DESIGN AND TESTING OF A SMALL-SCALE UPDRAFT GASIFIER FOR GASIFICATION OF EASTERN REDCEDAR

By

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DESIGN AND TESTING OF A SMALL-SCALE UPDRAFT GASIFIER FOR GASIFICATION OF EASTERN REDCEDAR

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

CH_4 – Methane

C_2H_2 – Acetylene

C_2H_4 – Ethylene

C_2H_6 – Ethane

cm - centimeters

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

ER – Equivalence Ratio

H_2 – Hydrogen

HHV – High Heating Value

km - kilometers

m - meters

N_2 – Nitrogen

O_2 – Oxygen

SCFM – Standard Cubic Feet per Minute

CHAPTER I

INTRODUCTION

Figure 1: Eastern redcedar, *Juniperus virginiana*, in an Oklahoma field

If a pasture in Oklahoma is allowed to lie out of production, without being cultivated, mowed or sprayed, the owner might soon begin to notice the pointed tops of little evergreens sticking up past the grasses. Allowed to continue without interruption, the little evergreens will shoot up, and after a few years the owner will only see wisps of grass between the trees. Landowners across Oklahoma have battled this landscape phenomenon for years, utilizing pesticides and tree cutting, but the trees continue their takeover. *Juniperus virginiana*, or eastern redcedar (as shown in Figure 1), is the primary source of these trees invading the fallow land of our state.

Eastern redcedar grows in most of the United States east of the Rocky Mountains, ranging from South Dakota to southern Texas to southern Georgia to New England (Schmidt and Piva, 1996). A small strip along the Gulf coast and some of the higher elevations in the Appalachian Mountain range are the only areas in this range that do not have eastern redcedar growth. Because it is a pioneer invader, the tree is commonly found in prairies or oak barrens, old pastures, or limestone hills, often along highways and near recent construction sites (Farjon, 2005).

There are several products made from redcedar, including fenceposts, lumber, mulch, and cedar oil. However, the demand for each of these products is not great enough to provide a market for the abundance of eastern redcedar in Oklahoma. Converting redcedar to fuel would provide a market for it with inexhaustible demand. Gasification is one option for the conversion.

Gasification is the process of converting a solid, organic feedstock in a high temperature, oxygen deficient atmosphere to a mixture of gases, known as producer gas or synthesis gas. Though gasification of wood has been utilized to produce energy for decades, gasification of redcedar has been studied very little. There are few gasifier designs that have been published.

Gasifying redcedar would provide a two-fold benefit to the state of Oklahoma. First, there would be an added incentive for landowners to clear land, which would help to offset the cost of clearing pastures. This would mean more useful grazing land for decades to come, and that is important to our state where cattle is a big industry. Second, gasification will provide a new source of renewable energy. Incorporating as many renewable energy sources as possible to offset non-renewable, imported oil is an important goal in both Oklahoma and the entire United States of America.

Gasification of eastern redcedar could have a great impact on the perception of redcedar in Oklahoma. In addition to providing a source of “green” energy, it will add value to the currently-considered-nuisance plants taking over the landscape.

However, existing gasifiers at Oklahoma State University were not available for gasification of redcedar because the byproducts of gasifying redcedar were not known and could potentially damage the existing gasifiers. Published designs for gasifiers of the type desired for this research were not found. Therefore, before gasification of redcedar can be studied, a new gasifier must be designed and constructed.

Objectives

The main goal of this project is to examine the feasibility of gasification of redcedar as a means of adding value to the crop. The two specific objectives are:

- Provide a detailed design of an updraft gasifier that can be used with a variety of feedstocks including eastern redcedar mulch
- Test the quality and quantity of producer gas produced by the new gasifier using eastern redcedar mulch as a feedstock

CHAPTER II

REVIEW OF LITERATURE

Eastern Redcedar

Physiology

To fully understand the feedstock for this research, the physiology of eastern redcedar is detailed here. The scientific classification of eastern redcedar is as follows:

- Kingdom: *Plantae*
- Division: *Pinophyta*
- Class: *Pinopsida*
- Order: *Pinales*
- Family: *Cupressaceae*
- Genus: *Juniperus*
- Species: *J. virginiana*

Juniperus virginiana grows slowly and may never be larger than a dense bush when growing in poor soil. Mature redcedar is five to twenty meters tall and can be as tall as thirty meters. The single trunk is short and thirty to one hundred cm in diameter, with large specimens reaching 170 cm in diameter. The oldest tree, found in Missouri, was 795 years old (Wikipedia, 2008). Individual trees may be male or female and reach sexual maturity at about 10 years of age (Redcedar Task Force, 2002).

Redcedar seeds are small and brown; and one to four seeds are contained in a green to whitish-blue cone appearing like berries on the tree (Redcedar Task Force, 2002). These berries occur only on the female trees and are usually found in heavy amounts. Mature trees produce some seeds nearly every year but good crops occur only every two to three years (Redcedar Task Force, 2002). Pollen cones contain three to seven pairs or trios of sporophylls. Each sporophyll has two to eight pollen sacs. Globose to ovoid seed cones mature in one year and are similar in size (FNA).

Redcedar draws its name from its fragrant bright red to dull red heartwood that is very resistant to decay. The sapwood is nearly white and thin (U. S. Forest Products Laboratory, 1974). The U. S. Forest Products Laboratory (1974) describes the wood as "moderately heavy, moderately low in strength, hard, and high in shock resistance, but low in stiffness. It has very small shrinkage and stays in place well after seasoning. The texture is fine and uniform. Grain is usually straight, except where deflected by knots, which are numerous."

Bark of redcedar is brown with thin strips peeling away from trunk and larger branches. Branches can be pendulous to ascending with branchlets generally erect but sometimes lax to flaccid (FNA).

Like other species of the genus *Juniperus*, the evergreen leaves of redcedar are cylindrical and tapering. The green leaves can become reddish brown in winter (FNA). The branchlets are variously oriented and do not flatten into sprays. Adult leaves are pressed close, divergent, and scale-like (Adams, 1970).

Impact on Oklahoma Rangeland

The size and growth patterns of eastern redcedar found in Oklahoma make it low-quality for use as a raw material in the lumber industry, and there is no substantial market for it (Bidwell et al, 2000). This fact has contributed to the fact that eastern redcedar often takes over crop and pasture land and becomes a pest in Oklahoma farm and ranch land (King and Lewis, 2000). The decrease in open range also negatively affects wildlife species that need this range for habitat (Adams, 1987).

In a 2004 news release, the Noble Foundation stated that, “Due mainly to fire suppression, eastern redcedar and ashe juniper (redcedar) had invaded almost 1.5 million acres (6,000 square km) in Oklahoma by 1950, 3.5 million acres (14,000 square km) by 1985 and 6 million acres (24,000 square km) by 1994. Currently, the Oklahoma Natural Resources Conservation Service estimates that Oklahoma is losing 762 acres (3.0 square km) of rangeland, one of the state’s most diverse and valuable ecosystems, per day.”

The Noble Foundation news release went on to say, “According to research, two hundred-fifty redcedar trees per acre (1 tree per 16 square meters) covering 28 square feet (2.6 square meters) each (a six-foot (1.9 meters) crown diameter), about one tree every 13 feet (4.0 meters), would reduce herbaceous production (grasses and forbs) by 50 percent.” A 50 percent reduction in grasses would directly correlate to a 50 percent reduction in the number of cattle that could graze the acreage. With cattle being an important industry in Oklahoma, this type of reduction only enforces the concept of redcedar being a nuisance in Oklahoma.

Current Uses of Eastern Redcedar

While redcedar can be considered a nuisance plant in Oklahoma and other areas, it is in commercial production in the southern Appalachian Mountain Range and Cumberland Mountain Range (U. S. Forest Products Laboratory, 1974). It is the hope of many to promote commercial production in Oklahoma.

Many associations have been created to spread information about eastern redcedar. The Aromatic Cedar Association (formerly the Oklahoma Redcedar Association) lists its goals as: “to provide information regarding the management and utilization of ‘aromatic cedar’; to connect businesses, individuals and government agencies together; and to promote and develop the eastern redcedar industry.” The Aromatic Cedar Association holds annual conventions to promote its goals. The convention objective of the 2008 convention held at the Payne County Expo Center in Stillwater, OK, was “to provide a common forum for the discussion of eastern redcedar and similar species, with particular emphasis on utilization and product marketing”. Topics presented at the convention included biomass energy and carbon credits, wood pellets for fuel, adding value to redcedar, how to start and maintain a business, redcedar control programs, grant possibilities, and cellulosic ethanol. This convention’s objective and presentations demonstrate the desire of many people to utilize this natural resource so that it may be regarded as such instead of as a nuisance plant.

There are many products made from redcedar. Current commercial uses of redcedar include:

Fenceposts

Because of its durability, eastern redcedar has long been used for fenceposts. Posts made from redcedar are very resistant to rot after seasoning (Ferguson, 1974). Often, the bark and sapwood will degenerate from the post leaving the red heartwood post (Ferguson, 1974). The wood shrinks very little during drying and is not greatly affected by changes in atmospheric moisture making it stay well in place after seasoning (Ferguson, 1974). It is moderately hard but very workable with a straight grain except for knots that are harder than surrounding wood but usually tight (Ferguson, 1974). The wood splits easily and holds nails reasonably well (Ferguson, 1974). Many of the nuisance trees in Oklahoma are of a size which would be useful for fenceposts, but the demand is not great.

Lumber

The wood can also be used for lumber and has been valued for its beauty and resistance to rot for over 3,000 years (Redcedar Task Force, 2002). However, the lumber is rarely used for its structural strength due to the many knots occurring in the wood because of the high number of limbs, but these knots only add to the attractiveness of the wood (U. S. Forest Products Laboratory, 1974). Redcedar wood is generally chosen for its beauty and its anti-fungal and anti-microbial properties, so the presence of the dark, tight or sound knots in its wood does not pose a problem (U. S. Forest Products Laboratory, 1974). Because it deters moths, the lumber is often used for chests, wardrobes, or closets (U. S. Forest Products Laboratory, 1974). It is also utilized as flooring, novelties, pencils, scientific instruments and small boats (U. S. Forest Products Laboratory, 1974). However, only large trees make good lumber, and makers do not utilize trees of the size found in most Oklahoma pastures (Redcedar Task Force, 2002).

Mulch

The color, aroma, and insect deterring capability of redcedar mulch make it a favorite type of mulch among gardeners and landscapers. The wood may be shredded or chipped, generally after the trees have been allowed to dry for several weeks, or may be a by-product of lumber processing. There are several redcedar mulch companies in Oklahoma including Eastern Redcedar Mulch located in Stillwater which sells redcedar shavings to wholesalers that supply products to Lowe's and other retailers in the region. The company describes its product as "lightweight, easy to handle, and has an aromatic aroma which is pleasing to smell. It is a natural product free from added coloring or dyes. Its color is best described as a mix of several shades of reddish-brown and blonde. Because of the nature of redcedar, this mulch is longer lasting than hardwood bark mulch. It is more fibrous, yet it still retains a consistent, fine texture. Redcedar mulch provides good moisture retention and weed control. Also, because it does not decompose very quickly, it provides long-lasting, effective erosion control." While this is a product well suited for the redcedar in Oklahoma, as with fenceposts, the demand is not great enough to make a dent in the redcedar population.

Cedar Oil

The heartwood of a mature tree can be processed for the oil content, yielding cedar oil, which is used in perfumes as a fixative and is fairly valuable (Redcedar Task Force, 2002). These oils have a distinctive woody odor that may change as they dry out and are yellowish or darker in color, viscous, and deposit crystals when standing (FAO, 1995). The oils in the wood are different from the oils in the leaves and are more desirable. Cedar oils are used in a variety of fragrance applications such as soap, perfumes, household sprays, floor polishes, and insecticides and, in small quantities, as a clearing oil used in microscope work (FAO, 1995).

Oils can be removed from cedar wood by either distillation or extraction and are obtained differently depending on if lumber is also to be obtained from the timber. If so, sawdust and waste wood materials from the saw mill are taken to the distillery for steam distillation and recovery of oil in a normal manner. Sawdust should not be exposed to direct sunlight before distillation, otherwise oil yields and quality are diminished (FAO, 1995). If trees are not of quality suitable for lumber milling, whole trees may be cut, chipped, and steam distilled. Heartwood and stumps contain the most oil, but stumps are not widely utilized. Crude oil may be rectification to obtain fractions with different olfactory properties or to isolate individual constituents (FAO, 1995).

Cedar oils contain compounds such as cedrol and cedrene which contribute to the odor of the oil and are also valuable for conversion to other chemicals with fragrance applications making the oils useful both directly and as sources of chemical isolates (FAO, 1995). Oil yields vary broadly, in the range of 1-5 percent, according to the type of oil produced and whether it is produced from sawdust or chips. Heartwood is richer in oil than sapwood and commercial distillers of Texas cedarwood oil recognize higher yielding trees to be the older, slower growing ones with a strong, central axis (FAO, 1995). Currently there are no cedar oil facilities in Oklahoma, and because only a small percentage of Oklahoma redcedar would be of the high-yield type, it is not likely that a facility will be started.

Conventional Methods of Controlling Redcedar

Herbicides

Though often cost prohibitive, herbicides can be an effective method of controlling redcedar in certain situations. Bidwell et all (2009) recommends their use in treatment areas of less than 160 acres (0.64 square km) where trees are less than six feet (1.9 meters) tall and less dense than 250 trees per acre (1 tree per 16 square meters). Individual tree treatment with herbicides velpar or picloram is recommended. The average cost per acre for this treatment is expected to be $40, four times the cost to treat by burning and twice the cost to treat mechanically (Bidwell et al, 2009).

Controlled burns

The most aggressive stands of eastern redcedar tend to be in areas where naturally occurring range fires have been suppressed (Strizke and Bidwell, 1998). Correspondingly, the prevailing best management practice (BMP) for controlling and preventing encroachment of the trees is to use ecosystem maintenance methods, namely prescribed fire (Bidwell et al, 2009). Though no single practice is appropriate for every pasture, prescribed fire is considered a natural, environmentally appropriate, and cost-effective way to maintain ecosystems in prairies, shrublands, and forests (Bidwell et al, 2009).

Cutting

Bidwell et al describes many types of pastures and the recommended methods for controlling eastern redcedar in specific situations. While controlled burns are generally more cost effective, mechanically removing, or cutting, trees is sometimes the recommended treatment method, with cost per acre ranging $16-90 (Bidwell et al, 2009). The preference to cutting depends on the scale of the target area, the density of trees, and the size of trees. For example, in areas of less than 160 acres (0.64 square km) with trees less than six feet (1.9 meters) tall and with less than 250 trees per acre (1 tree per 16 square meters), cutting by hand is a viable option (Bidwell et al, 2009).

In larger areas, areas with larger trees, or with 250 trees per acre (1 tree per 16 square meters) or more, other methods of cutting are recommended. Where trees are less than six feet (1.9 meters) tall and less dense than 250 trees per acre (1 tree per 16 square meters), mowing or shredding is appropriate (Bidwell et al, 2009). Where trees are larger, heavier-duty equipment is required. Recommendations include hydraulic clippers, cedar hydraulic saws or bulldozers (Bidwell et al, 2009).

Eastern Redcedar Product Research

With a large supply of redcedar in Oklahoma, there has been some research into improving current uses or finding new uses for this plant. Published research includes:

- Cedar oil extraction processes have been studied at Oklahoma State University (Dunford et al, 2007; Payne et al, 1998).

- Particleboard production from eastern redcedar has been studied at OSU in conjunction with USDA Forest Service, Louisiana State University, and Virginia Polytechnic Institute (Cai, 2004).
- Gold et al explored the market forces at work in the eastern redcedar industry and discovered there is little pressure being exerted on the market by either suppliers or buyers. (Gold et al, 2005)
- There are also numerous articles and papers about effectiveness of prescribed burning and other methods for controlling eastern redcedar growth.

