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Assessing the suitability of various feedstocks for biomass gasification

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ASSESSING THE SUITABILITY OF VARIOUS FEEDSTOCKS FOR BIOMASS GASIFICATION

A Thesis

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Louisiana State University and
Agriculture and Mechanical College
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In

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by
Akshya Sharma
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ABSTRACT

Ten different types of feedstocks available in Louisiana were assessed for their suitability to produce SYNGAS in a down-draft biomass gasifier. The feedstocks tested for this research include: pine pellets, hardwood pellets, cypress mulch, pine bark nuggets, corn stover pellets, switchgrass pellets, sugarcane bagasse pellets, dairy manure pellets, and poultry litter pellets. The feedstocks were first analyzed for volatile & ash content, high heating value, moisture, and mass density. Feedstocks that met the analytical criteria and available in a form that is suitable for the down-draft gasifier at LSU were tested for gasification. The temperature profile within the gasifier and exiting oxygen concentrations were monitored for each of the tested feedstocks.

Results indicated that pine and hardwood pellets had moisture contents of 6.04 ± 0.5% and 5.39 ± 0.22%, respectively, which was considered optimum for gasification. However, corn pellets had higher moisture content (13.3 ± 0.44%) and had to be dried to 7 ± 1% moisture for successful gasification. Results also indicated that low ash and high volatile solids contents were critical for gasification. Pine pellets and hardwood pellets had the least ash (0.37 ± 0.1% and 0.85 ± 0.2%) and highest volatile solids (99.62 ± 0.1% and 99.14 ± 0.5%), therefore, performed best during gasification runs. Poultry litter and dairy manure pellets had more than 39% ± 0.8% ash and less than 62 ± 0.8% volatile solids, which made them unsuitable for gasification. Four feedstocks (Alfalfa, switchgrass, bagasse, and corn) had moderate levels (12.16% - 3.28 %) of ash contents, with alfalfa having the highest ash content. Out of these feedstocks with moderate ash contents, alfalfa pellets failed to gasify consistently. Cypress mulch and pine bark nuggets, although had the necessary properties for gasification (low ash, high volatile solids, acceptable high heating values, and low moisture), the mass density was too low and required continuous feeding. Although these feedstocks gasified, the frequent valve openings and closings and

constantly varying volumes of biomass inside the gasifier caused major temperature fluctuations. The actual suitability of these feedstocks can be tested either after densification (pelletization) or by incorporating an automated feeding system for the gasifier. The dairy manure pellets, switchgrass pellets, bagasse, and chicken litter pellets could not be tested in the gasifier due to unavailability in these pellets in the market in bulk volumes. The in-house hammermill and pelletmill were not found to be undersized for large scale production of pellets.

The exiting SYNGAS (SYNthesis GAS) was passed through adjacent sampling unit for quantification of tars and particulates gravimetrically. Of the 5 feedstocks that were tested for gasification, syngas from pine pellets had very high tar and particulate concentration, as high as 0.80399 ± 0.183 g/Nm^3 and 4.06377 ± 0.721 g/Nm^3 respectively. However, the same values were lowered to 0.26 g/Nm^3 (tars) and 1.2 g/Nm^3 (particulates) after passing the gas through a tar cracking catalyst bed maintained at 250˚C

CHAPTER 1: INTRODUCTION

1.1 Introduction

Due to depleting fossil fuel supplies and increasing energy consumption resulting from increasing populations and economic developments, it is critically important to explore alternative energy sources for ensuring a sustainable future. Biomass is a clean and renewable alternative and can be an excellent substitute for conventional fuels. Renewable fuels are cleaner fuels compared to traditional petroleum and coal, which reduce air pollution and lower greenhouse gas emissions[1]. The Figures 1.1 and 1.2 shows that the consumption of finished petroleum products and liquefied petroleum products increased by 37.5% and 26.5%, respectively, over the past three decades[2].

The dependency on non-renewable energy sources can be considered a major cause of production of vicious heat-trapping gases leading to the well-known phenomenon of "global-

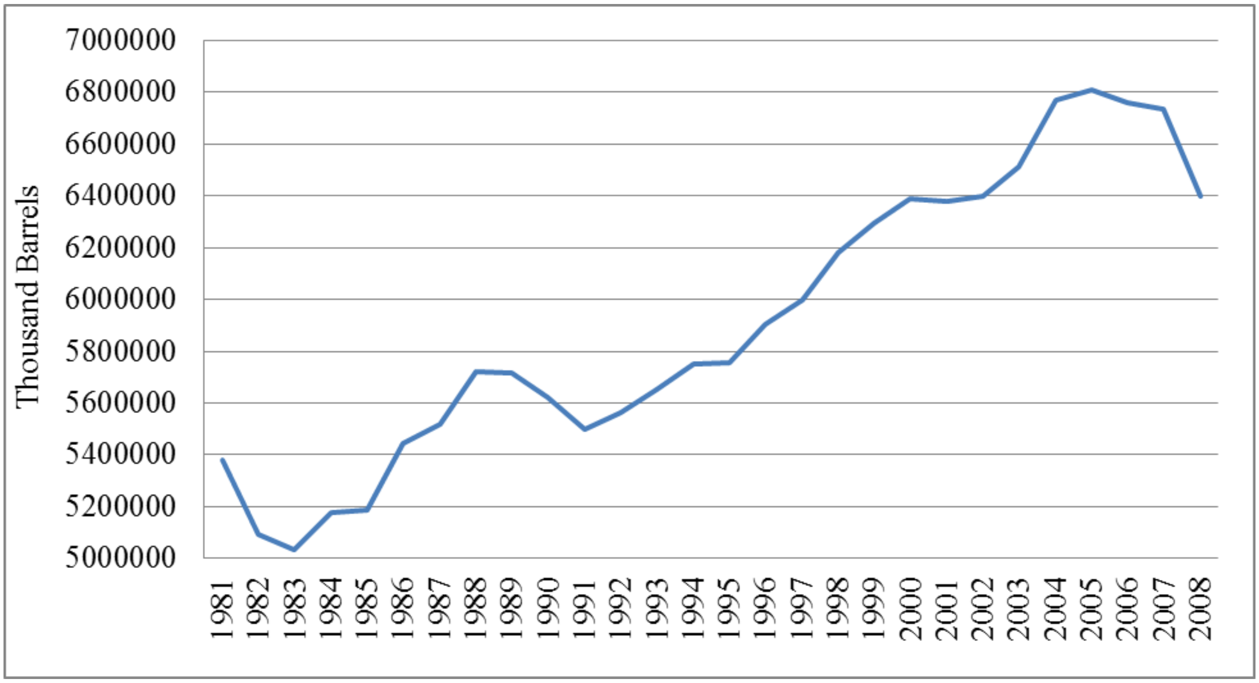


Figure 1.1: Historical trends in United States finished liquefied petroleum gases in thousands of barrels. Source – Energy Information Administration[2]

warming". Dincer (2001) associated increase in global warming to the increase in emission of NO_x, SO_x and CO2[3]. Goudie (2006) predicted some major impacts of global warming such as change in balance between snow and rain, melting of glacier ice and of permafrost and impact of sea level rise on coastal deltas[4]. The European Environment Agency stated that "Glaciers are an important freshwater resource and act as water towers for lower-lying regions. Projected changes in precipitation, snow-cover patterns and glacier storage will alter run-off regimes, potentially leading to higher water stress in summer, floods and landslides in winter and higher inter-annual variability. This will have serious consequences for freshwater supply, river navigation, ecosystems fed by water from rivers, irrigation facilities, and power generation. Observed and projected reductions in permafrost, and glacier retreat, are also expected to increase instabilities and natural hazards including glacier lake outbursts, rock-ice avalanches and landslides all of which may damage infrastructure[5]."

In the US, the motivation to discover an alternate source of renewable energy is driven by

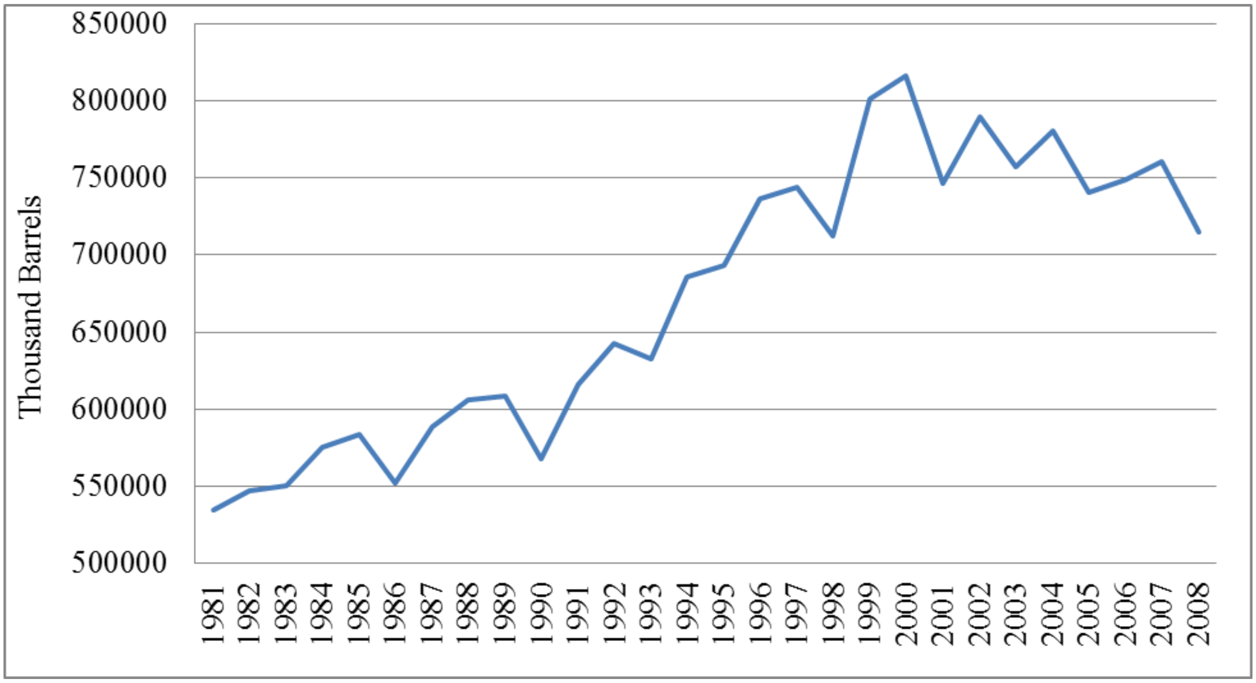


Figure 1.2: Historical trends in United States finished petroleum products in thousands of barrels. Source – Energy Information Administration[2]

depleting fossil fuel resources and heavy dependence on foreign energy. Apart from the renewable aspects, these fuels also bring in a major incentive, namely a cleaner environment, with fewer NO_x, SO_x and CO_2 emissions. Stevens (2001) stated that plant growth "recycles" CO_2 from the atmosphere, and the use of biomass resources for energy and chemicals results in low net emissions of CO_2[6]. According to Rezaiyan and Cheremisinoff (2005), the emissions of NO_x and SO_x from biomass facilities were also typically low and this helped the biomass technologies to meet local and regional environmental regulations and reduce emissions that contribute to acid rain[7].

Figures 1.3 show that biofuels contribute 9% of all energy consumptions on the planet. According to McKendry (2002), biomass has always been a major source of energy for mankind

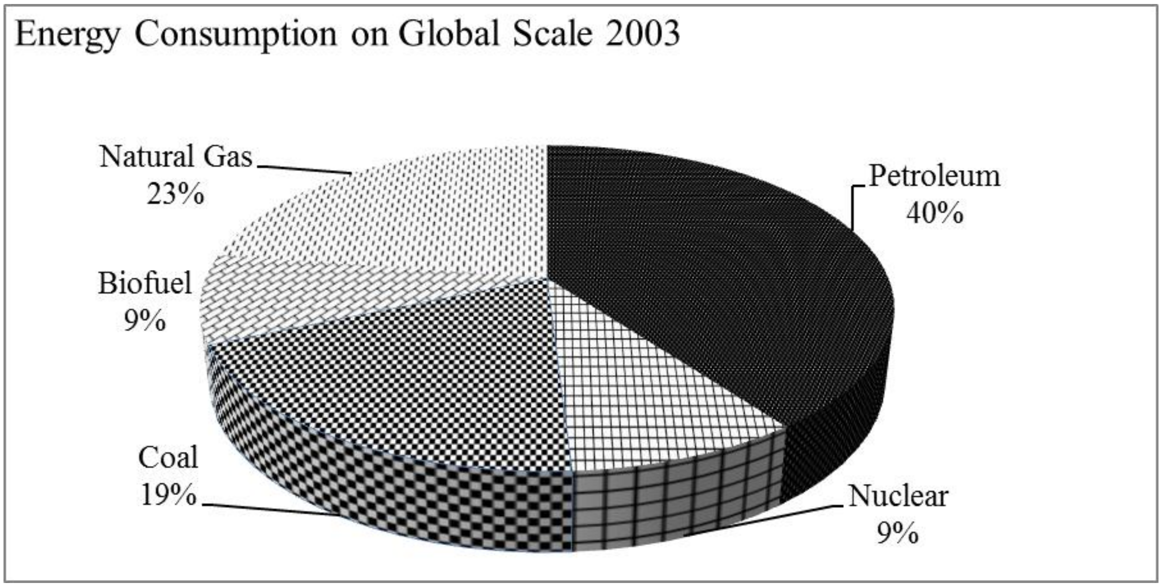


Figure 1.3: Energy Consumption on a Global Scale – Only 9 % of energy needs were fulfilled by biomass and approximately 80% of energy is driven from non-renewable sources of energy[2].

and is presently estimated to contribute of the order 10 – 14% of the world's energy supply[8]**.** Theoretically, biomass has the capacity to provide 100 percent of the world's energy requirement; however, current production approaches and use of biomass for energy is not sustainable[9]. Babu (1992) mentioned that biomass could be a major component of renewable energy resources, which was gaining worldwide recognition as an environmentally compatible fuel. It was estimated that the annual yield of biomass was approximately eight times the world's annual energy use[10]. Hall (1991) construed that there was a significant potential to improve upon its current contribution of 10 ~ 14% to the world's energy consumption[11].

1.2 Use Biomass as Biofuel & Gasification Fundamentals

Massive consumption and unavoidable scarcity of petroleum products have concerned world economy. The objective behind this thesis was to identify abundant biomass feedstocks in Louisiana which have the potential to be used as a gasification fuel. For gasification applications, an ideal biomass feedstock was expected to:

1) be renewable and readily available in sufficient quantities.
2) be cost-effectively processed for gasification.
3) result in sufficient combustible gases (H_2 and CO).
4) be environmentally acceptable (Low NO_x, SO_x and ash).
5) have sufficient BTU value to be processed further.
6) produce low residues in exiting gas (tars and particulates in this case)

Wang and co-workers (2009) have pointed out that there is a growing market for biofuels in the production of briquettes and pellets for domestic purposes, since biomass pellets can be used in grate furnaces and fluidized bed combustion while offering advantages, such as easy storage and transport, lower pollution, lower dust levels and higher heating values[12]. Furthermore, Rhen and co-authors (2007) stated that, the pellets offer the same advantages for automation and optimization as the petroleum-derived fuels, but with higher combustion efficiency and a lower amount of combustion residues[13].

Table 1.1 shows the feedstocks which were used in this thesis. The availability of biomass feedstocks and rationale behind selecting them are discussed in chapter 2.

Table 1.1: Different feedstocks used in this thesis, which were either plant based or animal waste based feedstocks

Plant Based Feedstocks	**Animal Waste Based Feedstocks**
Pine pellets	Chicken litter pellets
Hardwood pellets	Dairy manure pellets
Switchgrass pellets	
Alfalfa pellets	
Bagasse pellets	
Corn pellets	
Cypress mulch	
Bark nuggets	

Gasification could utilize the waste, biomass and byproduct by turning them to carbonaceous fuel or char. Gasification Technology Council stated that biomass has heat-producing capacity; equivalent to that of some common non-renewable resources used for energy generation. The environmental benefits of gasification are:

- Gasification enables the use of domestic coal, petcoke, and biomass to produce electricity with significantly reduced environmental impacts compared to traditional combustion technologies.
- Because the SYNGAS is cleaned before combustion, gasification plants produce significantly fewer quantities of criteria air pollutants such as nitrogen oxides (NO_X) and sulfur dioxide (SO_2).
- Gasification enables the recovery of available energy from low-value materials (such as petcoke and municipal solid waste), thereby reducing both environmental impacts and disposal costs.

- The byproducts from gasification (sulfur and slag) are non-hazardous under federal law and are readily marketable.
- Gasification plants use significantly less water than coal combustion plants, and can be designed as zero liquid water discharge facilities.
- CO_2 can be captured from a gasification-based plant using commercially proven technologies prior to combustion of the SYNGAS in the gas turbines[14].

Figure 1.4 shows how a gasification plant works with air or oxygen as gasification agent. The economic benefit of gasification is: - It converts low-value feedstocks to high value products, thereby increasing the use of available energy while reducing disposal costs[14]. An alternate source of energy can mitigate the detrimental effects of using fossil fuels as primary source of energy. The cost of production will come down as logistics are likely to improve with higher biomass volumes.

