergency shutdown with or without notice can occur. In this situation, the operator needs to quickly respond and make the correct decision to avoid problems such as overheating.

- Burn down

- 1) Confirm the Burndown temperature setpoint on Panel View (This is the temperature at which the gasifier will automatically shift to the Shutdown mode, at which point the boiler's knife gate and the gasifier's air intake damper close, and the auger, airlock, and turntable motors are all disabled. The setpoint is typically set at 275 °C (~ 525 F) degrees, but can be adjusted as desired.)
- 2) Activate the Burndown mode (This disables adding fuel from the metering bins into the gasifier.)
- 3) Monitor syngas temperature (It is normal to reach 1,250 F degrees, and not unusual to reach 1,400 F degrees, though the gasifier operator should start reducing air intake by the time 1,200 F is reached. This is done by closing the intake damper to a degree where the syngas temperature decreases. There is a lag time of approximately 30 seconds to two minutes before the temperatures start dropping, depending on the degree from which closing the damper starts. The wider it was open, the longer it takes to start decreasing.)
- 4) Open the air intake damper, by degree, when the syngas temperature decreases (This is done on an "as desired" basis. Burndown occurs more quickly by allowing more air into the gasifier, and if the syngas temperature falls below 800 F degrees. If the temperature begins to approach 1,200 F degree, the air intake damper can again be closed to a degree where the temperature begins to fall.)
- 5) Once the Burndown set point is reached, the gasifier will automatically shut down.
 - Standard Shutdown

- 1) When temperature gets below 300 degree F, run the auger for another 30-60 minutes.
 - 2) Close the air damper, disable all drive motors and then close the slide gate.
 - 3) The gasifier internal temperature and syngas temperatures normally increase after Shutdown, but rarely more than 100 F degrees.
 - 4) If temperatures increase by more than the amounts expected, the operator should check to ensure the boiler slide gate and gasifier air intake damper are closed.
 - 5) Push the manual E-Stop Button (It turns red all controls for the gasifier are manually disabled.)
 - 6) Notify the Hurst boiler operator that the gasifier is shutdown (He will then change the gasifier status from Hurst Enable to Hurst Disable, preventing any further operation of the gasifier.)
 - 7) Empty the ash/char receptacle into the Hurst boiler ash dumpster
 - 8) Close the outdoor biomass (shelled corn) storage bin slide gate if temperatures are expected to fall below freezing (Freezing temperatures can cause moisture in the biomass to freeze and plug the flexible auger system feeding into the gasifier metering bins.)
- Emergency Shutdown
- Case I: If emergency shutdown occurs with notice at least 5 minutes before slide gate shutdown,
- 1) Decrease the turntable to the lowest point
 - 2) Fully open air damper

- 3) Monitor temperature and flow rate (Temperature should be decreasing because of the cooling effect of higher flow)
- 4) Slide gate shutdown
- 5) Fully close air damper

Case II: if slide gate immediate shutdown without any notice,

- 1) Slide gate shut down
- 2) Decrease the turntable to the lowest point (to release the heat contained in the char)
- 3) Fully close air damper
- 4) Monitor temperature (Temperature should be slowly decreasing, same as burning down process)

(When Case I happens, decreasing the turntable to the lowest point and fully opening of the air damper enable burning down and maximize instant cooling. When emergency shutdown occurs, the air can be much cooler. Then closing the air damper the temperature takes time to get back to normal. While under Case II, there is no response time before slide gate shutdown. Then fully close of the air damper helps slowly burning down and system cooling down.)

APPENDIX B GAS CHROMATOGRAPHY CALIBRATION GAS

The calibration gases include three bottles of standard gases at different concentrations made by Praxair, Iowa. The concentrations for the calibration gas are listed in Table App.1.

Table App.1 Gas Chromatography calibration gas

Gas	Concentration1 (%)	Concentration2 (%)	Concentration3 (%)
Oxygen	1	1.5	2
Hydrogen	2	2.5	3
Methane	2	1.5	1
Carbon Dioxide	16	14.5	13
Carbon Monoxide	5	10	15
Ethane	0.5	1	1.5
Ethylene	1.5	1	0.5
Propane	1.5	1	0.5
Acetylene	0.5	1	1.5
Nitrogen	70	66	62
Total	100	100	100

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