Eastern Redcedar Suitability for Gasification

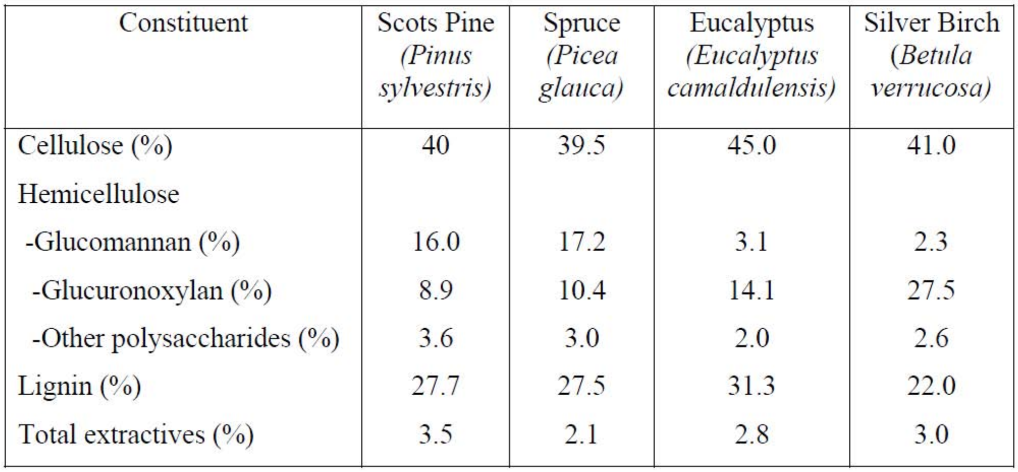
Because green eastern redcedar, including needles, is about 33 percent moisture (Ferguson, 1974), it should be suitable for gasification without pre-drying as prior studies have shown gasification of biomass with moisture contents as high as 50 percent in an updraft gasification system (VTT, 2002). No pre-drying will mean a faster, more efficient system. Chipping the wood produces small, fairly uniform shreds, and this will be a more energy efficient way of reducing wood particle size than pelleting, which is sometimes utilized as a means of reducing feedstock particle size for gasification. Also, oils are very combustible, which should produce high temperatures in the combustion zone.

Chemical Composition

Though wood composition varies based on species, growing conditions, etc. all wood is essentially composed of cellulose, hemicelluloses, lignin, and extractives

(Sjostrom, 1993). The major chemical composition of some wood species is shown in Table 1.

Table 1: Chemical composition of some wood species
(Sjostrom, 1993).



Constituent	Scots Pine *(Pinus sylvestris)*	Spruce *(Picea glauca)*	Eucalyptus *(Eucalyptus camaldulensis)*	Silver Birch *(Betula verrucosa)*
Cellulose (%)	40	39.5	45.0	41.0
Hemicellulose				
-Glucomannan (%)	16.0	17.2	3.1	2.3
-Glucuronoxylan (%)	8.9	10.4	14.1	27.5
-Other polysaccharides (%)	3.6	3.0	2.0	2.6
Lignin (%)	27.7	27.5	31.3	22.0
Total extractives (%)	3.5	2.1	2.8	3.0

According to Reed and Desrosiers (1979), generic formulas are sufficient for many gasification calculations. Reed and Desrosiers (1979) state that biomass is a mixture of ~50% cellulose, 25% hemicellulose and 25% lignin, and all biomass can be approximated with $CH_{1.4}O_{0.6}$.

Gasification

Goal of Gasification

Gasification is the conversion of solid, organic material to a mixture of combustible gases by partial oxidation at elevated temperatures (500-1400°C) (Rajvanshi, 1986). This conversion is caused by combusting the solid material with limited oxygen to produce an exhaust gas known as producer gas, or synthesis gas (Richey, 1984). Producer gas consists of carbon monoxide, hydrogen, carbon dioxide, methane, traces of higher hydrocarbons such as ethane and ethylene, water vapor, nitrogen (if air is the oxidizing agent) and various contaminants such as small char particles, ash, tar and oil. This producer gas must contain enough carbon monoxide, hydrogen, acetylene and other hydrocarbons to be combustible (Mayer, 1988).

History of Gasification

For the past two centuries, gasifiers have been used in some capacity. During the Industrial Revolution, gasifiers produced town gas for lighting (Mayer, 1988). This combustible gas was produced as a byproduct of the large quantities of coal that were coked prior to use in smelting operations. In 1839, Bischaf patented a simple process for gasifying coke, which became the first commercial updraft, fixed bed gasification system. Later, gasification producer gas was used to fire internal combustion engines, the first attempt occurring in 1881 (Stassen and Knoef, 1993). During World War II, the German military bolted gasifiers on their motor vehicles to produce fuel when oil imports were blockaded. After the War, accessibility of affordable fossil fuels caused decline in the producer gas industry (Loewer et al, 1982).

Since the energy crisis of the 1970’s, gasification has been examined as a means of converting biomass to conveniently-usable fuel to offset petroleum usage (Stassen and Knoef, 1993). The chemical energy stored in organic materials can be converted to more usable forms through one of three conversion schemes: biochemical, chemical or thermo-chemical. Biochemical and chemical conversion methods are only possible with certain types of biomass material, but most biomass materials can be thermo-chemically converted, making it a favorable option (Sims, 2003). Gasification is a thermo-chemical conversion technology which has attracted significant interest because it offers highest efficiency, or most usable energy, as compared to combustion (Sokhansanj et al, 2003; Zhou et al, 2003).

In addition to reducing dependence on petroleum, gasification has been studied recently as a value-added process for handling some byproducts. Byproducts that would typically be disposed of by land filling, incineration, or microbial decomposition could be gasified as an alternative process to the traditional disposal methods which are sometimes unavailable, expensive, or cumbersome (Bowser et al, 2004).

Gasification provides several possible advantages to direct combustion of byproducts (Richey, 1984). Gasification produces minimal air pollution (Richey, 1984). Direct-drying of the product is possible without using a heat exchanger, which increases efficiency and reduces equipment expense as compared to combustion (Richey, 1984). With 80-90% of heat recovered, gasification provides a more efficient conversion of biomass to heat for thermo applications. Combustion rate can be controlled by regulating primary air flow. Perhaps the most significant advantage of gasification is that in addition to the recoverable waste heat generated by direct combustion, gasfiers provide usable process fuel (Richey, 1984).

Gasification Chemistry

The mechanism of pyrolysis and gasification is described in Reed (1981). This paper proposes that combining biomass with heat will produce only char, but gasification requires a thermodynamic change in the composition of the biomass. The paper goes on to describe the expected reactions at various reaction temperatures. Drying occurs at temperatures less than 120˚C; pyrolysis occurs at 200-800˚C; char is gasified at 800-1100˚C; finally, char is combusted at 800-1500˚C (Reed, 1981).

Many different chemical reactions are involved in the processes of pyrolysis and gasification. These reactions, which depend on the process parameters and use $C_6H_{10}O_5$ to model biomass, include (D.L. Klass, 1998):

Pyrolysis reactions	Enthalpy
$C_6H_{10}O_5 \rightarrow 5\ H_2 + 5\ CO + C$	209 kJ @ 1000K
$C_6H_{10}O_5 \rightarrow 3\ H_2 + 5\ CO + CH_4$	120 kJ @ 1000K
$C_6H_{10}O_5 \rightarrow 2\ H_2 + 4\ CO + CH_4 + H_2O + C$	-16 kJ @ 1000K
$C_6H_{10}O_5 \rightarrow H_2 + 3\ CO + 2\ CH_4 + CO_2$	-140 kJ @ 1000K
$C_6H_{10}O_5 \rightarrow H_2 + 3\ CO + CH_4 + 2\ H_2O + 2C$	-152 kJ @ 1000K
$C_6H_{10}O_5 \rightarrow 2\ CO + 2\ CH_4 + CO_2 + H_2O + C$	-276 kJ @ 1000K

Air gasification reactions	Enthalpy
$C_6H_{10}O_5 + 0.5\ O_2 \rightarrow 5\ H_2 + 6\ CO$	96 kJ @ 1000K
$C_6H_{10}O_5 + O_2 \rightarrow 4\ H_2 + 6\ CO + H_2O$	-142 kJ @ 1000K
$C_6H_{10}O_5 + O_2 \rightarrow 5\ H_2 + 5\ CO + CO_2$	-180 kJ @ 1000K
$C_6H_{10}O_5 + 1.5\ O_2 \rightarrow 3\ H_2 + 6\ CO + 2\ H_2O$	-389 kJ @ 1000K
$C_6H_{10}O_5 + 1.5\ O_2 \rightarrow 5\ H_2 + 4\ CO + 2\ CO_2$	-464 kJ @ 1000K
$C_6H_{10}O_5 + 2\ O_2 \rightarrow 5\ H_2 + 3\ CO + 3\ CO_2$	-745 kJ @ 1000K

Gasification Technologies

Biomass gasification systems are either fixed or fluidized beds. Fluidized bed gasifiers are generally only cost effective in large-scale applications, those that generate over 15 MW (VTT, 2002). Fixed bed systems are more suitable for small-scale heat and power applications and generally feature simple construction (Reed and Das, 1998). Characteristics of fixed bed gasification include high carbon conversion, long solid residence time, low gas velocity and low ash carry-over (Barker, 1996; Carlos, 2005). Tar removal is a chief problem, and progress is being made in thermal and catalytic conversion of tar (Riva, 2006). Before use in many applications, producer gas must be cleaned and cooled, generally using a filtration system of cyclones, wet scrubbers and dry filters (Demirbas, 2002; Rajvanshi, 1986).

Within the categorization of fixed bed gasifiers, there are several reactor designs classified according to the path of the gasifying agent through the gasifier. These include updraft, downdraft, crossdraft and two stage gasification systems. Gasifying agents can be air, steam, oxygen, or a mixture of these (Stassen and Knoef, 1995). Further classification may be made based on the function of the producer gas: thermal applications make use of heat gasifiers, and engine applications make use of power gasifiers (Reed and Das, 1988). Classification of the gasification system, operating conditions, and type of biomass feedstock all affect the composition and level of contamination of the producer gas (Bridgwater et al, 1999). Due to their relatively simple design considerations, only downdraft and updraft fixed bed systems will be relevant to this project and examined in this review.

Downdraft Gasification

Downdraft gasifiers may have a throat (Imbert type) or be throat-less (open core type). Imbert systems feature co-current flow of gases and solids (Figure 2) through a descending packed bed, which is supported by the constriction of the throat (Reed and Das, 1988). Biomass feedstock enters at the top and is dried and pyrolysed before being partially combusted by the gasifying media. Maximum mixing of gases occurs in high temperature regions due to the constriction at the throat (Clarke, 1981). This aids in cracking tars to primarily carbon monoxide and hydrogen so producer gas from downdraft gasifiers has less tar than updraft gasifiers. However, the throated design causes a great sensitivity to particle size and density and is limited to feedstocks with uniform, small particle size and operations of less than 500 kW (Chopra and Jain, 2007).

Throat-less gasifiers also feature co-current flow of gases and solids (see Figure 2). This type of downdraft system was developed to overcome the problem of bridging and channeling in throated systems (Stassen and Knoef, 1993). Feedstock and air move downward from the open top, which ensures uniform and easily-controlled operation. Hot producer gas is drawn out the bottom of the chamber through a grate (Sims, 2003). Tar generation is as low as 0.05 kg tar/kg gas (Tiwari et al, 2006). The design is suitable for small-sized feedstocks with ash content of up to 20% (Jain et al, 2000b).

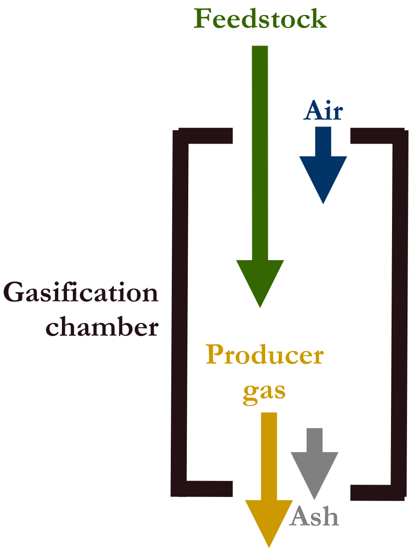


Figure 2: Schematic of gas and solid movement through a downdraft gasifier.

Updraft Gasification

Updraft gasifiers are also known as counter-current gasifiers, as biomass feedstock flows in the opposite direction to the gasifying agent (Figure 3). Feedstock enters from the top of the reaction chamber and moves slowly downward through the drying, pyrolysis, gasification and combustion zones (Figure 4). Finally ash exits downward through the grate and is removed (Reed and Das, 1998). The gasifying agent enters through the grate at the bottom of the chamber, undergoes thermo-chemical reactions with feedstock as it moves upward through the zones, and producer gas exits through the top of the reaction chamber. The direct heat exchange from gas to entering feedstock produces high thermal efficiency in updraft gasifiers (Stassen and Knoef, 1993). Producer gas exits at a relatively low temperature (80-300 ˚C) and contains high amounts of oils and tar (10-20%) because the products of the pyrolysis and drying zones exit directly with producer gas rather than being decomposed (VTT, 2002). Dust content in producer gas is generally low due to low gas velocities and the filtering effect of the upper zones (Carlos, 2005)

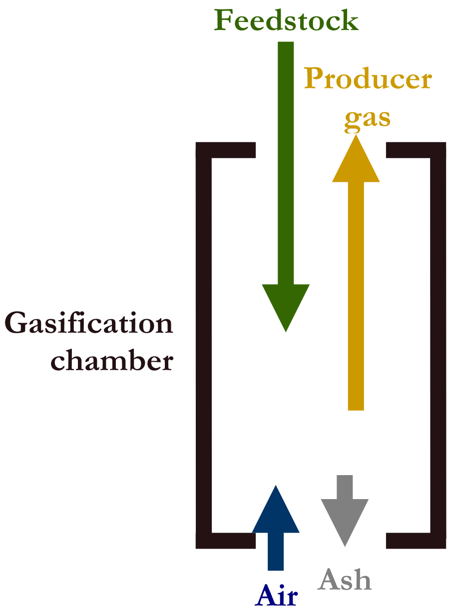


Figure 3: Schematic of updraft gasification reaction chamber.

Due to varying operating and feedstock parameters, efficiency values reported for updraft gasifiers also varies greatly. Rajvanshi (1986) states the average conversion efficiency for wood gasification is 60-70%. FAO (1986) lists expected conversion efficiency between 60 and 75% for a mechanical application system and as high as 93% for thermal applications, depending on type and design of the gasifier as well as on the characteristics of the fuel. Bowser et al (2005) reported cold gas efficiency values for the updraft gasification system using air as the gasifying agent as 58% for wood pellets, 47% for meat byproduct sludge, and 60% for a mixture of half wood pellets and half meat byproduct sludge.

Many commercial biomass gasification systems are currently successfully utilizing updraft technology. Examples of these systems are Primenergy, LLC, Tulsa, OK; VIDIR Machine, Inc., Clermont, FL; and Carbona Corporation, Atlanta, GA (Bowser et al, 2004).

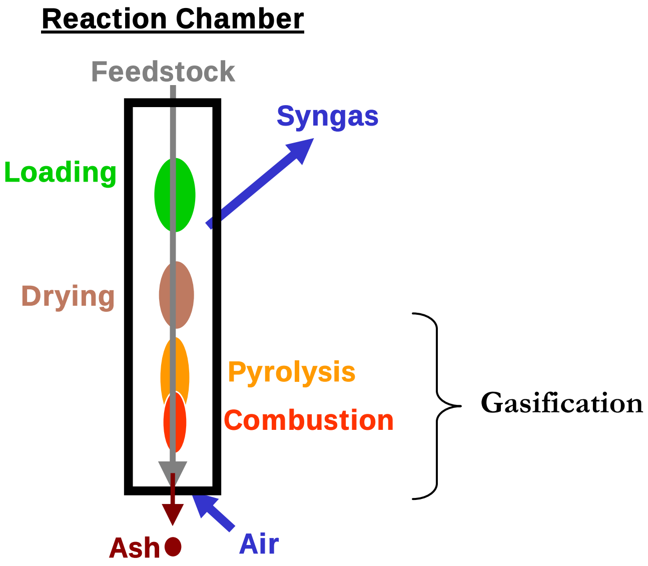


Figure 4: Schematic of zones and feedstock and air in an updraft gasification system.