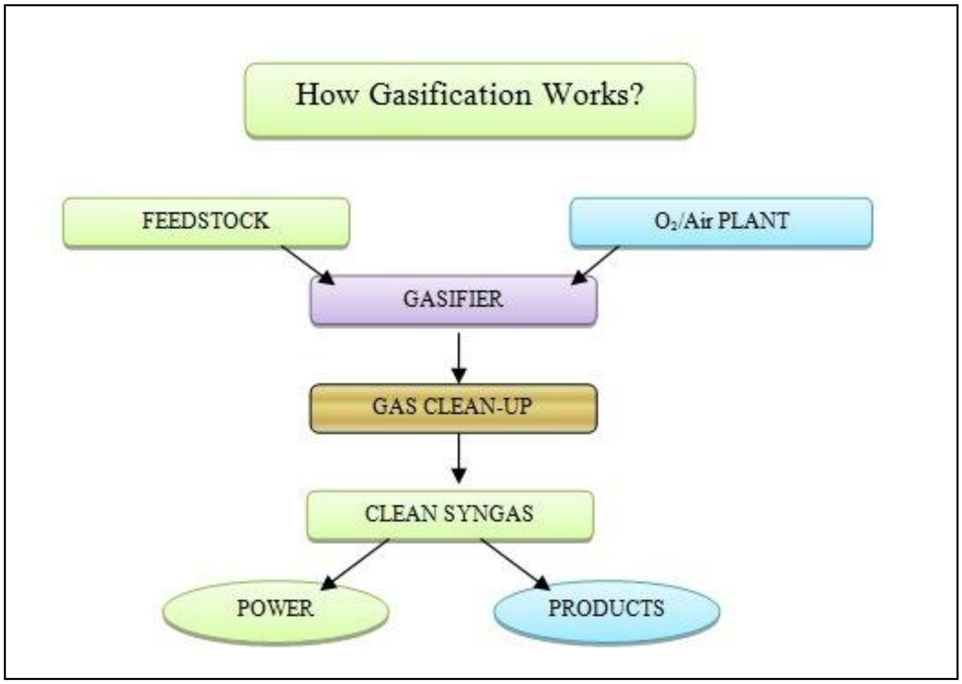


Figure 1.4: This flowchart shows the basic steps involved in a biomass gasification plant with air or oxygen used as a gasification agent[14].

1.3 Research Objective

The overall objective behind this study was to identify ideal feedstocks for gasification. Ten different feedstocks were evaluated for their suitability for gasification. A pilot scale biomass gasification unit with a capacity of 40 – 50 lbs. was used for conducting the experiments. Specific objectives of this thesis research are to:

a) Characterization of the various feedstocks: The feedstocks used in this thesis were tested for high heating values, moisture content, density, volatile solids and ash percent. These properties indicated whether the feedstocks were suitable to be used as a gasification fuel.

b) Quantify the tars and particulates in the exit syngas: The gravimetric analysis of tars and particulates supplements the gasification results and denotes whether or not a feedstock qualifies for gasification. The concentration of tars and particulates will give an opportunity to understand the behavior of different feedstocks inside the gasifier.

c) Quantify the composition of resulting SYNGAS: The resulting composition of the SYNGAS determines heating value, efficiency of conversion, and its value as a thermal or chemical feedstock. For the use of SYNGAS as an alternate source of energy, quantification of combustible gases present in the SYNGAS was an important step.

CHAPTER 2: LITERATURE REVIEW

Biomass is abundantly available around the world. According to Biomass Energy Facts (2008) biomass has been the fourth largest source of energy worldwide following fossil fuel. The School of Renewable Natural Resources at Louisiana State University has compiled records of availability of feedstocks in the state. This chapter focuses on some emerging technologies in the field of renewable resources and some commonly used gasification technologies[8.]

2.1 Biomass and Bioenergy Overview

The current practices on bioenergy have instigated a revolution in energy production and studies related to biomass. The initiative to utilize biomass will help industries and communities both environmentally and economically.

- Agrilectric Power, in Lake Charles, utilizes the rice hulls that were produced from their farms to produce electricity. The plant consumes 300 tons of rice hulls per day, generating 13 megawatts of electricity[15].
- Temple-Inland Corporation had a paper mill in Bogalusa that used sawdust and logging slash to fire boilers at their plant. After heat was used in the paper making process, the excess heat was used to generate electricity, which was enough to supply about 60 megawatts or 75% of its annual energy needs[15].
- According to Louisiana Biomass and Bioenergy Overview, (2007), Louisiana has three major landfills that have been producing bioenergy through the methane pathway. Another 10 landfills were identified as candidates to join this program[15].

- Some parishes in the state of Louisiana which produce abundant biomass are listed here. Table 2.1 shows approximate dry tons of biomass produced and the feedstocks which were used in this thesis.

- Parishes such as Vernon, Beauregard and Winn contribute to an annual production of approximately 70,000 dry tons of pine logging residue[16].
- Union, Sabine and Bienville produce pine as well as hardwood logging residue above 80,000 dry tons[16].
- Vernon, Beauregard and Winn are some of the highest producers of hardwood. These parishes contribute approximately 90,000 dry tons to hardwood logging[16].

Table 2.1 Estimated dry tons of feedstock available in Louisiana[16]

S No.	Feedstock Names	Feed Stock Dry tons
1	Pine	1,122,618
2	Hardwood	10,951,714
3	Switchgrass	N/A
4	Alfalfa	N/A
5	Cypress	N/A
6	Bark Nuggets	196,945
7	Bagasse	163,430
8	Poultry Litter	273,478
9	Dairy Manure	47,449
10	Corn Stover	125,000
	Total	**12,880,634**

N/A = Information Not Available

- Beauregard was the highest rated bark-wood producing parish. The parish produced approximately 110,000 dry tons of bark-wood annually. Beauregard has had abundant supply of different crop residues and crop by-products which also included sugarcane bagasse[16].
- Iberia and Iberville produce 61,250 tons and 20,000 tons of bagasse respectively.

2.2 Introduction to Gasification

According to Souza-Santos (2004) gasification is the process where gaseous species are obtained from a solid fuel, through an assembly of chemical reactions and physical transformation[17] .The main components of the gaseous mixture are H_2, CO, CO_2, H_2O, CH_4 and other hydrocarbons. A more detailed process has been described in this section.

2.2.1 Drying

This process occurs at temperatures below 107˚C, resulting in a release of water vapors from the surface and the inner pores of the solid fuel. Some of the more volatile organic and inorganic components of the fuel may also be released[18].

2.2.2 Pyrolysis

Lewis and co-authors (1980) stated that pyrolysis is an endothermic process which requires heat to drive the chemical reactions that produce SYNGAS comprising mainly of CO and H_2[19]. According to Wei (2005) biofuels begin to pyrolyze at temperatures above 200°C. The proportion of components is influenced by the chemical compositions of biofuels being fed and the operating conditions of the gasifier[20]**.** Pinto and researchers (2009) stated that pyrolysis, also known as devolatilization, is a high temperature process that transforms the structure of the solid fuel and generates char, tars and gases from the feedstock. The main composition of SYNGAS is H_2, CO and CH_4. Tar fraction includes heavier organic compounds that were gaseous when released during pyrolysis or were condensed as liquid drops. Char is composed mainly of carbon and the mineral matter present on the solid fuel[18].

Wei (2002) explained the process of thermal decomposition as**.**

$$C_6H_{10}O_5 + \text{Heat} \rightarrow y{*}C_xH_z + q{*}C_xH_nO_k + CO + C \qquad (2.5 - 1)^{20,\,21}$$

The proportion of various end products is governed by feedstock properties and operating parameters. Pyrolysis is used as an independent process or as a pretreatment for gasification.

$$\text{Biomass} + \text{Heat} \rightarrow H_2 + CO + CH_4 + \text{other products} \qquad (2.5 – 2)$$

When concentrating on H_2 production: - water – gas shift reaction can be feasible.

$$CO + H_2O + \text{Heat} \rightarrow CO_2 + H_2 \qquad (2.5 – 3)$$

Oxidation reactions take place when air is injected in the gasification chamber (from the sides).

2.2.3 Combustion

Combustion is an endothermic process which takes place in presence of oxygen as a combustion supporting agent. The product of combustion is mainly heat and CO_2. Out of all the energy derived from biomass, the majority of energy is currently produced using combustion systems. In conventional combustion-based systems, biomass is burned to produce heat, which is used to generate steam. The electricity generation efficiency of these systems ranges from about 20% in older systems to over 30% in newer ones[6].

Differences between Gasification and Combustion: Gasification is a controlled form of producing SYNGAS, which can be further used in various applications where as combustion is purely a heat generating process.

2.2.4 Gasification

Brown (1994) stated that gasification describes the process in which oxygen-deficient thermal decomposition of organic matter primarily produces synthesis gas. It includes pyrolysis and combustion. Gasification has more potential for near-term commercial application than other thermochemical processes. Some benefits of gasification over combustion were more flexibility in terms of energy applications, more economical and thermodynamic efficient and potentially lower environmental impact[22]. An efficient gasifier will decompose high-molecular-weight organic compounds released during pyrolysis into low-molecular-weight, non-condensable compounds in a process referred to as tar cracking. Undesirable char that is produced during gasification will participate in a series of endothermic reactions at temperatures above 800ºC, which converts carbon into a gaseous fuel. Typically gaseous products include: CO, H_2, and CH_4. Fischer Tropsch processes may be used to upgrade gaseous products to liquid fuels through the use of catalysts. Typically, gasification requires feedstocks that contain less than 10% moisture[6].

Gasification is a proven manufacturing process that converts hydrocarbons such as coal, petroleum coke (petcoke) and biomass to a SYNGAS, which could be further processed into different forms of energy. Gasification is a partial oxidation process that yields CO and H_2. Combustion is a complete oxidation process that results in thermal energy (heat), solid waste and air pollutants such as NO_x, SO_x[14] (Table 2.2). The International Energy Agency (IEA) discussed and issued various gas cleaning standards. Graham and co-workers (1996) stated that biomass-based energy production (bioenergy) generates NO_x and SO_x emission than certain fossil fuel-based systems, such as coal and oil. It also does not create the potential negative environmental effect associated with coal mining or nuclear waste disposal[23]. The NERL (Pacific Northwest

Table 2.2: Difference in gases released when biomass was combusted to when the biomass was gasified under bleak oxygen supply[14].

Constituents (of Coal)	**Gasification**	**Combustion**
Carbon	CO	CO_2
Hydrogen	H_2	H_2O
Nitrogen	N_2	NO_X
Sulfur	H_2S	SO_2
Oxygen	—	O_2

National Laboratory) report mentions various gasification technologies which can be accessed on the basis of best productivity and feasible endurance of functional part of the system[6].

Gasification technology can accommodate different feedstocks, including waste wood from furniture, municipal solid waste, horse bedding pellets (pine pellets used in this project), hurricane waste, wasted tree products (cypress mulch and bark nuggets). Table 2.3 shows the various reactions occurring inside a gasifier.

Table 2.3: Mechanism of gasification and combustion reactions which takes place inside a gasifier[24].

Designation	**Mechanism**	**Equation #**
Oxidation	$C + O_2 \Leftrightarrow CO_2$	1
	$C + 1/2O_2 \Leftrightarrow CO$	2
Boudouard	$C + CO_2 \Leftrightarrow 2CO$	3
Water Gas : Primary	$C + H_2O \Leftrightarrow CO + H_2$	4
Secondary	$C + 2H_2O \Leftrightarrow CO_2 + 2H_2$	5
Methanation	$C + 2H_2 \Leftrightarrow CH_4$	6
Water – Gas Shift	$CO + H_2O \Leftrightarrow CO_2 + H_2$	7
Steam Reforming	$CH_4 + H_2O \Leftrightarrow CO + 3 H_2$	8
	$CH_4 + 2H_2O \Leftrightarrow CO_2 + 4 H_2$	9
CO_2 Reforming	$CH_4 + CO_2 \Leftrightarrow 2 CO + 2H_2$	10
H_2 Reforming	$CO + 3 H_2 \Leftrightarrow CH_4 + H_2O$	11

Gasification reactions between carbon and oxygen (1) and (2) were exothermal and as long as they occurred in sufficient scale, provided the required energy for driving the pyrolysis reactions. The resulting products were CO_2 and CO in different proportions.

According to Boudouard reaction (3), solid carbon may react with CO_2 producing CO. This is an endothermic process that occurs mainly at temperatures higher than 786.85°C and is inhibited by the presence of CO.

Water gas reactions (4) and (5), involve solid carbon and water vapor, are endothermic and favored by higher temperatures and lower pressures[24].

Methanation or hydrogasification, (6) occurs between carbon and hydrogen. It is generally very slow, but favored at higher pressures. Increasing temperature may cause a displacement of the chemical equilibrium of the homogenous “water – gas shift reaction” (7), between CO, water vapor, hydrogen and CO_2. This reaction may have a very clear effect on the composition of the obtained gaseous mixture, changing the ratio CO/H_2[18].

Methane and all other hydrocarbons present in the gas phase may suffer several reforming reactions (8) and (10), with either water vapor or CO_2, increasing CO, H_2 or methane concentration. These reactions, being endothermic processes are the cause of increasing hydrocarbon concentration that was observed at higher temperature.

Hydrogen reforming (11) occurs between CO and H_2 with the production of methane and water vapor. This reaction, while causing an increase of the gas heating value, generally occurs at a low extent, except at higher pressure or under the effect of appropriate catalysts[18].

2.3 Gasification and Its Technologies

Gasification, as a technology, could be used to produce cheap consumable gas from by-products and waste products. In the past, different researchers have concentrated on testing different sources of fuel and converting them to valuable energy sources.

The United States Department of Energy (1999) stated “gasification technology is bound to reduce the hazardous gas emission in the environment producing a wide variety of products, which can be used in a number of places. The technology should be able to utilize all carbon based feedstock, and of all the available technologies biomass gasification fulfills all these requirements to produce a commercial fuel[25]. United States Department of Energy monitored the progress in the field of gasification and concluded that the growth of gasification power touched 45,001 MWth of SYNGAS output by 2004 at 117 operating plants around the world[26].

Zainal and coworkers (2001) demonstrated that the scarcity of fossil fuel in Sweden during the era of World War II was the driver behind the domestic hardship and the government suffered extreme losses. To recuperate from these losses during the war the government of Sweden turned to biomass as major source of alternate fuel to be used in furnaces and boilers. Zainal and coworkers explained the setbacks of coal as fuel due to the presence of sulfur[29]. The Figure 2.1 showed a pattern of some planned and some unplanned gasification projects since 1970's.

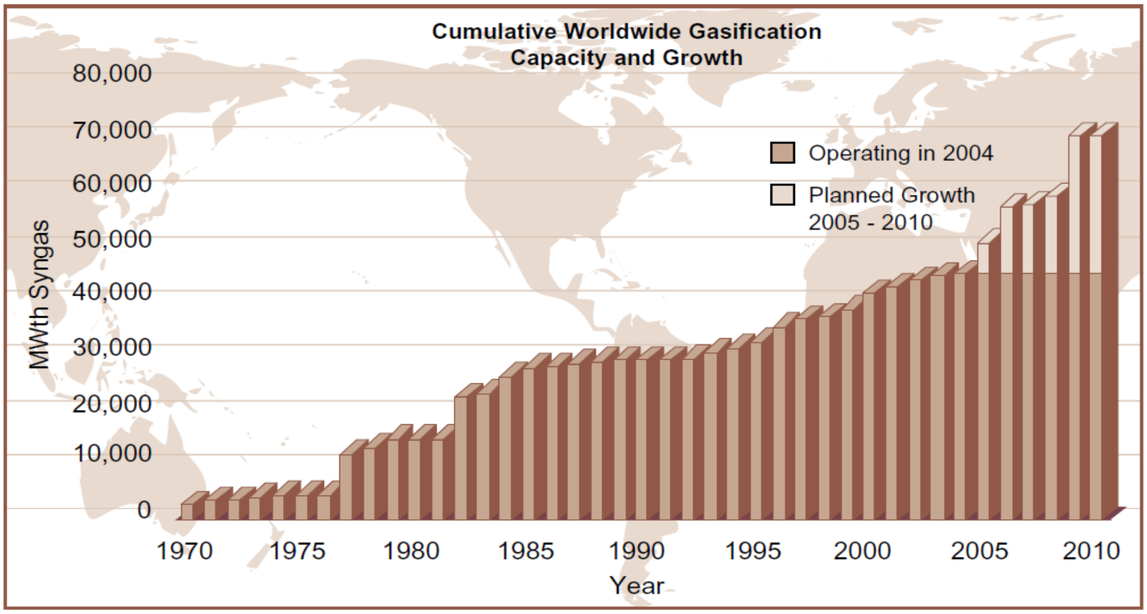


Figure 2.1: Cumulative worldwide gasification capacity and growth from past four decades[28].

Narvaez and researchers (1996) studied biomass gasification of a small pilot plant in a bubbling fluidized bed and effect on the performance of the gasifier[30]. Delgado and co-researchers (1997) discussed the cleaning of the raw hot gases from a bubbling fluidized bed biomass gasifier using cheap calcined minerals or rocks downstream from the gasifier[31].

Goldman and co-researchers (1997) demonstrated the possibility of a two-phase counter-flow concept as a means of providing super adiabatic conditions, which were expected to enhance a weak exothermic reactions and endothermic gasification reactions in the reforming zone[32]. Paisley and Anson (1997) developed and commercially demonstrated a high through-put gasification-based power generating system[33]. Overend (1991) stated that the heat load for conventional power production using boilers and steam turbines is estimated to be 14.8 to 16.9 MJ/kWh (14,000 to 16,000 Btu/kWh), which could be reduced by 25% to 35% by resorting to integrated gasification combined-cycle for power production schemes[34].

There is a great interest in developing and commercializing innovative biomass energy conversion technologies due to the importance of biomass in many countries. In the Biomass Action Plan – COM 628, the European Commission recommended measures to increase biomass use from 69 Mtoe (Million Tons of Oil Equivalent) in 2003 to about 150 Mtoe in 2010. Biomass gasification may play an important role in achieving this goal as the gases produced after cleaning procedures can substitute for fossil fuels in conventional and advance energy conversion devices and can also be used as SYNGAS[35].

Stiegel and co-authors (2001), who monitored the fuel processing technologies which are under development or are currently operating, found that in 2001 there were 128 plants worldwide, with 366 operating gasifiers. It was projected that by 2006, an additional 33 plants with 48 gasifiers were expected to venture, adding another 18,000 MW_{th} of SYNGAS capacity. Most of the new growth occurred in the developing nations in the Pacific Rim. The second largest growth of such plants was projected to be in Western Europe, where refineries would need to fully utilize the available feedstock while reducing fuel oil production. It was also stated that the maximum gasification derived fuel is generated from coal and petroleum by-products[36].

Marechal and co-authors (2005) studied energy projects in Switzerland and found that many were running on residential wood supply. One such project was "*From Wood to Methane"* which involved several academic institutes such as the Paul Scherer Institute, PSI; the Ecole Polytechnique Fe´de´ rale de Lausanne, EPFL; and the Swiss Federal Laboratories for Materials Testing and Research (EMPA) and one private partner. The aim of the Swiss project was to develop a 10-20 MW_{th} semi-industrial plant to produce SYNGAS from wood whose quality matches natural gas and then transported by existing high pressure Swiss Natural Gas Network[37]. Table 2.4 shows some major gasification projects around the world and gives an approximate energy produced by each.

Table 2.4: Major biomass gasification demonstration projects and commercial plants[18]

Country	**Biomass Gasification Technology**
Austria	8 MWth TUV FICFB BMG CHP demonstration at Gussing 2 MWth down-draft BMG CHP at demonstration at Wr. Neustadt
Belgium	Up to 600 k We for small-scale power, Xylowatt sa
Canada	50 MWth for synthesis gas/MeOH, Biosyn Uo ti 13 MWth for co-firing, Nexterra
Denmark	5 MWth VØlund up draft CHP demonstration at HarbØre 70 KWth, Viking 2-stage gasification and pwer generation at Lyngby 3 + MWth, TK energi 3 stage, gasification process demonstration at GjØl (an 833 KWth plant is demonstrated in Japan) 30 MWth Carbon Renugas fluiaized bed CHP demonstrated at Skive
Finland	4 to 5 MWth Bioneer up-draft gasifier (8 in Finland and one in Sweden) 60 MWth, Foster Wheeler Energy CFB co-firing plant at Lathi (50 to 86 MWth co-firing plant in Ruien, Belgium) 40 MWth Foster Wheeler Energy fluidized bed metal recovery gasifier in Varkaus 7 MWth NOVEL Up draft demonstration at Kokemaki 1.8 MWe + 3.3 MWth for CHP, NOVEL
Germany	130 MWth commercial waste to methanol plant at Schwarze Pumpe 100 MWth Lurgi CFB gasifier firing cement kiln at Rudersdorf .5 MWth Fraunhofer Umsich CFB pilot plant at Oberhausen MWth CHOREN Carbo – V 2 – stage entrained pilot plant in Freiberg 3-5 MWth Future Energy pyrolysis/entrained flow GSP gasifier in Freiberg 75 MWe and MeOH, Future Energy
Italy	15 MWth TPS CFB RDF plant at Greve in Chianti 500 KWth ENEA CFBG pilot plant at Trisaia (similar plant in operation in

Table 2.4 Contd.

	China)
Netherkabds	85 MWth AMER/Esent/Lurgi CFB gasification co-firing plant at Geertruidengerg, Biomass co-gasification at 250 MWe (35 MWe from biomass) Shell entrained coal gasification plat at Willem- Alesander Centrale 3 MWth CFBG Plant in Tzum NL Several pilot plants at ECN, Petten ~30% of 250 MWe, Shell/ Buggenum (co-gasification) ~50% of (4x300) MWe, Shell/ Magnum
New Zeland	Fluidyne commercial down-draft gasification plant (2 MWe Plant in Canada) AB Powerhearth Ltd down-draft BMG (3 MWe plant in Maine, USA) 2 MWth Page Macrae updaraft BMG plant at Tauranga
Sweden	Bioneer up-draft BMG plant 6 MWe, 9 MWth for CHP, Bioflow 30 MWth Foster Wheeler Energy CFBG at Karlsbog paper mill 20 MWth Foster Wheeler Energy CFBG at Norrsudet paper mill 30 MWth Gotaverken CFBG at Sodracell paper mill 18 MWth Bioflow/Sydraft/Foster Wheeler Energy CHP demonstration at Varnamo
Switzerland	200 KWe Pyroforce down draft BMG system at Spiez (scale-up to 1 MWe plant in Austria)
UK	100 KWe Rural Generaton downdraft BMG system in Northern Ireland Upto 250 KWe Bimass Engineering Ltd., down draft BMG CHO system in Northern Ireland Upto 300 KWe Exus Energy down draft BMG CHP system in Northern Ireland Charlton Energy rotary kiln waste gasification in Gloucestershire Compact Power two-stage waste gasification plant in Bristol
USA	Upto 120 MWth Primenergy gasification/combustion system (6 in USA and 1 in Italy) Upto 22 KWe Community Power Corporation small modular down draft gasification system FERCo SilvaGas dual CFBG process RENUGAS fluidized bed BMG process Integrated TCC+Biologaical Conversion 11.5 million Gas of EtOH/year, Taylor Gasification.

2.4 Feedstocks Tested for Gasification

Ferreira and co-authors (1994) stated that United Kingdom was using different feedstocks and energy plantation such as willow trees and e*uohorbia characias* for experiments. They also talked about using poplar, sorghum and miscanthus in Netherlands, of which miscanthus and sorghum are C_4 crops characterized by high rate of carbon assimilation[38]. According to Sims (1994), New Zealand was making use of *pinus radiata* for biomass gasification[39].

Zainal and researchers (2002) studied the behavior of a downdraft biomass gasifier using furniture wood and wood chips. The studies explained the effect of equivalence ratio on gas composition, calorific value and the gas production rate[21]. His and coworkers (2008) experimented on a downdraft biomass gasifier for the characteristics using *red lauan and white lauan* wood cubes of 15 x 15 x 15 mm as fuel[40]. The successful gasification of black liquor and waste biomass could improve energy self-sufficiency and help achieve reduced levels of emissions to the air. Bailey and co-authors (2000) demonstrated efficient electrical conversion of black liquor using gasification when combined with clean-up technologies and gas turbines. The authors also studied the development of gas clean-up technologies for gas turbines that run on waste streams. More cost-effective options can be derived by combining gas clean – up technologies when using diversified feedstock in gasification process. By combining clean-up technologies with gasification processes, the chemical industry will benefit from a diversified fuel feedstock, and more cost-effective options were described[41].

According to United States Department of Commerce (2000) across all facilities in SIC 26 (Standard Industrial Classification, 9914 business), the pulp, paper, and allied products industry is the largest consumer of process water and the third largest consumer of energy (behind the chemicals and metals industries)[42]. Narvaez and co-workers (1996) suggested that the waste produced from paper and pulp industries was either used in heating up the boilers or was discarded due to low productive quality which contributes to lowering the cost efficiency. The practice of self-sufficiency was more applicable to paper and pulp industries as they were ranked number four in the country for fossil fuel consumption[43]. Stiegel and co-workers stated that paper and pulp industries could be counted as a major contributor to the emergence of gasification technologies in the state[36].

The production of CO, H_2 and CH_4 at a constant rate may act as a sustainable energy source for industrial purpose. Texaco Express Lubes, a multi-million dollar corporation, made use of gasification for extracting SYNGAS from the sludge (silicon beds)[44].

2.4.1 Characteristics of Feedstocks Studied

Hughes and Larson (1997) modeled a simulation to show effect of varying moisture content in the feed of a biomass gasifier[45]. Jorapur and Rajvanshi (1997) reported the commercial scale (300 kW) development of a gasifier making use of low-density biomass (sugar cane leaves and bagasse, bajra stalks, sweet sorghum stalks). They concluded that preheating the air can shorten the time required for attaining the steady state. The variable operating parameters used or modified in their thesis were air flow rate, air preheating temperatures, air/fuel ratio, fuel moisture content (which affected fuel conversion rate), specific gasification rate, gas heating values (HHV of gas), and H/C ratio as well as hot and cold gas efficiency[46].

Skoulou and co-authors (2008) compared the gasification characteristics of olive tree cuttings and olive kernels and discovered that olive tree cuttings have higher LHV to those of olive kernels and that olive kernels produced higher char sand content of fixed carbons· Further in their study they observed that, various factors such as ash, moisture content and volatile solids affected the producer gas composition. The production of carbon monoxide varied in both feedstocks[47].

2.5 Different Gasifier Designs

There are many different types of gasification technologies available for converting woody biomass to SYNGAS, primary of which are the fixed bed, fluidized bed and circulating bed biomass gasifier. Olofsson (2005) described the following sections where description of different designs has been discussed[48].

2.5.1 Fixed-Bed Biomass Gasifier

a) Up-Draft Biomass Gasifier

Fuel is fed at the top and the gasifying medium (air or oxygen and/or steam) is introduced at the bottom and producer gas is drawn up through the fuel (Figure 2.2). Air is supplied through a grate on which fuel rests. Complete combustion takes place at the bottom of the bed in the

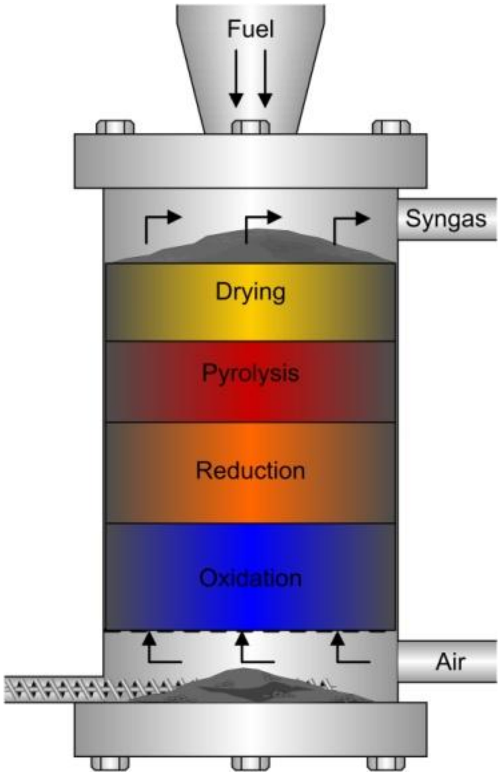


Figure 2.2: Up-draft biomass gasifier: Fuel enters from the top and air is injected from the bottom. High efficiency gasifier with poor quality syngas[48].

oxidation zone where CO_2 and H_2O are formed at 1000°C. The hot gases are then passed through the reduction zone where these gases are reduced to H_2 and CO and cooled to 750°C. Further up the bed the reduced gases pyrolyze the downward flowing biomass which forms large amounts of tars and other products of incomplete gasification (PIG). Finally the gases dried the incoming wet biomass and leave the reactor at ~500°C[48].

b) Down-Draft Biomass Gasifier

Fuel is fed from the top of the gasifier and the gasifying medium is introduced into a downward flowing packed bed (Figure 2.3). The SYNGAS is then drawn off near the bottom. This gasifier has relatively distinct oxidation, reduction, pyrolysis and drying zones. The downdraft gasifiers normally reaches relatively low tar levels since the tar produced in the

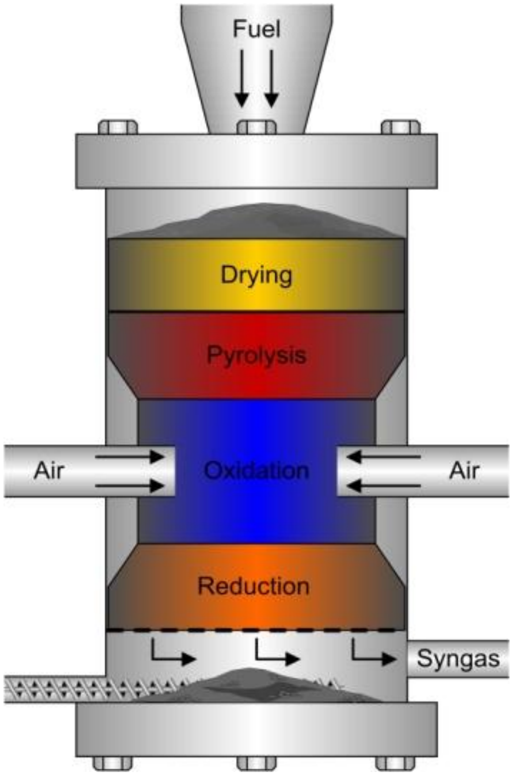


Figure 2.3: Down-draft biomass gasifier. Fuel enters from the top and air is injected from the sides. Average efficiency gasifier with low quality syngas (tars produced) [46]

pyrolysis stage is thermally cracked when it passes through the homogenous high-temperature combustion zone. However, in practice this is hard to achieve since the tar slipped through the "cold" parts of the combustion/oxidation zone without being converted to char or gaseous fuel. Another drawback of this system is that a large portion of the fuel-energy is converted into heat with a low heating value SYNGAS[48].

2.5.2 Fluidized-Bed Biomass Gasifier

a) Bubbling Fluidized-Bed Gasifier (BFBG)

The fuel is fed into or above the sand bed and the gasification agent is introduced from the bottom at speeds of 2-3 m/s which results in bubbles which travel up through the bed (Figure 2.4). The speed of the fluidizing agent is of great importance for the size and speeds of the

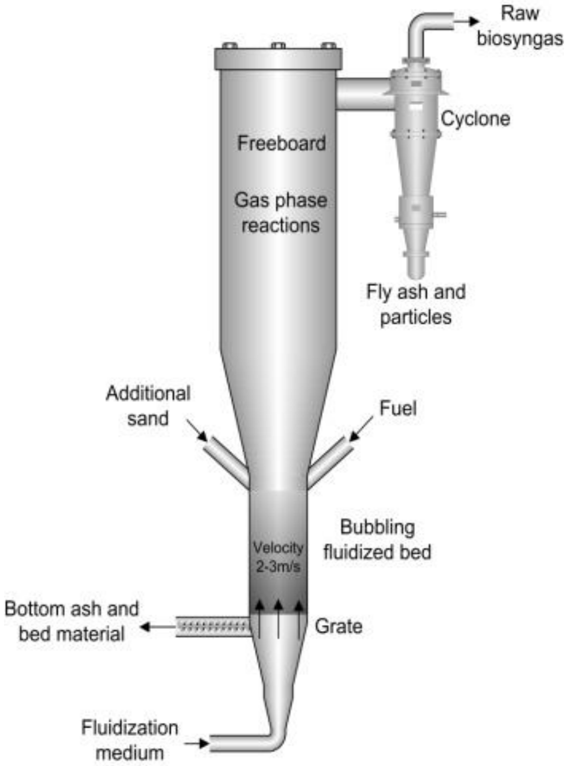


Figure 2.4: Bubbling fluidized-bed gasifier. Fuel is fed from the top. Design is complex and output gas is poor in quality [48]

bubbles and influences the mixing and heat exchange between the fuel particles. The SYNGAS is drawn off from the top of the reactor via a cyclone to separate sand and fly ash from the SYNGAS[48].

b) Circulating Fluidized-Bed Gasifier (CFBG)

Fuel is fed into the sand bed and the gasifying medium is introduced from the bottom at speeds of 5-10 m/s (Figure 2.5).This is sufficient to suspend the bed particles throughout the entire reactor, causing a portion of the sand and char to exit the reactor along with the producer gas stream. The “entrained” particles which accompany the gas out of the gasifier unit are captured in a cyclone which recycles the bed material. SYNGAS is drawn of from the top of the cyclone[48].