Comparison of Updraft to Downdraft Gasification Systems

The oldest and simplest fixed bed gasification system, updraft gasifiers are more robust than other types of fixed bed gasifiers (Chopra and Jain, 2007). Updraft systems can handle feedstocks with ash content of up to 15% compared with 5% for Imbert downdraft systems. They can also handle higher moisture content feedstocks, up to 50% compared to 20% in downdrafts (VTT, 2002). Updraft gasifiers are also less sensitive to variations in particle size and quality in feedstock. Downdrafts have lower overall efficiency due to the high amount of heat carried out by the hot gas (Clarke, 1981). However, downdraft gasifiers are suitable for both thermal and engine applications while updraft gasifiers are generally only suitable for thermal applications without considerable cleanup of producer gas (Reed and Das, 1988).

Prior Studies of Gasification of Wood

A study by the Food and Agriculture Organization (FAO) in 1986 took into account several dozen commercial wood gasifiers when publishing a study on using producer gas as fuel for an internal combustion engine. Table 2 gives typical gas compositions as obtained from commercial wood gasifiers operated on low to medium moisture content fuels (<20 percent). These numbers will be used as a gauge of the quality of producer gas from the system detailed in this document, with considerations for the size difference in a commercial gasifier and the pilot-scale gasifier designed for the current study.

Table 2: Composition of gas from commercial wood and charcoal gasifiers (FAO, 1986).

Component	Percent of Producer Gas (mol %)
Nitrogen	50 - 54
Carbon monoxide	17 - 22
Carbon dioxide	9 - 15
Hydrogen	12 - 20
Methane	2 - 3

Depending on type and design of the gasifier as well as on the characteristics of the fuel, efficiency may vary between 60 and 75 percent, and, in the case of thermal applications, total efficiency can be as high as 93 percent (FAO, 1986). For wood at 20 to 25 percent moisture, producer gas lower heating values of 13,000 to 15,000 kJ/kg were observed (FAO, 1986).

Ashes can cause a variety of problems in up or downdraft gasifiers because slagging, caused by melting and agglomeration of ashes, can lead to excessive tar formation and to air-channelling which can lead to a risk of explosion, especially in updraft gasifiers (FAO, 1986). Whether or not slagging occurs depends on the ash content of the fuel, the melting characteristics of the ash, and the temperature pattern in the gasifier (FAO, 1986). In general, no slagging is observed with fuels having ash contents below 5 to 6 percent, and ash content of wood is normally 0.75 to 2.5 percent (FAO, 1986).

For each temperature, in theory, the ratio between the product of the concentration of carbon monoxide (CO) and water vapor (H_2O) and the product of the concentrations of carbon dioxide (CO_2) and hydrogen (H_2) is fixed by the value of the water gas equilibrium constant (K_{WE}) (FAO, 1986). The equilibrium composition of the gas will only be reached in cases where the reaction rate and the time for reaction are sufficient, and the reaction rate decreases with falling temperature (FAO, 1986). In the case of the water gas equilibrium, the reaction rate becomes so low below 700°C that the equilibrium is said to be "frozen" and the gas composition then remains unchanged (FAO, 1986). Therefore, the hottest part of the gasification chamber should be maintained above 700°C to maintain high reaction rates.

Gaur et al (1998) provides a proximate analysis of many types of wood. The study concluded the composition of the various woods was not different enough to cause variation in gasification characteristics, if the wood feedstocks were gasified at similar moisture contents (Gaur et al, 1998).

Prior Studies of Gasification of Redcedar

The percentages of the three main components of wood are very similar in redcedar as in all biomass: roughly 50% cellulose, 25% hemicellulose and 25% lignin

(Reed and Desrosiers, 1979). However, cedar oils, composed primarily of cedrol and cedrene (FAO, 1995), may cause unique circumstances when gasifying redcedar. Therefore, prior studies of gasification of redcedar were sought.

Though gasification of wood has been utilized to produce energy for decades, gasification of redcedar has been studied very little. One study on redcedar gasification was carried out at Okayama University. This study utilized a fairly complicated, double bed, catalytic gasification system. The process also requires wood to be dried and homogenized into pellets (Fuel Research, 2008). The focus of this study was the use of iron oxide catalysts to promote catalytic activity in biomass tar decomposition. The researchers concluded, “The activity of the iron oxide catalysts for tar decomposition seemed stable with cyclic use but the activity of the catalysts for the water gas shift reaction decreased with repeated use (Fuel Research, 2008)." No information about gas composition or conversion efficiency was published.

CHAPTER III

UPDRAFT GASIFIER DESIGN

The purpose for the design detailed in this chapter was to create a gasifier that could be used to test the feasibility of gasification of a mulched eastern redcedar feedstock and be useful for testing alternative feedstocks in the future. Mulching was chosen as the method for reducing eastern redcedar particle size because mulching requires about one third of the power as pelletizing wood (FAO, 1986). Because of its simplicity and versatility, a fixed bed, updraft configuration was used, as shown in Figure 5. To allow for longer steady states when testing various feedstocks a semi-continuous feed system was utilized.

The sizes of components used for this gasifier design were chosen based on the conversion rate desired for the system and the desire to use off-the-shelf sizes for components. The conversion rate of biomass to producer gas per square inch of cross-sectional area in the gasification chamber was estimated based on the conversion rate in the Bowser et al (2005) updraft gasifier. The estimated conversion rate of 5.9 lb (13 kg) per hour was chosen because the volume was manageable and the gasification chamber could be constructed of 8-inch (20 cm) diameter pipe.

Figure 5: Fixed bed, updraft gasifier designed for this study.

The basic design of the gasifier was inspired by the work of Bowser et al (2005). The Bowser et al gasifier, shown in Figure 6, is an updraft, batch gasifier with the basic design inspired by the work of Patil and Rao (1993). Bowser et al made improvements to the Patil and Rao gasifier including a motorized scraper blade, improved sensors, off-the-shelf pipe and pipe fittings for body components, portability and quick disassembly. The gasifier has three basic components: gasifier body, scraper and scraper drive, and support frame. The machine was fabricated in the Biosystems and Agricultural Engineering machine shop at Oklahoma State University.

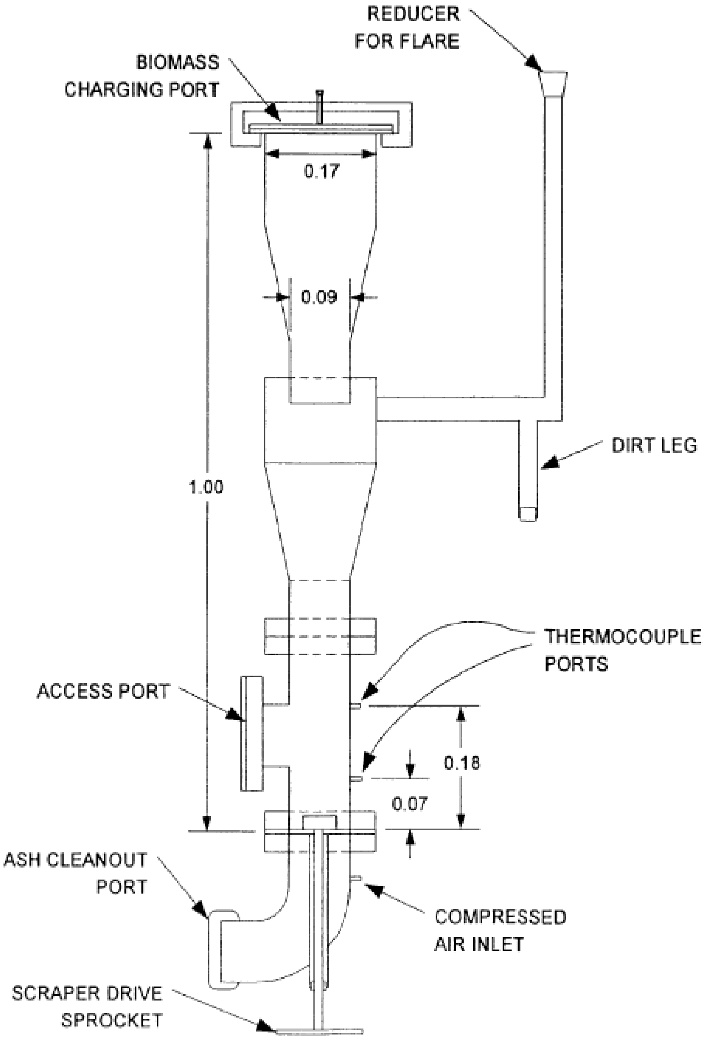


Figure 6: Schematic of updraft, batch gasifier designed by Bowser et al (2005). Dimensions in meters.

The body of the Bowser et al gasifier is mild steel, 8- and 4-inch (20 and 10 cm) diameter, schedule-40 pipe, with pipe fittings welded or bolted together and insulated with a calcium silica insulation blanket (McMaster Carr, Chicago, Ill.). The upper section of the gasifier body provides storage for feedstock, which is loaded through the biomass charging port. The body diameter has a reduction from 8- to 4-inches (20 to 10 cm) intended to reduce pressure on the lower column during operation and to provide some headspace where the flue pipe attaches to the gasifier body. However, this reduction acts as a bottleneck to feedstock during operation, compressing the biomass as it moves down and stopping flow.

The midsection of the gasifier body includes the combustion chamber, thermocouple ports, producer gas exhaust pipe, and access port. The combustion chamber was fabricated from a 4-inch (10 cm) Tee with flange ends. The projecting end of the Tee was used as an access port. Thermocouple fittings were pass-through, compression fittings from Omega Engineering (Stamford, Conn.). The producer gas exhaust pipe included a "dirt leg" to help remove condensed tar.

The lower portion of the gasifier included an ash grate, rotating motorized scraper assembly, ash receptacle, compressed gas inlet, and ash cleanout port. Ash particles fell through the grate and accumulated in the ash receptacle.

Two type-K thermocouples (Omega Engineering, Stamford, Conn.) were inserted radially through the compression fittings into the gasifier body at 4 and 10 inches (10 and 25 cm) above the surface of the ash grate. All temperatures were recorded during system operation using a data logger (model Hydra 2635A, Fluke Corporation, Everett, Wash.) connected to a laptop computer.

Notable changes to this design include:

- An air-locked hopper and screw conveyor to deliver feedstock and make the system capable of operating as a continuous system for short periods of time rather than batch. This allows for a longer steady-state and more accurate analysis of what a pilot-scale system would produce.
- A larger diameter (8- inch (20 cm) rather than 4- inch (10 cm) inner diameter) combustion chamber to reduce the effects of the walls on biomass movement.

- No bottlenecks in the gasification chamber. Removal of the bottlenecks allows material to move downward through the system more freely rather than packing into the reduced area.
- An agitator/stir rod that extends to the top of the gasifier and incorporates an auger to dislodge any coagulated particles and press biomass down.
- More thermocouples to monitor temperature gradients inside the gasifier.
- An insulation shell comprised of a 14-inch (36 cm) diameter pipe, hinged halfway around diameter. The 3-inch (8 cm) space between the shell and the gasification chamber is filled with Kaowool “RT” insulation blanket (Thermal Ceramics, Augusta, GA). This method of insulating the gasifier replaces taping insulation to the outside of the gasifier.
- The producer gas outlet is straight, allowing tar to drip back into the gasifier rather than collecting in the elbow and causing pressure build-up when producer gas cannot escape. Also, there is no “dirt leg” on the producer gas arm.
- There is no side access port on the gasifier. This port was difficult to insulate and keep from leaking producer gas. Instead, the combustion zone is initially lit through the ash port.

The gasifier consists of five fundamental components: hopper and feedstock auger, gasifier body, agitator and scraper system, support frame, and data collection system. The entire unit was fabricated in the Biosystems and Agricultural Engineering Laboratory fabrication shop at Oklahoma State University. A schematic of the design can be seen in Figure 7.

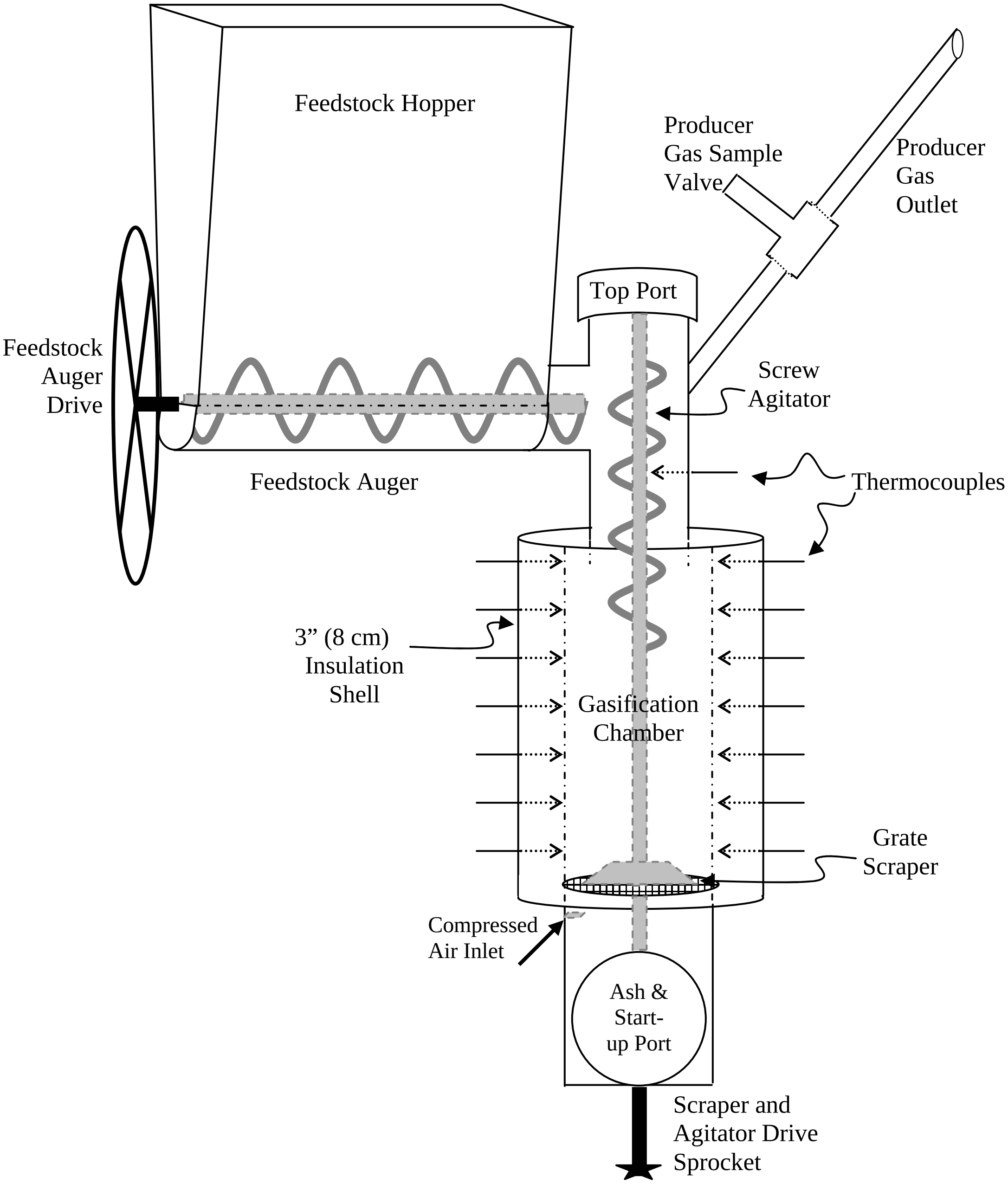


Figure 7: Schematic diagram of gasifier
showing vertical section of side view with major features labeled.