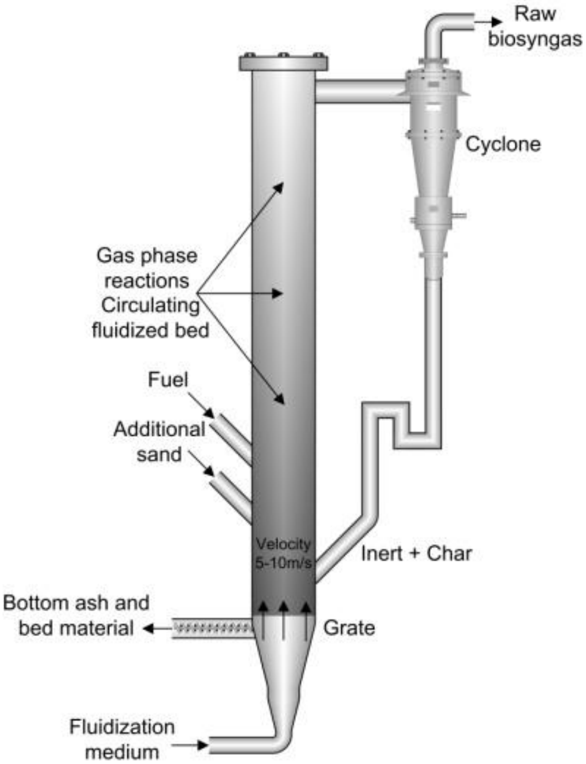


Figure 2.5: Circulating fluidized-bed gasifier: Fuel is injected at the center and the gasification agent is injected at the center. Design is complicated and high quality of tars and particulates present in output gas[48].

2.5.3 Entrained Flow-Down Flow Gasifier

Fuel, as gas, solid powder or slurry, is mixed with a steam/oxygen stream and is converted in a turbulent powdered flame at high temperatures (above 1200°C) in a very short time (a few seconds) (Figure 2.6). At these high temperatures, an almost tar-free SYNGAS and a leach-resistant molten slag are produced. This technology is applied at moderate pressures in combination with fine fuel powders for sufficient carbon conversion. The hot gas flows downwards into a radiant SYNGAS cooler where high pressure steam is produced. The SYNGAS is passed over the surface of a pool of water at the bottom of the radiant SYNGAS cooler and exits the vessel. Slag is dropped into the water pool and is fed from the radiant SYNGAS cooler sump to a lock hopper[48]. Table 2.5 shows some complexities, advantages and disadvantages of using these technologies.

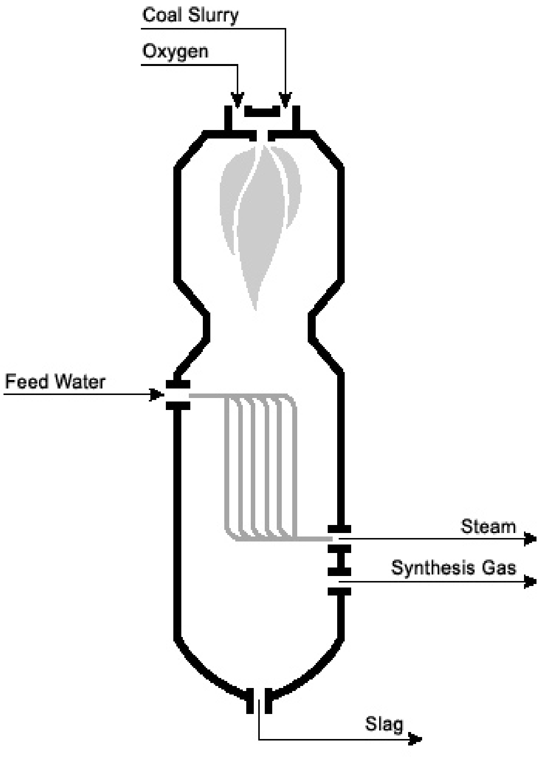


Figure 2.6: Entrained flow – down flow gasifier: Fuel is fed from the top and gasification agent (steam or air) is injected at the center. Quality of producer gas is good but the design is extremely complex.[46]

Table 2.5: Different gasifier designs and the characteristics which affect the production of SYNGAS from these designs[48].

Properties Of Gasifier	**Fixed Bed**		**Fluidized Bed**		**Entrained Flow**
	Up-Draft	Down Draft	Bubbling Bed	Circulating Bed	
Fuel Fed	Top	Top	Top	Center	Top
Combustion Zone	Bottom	Center	N/A	N/A	N/A
Reduction Zone	Center	Bottom	N/A	N/A	N/A
Pyrolysis Zone	Top	Top	N/A	N/A	N/A
Drying Zone	Top	Top	N/A	N/A	N/A
Oxidation/Combustion Zone	Bottom	Center	N/A	Top	Top
Gasification Agent	Air	Air	Air	Air	Steam/ Oxygen
Gasification Agent Intake	Bottom	Center/ Downward Flow	Bottom	Center/ Downward Flow	Top
Shape, Size And Moisture Of The Material	Not Critical	Critical	Not Critical	Not Critical	Critical
Design	Simple	Simple	Complex	Complex	Complex
Composition Of Gas (HHV)	Good	Average	Poor	N/A	Good
Quality Of SYNGAS (HHV)	Poor	Low	Poor/ High Particulates	Poor/ High Particulates	Good / Tar Free
Quantity Of Tars	High	Average	High	High	Low
Process Optimization	Poor	Poor	N/A	Good	Good
Carbon Conversion Rate	Good	Average	High	Average	High
Bed Agglomeration	N/A	N/A	Yes	Yes	No
In-Bed Catalytic Conversion	N/A	Possible	Not Possible	Possible	Possible

**N/A = not available

CHAPTER 3: GASIFICATION METHODOLOGY

A down draft biomass gasifier was used to conduct all the experiments at Louisiana State University. Six thermocouples were inserted in the gasification unit for temperature measurements. Two thermocouples (Thermo 7 and Thermo 8) were inserted on the flaring unit to record the temperatures of the exiting gas. Two oxygen sensors were used, first inside the gasification chamber and the second at exiting path below the flaring unit (Figure 3.1).

3.1 Gasifier Description

The gasifier used in this analysis was an experimental prototype, pilot scale and batch fed down-draft biomass gasifier. It had a capacity to hold approximately 40 – 50 lbs. feedstock. The gasifier consists of three major parts —

1. Gasification Unit
2. Sampling Unit
3. Flaring Unit

3.1.1 Gasification Unit

Figure 3.1 shows a schematic the gasification system used for this study. Feedstock was fed manually through two 6” dia. stainless steel knife gates, which served as an airlock system. The gasification unit was capable of holding 40 – 50 lb. of feedstock and could be fed again in small batches of 10 – 12 lb. of feedstock. The feedstock rested on a metal mesh which hung firmly from two ends and was connected by detachable hooks on the other two sides for cleaning ash. A low pressure blower supplied the gasification agent (ambient air) to the four air intake ports (shown in Figure 3.1). The biomass feeding rate was dictated by the density of the feedstock and the rate of air intake.

3.1.2 Sampling Unit

A sampling unit was used to collect samples of tars and particulates in the SYNGAS during a gasification run. A vacuum pump () was used to draw a small flow (approximately 10 SCFH) from a slip-stream (shown in Figure 3.1). The sampling unit consisted of an oven maintained at 250˚C, a Millipore stainless steel pressure filter holder, a 0.7 µm 90 mm Ø filter (Whatman: GF/F Cat No 1825 090), 1/8" copper tubing and four acetone bottles for tar collection (Figure 3.2).

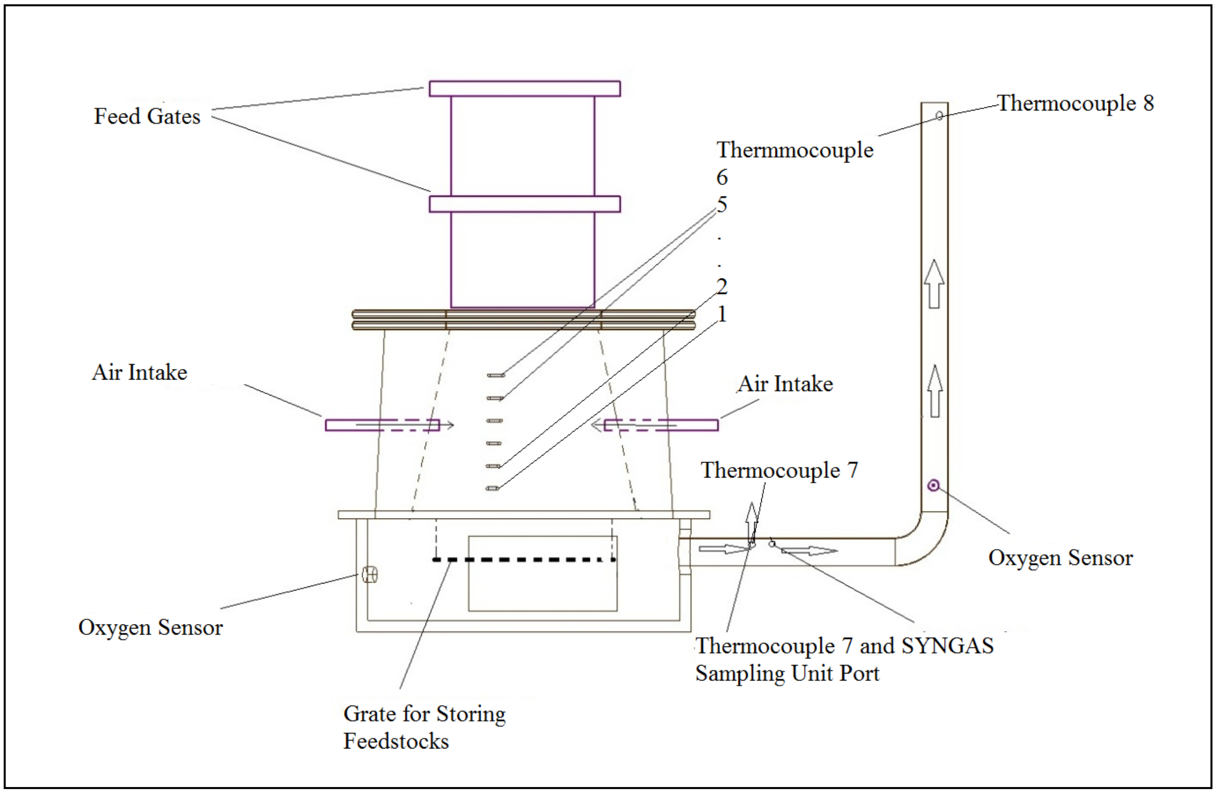


Figure 3.1: Gasification Unit. The central unit houses the thermocouples. The air intake on the sides provided the gasification agent (air). The feed gates were used to feed feedstock into the gasification unit in a batch process. The thermocouples on the gas exiting end and oxygen sensors inside and outside are also shown.

The particulate collection system employed a glass fiber filter, placed in a stainless steel Millipore pressure filter holder assembly (cat # YY3009000). This filter was used because of its tight specifications of 0.6 µm - 0.8 µm particle retention and pure borosilicate glass structure[49]. The filter holder and the filter were kept in an oven maintained at 250˚C to minimize condensation of tars. The SYNGAS produced in the gasifier was drawn from the sampling port, through 1/8" copper tubing, filter holder assembly and a series of acetone bottles to dissolve any tars. The particulates and tars were quantified gravimetrically (described in section 3.3.4).

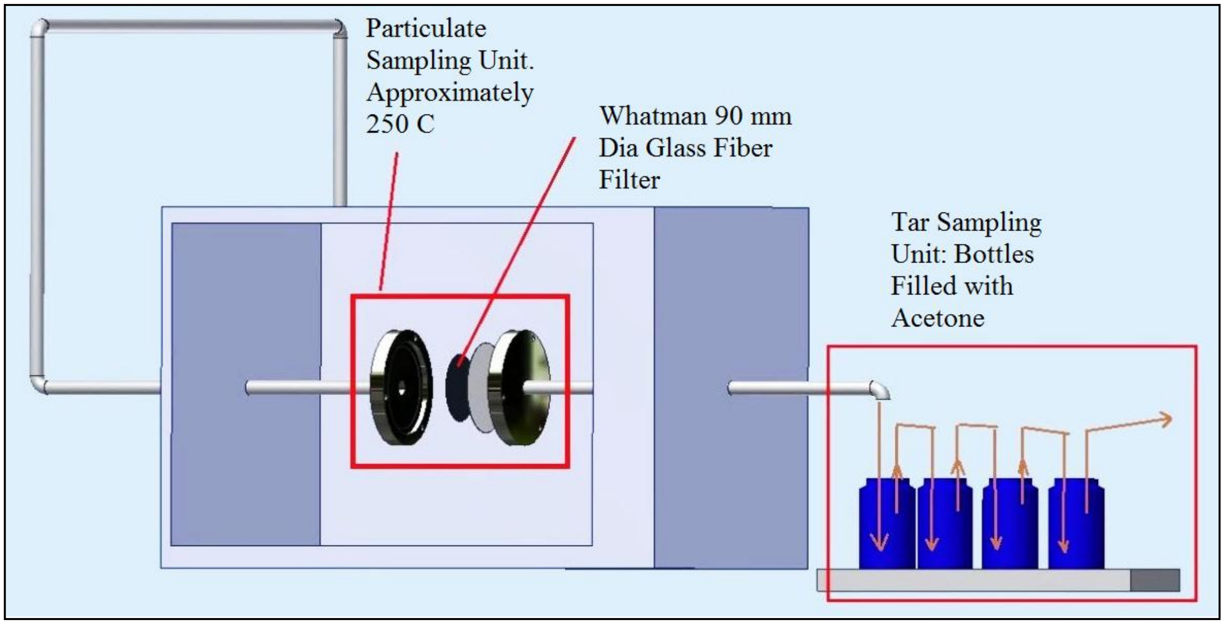


Figure 3.2: Sampling Unit. The filter paper is used to trap particulates and acetone bottles are used to dissolve tars

3.1.3 Flaring Unit

A flaring unit was used to safely dispose the large quantities of SYNGAS (~245 CFM) produced by the gasifier (Figure 3.3). Two thermocouples and an oxygen sensor were attached in the flaring unit to monitor exit gas temperatures and to indicate the presence of any oxygen. As an extra measure of safety, a second oxygen sensor was added near the grate area of the gasifier. To prevent any internal flash explosions, the flare was lit only after the oxygen levels dropped to zero (or undetectable) at both the oxygen sensors. Additionally, to prevent any back flash during the operation of the flare, a wire-mesh type of back flash arrestor was installed on the pipe carrying SYNGAS to the flaring unit (shown in Figure 3.3). Typically, commercial gasifiers have gas cleaning devices or catalytic cleaning modules for generating tar-free SYNGAS[50].

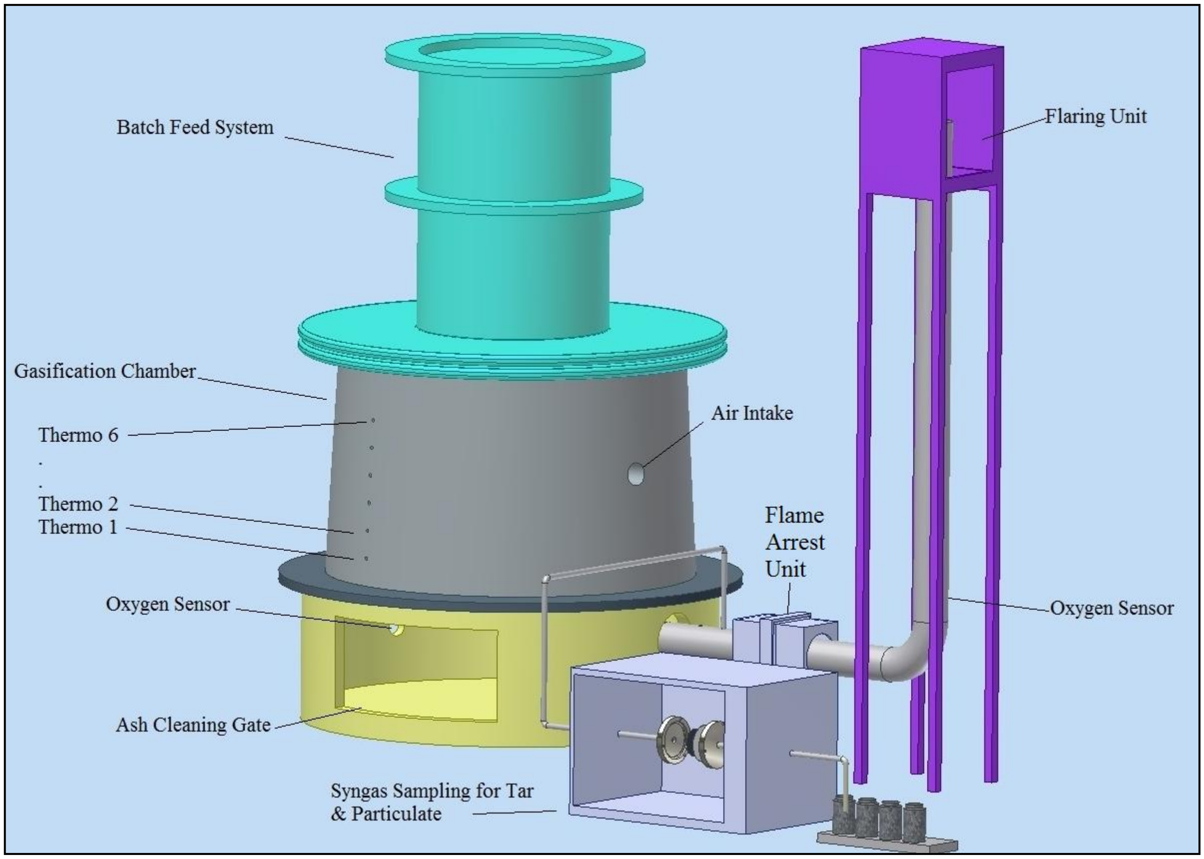


Figure 3.3: Down-draft biomass gasifier at Louisiana State University. A) Gasification Unit: The feed was fed in this unit. It also shows the thermocouples. B) Sampling Unit: Figure 3.2. C) Flaring Unit: The gas produced in the gasification unit was flared in the flaring unit

3.2 Gas Composition Quantification

Gas Chromatography was done with the help of SRI Instruments® Gas Chromatographer 8610 C (Figure 3.4), with helium as the carrier gas were studied. The analytical performance of the detector for the determination of some permanent gases such as H_2, N_2, O_2, Air, CO, CO_2 and CH_4 was proven to be ideal when helium was the carrier gas[51]. Predetermined peaks shown in Figure 3.5 represent the composition of SYNGAS.