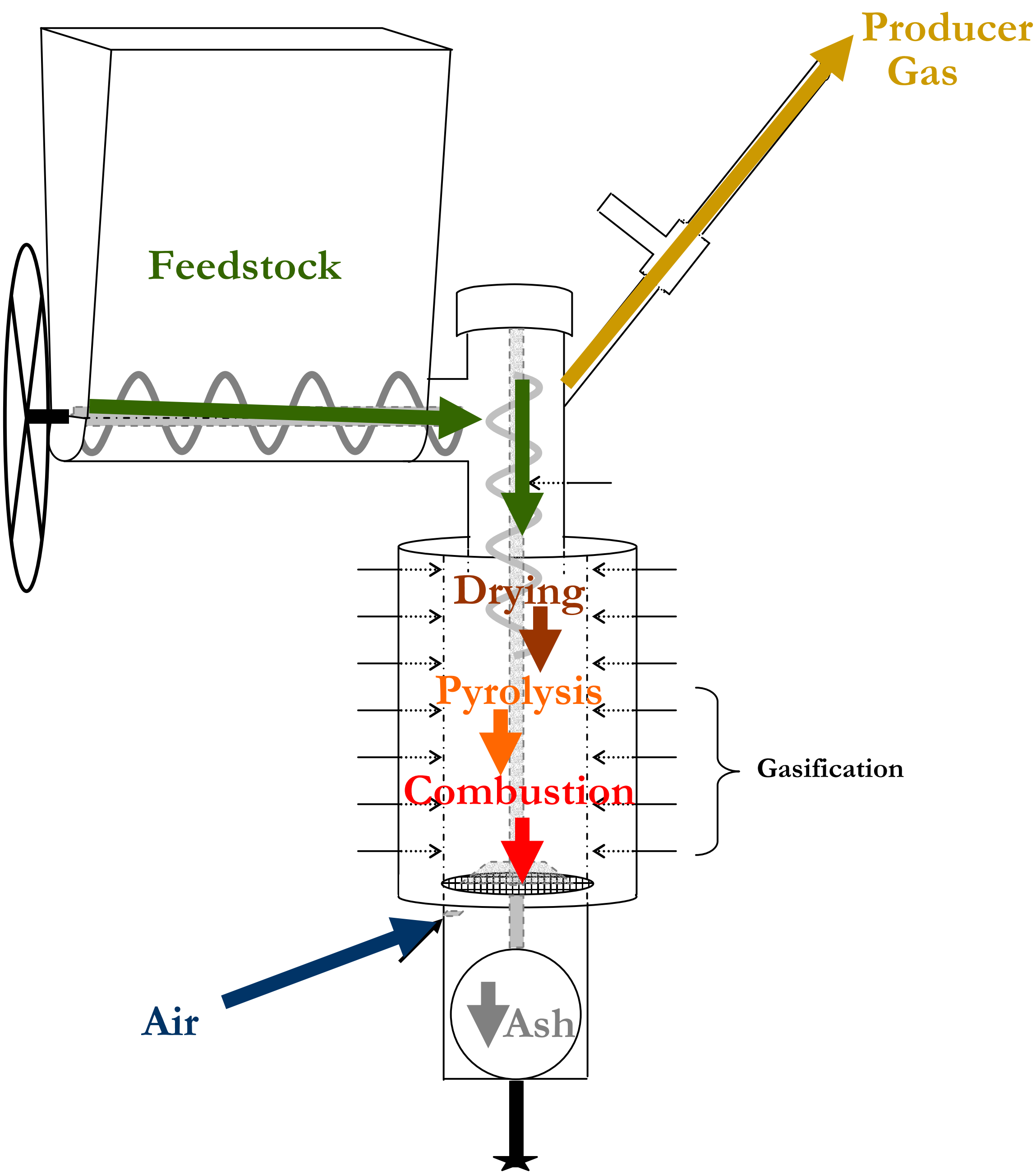


Figure 8: Schematic showing gas and feedstock flow through the gasifier and the approximate location of the drying, pyrolysis and combustion zones in the gasification chamber.

Figure 8 is a graphic of gas and solid flow through the gasifier. As feedstock passes downward through the body of the gasifier, it passes through drying, pyrolysis, and combustion zones. In the drying zone, moisture is driven off with exiting producer gas. Temperature increases as the biomass moves into the pyrolysis then the combustion zone. Air meets the biomass in the combustion zone where solids from the pyrolysis zone are completely combusted providing heat to fuel pyrolysis reactions, as well as carbon dioxide and water vapor from the combustion reactions. Carbon dioxide, water vapor, and heat move upward from the combustion to pyrolysis zone where they react with biomass to produce the components of producer gas.

Hopper and Feedstock Auger

The hopper stores feedstock. The auger feeds feedstock into the top of the gasifier during operation. The hopper is constructed of 0.125-inch (0.32 cm) mild steel. The top of the hopper is a removable plate made of the same material that is sealed during operation with a rubber gasket and C-clamps (Figure 9). A Campbell Hausfeld pressure gauge (South Pasadena, California) with a 0-20 atmosphere range is located near the top of the bin and a pop-off pressure release valve fabricated in the BAE machine shop is situated in the top door as safety precautions. A 14-inch by 16-inch (36 by 41 cm) secondary door (Figure 9) is situated in the middle of the top door to provide easy access to the bin.

Figure 9: Top view of hopper
showing secondary door, pressure release valve and C-clamps sealing top to bin during operation.

The end of the hopper is trapezoidal in shape with a trough bottom for the auger. The trapezoid is 6 inches (15 cm) wide at the base, 41 inches (104 cm) wide at the top, and 30 inches (76 cm) high. The sidewalls angle out thirty degrees, as shown in Figure 10. The bin width is 24 inches (61 cm). The total volume of the bin is 9.7 cubic feet (0.27 kiloliters), nine times the volume of the gasifier.

The auger shaft is 1-inch (2.5 cm) diameter steel rod. The auger flighting was manufactured by Replacement Flighting Supply (Aurora, NE) from standard mild steel. Auger pitch is 6 inches (15 cm), and flighting diameter is 5.5 inches (14 cm). The auger extends 27 inches (69 cm) to the edge of the gasifier body. The feedstock auger drive is powered by a hand crank wheel located on the outside end of the bin (Figure 10).

Due to flow properties of mulched redcedar, an internal agitator was added to the bin. This consists of a 24-inch (0.6 meters) by 24-inch (0.6 meters) section of 2-inch (5 cm) square metal mesh mounted on two rods as shown in Figure 11. The mesh is positioned vertically along the internal width of the bin above the auger with the rods extending through the wall of the bin (Figure 10). If feedstock flow becomes blocked, the rods can be moved to agitate the feedstock in the bin with the mesh and free the flow into the auger.

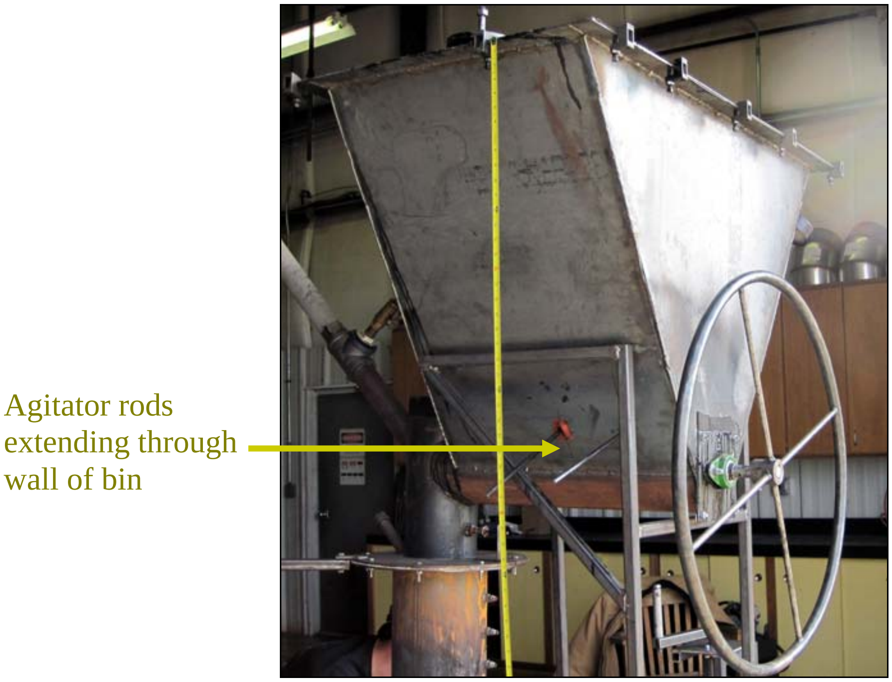


Figure 10: Gasifier bin showing agitator rods extending through side of bin.

Figure 11: Internal view of hopper bin showing agitator.

Gasifier Body

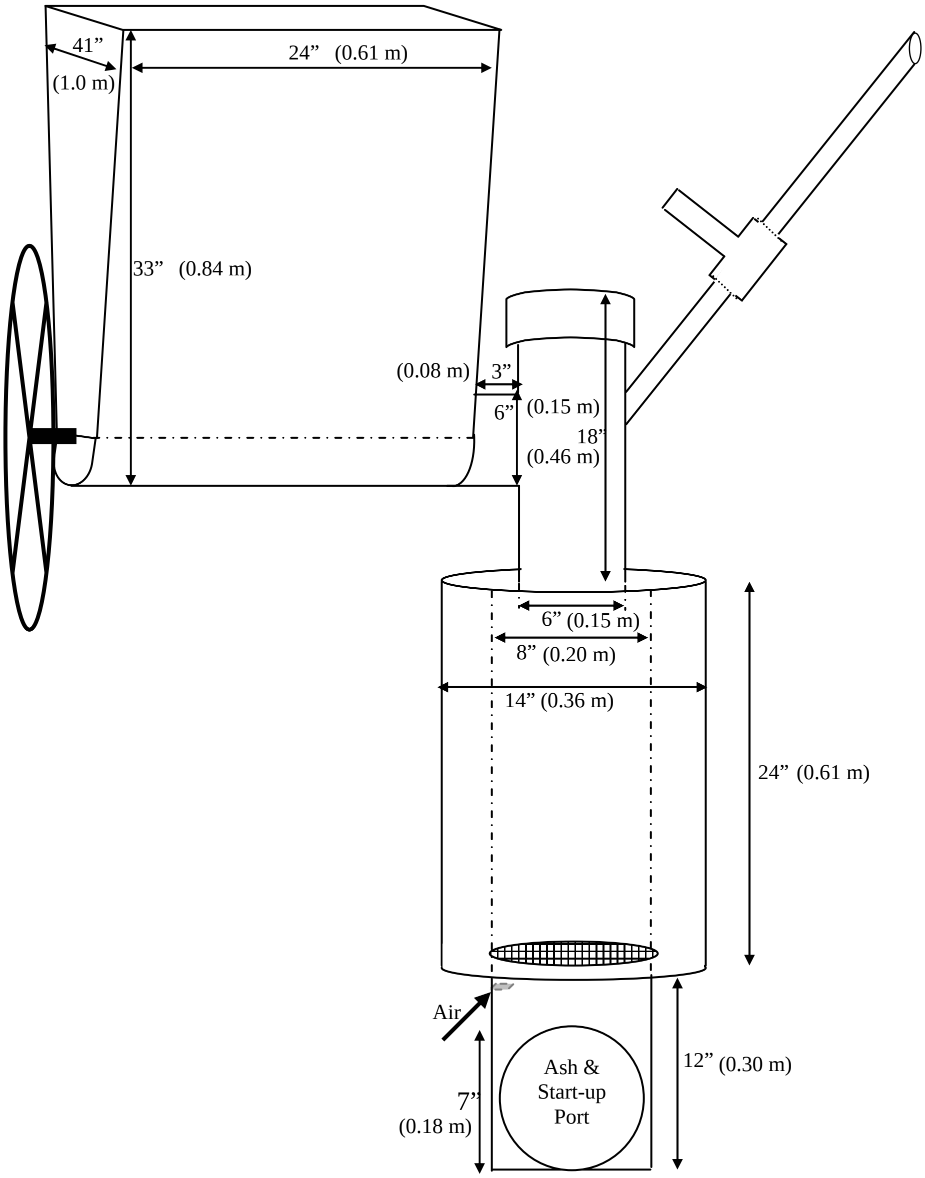


Figure 12: Schematic diagram of gasifier showing dimensions of major features.

The main body of the gasifier is manufactured of mild steel, 6- and 8- inch (15 and 20 cm) diameter, schedule-40 pipe. The 6-inch (15 cm) pipe extends 3 inches (8 cm) inside the 8-inch (20 cm) pipe. A 0.25-inch (0.64 cm) thick, mild steel washer is welded at the top of the 8-inch (20 cm) pipe to make the joint air tight.

The 24-inch (61 cm) section of 8-inch (20 cm) pipe that is the gasification chamber is surrounded by a 14-inch (36 cm) diameter shell of mild steel, schedule-5 pipe. The shell is hinged on one side and features snap locks on the opposite side. The 3-inch (8 cm) gap between the shell and the gasification chamber is filled with Kaowool "RT" insulation blanket (Thermal Ceramics, Augusta, GA). Gaskets cut from the same insulation were used as heat-resistant seals in bolted joints.

A bolted flange is located 1.5 inches (3.8 cm) above the ash grate to allow gasifier disassembly for cleaning and maintenance (Figure 13). The flange is forged from mild steel and connected with 0.5-inch (1.3 cm) bolts. The grate is not permanently attached to the gasifier body, but rather rests on a steel ledge to allow for further disassembly.

Figure 13: Bottom section of gasifier
unbolted and removed showing grate and scraper

From the bottom of the ash receptacle to the top port is 54 inches (1.4 m). Both the top and ash ports are 6-inch (15 cm) diameter screw-on, mild steel caps. The screw threads seal the openings during operation.

Fifteen K-type thermocouples (TJ36-CAXL-14U-12, Omega Engineering, Stamford, CT) allow temperature monitoring of the gasification chamber. Thermocouples pass through holes in the insulation shell and then through 0.25-inch (0.63 cm) compression fittings (Omega Engineering, Stamford, CT) into the gasification chamber. Each thermocouple enters the gasifier body radially, and the tips extend 0.5 inches (1.3 cm) into the gasification chamber. One thermocouple is positioned 3 inches (8 cm) above the point where the 8-inch and 6-inch (20 and 15 cm) pipes join to monitor temperature where producer gas exits and feedstock enters. In the gasification chamber, two vertical columns with seven thermocouples in each are positioned 180° from each other as shown in Figure 14. The lowest thermocouple position in each column is 3 inches (8 cm) above the ash grate with each thermocouple spaced 3 inches (8 cm) on center from bottom to top to provide information on the gradient of temperatures inside the gasification chamber.

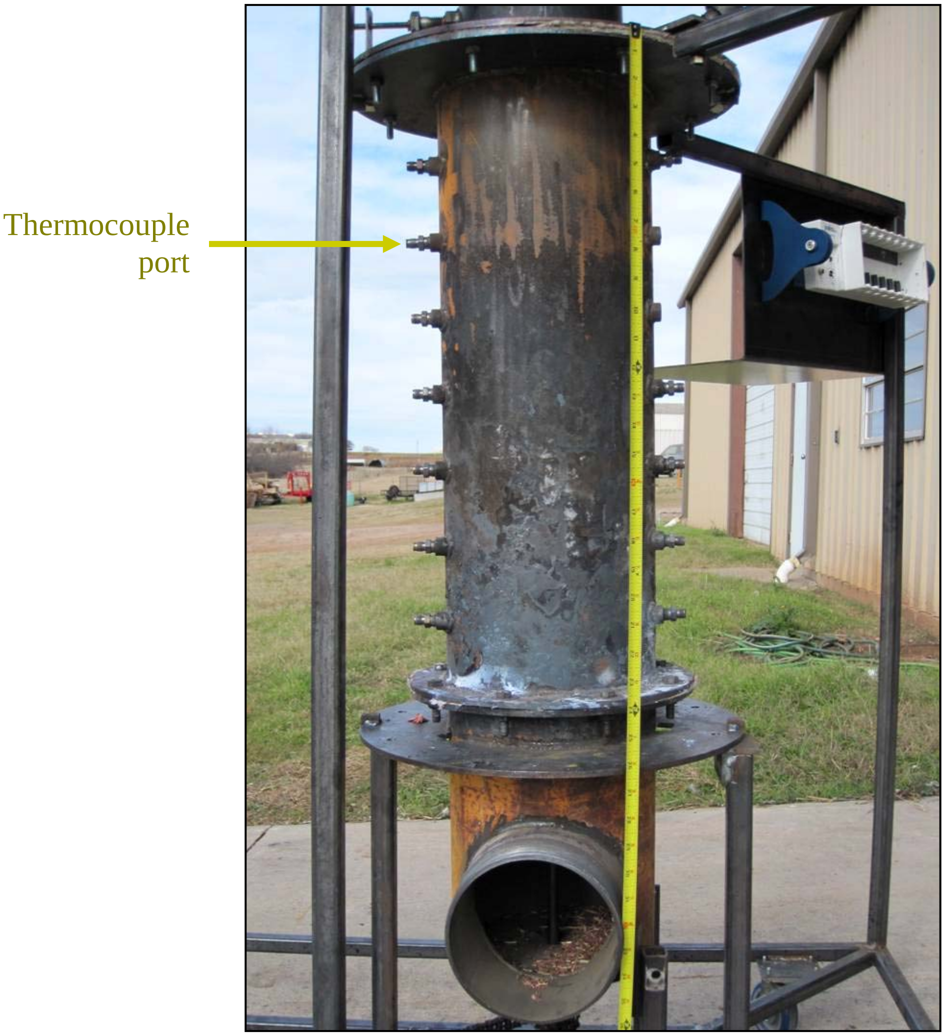


Figure 14: Thermocouple placement in gasification chamber and National Instrument chassis module in the background.

The producer gas outlet pipe is fabricated from 2-inch (5 cm) diameter mild steel pipe and includes a gas sampling valve. The sampling valve consists of a 2-inch (5 cm), 1-inch (2.5 cm) Tee joint with a 1-inch (2.5 cm) ball valve. The entire producer gas outlet is 60 inches (1.5 m) long and allows gas to be flared off during operation.

The bottom of the gasification chamber is an ash grate made of 0.25-inch (1.3 cm) thick carbon steel with 0.125-inch (0.32 cm) diameter circular holes cut through as shown in Figure 15. Ash falls through the grate to the ash receptacle below. The ash receptacle is 12 inches (30 cm) high and a continuation of the 8-inch (20 cm) diameter pipe used for the gasification chamber. The receptacle can be accessed by removing the cap on the ash port.

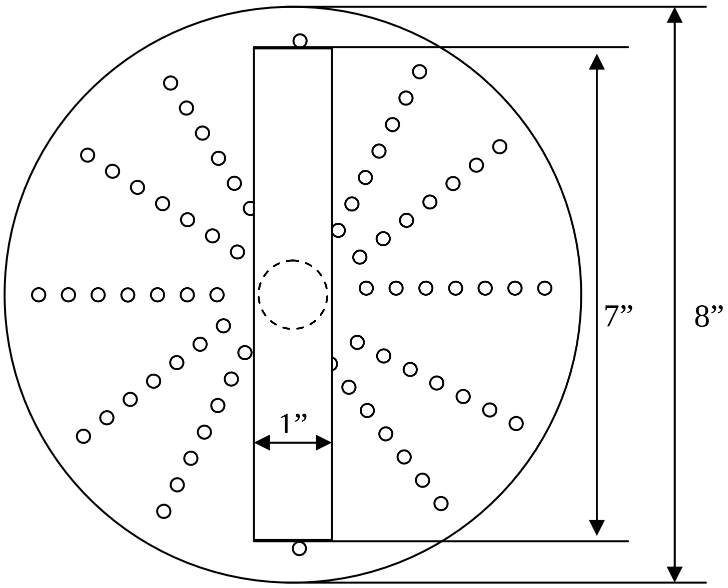


Figure 15: Schematic diagram of top view of ash grate and scraper inside gasifier.

The compressed air inlet is located 2 inches (5 cm) below the ash grate and was a hose barb sized to connect to a 0.25-inch (0.64 cm) pneumatic hose. Just above the air inlet, a 1-inch (2.5 cm) by 2-inch (5 cm) piece of 0.25-inch (0.64 cm) thick mild steel is welded to the gasifier body to serve as a baffle to incoming air. The baffle creates a turbulent flow of air rather than a jet of air passing through a small section of the ash grate.

Agitator and Scraper System

The scraper and grate, shown in Figure 13, were custom fabricated of mild steel. The scraper is 1 inch (2.5 cm) high and scrapes the top of the grate. The scraper is rotated on a 1-inch (2.5 cm) steel rod powered by a hand crank that is also custom fabricated with a 2:1 gear reduction**.**

In order to break up agglomerated biomass in the pyrolysis and combustion zones of the gasifier, which cause channeling of air and reduces gasification efficiency, agitation of these zones is desired. An agitator, custom fabricated of mild steel, extends from the scraper to the top port. The top of the 1-inch (2.5 cm) agitator rod fits into a slot in the top port to keep the rod centered. The bottom of the agitator rod is welded to a fitting made to fit over the scraper (Figure 16). The thicker middle section of the scraper bar (Figure 13) fits into a gap on the agitator rod fitting. When the agitator is fitted over the scraper, it turns with the scraper. Corners between the rod and fitting (Figure 16) strengthen the part so it can withstand the torque in the high temperatures of the gasification chamber.

Figure 16: Bottom of agitator rod displaying piece that fits over scraper rod.

Two agitator designs were fabricated and tested. Figure 17 shows the first design which featured 3-inch (8 cm) by 1-inch (2.5 cm) rectangles mounted at 15° angles used to break up coagulations of material in the gasification chamber and push the feedstock downward. However, this design resulted in a bent rod due to the horizontal pressure exerted on the rod by forcing the rectangles against the biomass packed in the gasifier.

Figure 18 shows the second agitator design which features an auger. The auger begins 5 inches (13 cm) from the top end of the auger shaft and extends 18 inches (46 cm) downward. The shaft is 1-inch (2.5 cm) diameter from the bottom of the auger upward and 1.5-inch (3.8 cm) diameter downward to provide greater strength in the hottest part of the gasification chamber. The flighting diameter and pitch are both 3 inches (8 cm). This design pushes the feedstock downward to break up coagulations, collapse material bridging, and keep the producer gas outlet free of feedstock.

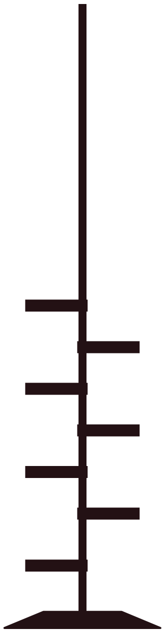


Figure 17: Schematic of first agitator design.

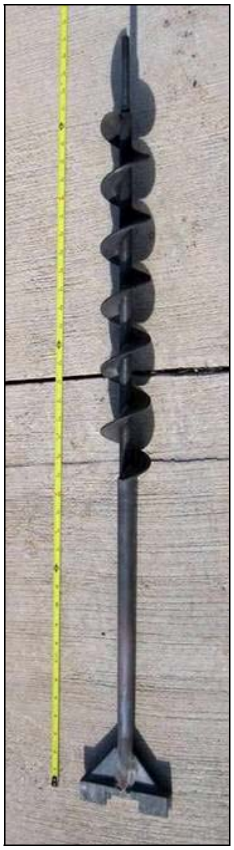


Figure 18: Second agitator design.

Support Frame

The support frame for the gasifier system was made of a framework of 1-inch (2.5 cm) square tubing as shown in Figure 19. The frame supports the hopper, the gasifier body, the scraper/agitator drive hand crank, and provides a shelf for a laptop computer and the National Instrument module, which is described below. Swiveling casters fixed to the base of the frame make transport of the system possible.

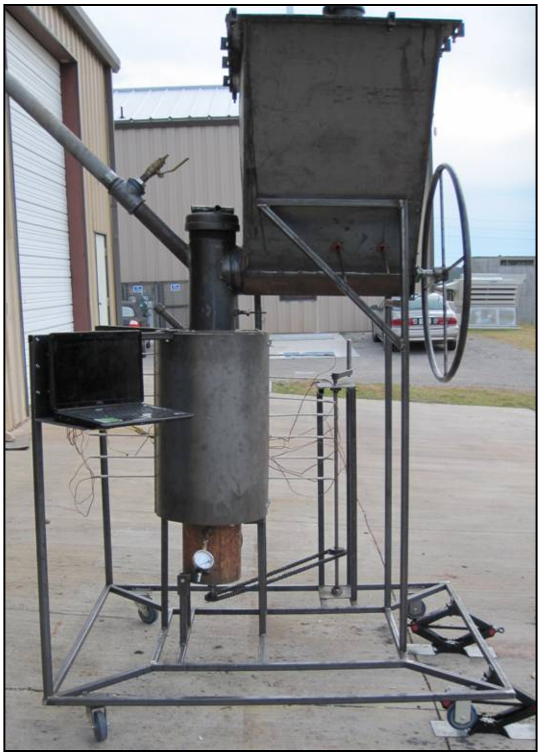


Figure 19: Gasifier showing support frame fabricated of one-inch (2.5 cm) square tubing.

Data Collection System

Figure 20 shows the air flow meter (Part # 9909K13, McMaster-Carr, Santa Fe Springs, CA) and ball valve used to monitor and regulate compressed air flow into the gasifier.

Figure 20: Air flow meter and ball valve at air inlet.

Fifteen K-type thermocouples (TJ36-CAXL-14U-12, Omega Engineering, Stamford, CT) are attached to a sixteen-channel thermocouple module (NI 9213 16-ch TC, 24-bit C Series module, National Instruments, Austin, TX) in a National Instruments chassis (cDAQ-9172 8-slot USB 2.0 Chassis for CompactDAQ, National Instruments, Austin, TX). The chassis is connected to the USB port on a laptop (Dell Inspiron 15, Dell Inc, Round Rock, TX) with a LabVIEW software package (National Instruments, Austin, TX). The custom LabVIEW virtual instrument was designed by the author to record the thermocouple measurements in a Microsoft Excel file.

Samples of producer gas are taken through the ball valve in the producer gas outlet (see Figure 21) where the flow is reduced to a 0.25-inch (0.64 cm) opening. For sampling, an 18-inch (46 cm) length of rubber tubing is connected from the reduced opening to a gas sampling bag (Chemware Tedlar PVF Gas Sampling Bags, VWR#32310-309, VWR International, LLC, West Chester, PA).

Figure 21: Producer gas outlet with sampling port.

CHAPTER IV

EXPERIMENTAL SETUP

Eastern Redcedar for Study

Figure 22: Eastern redcedar mulch used as feedstock in this study

The mulched eastern redcedar used for this study (Figure 22) was obtained from Eastern Redcedar Mulch Company. This was the only company in Oklahoma commercially producing mulch from eastern redcedar in 2009. All mulch used in this study was produced from mature trees cut in February 2009 and allowed to dry before being mulched in late October 2009. According to Aaron Newton of Eastern Redcedar Mulch Company (Rowland, 2009), an 8-9 month drying period reduces the power required to mulch by 1/3 as compared to a 4 month drying period. Trees dried for two months or less generally contain enough sap for particles to stick to the moving parts of the mulcher (Rowland, 2009).

Mulching was accomplished with a Rotochopper MC 166 (Rotochopper, Inc., St. Martin, MN) with a 2.5 inch (6.4 cm) screen. The results of an analysis performed to determine particle size distribution of the mulch are reported in Table 3. Sieves were U.S. Standard Sieve Series made by Fisher Scientific Company, Pittsburg, PA. Stacked sieves with sample were shaken horizontally 100 times, and then the weight of particles retained in each sieve was recorded.

Results show that 81% of the particles were too large to pass through a #4 Standard Sieve. These particles ranged in size from 0.25 inches by 0.25 inches by 0.1 inches to 1 inch by 3 inches by 1 inch. Particles remaining in pan were smaller than 0.13 inches by 0.13 inches by 0.1 inches. Particles remaining in the #7 Standard Sieve were between 0.13 inches by 0.13 inches by 0.1 inches and 0.25 inches by 0.25 inches by 0.1 inches.

Table 3: Results of particle size analysis.

Standard Sieve	Mesh Size (in.)	Percent of Total
# 4	0.187	81.1%
# 7	0.111	8.9%
Pan		9.9%

Moisture content of the mulch was determined using ASTM Standard 1775-01. The mulch was found to have 15.7 ± 4.3% moisture content (wet basis) during three moisture content tests conducted during the period when gasification tests were performed. Energy content of mulch was found to be 18.99 ± 0.02 kJ/g using a bomb calorimeter (Model 1261 ISOPERIBOL, Parr Instrument Company, Moline, IL) using the procedure described in the operator's manual. This high heating value is less than that reported for other woods by Gaur et al (1998), Table 5.

Midwest Laboratories in Omaha, NE, provided the proximate analysis, shown in Table 4. The dry matter is higher than that reported for other woods by Gaur et al (1998), Table 5. The ash content is comparable to ash contents reported by Gaur et al (1998).

Table 4: Proximate analysis of eastern redcedar for this study
provided by Midwest Laboratories.

Moisture (%)	11.38
Dry Matter (%)	88.62
Ash (%)	1.37
Sulfur (%)	0.02
Phosphorus (%)	0.02
Potassium (%)	0.06
Magnesium (%)	0.02
Calcium (%)	0.43
Sodium (%)	<0.01
Iron (ppm)	30
Manganese (ppm)	86
Copper (ppm)	2
Zinc (ppm)	5

Table 5: Proximate analysis of various woods
(Gaur et al, 1998).

Wood Name	Volatiles	Ash	Sulfur	High Heating Value
	%	%	%	kJ/g
Black Locust	80.94	0.80	0.01	19.71
Douglas Fir	81.50	0.80	0.00	21.05
Hickory	-	0.73	0.00	20.17
Maple	-	1.35	0.00	19.96
Ponderosa Pine	82.54	0.29	0.03	20.02
Poplar	-	0.65	0.00	20.75
Red Alder	87.10	0.40	0.07	19.30
Redwood	83.50	0.40	0.00	21.03
Western Hemlock	84.80	2.20	0.10	20.05
Yellow Pine	-	1.31	0.00	22.30
White Fir	83.17	0.25	0.01	19.95
White Oak	81.28	1.52	0.01	19.42
Mango Wood	85.64	2.98		19.17

Gasifier Startup and Operation

A large part of the process involved in testing a new gasifier design is determining the appropriate operating procedures for the new system and a given feedstock. After preliminary testing, the following standard system startup and operation procedures were adopted for testing mulched eastern redcedar feedstock in this gasifier:

1. The hopper was filled and sealed.
2. Top port was sealed. Ash/startup port left open.
3. The LabVIEW data logger virtual instrument was initialized and temperature recording began.
4. Seven revolutions of the feedstock auger were loaded into the gasification chamber for a bed depth of approximately 7 inches (18 cm). Throughout operation, the scraper/agitator was operated in conjunction with the feedstock auger to ensure that feedstock moved downward appropriately in the gasification chamber. Both the stirrer and the auger were operated counter clockwise.
5. Airflow was set to 4 SCFM (0.11 m^3/min).
6. A weed burner type, 50,000 BTU propane torch with a 15” angled handle was inserted through the ash/startup port and operated just below grate. The torch burned there for 3-5 minutes until the two lowest thermocouples read temperatures of about 40°C and smoke began to come out of the producer gas outlet.
7. When the feedstock in the gasification chamber was obviously lit, the torch was removed and the port was sealed with the cap.