For this analysis the GC was pre-heated for approximately 20 minutes. Collected

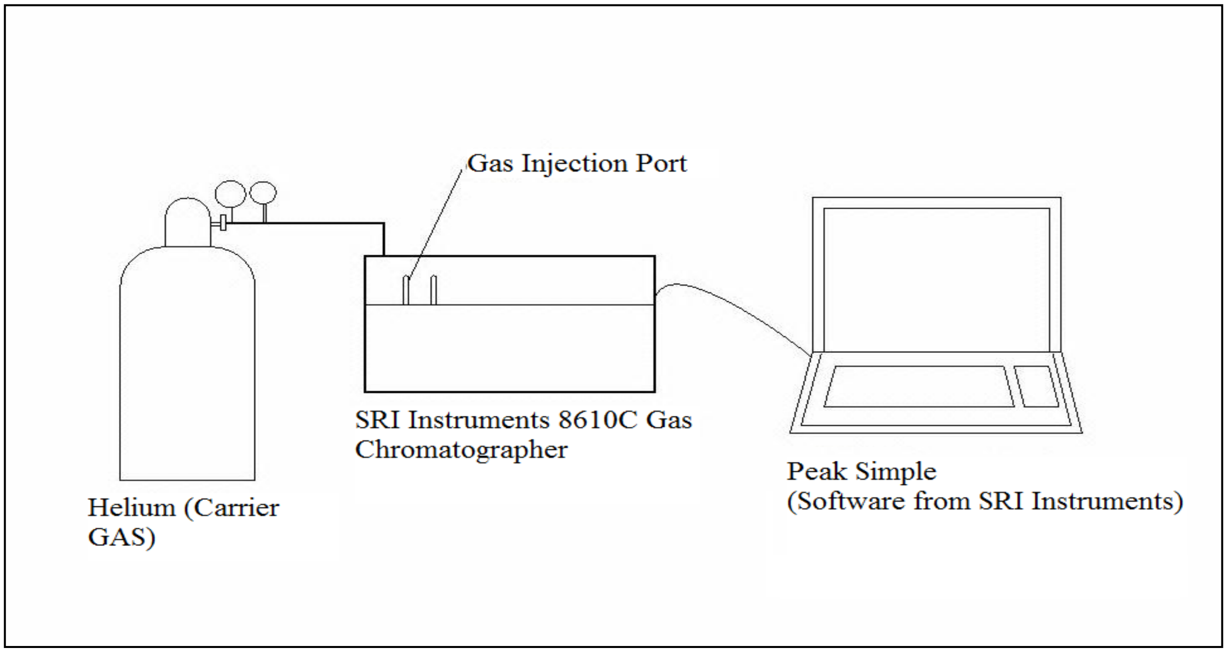


Figure 3.4: SRI Instruments® Gas Chromatographer 8610 C– The gas was injected via 10 ml syringe in the injection port.

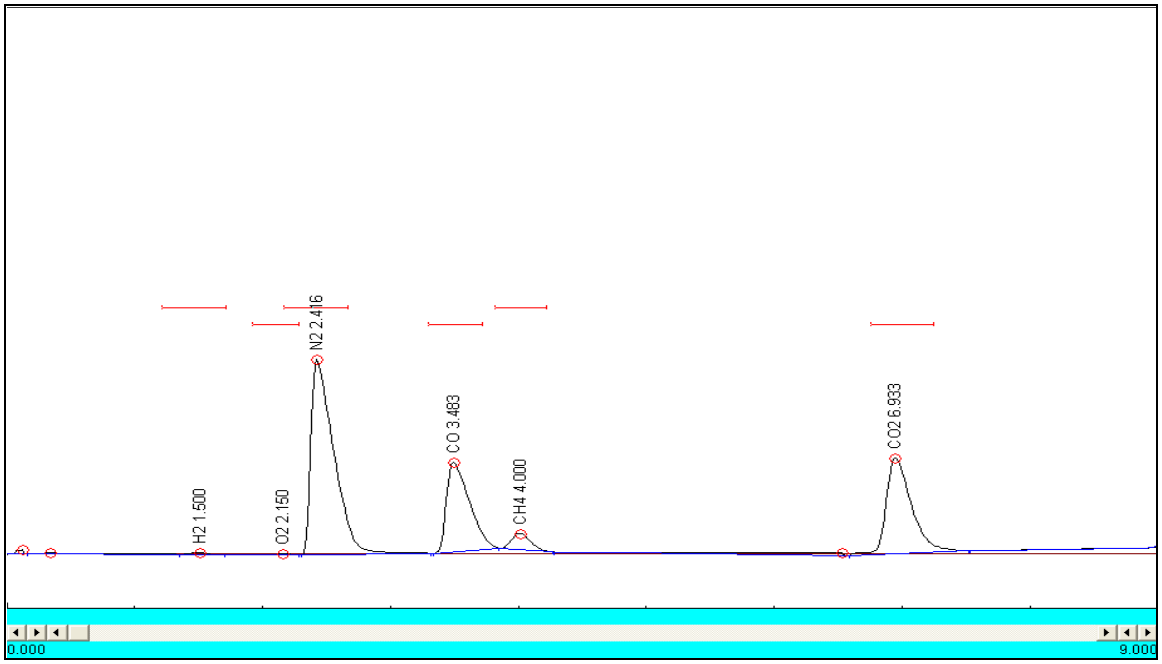


Figure 3.5: GC output of the representative SYNGAS: First peak – H_2, Second peak – O_2, Third peak – N_2, Fourth peak – CO, Fifth for – CH_4 and the sixth peak for CO_2

SYNGAS was injected in the input port with a 10ml syringe. The GC was initiated from 40˚C to reach a temperature of 160˚C in a 9-minute analysis interval.

3.3 Testing of Feedstock Characteristics

Six different parameters were tested to evaluate the thermal and physical properties of the various feedstocks.

3.3.1 High Heating Value (HHV) or Calorific Value of Feedstocks

Sheng and co-authors (2004) define heating value, also called calorific value or heat of combustion, as the energy content of a biomass fuel[52]. Anuradda and co-authors (1996) stated that the heating value was necessary to determine the suitability of biomass for pyrolysis, carbonization, liquefaction and gasification[53].

Bomb calorimetry was performed by following the ASTM D2015 standard method. Parr Instruments® 1108 Oxygen Bomb was used to perform calorimetry analysis (Figure 3.6). The bomb was filled with 60 psi of oxygen. A fuse wire was connected between the two electrodes of

Figure 3.6: 1108 Oxygen Bomb: The chamber is filled and sealed with approximately 60 psi of O_2. A sparking current is passed through the two electrodes for creating the explosion inside the bomb.

the bomb. It was then fired with the help of an electric source to produce a spark inside the bomb which combusted the fuel. This bomb was immersed in a water jacket (Figure 3.7). A thermocouple was attached to the water jacket which recorded the temperature of water due to the heat released by the feedstock. Gross heat was calculated by using a template provided by Parr Instruments®. The formula used in this template is shown below.

$$\mathbf{HHV = \frac{((T * E_c) - Yh - Yh2 - Yf)}{m} \quad kcal/kg \qquad (3.3-1)}$$

where,

$$\mathbf{HHV_{btu} = HHV * 1.8\ btu/lb}$$

T = difference in minimum and maximum temperature. (ºC)

E_c = Energy Equivalent of the calorimeter, determined under standardization.

Yh = Correction in calories for heat of formation of nitric acid (HNO_3).

Yh2 = Correction in calories for heat of formation of sulfuric acid (H_2SO_4).

Yf = Correction in calories for heat of combustion of fuse wire. (cal)

m = mass of the fuel/feedstock (lb).

HHV_{btu}= High Heating value (btu/lb).

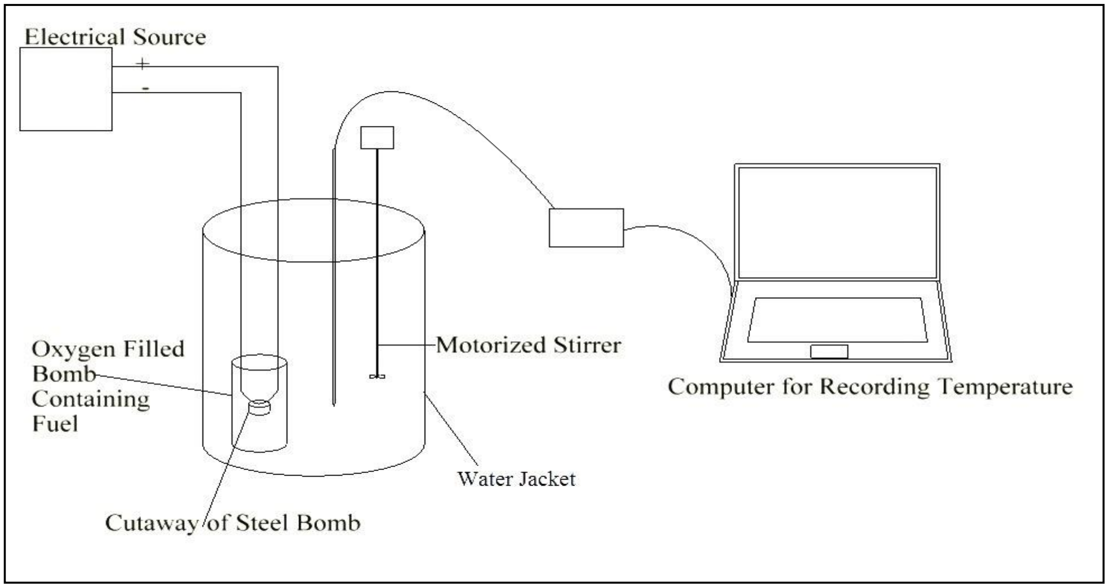


Figure 3.7: Bomb Calorimetry for calculation of high heating value

3.3.2 Density and Moisture Percentage

Moisture content of the fuel is referred to as inherent moisture plus surface moisture. Higher moisture contents reduce the thermal efficiency of the gasifier and result in low gas heating values. Igniting the fuel with higher moisture content becomes increasingly difficult and the gas quality and the yield are also poor[54]. Moisture of the feedstocks was calculated using ASTM D4442–07 standard test method for direct moisture content of wood.

a) Density

Density was determined from the following equation:

$$\mathbf{D = \frac{M}{V}} \qquad \mathbf{(3.3 - 2)}$$

where,

M = mass of the feed (kg)

V = Volume (m^3)

D = Density (Kg/m^3)

Ten samples were tested for finding the density and moisture content of the feedstock. Volume and mass of the feedstocks were measured and placed in the oven. The difference in masses (before and after oven drying) was used to calculate the density and moisture percentage using equations 3.3 – 2 and 3.3 – 3.

b) Moisture

$$\mathbf{M\% = \frac{(m_0 - m_1)}{m_1} * 100\ \%} \qquad \mathbf{(3.3 - 3)}$$

where,

M %= Moisture of the pellet, (%)

m_0 = Mass of the pellet before oven drying, (g)

m_1 = Mass of the pellet after oven drying, (g) (103˚C ± 2 for 2 hrs.)

3.3.3 Volatile Solids and Ash Percentage

Figure 3.8: Ash obtained after furnace treatment for volatile solids and ash percentage of different feedstock bagasse.

Volatile solids are defined as solids which are lost on ignition at 550˚C. Analysis of Volatile solids was used to quantify the organic weight present in the feedstock. This analysis was performed on ten samples from each feedstock following the ASTM E1755-01 standards.

The dried samples were placed inside a muffle furnace at 550°C for 30 minutes and the gravimetric analysis was used to determine the ash and volatile solid fractions of a feedstock using equations 3.3 – 3 and 3.3 – 4 respectively. Figure 3.8 show a sample of bagasse pellets after they were weighed for gravimetric analysis.

Ash content was calculated following ASTM D1102 – 84. Ash percent and volatile solids helped in determining whether or not the feedstock was capable of sustaining a complete gasification experiment.

a) Ash Percentage

$$\mathbf{A\% = \frac{(m_{ash} - m_{cont})}{m_s} * 100\ \%} \qquad \mathbf{(3.3 - 4)}$$

where,

A% = Percentage of Ash, (%)

m_{ash} = Mass of ash and container, (g)

m_{cont} = Tare mass of container, (g),

m_s = mass of moisture free solids in the prepared biomass sample, (g)

b) Volatile Solids

$$\mathbf{VS\ \% = \frac{(m_0 - m_1)}{m_0} * 100\ \%} \qquad \mathbf{(3.3 - 5)}$$

where,

VS% = Volatile Solids Percentage, (%)

m_0 = Dry Mass of the pellet, (g)

m_1 = Mass of the ash after furnace treatment, (g)

The density, moisture content ash percent and volatile solids of all the tested feedstock are represented in the appendix A 1.1.

3.3.4 Analysis of Tars and Particulates

Gravimetric analysis of tars and particulates was conducted on the samples recovered from the sampling unit (Figure 3.2) during the gasification experiments. To keep the tars from condensing in the exhaust lines, the exhaust lines were insulated to maintain elevated temperature. Pinto and coworkers (2009) identified the production of tars in SYNGAS as one of the main challenges of current gasification studies. Their aim was to achieve the production of SYNGAS with the right characteristics to allow its use in motors, turbines or fuel cells, which meant very low contents of tar, sulfur, nitrogen and halogen compounds[18].

Procedure

Tar and particulate samples were collected during gasification in triplicate as follows:

A new, pre-weighted GF/F and 200 ml of acetone, divided in four air sealed bottles, were placed in the sampling unit as shown in Figure 3.2.

The oven containing the GF/F was placed was pre-heated and maintained at 250˚C.

The collection of tars and particulates was done when Thermo 2 (Figure 3.1) reached approximately 650˚C. The sampling was started with a vacuum pump, connected after the acetone-bottles of the tar sampling unit. The flow gas through the sampling unit was regulated to 10 scfh (standard cubic feet per hour) for 30 minutes per sample.

This sampling procedure was repeated three times in a single gasification experiment to obtain a set of triplicate samples.

Determination of particulates concentration: GF/F was placed in an aluminum pan, which was placed in an oven at 105˚C for 2 hours. The aluminum pan was cooled in a desiccator for 30 minutes. The GF/F was weighed for gravimetric analysis to get the concentration of particulates.

Determination of tar concentration: 200 ml of acetone was reduced to 10 ml in a rotovap. This 10 ml of acetone was evaporated under a fume hood in a pre – weighed aluminum pan was dried in an oven at 105˚C for 2 hours. The pan was measured for gravimetric analysis. Concentrations of tars and particulates were calculated using equations 3.3-6 and 3.3-7. In this analysis, deposition is defined as:

Deposition on GF/F and Aluminum Pans

$$\mathbf{D_{gff} = \frac{(W_0 - W_1)}{V} \quad g/Nm^3} \qquad \mathbf{(3.3 - 6)}$$

where,

W_0 = weight of the GF/F or pan before, (g)

W_1 = weight of the GF/F or pan after, (g)

V = Volume of gas passing, (cfm)

D_{gff} =Deposition on Glass fiber filter paper, (g/Nm^3)

Volume of gas passing the sampling unit was measured with a SCFH (Standard Cubic Flow per Hour) flow meter. The conversion of SCFH (Cubic Foot / hour) to CFM (Cubic Foot / min) is shown in equation 3.3 – 7 through 3.10.

$$\mathbf{V = \frac{(10\ ft^3 * (0.3048\ m)^3\ ) * \ (30/60)\ hr}{1\ hr * ft^3}} \qquad \mathbf{(3.3-7)}$$

3.3.5 Use of Tar Cracking Catalyst

An analysis with a tar cracking catalyst was performed to understand the effect of catalyst on the tars produced by a feedstock (pine alone was tested because of limited availability of catalyst). Figures 3.9 through 3.11 shows the microscopic images of the surface of the catalyst at temperatures 450˚C, 550˚C and 650˚C. The surface of the catalyst was scanned for any deformations. The catalyst was placed in a furnace at 300˚C in a 9 cm long metal tube of 2.5 cm diameter. Two meshes of similar diameter were placed at each end of the tube for keeping the catalyst in place. 40 mg of a proprietary catalyst (Albemarle Alumina Extrudates) was packed in the tube and the flow of gas, with the help of the vacuum pump, was maintained at 10 SCFH (1.6666 cfm). The whole assembly was placed between the exiting port on the gasifier and particulate collection unit of the sampling unit.