8. Feedstock was augered in until the scraper/agitator met acute resistance, signifying the gasification chamber was full of feedstock.
9. Air flow was adjusted to the flow being tested at that time. Airflows tested in this study ranged from 4.5 to 8.0 SCFM (0.13 to 0.23 m^3/min).
10. Throughout operation, the scraper/agitator was rotated 1-2 revolutions every 2-3 minutes, in addition to when feedstock was augered in, to keep the feedstock moving downward through the gasifier.
11. Feedstock was augered in as often as necessary to maintain resistance for the scraper/agitator signifying a full gasification chamber.
12. Hopper agitator was used when necessary to maintain flow in the feedstock auger.
13. The flare was ignited when possible.
14. Gas samples were taken when the bed temperature stabilized and the flare appeared largest and most consistent.
15. When all samples for a day had been collected, the gasifier was allowed to cool before being cleaned or moved.
16. The amount of biomass remaining in the hopper was measured to establish a rough flow rate for the completed gasification session.

When collecting samples, the test pattern consisted of setting the air flow to the desired equivalence ratio, achieving a steady temperature profile (as shown in Figure 23), then collecting three gas samples. Samples were collected in 5-minute increments. A set of 3 gas samples at the given ER is referred to as a test run. After completing a test run, the air flow could be adjusted to the next ER to be tested or the feedstock remaining in the gasifier could be converted before the gasifier was allowed to cool off and be stored until the next test run. When adjusting to the next ER, the gasifier would operate at the new ER for at least 15 minutes before samples were collected.

Feedstock residence time in the gasification chamber was calculated based on the average feed rate. The average feed rate was 0.5 auger revolutions per minute, or 0.027 lb/min (0.06 kg/min). The density of the redcedar mulch was calculated to be 9.4 lb/ft^3 (0.15 g/cm^3). This gives an average residence time of 22 minutes inside the gasification chamber.

Testing occurred between October 2009 and March 2010. The weather was cool (35-55°F) and clear (50-85% relative humidity) on testing days.

Gas Sampling and Analysis

Gas samples were collected in gas sampling bags (Chemware Tedlar PVF Gas Sampling Bags, VWR#32310-309, VWR International, LLC, West Chester, PA). Samples were collected regardless of when biomass was added because sampling just before, just after, or several minutes from when biomass was augered in did not affect gas composition. After the temperature profile in the gasifier stabilized to less than 10% variation in temperature at each thermocouple over 3 minutes, the sampling valve was opened, and the producer gas outlet was covered, forcing producer gas out of the valve and into the sampling bag until the bag's capacity was reached. Three gas samples were obtained at each air flow tested. Gas samples were allowed to cool in the bag to condense water and vapors from the gas onto the walls of the gas bags. Gas-tight syringes (Cole Parmer, Vernon Hills, Ill.) were used to remove a volume of producer gas from each bag through a septum. The producer gas was then injected into the gas chromatograph (model CP-3800, Varian, Inc., Palo Alto, CA) for analysis with the instrument setup reported by Cateni et al (2003). Repeated gas chromatograph injections taken from the same gas sample had results with deviations of 0-4.3% for each gas component which is less than 5%, the accuracy reported by the manufacturer for this gas chromatograph.

Cold Gas Efficiency

Cold gas efficiency was calculated at each air flow as the output energy (heating value of the producer gas) divided by the input energy (heating value of the biomass). Heating value of biomass was determined by bomb calorimetry. A bomb calorimeter (Model 1261 ISOPERIBOL, Parr Instrument Company, Moline, IL) was used to measure the heating value of the mulched redcedar using the procedure described in the operator's manual. Composition of producer gas samples was obtained by gas chromatography. Since the nitrogen component of the producer gas originates with the air, its weight percentage is not included in cold gas efficiency calculations. The heating value of the sample was calculated as the sum of the chemical energy contents of each component. The cold gas efficiency is expressed on a weight basis. The method for calculating cold gas efficiency is: (heating value of the producer gas in kJ/kg) / (heating value of the biomass in kJ/kg).

CHAPTER V

RESULTS AND DISCUSSION

After design and construction of the new gasifier, the next goal was to test its operation using redcedar mulch as the feedstock.

Equivalence Ratio

Equivalence ratio (ER) is the ratio of oxygen supplied to oxygen required for complete combustion of biomass. Stoichiometric calculations using standard air composition and documented biomass composition (Reed and Desrosiers, 1979) gives equivalence ratios for these airflow rates as shown in Table 6. Equivalence ratios were calculated by:

- Combustion O_2 demand as given by Reed and Desrosiers (1979) for chopped evergreen wood is 249 SCFM O_2/lb wood (3.2 m^3/min O_2/kg wood).
- Feed rate of mulched redcedar into gasifier was approximately 0.5 auger revolutions per minute for all tests. Each auger revolution fed in 0.054 lb (0.12 kg) mulch giving a feed rate of 0.027 lb/min (0.06 kg/min) and a combustion O_2 demand of 6.8 SCFM (0.19 m^3/min).
- Inlet airflow was converted to inlet O_2 flow by multiplying by 21%.
- The inlet O_2 flow was divided by the combustion O_2 demand to give ER.
- Example: ER = (4.50 SCFM air * 21%) / (6.8 SCFM O_2) = 0.138

Reed and Desrosiers (1979) list 0.25 as the ER for gasification, 0.0 as the ER for pure pyrolysis and anything between as producing mixed pyrolysis and gasification. According to these calculations, the 5.75-7.0 SCFM (0.16 to 0.20 m^3/min) air flows used in this study provided for mixed pyrolysis and gasification, with more gasification than pyrolysis.

Table 6: Given air flow rate and corresponding equivalence ratio.

Airflow (SCFM)	Equivalence Ratio
4.50	0.138
5.00	0.154
5.75	0.177
6.50	0.200
7.00	0.215
8.00	0.246

Operating Temperature

Airflow rates ranging from 4.5 to 8.0 SCFM (0.13 to 0.23 m^3/min) were tested. This range was chosen based on the temperature profile in the gasification chamber. Below 4.5 SCFM (0.13 m^3/min), temperatures in the combustion zone were below 550°C, which is not high enough in the combustion zone to allow for proper gasification. Above 8.0 SCFM (0.23 m^3/min), the temperatures climbed and fell rapidly due to turbulence in the gasification chamber and a steady-state could not be obtained. Stable performance of the gasification system was demonstrated for airflows ranging from 5.75 to 7.0 SCFM (0.16 to 0.20 m^3/min), and therefore 9 samples were collected at flow rates in this range as opposed to 3 samples collected at tested flow rates outside this range as shown in Appendix A. An example of temperatures at various heights above the ash grate is shown in Figure 23 with 1 sample point every second.

Figure 24 shows the average temperature of the 2 lowest thermocouples, located in the combustion zone of the gasification chamber, as ER was varied from 0.138 to 0.246. The standard deviation of temperature at each sample point during sampling at each equivalence ratio is shown by the error bars. Higher air flows allowed the combustion zone to be maintained at temperatures averaging about 150 ˚C above temperatures at lower air flows. At an ER of 0.154, the temperature was 575 ˚C, and as the ER was increased to 0.200, the temperature increased to 775 ˚C. Above ER of 0.200, the temperature of the combustion zone did not change noticeably as ER was varied.

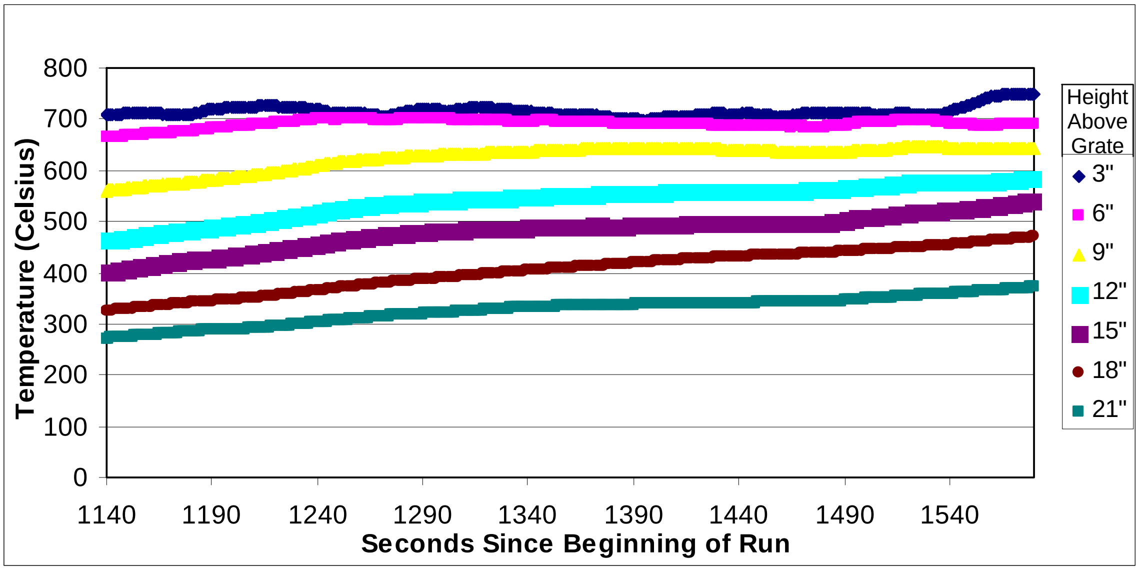


Figure 23: Example temperature profile inside the gasifier during a gasification test.

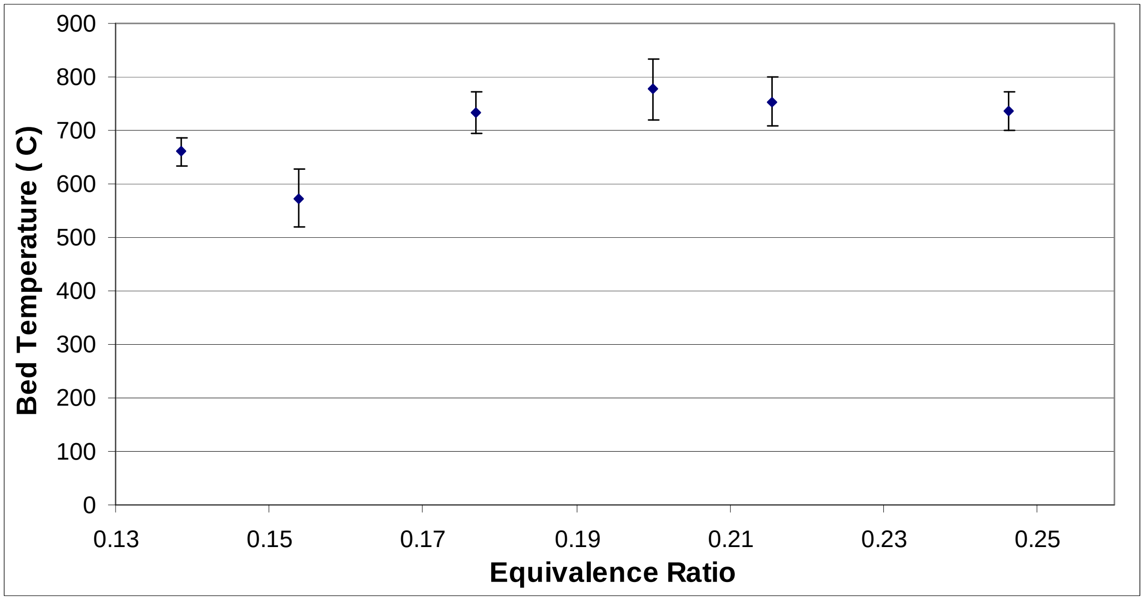


Figure 24: Average gasification temperature in the combustion zone at given equivalence ratios. Standard deviations are shown by error bars. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Tar and Water Production

Tar production was minimal, with no noticeable tar build up in the system. Weight of gas in gas bags including tar and water was recorded for samples at 5.75, 6.5, and 7.0 SCFM (0.16, 0.18, and 0.20 m^3/min) and is shown in Table 7. The method of collecting samples does not allow separation of tar and water because evaporation of the water would also vaporize many of the known components, such as benzene, in gasifier tar. Statistical t-test shows no statistical relationship between sample weight and ER.

If the entire weight of the tar and water collected is taken to be tar, the amount of tar in the gas would be in the range of 1-160 g/Nm^3 reported by Milne et al (1998) for updraft gasifiers. These values are also very near the 100,000 mg/m^3 average tar content for updraft gasification reported by Neeft et al (1999). The reported values for Milne et al (1998) and Neeft et al (1999) were dry tar, and the values reported for this research include water weight.

Ash recovery was not consistent because ash was lost with producer gas during periods of very turbulent air/gas flow. Therefore, ash recovery weights were not reported.

Table 7: Average weight of gas, tar, and water collected in 1.6 L gas bag.

Airflow (SCFM)	Airflow (m^3/min)	Tar + Water (g/m^3gas)
5.75	0.16	83
6.50	0.18	125
7.00	0.20	83

Producer Gas Composition

Gas analysis at tested ERs is summarized in Figure 25 through Figure 30. Each point represents the average mole percentage of that component in analyzed samples which included nitrogen. Nitrogen (N_2) does not react during the gasification process and, therefore, can be viewed as a tracer gas in the compressed air. Error bars show standard deviation.

Figure 25 displays hydrogen percentage in producer gas at given ERs. Hydrogen is at its highest percentage of gas at 0.200 ER. The standard deviations at the extreme ERs tested demonstrate the variation experienced at those airflow rates. Since hydrogen is a high energy component desirable in producer gas, the trend in hydrogen shows most favorable production about 0.2 ER.

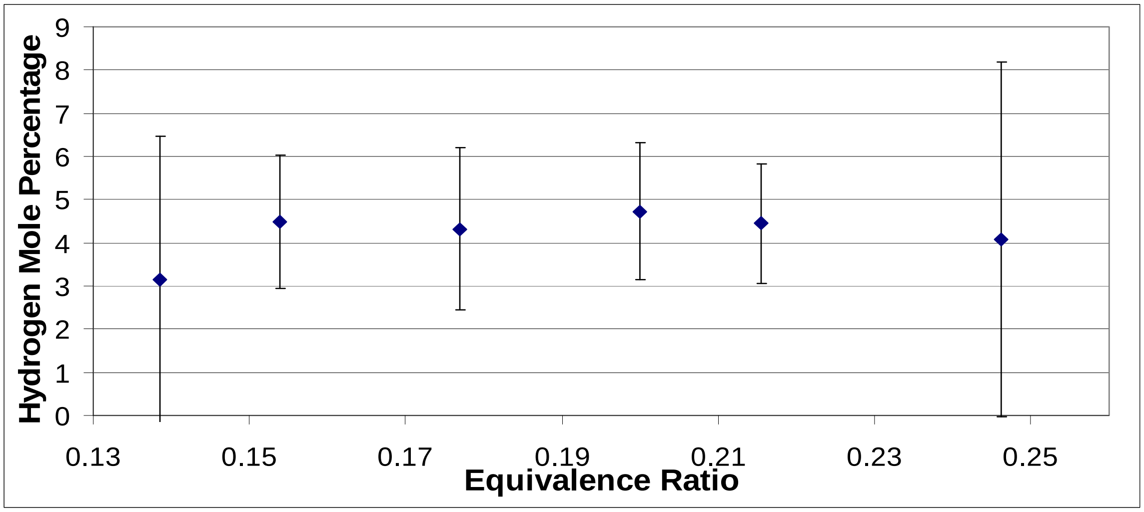


Figure 25: Percentage of hydrogen in producer gas at given ERs.
Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Figure 26 displays methane percentage in producer gas at given ERs. Methane shows little trend over the range of ERs tested.

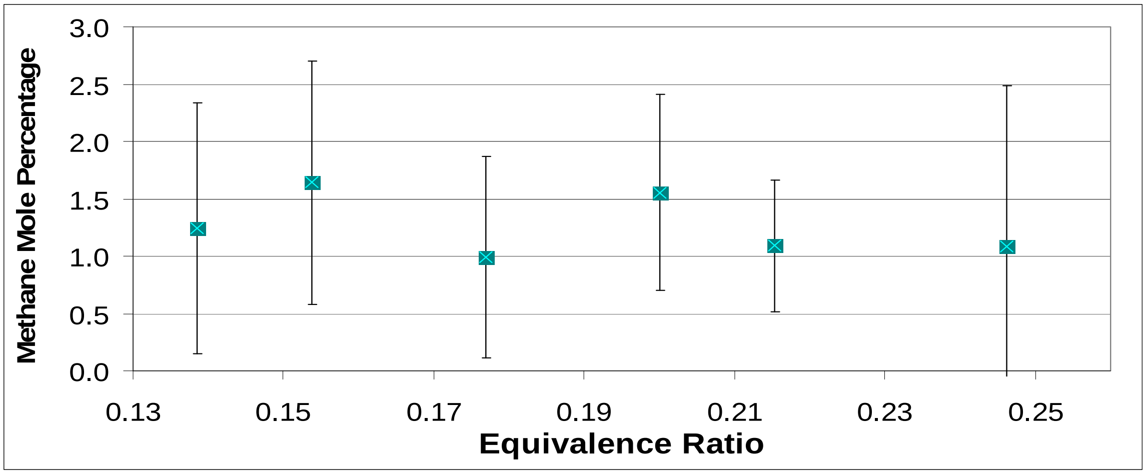


Figure 26: Percentage of methane in producer gas at given ERs.
Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Figure 27 displays carbon monoxide percentage in producer gas at given ERs. Carbon monoxide is at its highest percentage of gas at 0.177 ER. Since carbon monoxide is a high energy component desirable in producer gas, the trend shows most favorable production about 0.177 ER.

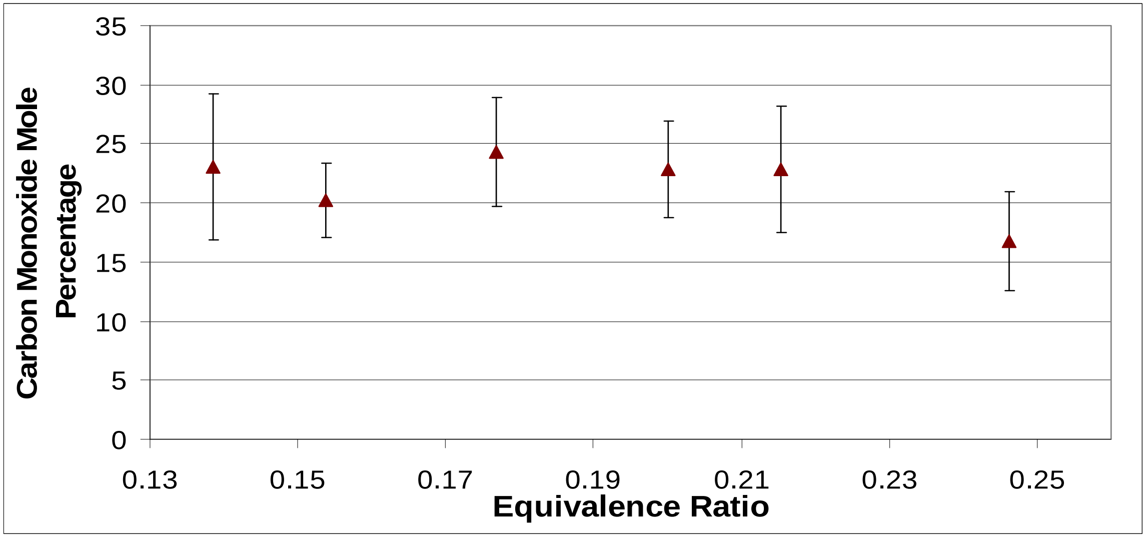


Figure 27: Percentage of carbon monoxide in producer gas at given ERs.
Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Figure 28 displays carbon dioxide percentage in producer gas at given equivalence ratios. Carbon dioxide shows very little trend. Carbon dioxide is a low energy, undesirable compound in producer gas, and, therefore, lower quantities are more desirable.

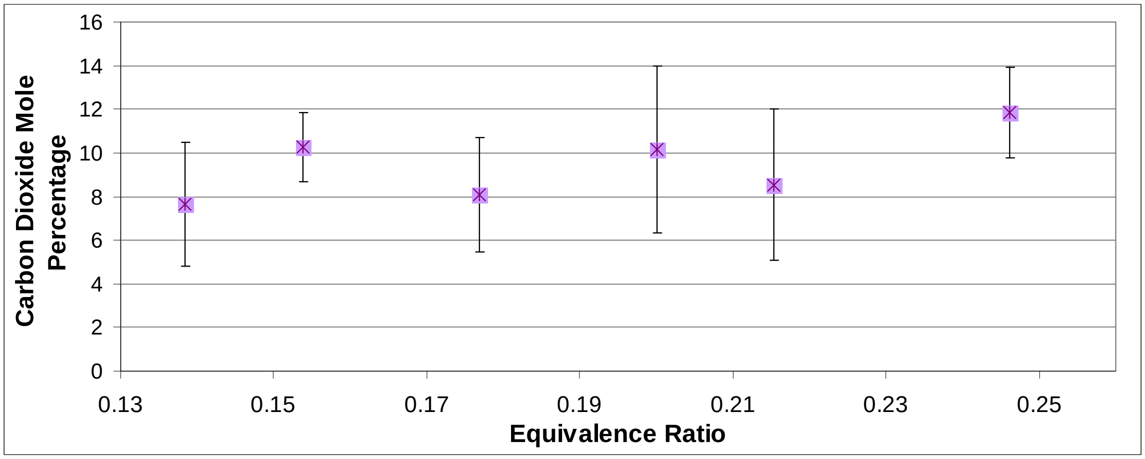


Figure 28: Percentage of carbon dioxide in producer gas at given ERs.
Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Figure 29 displays the percentages of the higher carbon compounds acetylene, ethylene and ethane in producer gas at given ERs. None of the three components show a trend over the range of ERs tested.

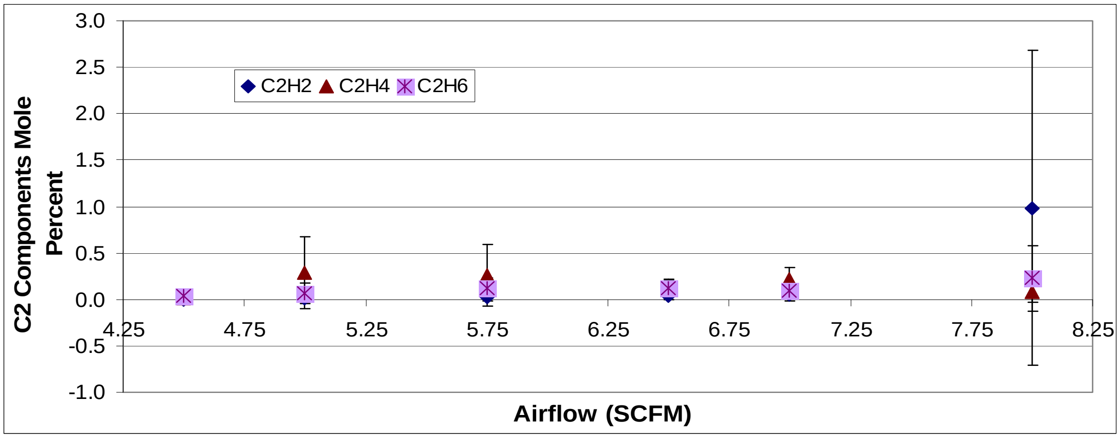


Figure 29: Percentage of higher carbon compounds in producer gas at given ERs.
Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Figure 30 displays the average percentage of nitrogen at each equivalence ratio. The lowest percentage of nitrogen is at 0.2 ER. Since nitrogen is inert during the gasification reactions, it can be viewed as a tracer. Since the percentage of nitrogen entering the gasifier remains constant, the lower nitrogen percentages in producer gas mean there is higher production of other producer gas components at those ERs. This trend points toward more efficient producer gas production at about 0.2 ER.

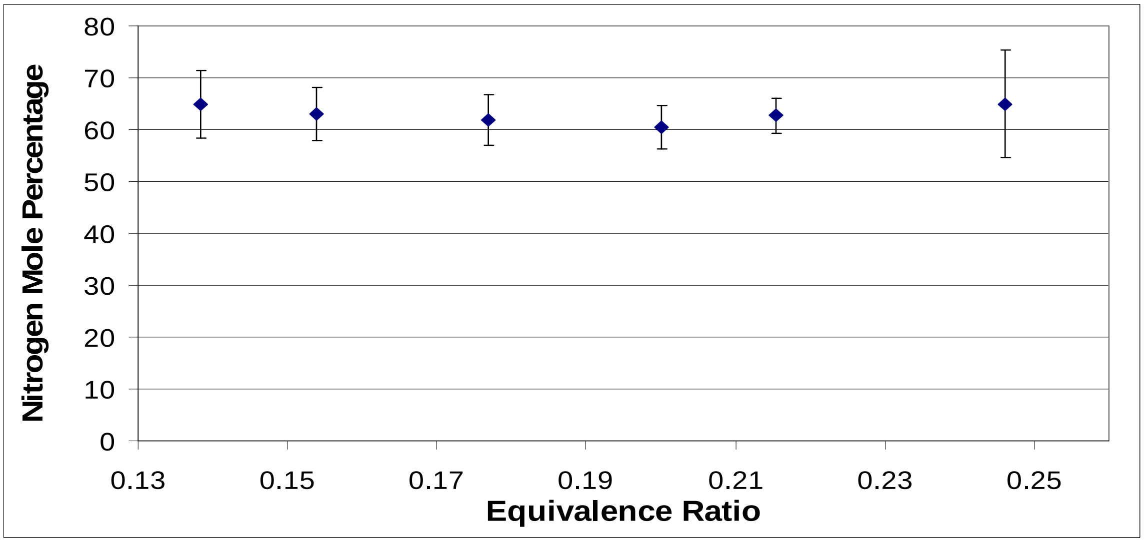


Figure 30: Nitrogen content in producer gas at various equivalence ratios.
Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Statistically significant differences between producer gas percentages at different ERs as calculated using a t-test are shown in Table 8. Different letter superscripts within a row denote statistically different groups in each component. There is no pattern of significant difference for any of the component gases at the equivalence ratios tested.

Table 8: Average percentages of each component of producer gas
at each tested equivalence ratio.
Letters denote statistically similar measurements (α=0.05) for each component. N=9 for ER=0.177-0.215,
and N=3 elsewhere.

Average Gas Composition						
Equivalence Ratio	**0.138**	**0.154**	**0.177**	**0.200**	**0.215**	**0.246**
H_2	3.14^{a}	4.50^{a}	4.32^{a}	4.72^{a}	4.45^{a}	4.08^{a}
N_2	64.88^{c}	63.03^{c}	61.84^{c}	60.48^{b}	62.74^{c}	64.94^{c}
CO	23.04^{ef}	20.22^{e}	24.34^{f}	22.80^{f}	22.80^{f}	16.77^{d}
CH_4	1.24^{g}	1.64^{g}	0.99^{h}	1.55^{g}	1.09^{gh}	1.08^{g}
CO_2	7.66^{i}	10.26^{ijk}	8.10^{i}	10.18^{j}	8.54^{i}	11.84^{k}
C_2H_2	0.00^{l}	0.01^{l}	0.02^{l}	0.03^{l}	0.05^{l}	0.99^{l}
C_2H_4	0.01^{m}	0.28^{m}	0.26^{m}	0.12^{m}	0.22^{m}	0.08^{m}
C_2H_6	0.03^{n}	0.06^{no}	0.13^{o}	0.12^{o}	0.10^{o}	0.23^{o}

Comparing the producer gas at 20% equivalence ratio (Table 8) to the average producer gas from commercial wood gasifiers reported in the FAO (1986) report shows several similarities and differences. Nitrogen (60.48%) is higher than the nitrogen range reported in FAO (50 – 54%). Carbon monoxide (22.80%) is at the high end of the range reported (17 – 22%). Carbon dioxide (10.18%) is in the range reported (9 – 15%). Hydrogen (4.72%) is much lower than the range reported (12 – 20%). Methane (1.55%) is lower than the range reported (2 – 3%).

Heating Value

The heating value of the producer gas is calculated as the sum of the percentage of each component multiplied by the pure gas heating value of that component. One heating value is reported for each test, reporting the average of the three samples taken in that test. Figure 31 displays the average high heating value of producer gas at various airflows. This graph clearly shows the producer gas contains more energy in the 0.177-0.215 ER range.

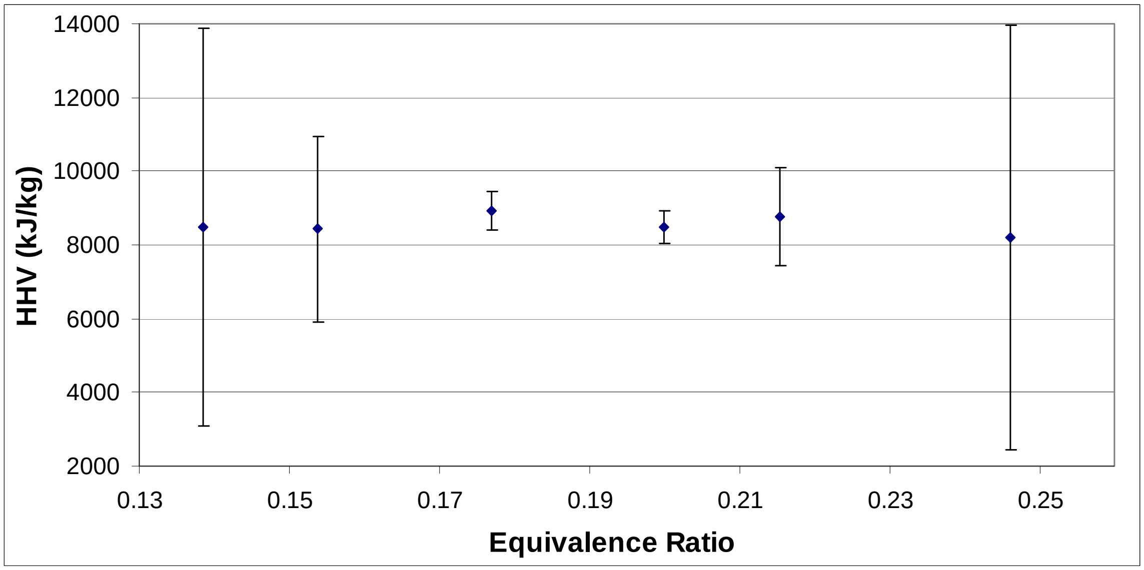


Figure 31: Average high heating value in kJ/kg of producer gas at each ER.
Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

Reed and Desrosiers (1979) reported an average high heating value for biomass of 22,200 kJ/kg. Rao (2004) reported high heating values for the updraft gasification system using air as the gasifying agent as 10,800 kJ/kg for wood pellets, 10,900 kJ/kg for meat byproduct sludge, and 12,000 kJ/kg for a mixture of half wood pellets and half meat byproduct sludge.

Cold Gas Efficiency

The cold gas efficiency is calculated as the heating value in the producer gas divided by the heating value of the biomass on a per weight basis. Since the nitrogen component of the producer gas originates with the air, its percentage is omitted for cold gas efficiency calculations. The cold gas efficiency ranges from 43% to 47% and follows the same trend as the heating value, as shown in Figure 32. This graph shows that the highest conversion efficiency is obtained at 0.177-0.215 ER for this gasifier.