Once the vacuum pump was switch on the collection of tars and particulates was done by following the procedure mentioned in section 3.3.4. The gravimetric analysis of collected tars and particulates was also done following the same procedure as mentioned above (section 3.3.4)

3.4 Analysis of Temperature Profile and Oxygen Sensor Reading

a) Temperature Profiles

A gasification temperature profile depends on density, moisture, ash percentage, BTU value and volatile solids of feedstock. It also depends on gasifier construction, insulation quality, positioning of thermocouples inside the gasification chamber and air flow inside the gasification unit.

Table 2.3 shows the various gasification reactions and illustrates the various exothermic and endothermic processes inside the gasifier. A temperature profile was helpful in analyzing the different mechanisms inside a gasifier such as oxidation zone, pyrolysis zone and reduction zone. At temperatures above 750-800°C, the endothermic nature of the H_2 production reactions (steam reforming and water-gas reactions) results in an increase in H_2 content and a decrease in CH_4 content with an increase in temperature. At temperatures above 850-900 °C, both steam reforming and the Boudouard reactions dominate, resulting in increases in CO content. High temperature also favors destruction and reforming of tar leading to a decrease in tar content and an increase in gas yield[55]. Different feedstocks were analyzed in this thesis for their temperature profiles for better understanding of their behavior inside a gasification chamber.

b) Oxygen Sensor Profile

Oxygen profiles from different feedstocks were employed for safety reasons and to check for leakages. Two oxygen sensors from a catalytic convertor of a regular automobile were used to measure the level of oxygen inside the chamber. These oxygen sensors monitored the amount of oxygen left in the gasification chamber and the exiting gas pipeline. A light on the display panel turned red indicating the chamber and exiting pipeline were depleted of oxygen. This indicated that gasification has initiated and it is safe to light the flaring unit.

For safety reasons these oxygen sensors were placed in two different spots. This precaution was taken in case of a failure of one of the two oxygen sensors.

1) Inside the gasification unit
2) In the pipeline leading to flaring unit.

3.5 Ultimate and Proximate Analysis

Every biomass has carbon, hydrogen and oxygen in major quantities. These are represented as ultimate analysis. The chemical formula for the biomass is generally represented by $C_XH_YO_Z$[66]. Raveendran and co-workers (1995) reported the results of studies on the effect of mineral matter present in biomass on the pyrolysis characteristics, product distribution and product properties. It was stated that, the main elemental constituents of biomass minerals are Si, Ca, K, Na and Mg, with smaller amounts of S, P, Fe, Mn and Al. These constituents occur as oxides, silicates, carbonates, sulfates, chlorides and phosphates[56].

Ultimate and proximate analysis helped in quantifying the feedstocks as a gasifying or a non-gasifying fuel. The presence of N, P and K signifies the inorganic material present in the feedstock. During thermo chemical processing of biomass, most of the nitrogen and sulfur are released into the atmosphere whereas much of the phosphorus and potassium remain in the ash[57]. Raveeendran and coworkers also stated small amounts of inorganic material, as is present in the biomass, are sufficient to alter the pyrolysis behavior to a large extent[56]. This analysis was conducted at the LSU Agcenter’s W.A. Callegari Environmental Center.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Introduction

Louisiana has a wide variety of feedstocks and biomass resources, which can be used as a fuel for gasification. As an example, the paper industry alone produces over 8.5 million wet tons of waste annually[9]. Ten different feedstocks/wastes were used for biomass gasification and were analyzed for their different physical and thermal properties. These analyses helped in assessing their suitability to be used as a gasification fuel. This chapter discusses the results from 8 different feedstock pellets (pine, hardwood, corn stover, alfalfa, switchgrass, sugarcane bagasse, dairy manure and poultry litter) and two raw plant-based feedstocks (cypress mulch and pine bark nuggets).

Based on the experiments conducted on the gasifier used in this research and laboratory analysis of the feedstocks some observations were noted which qualified different feedstocks as gasification and non – gasification fuel. Some of these observations are mentioned below.

a) Characteristics of an optimum gasification fuel: It was observed that the SYNGAS which consisted of $> 18\%$ CO and $> 15\%$ H_2 resulted in a steady flame resulted.

b) Ash content of an ideal feedstock: Feedstocks which had < 5-7% ash yielded SYNGAS with a gas composition of $> 19\%$ CO and $> 15\%$ H_2. High ash was observed in feedstocks with higher inorganic composition. The ultimate and proximate analysis of different feedstocks demonstrated high inorganic composition in feedstocks such as alfalfa, switchgrass, dairy manure and poultry litter. Off these feedstocks alfalfa failed to gasify and produce optimum quality SYNGAS (other feedstocks (switchgrass, dairy manure and poultry litter) were not tested in the gasifier due to unavailability).

On the other hand feedstocks with high volatile solids resulted in the production of optimum quality SYNGAS (low concentration of tars and particulates).

c) Moisture content of an ideal feedstock: Feedstocks with moisture content < 7% were considered ideal for gasification and resulted in SYNGAS with >19% CO and >15% H_2. It was observed that high moisture content affected the quality of producer gas. High tar concentration and extracts were observed in case of feedstocks with high moisture content. On the other hand, low moisture content > 3% resulted in fast gasification/combustion of feedstock and high feed rate was noted in that case.

d) Tar and particulate concentration in SYNGAS: The quality of SYNGAS was an important parameter when considering the concentration of tars and particulates in a gasification experiment with different feedstocks. The gravimetric analysis of tar and particulate concentration was affected by the inorganic material present on the feedstocks. High ash concentration in different feedstocks also affected the concentration of tars and particulates. Feedstock such as alfalfa resulted in high tar concentration and proximate analysis of alfalfa also showed high concentrations of potassium and phosphorous. Feedstocks with higher than 2000 mg/kg of potassium made a feedstock incapable of testing as a gasification fuel.

4.2 Composition of SYNGAS Generated from Various Feedstocks

McKendry P (2001) indicated that fuel with moisture content above 30% makes ignition difficult and reduces the calorific value of the product gas. For this reason, it was necessary to evaporate the additional moisture before combustion/gasification can occur[58]. Higher moisture content will increase H_2 and CH_4 but will lower CO however the gain in H_2 and CH_4 in the product gas does not compensate for energy lost due to reduced CO content of the gas and therefore gives a product gas with a lower calorific value[58].

Pine pellets resulted in gas composition of approximately 18.26% ± 1.59% H_2 and 18.02% ± 2.92% CO. These results were supported by the hypothesis that adequate combustible gas composition sustains a flare in the flaring unit. Banapurmath and co–authors (2009) also experienced a similar gas composition of 19% ± 3% CO and 18% ± 2% H_2 in a down – draft biomass gasifier used to produce approximately 17MW_{th} electricity[60]. Chawdhury and co-authors (2010) investigated the production of syngas from wood pellets and discovered the production of CO was between 19 to 22% and the production of H_2 was between 12 to 19 %[62]. Feedstocks which produced 15% of CO and 13% of H_2 were considered acceptable for gasification. Figure 4.1 shows the percentages of gases produced during gasification of pine pellets.

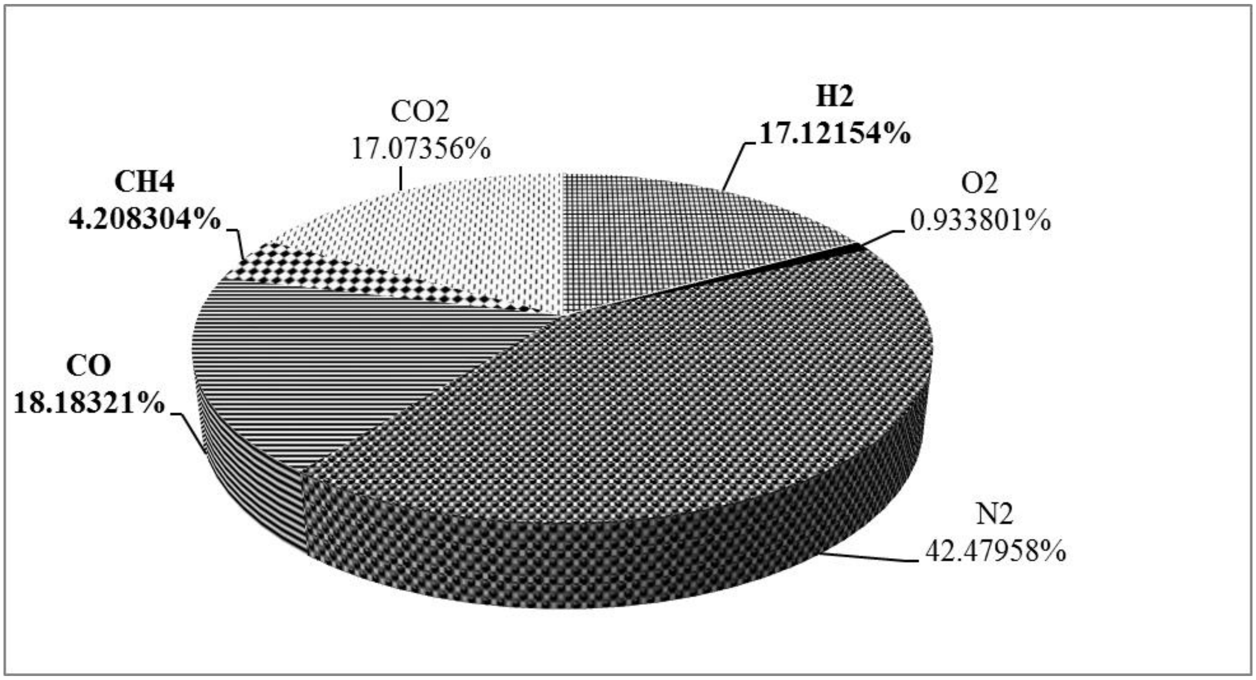


Figure 4.1: Composition of different gases in SYNGAS. Gasification of pine pellets resulted in almost 40% combustible gases.

Alfalfa resulted in low H_2 (<7.8%) and CO (<11.36%) because of high nutrient contents (figure 4.2). Boateng and co-authors (2006) tested alfalfa stem for pyrolysis and discovered that the percentage of CO produced was not more than 15% at 600˚C[63]. The alfalfa pellets tested for gasification in this research also resulted in less than 13% CO at 600˚C. Corn produced low percent of H_2 than cypress mulch. Factors which determined ideal characteristics of a gasification fuel did not qualify alfalfa, bark nugget and mulch as a gasification fuel, therefore, using alfalfa, bark nugget and mulch for CO production is not recommended, as their yield of CO was less than 13%. Tavasoli and co-authors (2009) found a similar pattern of 12% of H_2 and 16% of CO production when corn was tested in a downdraft gasifier[64]. Figure 4.2 shows an approximate percent of gases present in the composition of SYNGAS produced while testing the feedstocks for gasification.

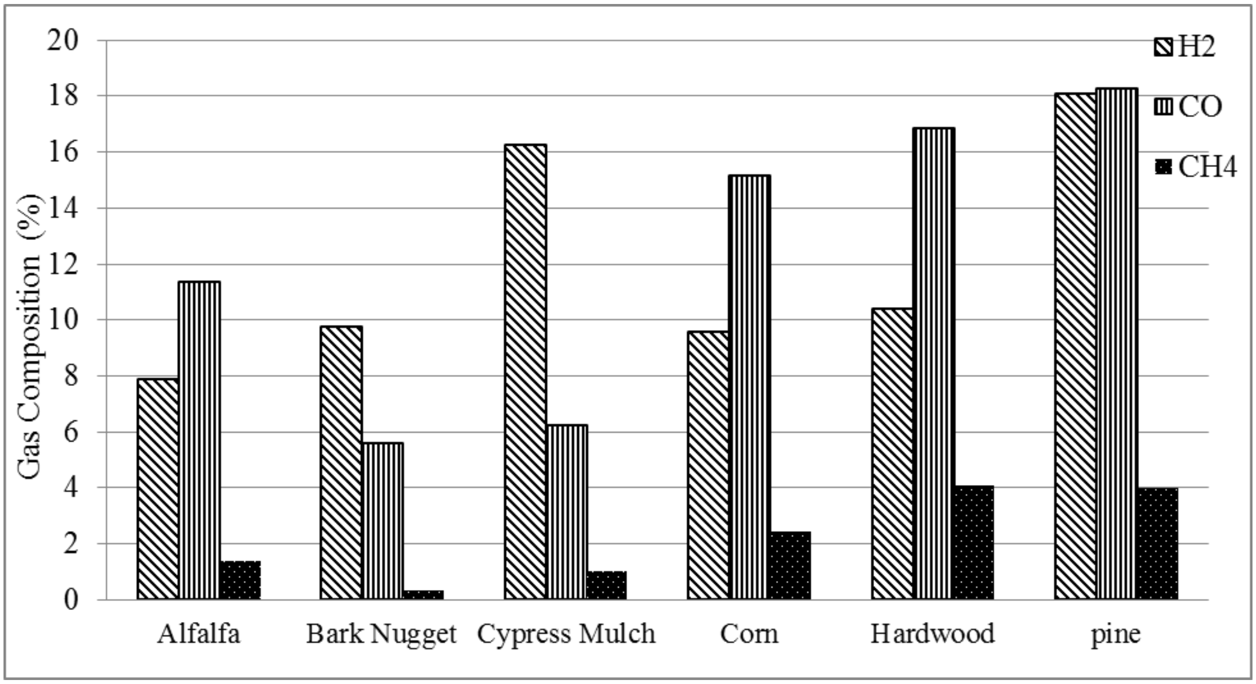


Figure 4.2: Comparison of different constituents of SYNGAS. Feedstocks with higher SYNGAS composition (>16% H2 and > 17% CO) were suitable for generating fuel.

Overall, highest combustible gases were generated by pine pellets (>18 % CO and 19 % H_2). These results were helpful in considering pine pellets to be an optimum fuel for SYNGAS production. Other analyses such as calorific value and volatile solids supported this result, as presented in the next paragraphs.

4.3 Characterization of Feedstocks

Anuradda and co-authors (1996) stated that the knowledge of various properties of biomass pyrolysis products relevant for energy conversion was essential for identifying the optimum utilization of each product[53]. Feedstock analysis and identification of its characteristics was an important aspect of gasification. Series of tests performed on different feedstocks helped in determining their characteristics. These tests were:

a) Finding the high heating value (HHV) or calorific value.
b) Finding the density.
c) Calculating the moisture content.
d) Calculating the volatile solid suspension (VSS).
e) Calculating the ash percentage.
f) Finding the nitrogen phosphorous & potassium content.

4.3.1 Calorific Value or High Heating Value – Bomb Calorimetry of Feedstocks

Calorific values of feedstocks were calculated from equation 3.3–1. Figure 4.3 shows the comparison of heating values generated by different feedstocks when tested in a bomb calorimeter.

Highest calorific value of approximately 8000 btu/lb. resulted from bomb calorimetry of pine pellets. This value is in agreement with the findings of Gil and coworkers (2010), who tested various feedstocks for their mechanical and combustion behavior and found that pine yielded in approximately 8300 btu/lb[65]. Calorimetry of bagasse yielded in approximately 6500 btu/lb. Kirubakaran and co-authors (2007) also discovered similar resulted when bagasse and corn stover was tested[66]. Demirbas (1997) tested corn stover pellets for high heating value and found approximately 7500 btu/lb[67]. This value was much higher than the heating value obtained for corn stover in this research (~5000 btu/lb). Hardwood pellets had a similar high heating value of 6000 btu/lb to that of Demirbas.

Calorific value of alfalfa pellets tested for this research was approximately 5000 btu/lb. High ash percentage (approximately 12 % ash) (high mineral content (phosphorous and potassium)) was likely responsible for low calorific values of alfalfa pellets in this analysis. However, DeLong, Boateng and coworkers (1995) found approximately 8000 btu/lb of calorific value when alfalfa was tested for high heating values. They reported that alfalfa had approximately 5.8 % ash[68,69]. This signifies that feedstocks with high ash percentage yielded low heating value.