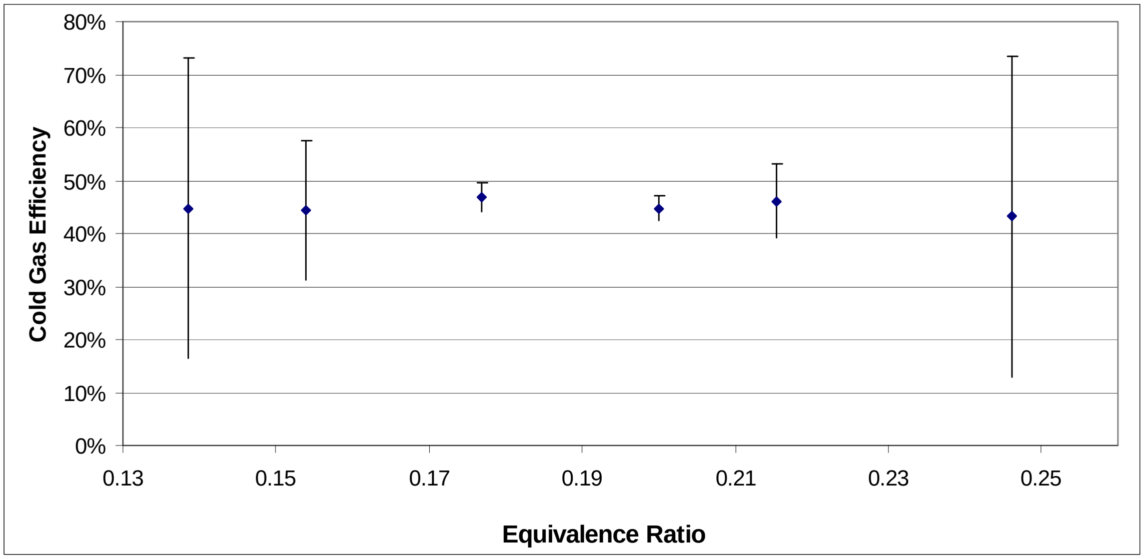


Figure 32: Cold gas efficiency based on producer gas samples collected at various ERs. Error bars show standard deviation. N=9 for ER=0.177-0.215, and N=3 elsewhere.

The t-test performed on high heating value and cold gas efficiency data revealed no statistically significant difference (α=.05) in either HHV or cold gas efficiency for any of the samples at the different equivalence ratios.

Reed and Desrosiers (1979) reported conversion efficiencies of 60-93% for wood feedstock. Bowser et al (2005) reported cold gas efficiency values for the updraft gasification system using air as the gasifying agent as 58% for wood pellets, 47% for meat byproduct sludge, and 60% for a mixture of half wood pellets and half meat byproduct sludge.

CHAPTER VI

CONCLUSIONS & RECOMMENDATIONS

An 8-inch (20 cm) diameter, updraft gasifier was designed and built for gasification of eastern redcedar mulch commercially available in Oklahoma. Unique features of the gasifier include:

- A simple design that can be used to test feedstocks with a variety of particle sizes, moisture contents, and ash contents
- A scraper/agitator system which deters air channeling as demonstrated by a stable temperature gradient and consistent combustion zone temperatures
- A feedstock hopper and auger which allows semi-continuous feedstock feed rate

Testing of the new gasifier with eastern redcedar mulch commercially available in Oklahoma was also completed. Specific findings include:

- Moisture content, ash content, and particle size suitable for gasification in this system without pretreatment.
- Tar production is below the level expected for an updraft gasifier. Though actual tar content of producer gas was not measured, the combination of tar and water weight in producer gas was measured. The weight of tar and water in producer gas averaged 83-125 g/m^3.

- Highest quality producer gas produced with equivalence ratio in the range of 0.177 to 0.215:
    - Hydrogen mole percentage averaged 4.32-4.72%.
    - Carbon monoxide mole percentage averaged 22.80-24.34%.
    - High heating value averaged 8486-8911 kJ/kg.
    - Cold gas efficiency averaged 45-47%.

The testing of this gasification system provides evidence that eastern redcedar can be utilized as a feedstock for gasification.

Suggestions for future research

Several design considerations can be made to improve the effectiveness of using this gasifier to test potential feedstocks:

- Operation of the system requires constant operator attention. Operation intensity could be reduced by the addition of motors to turn the auger and scraper/agitator.
- The addition of a continuous gas composition monitor would provide more information about the quality of gas being produced.
- A study of producer gas contaminants and ways to reduce them.
- Tar analysis should be performed.

Further consideration should be given to the energy balance required to prepare eastern redcedar for gasification:

- A study of power required to reduce redcedar particle size with a mulcher versus other particle reduction techniques.
- Cost analysis of gasification versus other methods of redcedar removal.

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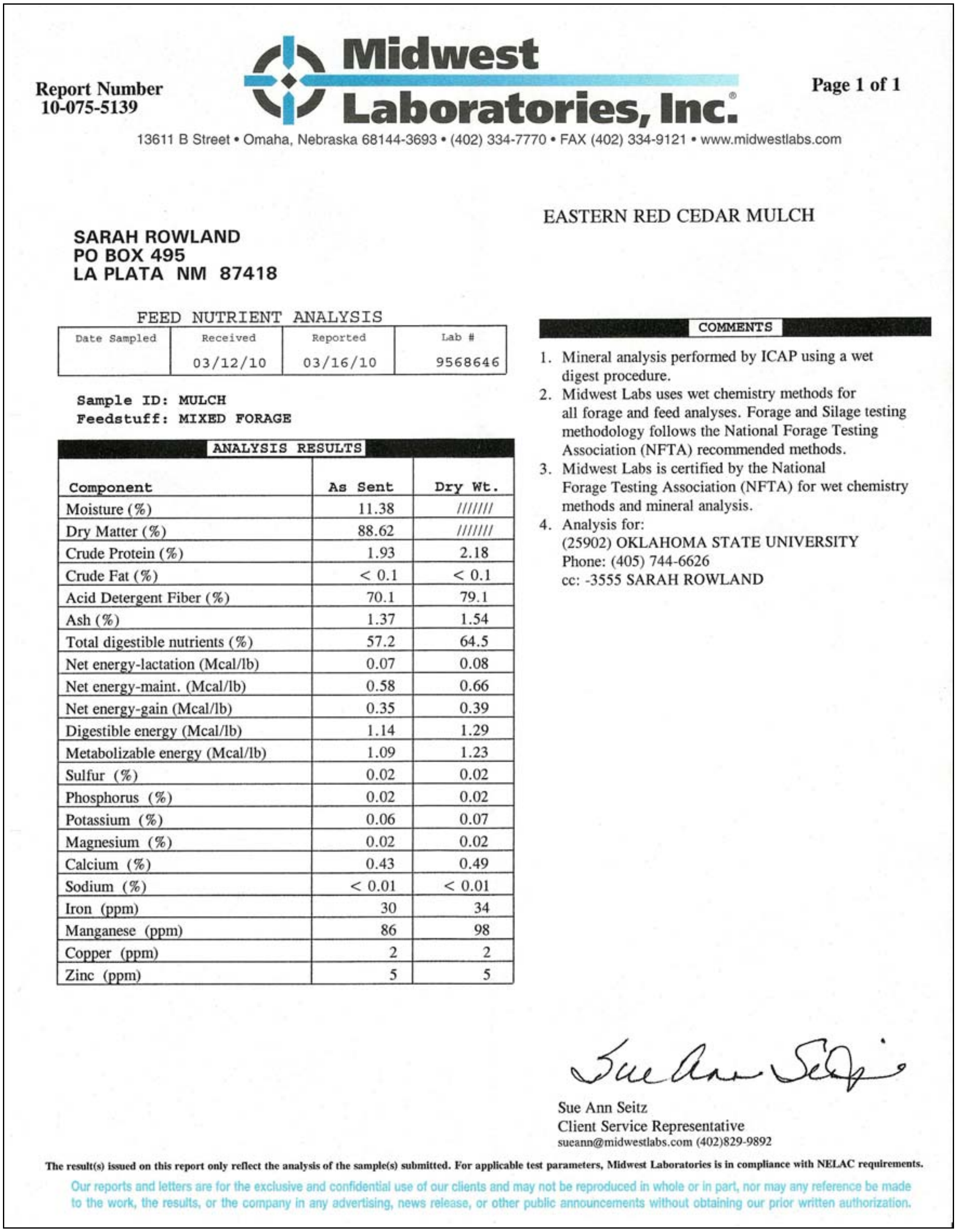
APPENDIX A: Producer Gas Sample Data

Equivalence Ratio	0.138	0.154	0.177	0.200	0.215	0.246
Airflow (SCFM)	**4.5**	**5**	**5.75**	**6.5**	**7**	**8**
Test Repetitions	1	1	3	3	3	1
Total Data Points	3	3	9	9	9	3
Raw HHV (kJ/kg)		18990				
Averages						
Bed Temperature	660	573	734	777	754	737
HHV (kJ/kg) w/o N2%	8488	8432	8911	8486	8752	8196
HHV (kJ/kg)	3032	3169	3415	3389	3288	3001
H2	3.14	4.5	4.32	4.72	4.45	4.08
N2	64.88	63.03	61.84	60.48	62.74	64.94
CO	23.04	20.22	24.34	22.8	22.8	16.77
CH4	1.24	1.64	0.99	1.55	1.09	1.08
CO2	7.66	10.26	8.1	10.18	8.54	11.84
C2H2	0	0.01	0.02	0.03	0.05	0.99
C2H4	0.01	0.28	0.26	0.12	0.22	0.08
C2H6	0.03	0.06	0.13	0.12	0.1	0.23
Cold Gas Efficiency	16%	17%	18%	18%	17%	16%
Cold Gas Efficiency w/o N2%	45%	44%	47%	45%	46%	43%
Standard Deviations						
Bed Temperature	26	55	39	57	46	35
HHV (kJ/kg) w/o N2%			524	441	1333	
HHV			277	64	596	
H2	3.31	1.54	1.88	1.59	1.38	4.11
N2	6.59	5.12	4.84	4.21	3.35	10.31
O2	0	0	0	0	0	0
CO	6.19	3.14	4.62	4.08	5.35	4.23
CH4	1.09	1.06	0.88	0.86	0.58	1.4
CO2	2.86	1.58	2.63	3.83	3.47	2.07
C2H2	0	0.02	0.04	0.04	0.07	1.7
C2H4	0.01	0.38	0.33	0.1	0.12	0.12
C2H6	0.05	0.11	0.11	0.08	0.07	0.35
Cold Gas Efficiency			1.5%	0.3%	3.1%	
Cold Gas Efficiency w/o N2%			2.8%	2.3%	7.0%	

APPENDIX B: Eastern Redcedar Analysis



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Page 1 of 1

EASTERN RED CEDAR MULCH

SARAH ROWLAND
PO BOX 495
LA PLATA NM 87418

FEED NUTRIENT ANALYSIS

Date Sampled	Received	Reported	Lab #
	03/12/10	03/16/10	9568646

Sample ID: MULCH
Feedstuff: MIXED FORAGE

ANALYSIS RESULTS

Component	As Sent	Dry Wt.
Moisture (%)	11.38	///////
Dry Matter (%)	88.62	///////
Crude Protein (%)	1.93	2.18
Crude Fat (%)	< 0.1	< 0.1
Acid Detergent Fiber (%)	70.1	79.1
Ash (%)	1.37	1.54
Total digestible nutrients (%)	57.2	64.5
Net energy-lactation (Mcal/lb)	0.07	0.08
Net energy-maint. (Mcal/lb)	0.58	0.66
Net energy-gain (Mcal/lb)	0.35	0.39
Digestible energy (Mcal/lb)	1.14	1.29
Metabolizable energy (Mcal/lb)	1.09	1.23
Sulfur (%)	0.02	0.02
Phosphorus (%)	0.02	0.02
Potassium (%)	0.06	0.07
Magnesium (%)	0.02	0.02
Calcium (%)	0.43	0.49
Sodium (%)	< 0.01	< 0.01
Iron (ppm)	30	34
Manganese (ppm)	86	98
Copper (ppm)	2	2
Zinc (ppm)	5	5

COMMENTS

1. Mineral analysis performed by ICAP using a wet digest procedure.
2. Midwest Labs uses wet chemistry methods for all forage and feed analyses. Forage and Silage testing methodology follows the National Forage Testing Association (NFTA) recommended methods.
3. Midwest Labs is certified by the National Forage Testing Association (NFTA) for wet chemistry methods and mineral analysis.
4. Analysis for:
   (25902) OKLAHOMA STATE UNIVERSITY
   Phone: (405) 744-6626
   cc: -3555 SARAH ROWLAND

Sue Ann Seitz

Sue Ann Seitz
Client Service Representative
sueann@midwestlabs.com (402)829-9892

The result(s) issued on this report only reflect the analysis of the sample(s) submitted. For applicable test parameters, Midwest Laboratories is in compliance with NELAC requirements.

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VITA

Sarah L. Rowland

Candidate for the Degree of

Master of Science

Thesis: DESIGN AND TESTING OF A SMALL-SCALE UPDRAFT GASIFIER FOR GASIFICATION OF EASTERN REDCEDAR

Major Field: Biosystems & Agricultural Engineering

Biographical:

Personal Data: Born in Denison, TX, on 31st December 1984, the daughter of Randal and Susan Cook

Education: Obtained high school diploma from Rock Creek Public Schools, Bokchito, OK in 2003. Received Bachelor of Science in Biosystems & Agricultural Engineering from Oklahoma State University, Stillwater, Oklahoma in 2008. Completed the requirements for the Master of Science in Biosystems & Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma in July, 2010.

Experience: Wentz Research Scholar at Oklahoma State University, Stillwater, OK (OSU) (2004-2005 and 2007-2008). Food Processing Research Assistant for OSU Biosystems & Agricultural Engineering Department (BAE) (Summer 2005). Waste/Biomass Management Researcher for OSU Animal Science Department (2006-2008). Project Team Leader for BAE Senior Design Project at OSU (2006-2007). Administrative Assistant for Sun Grant Initiative – South Central Region (Summer 2007). Departmental Recruiter for OSU BAE (2008-2009). National Science Foundation Graduate Research Fellow at OSU BAE (2008-2009).

Professional Memberships: American Society of Agricultural and Biological Engineers (ASABE)

Name: Sarah L. Rowland Date of Degree: July, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: DESIGN AND TESTING OF A SMALL-SCALE UPDRAFT GASIFIER FOR GASIFICATION OF EASTERN REDCEDAR

Pages in Study: 83 Candidate for the Degree of Master of Science

Major Field: Biosystems & Agricultural Engineering

Scope and Method of Study

Eastern redcedar is considered a nuisance by many people in Oklahoma where the plant is taking over approximately 762 acres (3.0 square km) of rangeland per day. Gasification of eastern redcedar is one alternative for providing a market by converting the trees to fuel.

There were two objectives of this research: (1) Provide a detailed design of an updraft gasifier that can be used with a variety of feedstocks including eastern redcedar mulch and (2) Test the viability of eastern redcedar mulch as a feedstock for gasification

The design aspect included drawing gasifier components, fabrication, testing, redesign, and retesting. Parts were fabricated in the Biosystems and Agricultural Engineering Laboratory. Operating procedures for the new design were established and used throughout the testing phase.

Mulched eastern redcedar was used as the feedstock for gasification. Optimal airflow was established based on consistent gasifier operation.

Findings and Conclusions

An updraft gasifier was designed for gasification of eastern redcedar mulch. Unique features of the design included: a simple design useful for testing feedstocks with a variety of particle sizes and moisture and ash contents, a scraper/agitator system which deters air channeling as demonstrated by a stable temperature gradient and consistent combustion zone temperatures, and a feedstock hopper and auger which allows semi-continuous feedstock feed rate.

Testing with eastern redcedar mulch resulted in best operation in the ER range of 0.177 to 0.215 for the 8-inch (20 cm) diameter gasification chamber as evidenced by HHV and cold gas efficiency. Moisture and ash content and particle size are suitable for gasification in this system without pretreatment. Gasification was complete, with no noticeable tar buildup in the gasifier. The testing of this gasification system provides evidence that eastern redcedar can be utilized as a feedstock for gasification. The design is original and provides a tool for future experimentation at Oklahoma State University and future construction of gasifiers of this type.

ADVISER'S APPROVAL: Dr. Danielle Bellmer