4.3.2 Moisture and Density Content

The densities of various feedstocks were calculated using equation 3.3 -2. The density of different feedstocks influenced their feed-rates. Low density feedstocks needed high feed-rates,

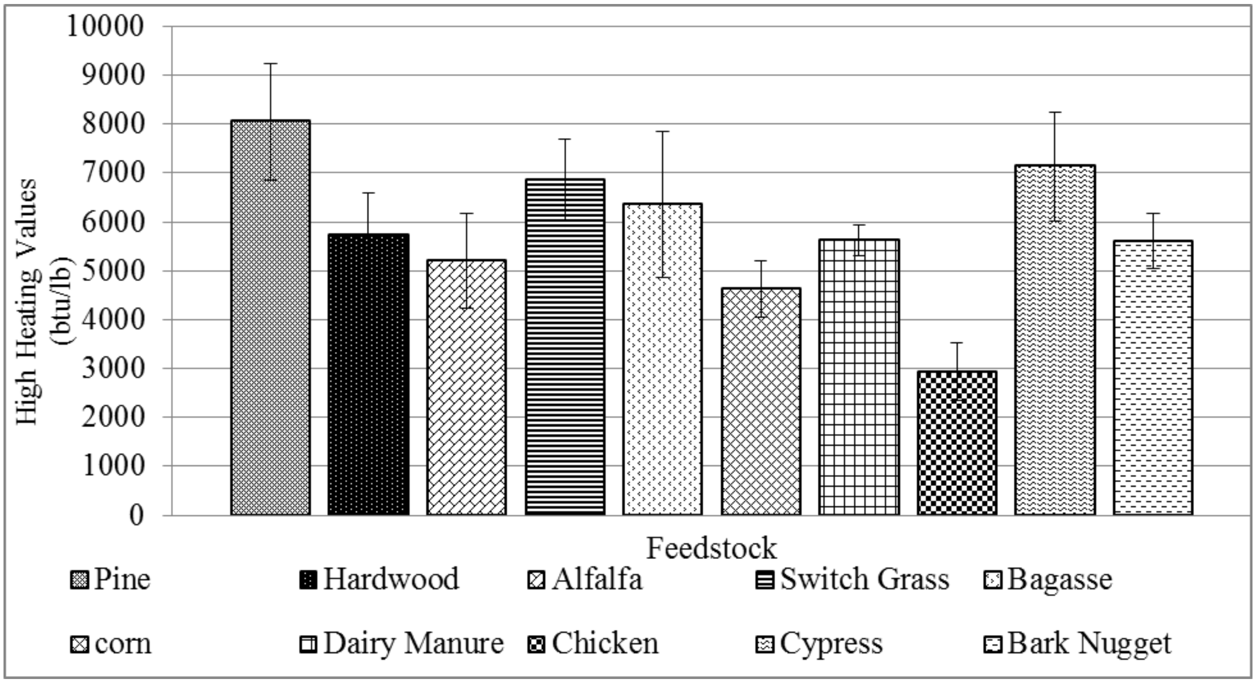


Figure 4.3: Comparison of high heating values or calorific values of different feedstocks. Higher calorific value signifies better energy content of a feedstock.

whereas mid-range density feedstocks had normal feed-rates. For example, feed-rate of cypress mulch, with density of 230 to 260 kg/m^3, was 18 lb/hr but feed-rate of compacted pine pellets, with density of 700 to 900 kg/m^3, was 6.5 lb/hr. High density feedstocks, such as dairy manure and poultry litter, ranging between 1000 to 1300 kg/m^3, could not be tested in the gasifier because of their unavailability in large quantities (> 200 lbs) in pelletized form. The 5 HP pelletmill failed to produce more than a few pounds of pellets. Figure 4.4 shows a comparison between different densities.

Wei (2009) analyzed the SYNGAS qualify from a down-draft biomass gasifier and discovered that moisture content affected gasification. Wei and co-authors (2009) stated that a difference in moisture content was reflected significantly in the temperature profile of the gasifying fuel[70]. High moisture content reduces the temperature achieved in the oxidation zone, resulting in the incomplete cracking of the hydrocarbons released from the pyrolysis zone.

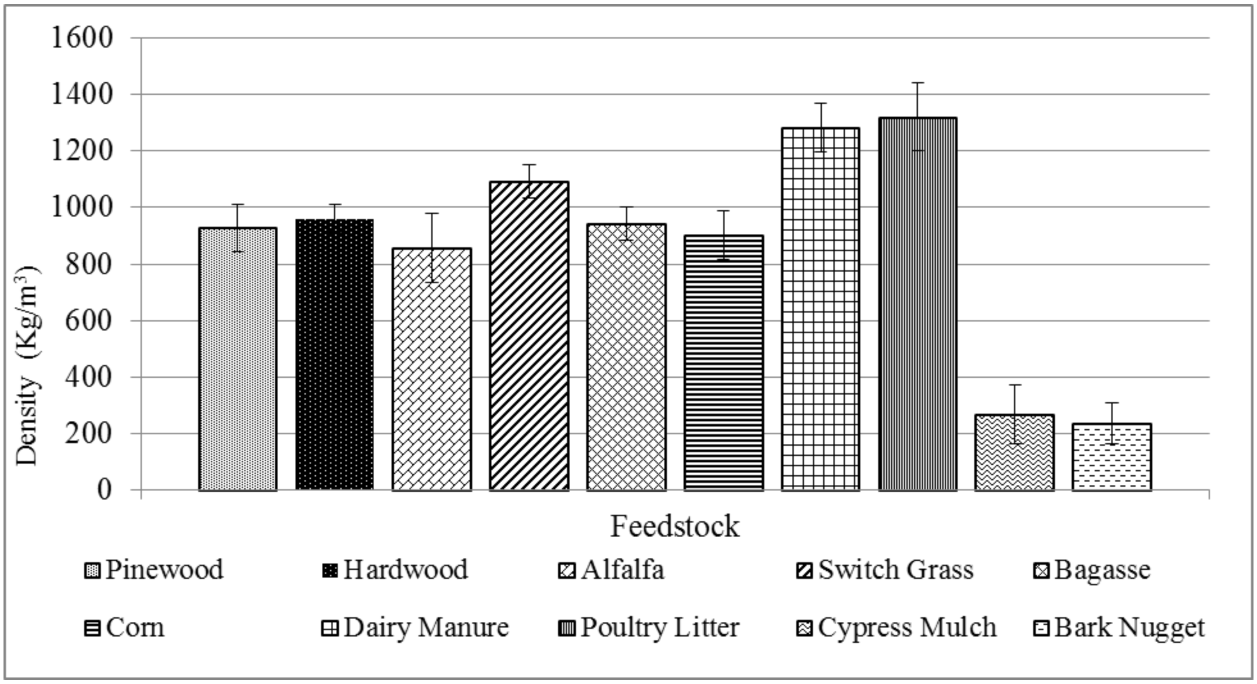


Figure 4.4: Density of Different Feedstocks Available – Extremely low density feedstocks did not gasify

Increased levels of moisture and the presence of CO produced more H_2 by the water gas shift reaction. The increased H_2 content of the gas produces more CH_4 by direct hydrogenation[58].

Moisture content was calculated using the equation 3.3–3. Moisture content below 7% is desirable for trouble free gasification. Pine and hardwood pellets had moisture around this range; therefore, was not subjected to additional drying. The moisture content of various feedstocks is depicted in Figure 4.5.

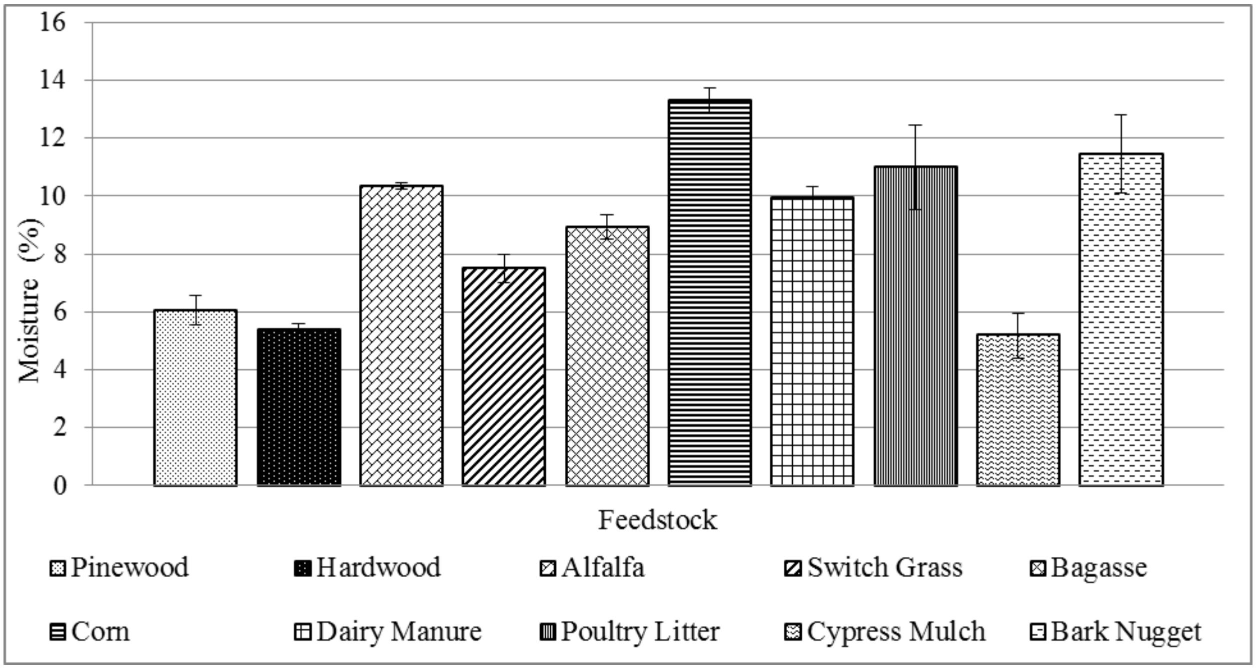


Figure 4.5: Moisture of different feedstocks. Feedstocks with moisture content < 7% was found to be ideal for gasification.

Optimum moisture content of 5.5% to 7% was found in pine and hardwood pellets. Corn stover pellets had close to 14 % moisture but it was dried to optimum moisture of 7%. Moisture of less than 7% was noted in cypress mulch. Akudo (2007) maintained 10% moisture of cypress mulch woodchips at the time of sampling for tars and particulates[71]. However, due to low density, which necessitated frequent feeding and valve opening, cypress mulch was found to be unsuitable for a batch feed system.

4.3.3 Volatile Solids and Ash Percentage

The average ash content in each feedstock is shown in Figure 4.6. The significance of ash content and volatile solids was discussed in section 3.3.3 with a brief procedure to calculate them. The equations 3.3 – 4 and 3.3 – 5 were used to calculate ash percentage and volatile solid percentage respectively. Carlson (1993) stated that chemical characteristics of the ash from energy generation will depend on a number of factors, including the type of feedstock, method of energy generation, air pollution control technology and power plant layout[72]. McKendry (2001) stated that high mineral matter can make gasification impossible. The oxidation temperature is often above the melting point of the biomass ash, leading to clinkering/slagging problems in the grate and subsequent feed blockages. Clinker formation was a problem for ash contents above 5%[59].

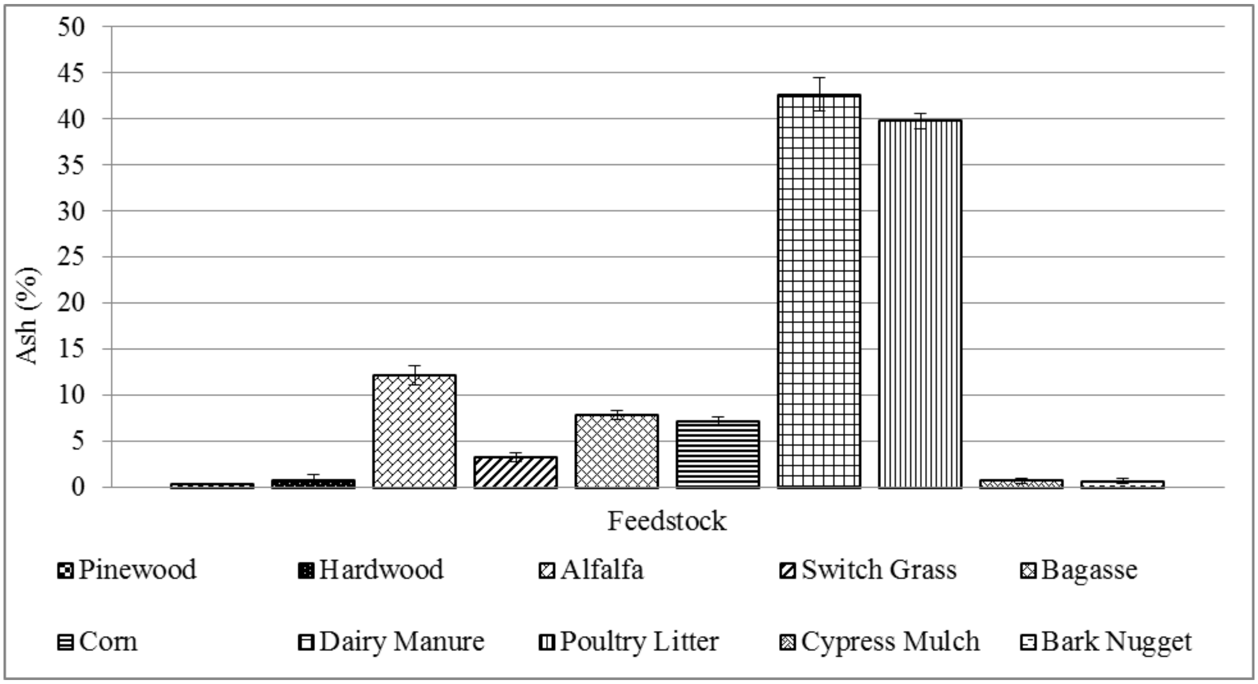


Figure 4.6: Ash percentage of different feedstock. Low ash percentage was desirable for gasification. Feedstocks with ash more than 10 % produced clinkers

In this analysis pine pellets had, as low as, 0.162 ± 0.1 % of ash and hardwood pellets had 0.85 ± 0.2 % of ash. Similarly, Gil (2010) found only 0.2 % ashes in pine sawdust[65]. Demirbas (1997) found approximately 1.7 % ash in pine and 2.7 % ash in hardwood[67]. Ash less than 8% and volatile solids greater than 90% were noted in cypress mulch bark nuggets, corn stover pellets, hardwood pellets and switchgrass pellets. As a result hardwood, corn and pine pellets gasified easily. Bowden and co-workers tested three different types of switchgrass available in northwestern Pennsylvania and found less than 5% of ash in all three samples of switchgrass[73].

Alfalfa had 12% ash and therefore failed to successfully gasify. DeLong (1995) found approximately 11.01 % of ash in the leaves of alfalfa from Olivia[68]. Chicken litter and dairy manure had approximately 40% ash. The higher ash content of the wastes collected for this research is likely due to use of sand as bedding for the dairy cows. The poultry litter had very

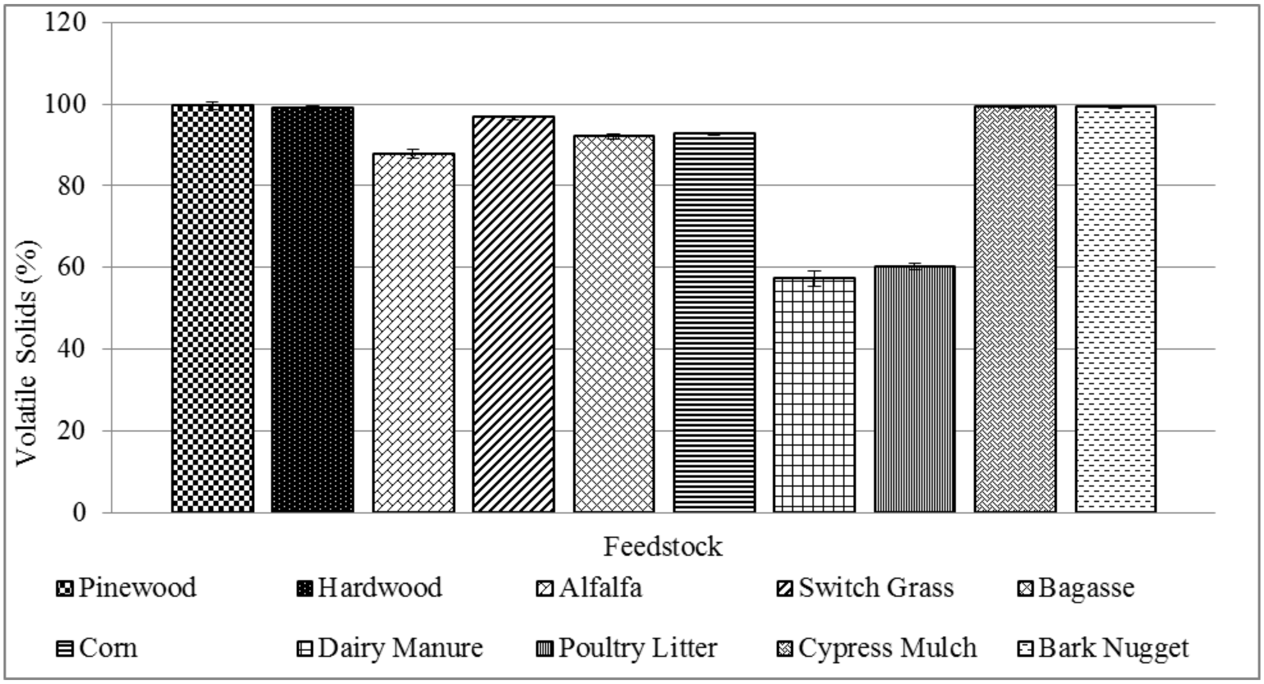


Figure 4.7: Volatile solids percent of different feedstock. High volatile solids percentage meant higher C content in the feedstock, in turn better calorific value

high mineral content and is heavily dependent on the ratio of bedding material (such as wood shavings, peanut hulls) and bird droppings.

Volatile solids content in different feedstocks is shown Figure 4.7. Alfalfa had in less than 85% of volatile solids. Dairy manure and chicken litter pellets had less than 60% volatile solids. High ash contentsand low volatile solids made dairy manure and chicken litter pellets inappropriate for gasification. These feedstocks did not qualify for gasification due to high mineral content (Chapter 4.1). Other feedstocks such as corn stover pellets had less than 6.69 ± .3% ash and more than 93± .3% volatile solids produced combustible gases and qualified as gasification feedstocks.

4.3.4 Analysis of Tars and Particulates

The concentrations of tars and particulates in the exiting gas were quantified. The

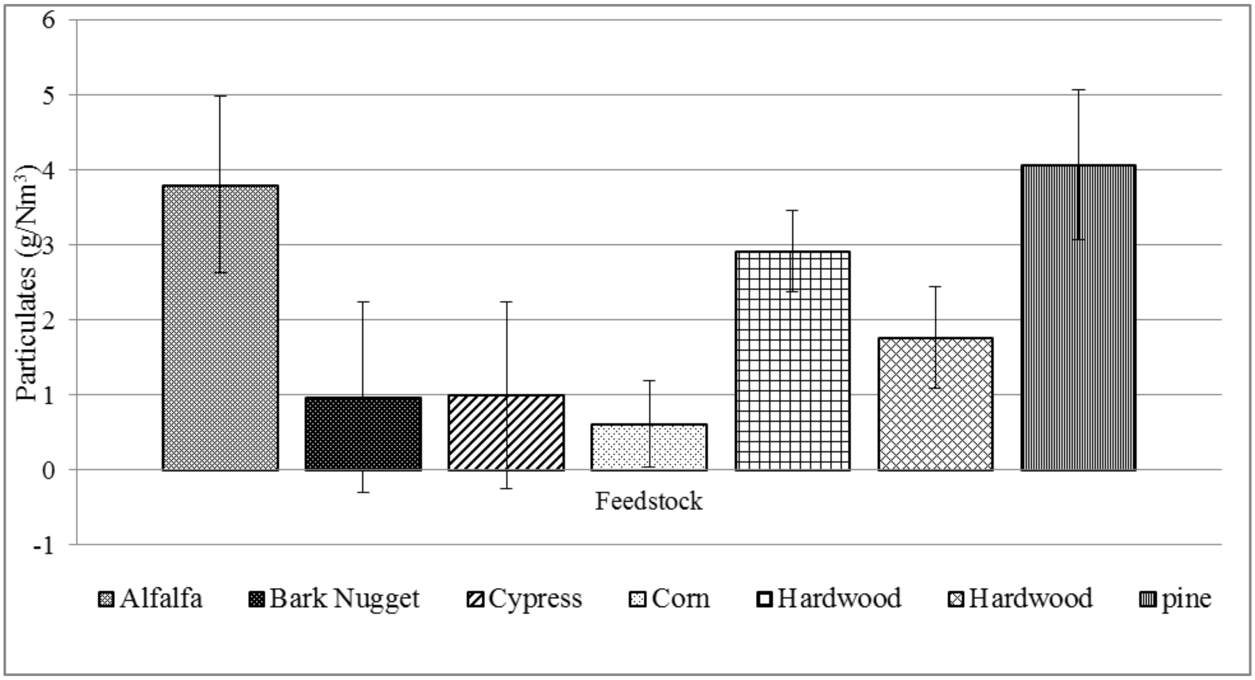


Figure 4.8: Comparison of particulates present in different feedstocks. High particulate concentrations lead to chocking of sampling lines and gas exit port.

sampling unit shown in section 3.3.4 was used to collect the samples. Figures 4.8 and 4.9 compare the tars and particulates present in different feedstocks, respectively. Gravimetric analysis of tars and particulates from a sample of syngas produced pine pellets indicated high tar and particulate concentrations. The particulate concentration varied between 0.6 g/Nm^3 to 4.6 g/Nm^3 and tars varied between 0.5 g/Nm^3 to 1.2 g/Nm^3. Figures 4.8 and 4.9 show pine pellets exhibiting high tar and particulate concentrations, as high as 0.80399 g/Nm^3 and 4.06377 g/Nm^3, respectively. Akudo (2008) observed similar tar concentration averaging 1.63 g/Nm^3 and particulate concentration averaging 3.84 g/Nm^3 [74]. High concentration of particulates (3.8 g/Nm^3) was observed in syngas generated from gasification of alfalfa pellets. Gasification of alfalfa pellets also formed clinkers, which caused clogging at the ash grate and the gas exit ports of the gasifier. Figure 4.10 to 4.13 shows the samples of tars and particulates collected for gravimetric analysis following the methodologies discussed in section 3.3.4.

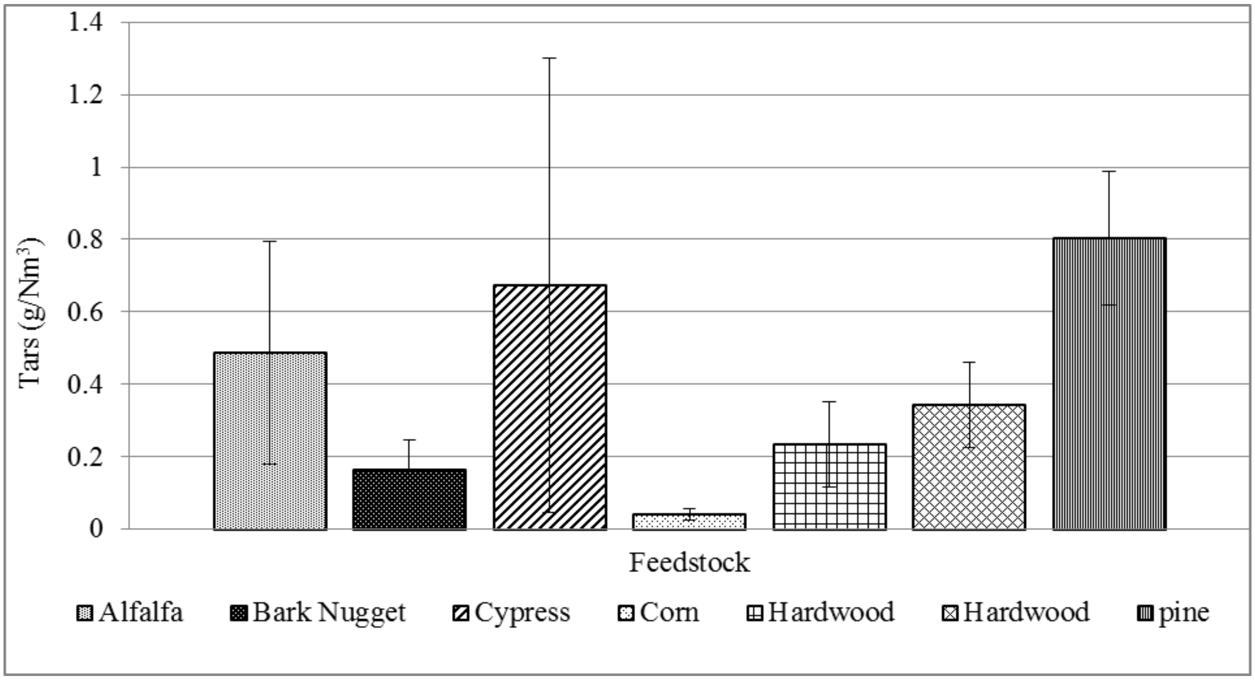


Figure 4.9: Comparison of tars present in different feedstocks. Higher tars resulted in clogging of gas exit port and grate.

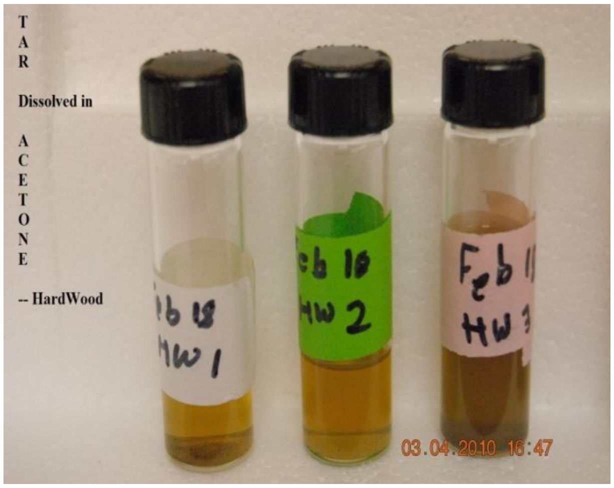


Figure 4.10: Tar collected in acetone from Hardwood

Figure 4.11: Tars and particulates from alfalfa feedstock.

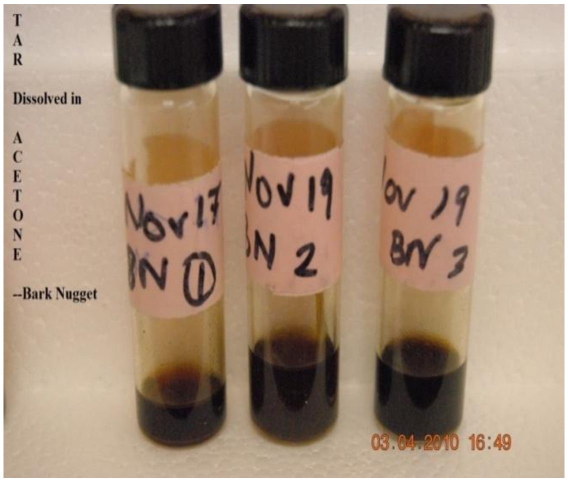


Figure 4.12: Tar collected in acetone from bark nugget

Figure 4.13: Dried tars from acetone (alfalfa feedstock)

4.3.5 Effect of Tar Cracking Catalyst on Tar Concentration

The tar concentration was reduced from 0.8 g/Nm^3 to 0.26 g/Nm^3 when a tar cracking catalyst was used to crack tars present in syngas produced by gasifying pine pellets. The catalyst was not expected to reduce the concentrations of particulates but, in the same experiment, the concentration of particulates was also reduced from approximately 4 g/Nm^3 to 1.2 g/Nm^3. The

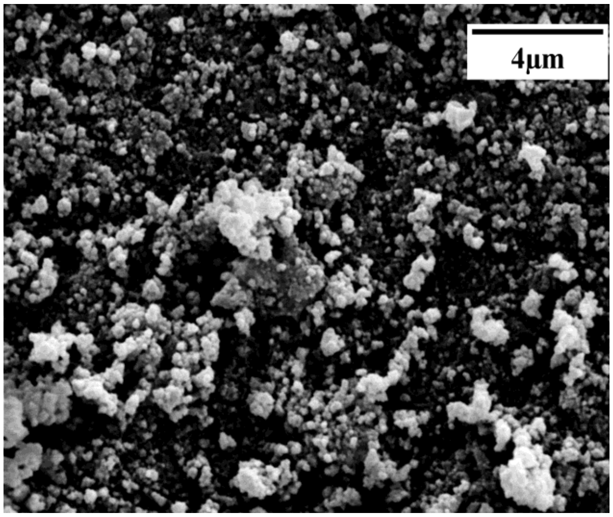


Figure 4.14: Tar cracking catalyst. Catalyst maintained at 550˚C. The surface did not crack or tarnish at this temperature.

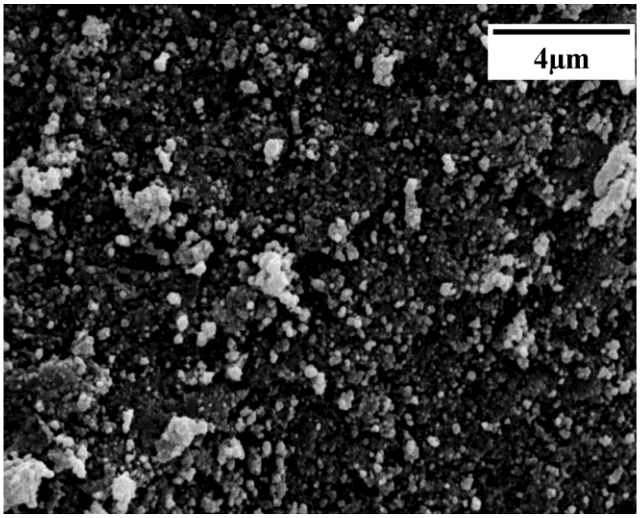


Figure 4.15: Tar cracking catalyst. Catalyst maintained at 450˚C. The surface did not crack or tarnish at this temperature

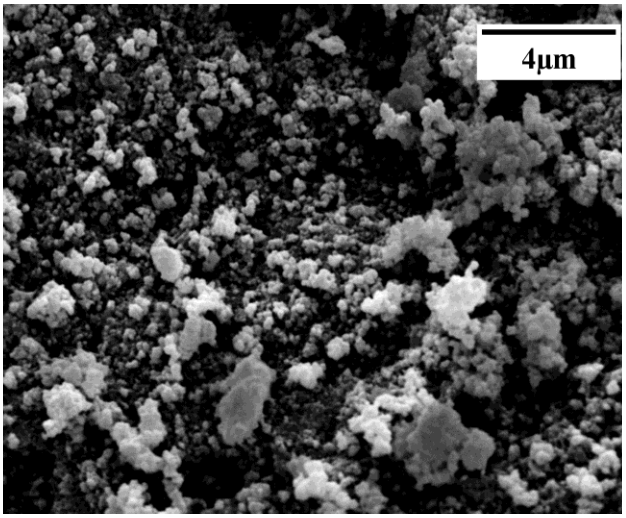


Figure 4.16 Tar cracking catalyst. Catalyst maintained at 650˚C. The surface did not crack or tarnish at this temperature.

catalyst was maintained at 550ºC in this experiment and was placed between the gas exit port and the particulate sampling unit.

Figure 4.17 shows the comparison of tars and particulates for pine pellets. Other characteristics such as moisture content, flow rate of gasification medium (air) and physical and chemical properties of the feedstock were not altered. Akudo and researchers (2008) observed the reduction in tar formation 0.85 g/Nm^3 to 0.09 g/Nm^3 when woodchips (cypress mulch) were tested in a down-draft biomass gasifier[74].

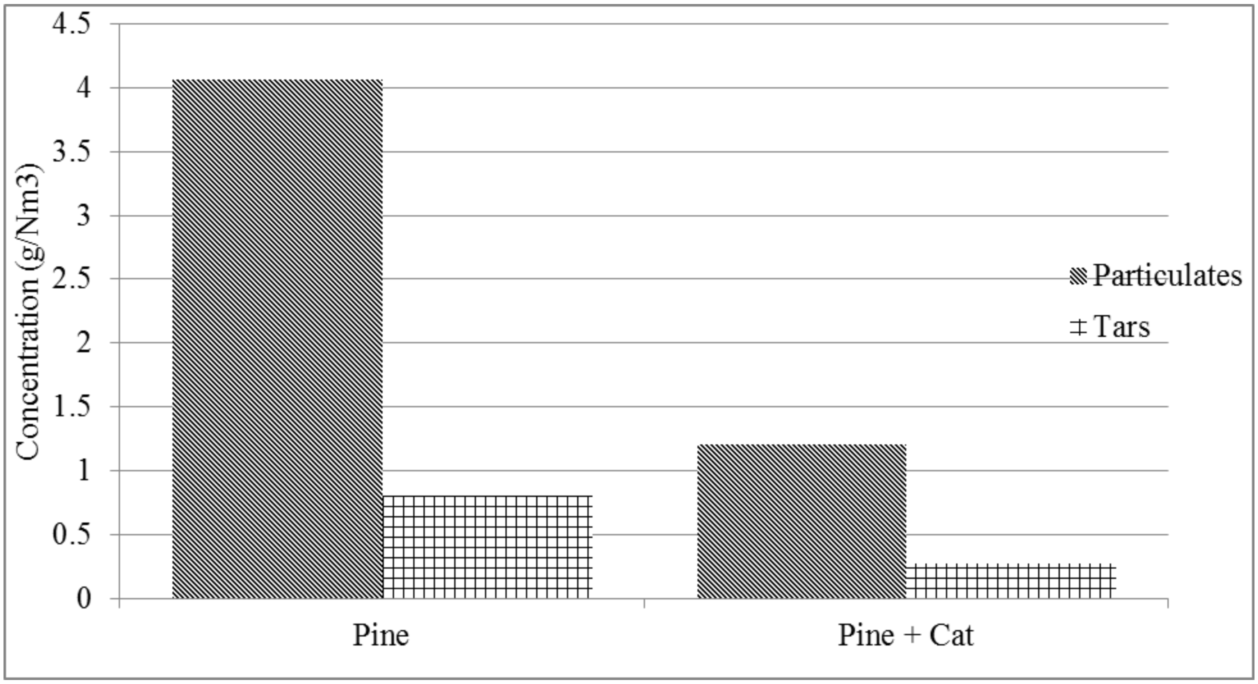


Figure 4.17: Concentration of Deposition of tars and particulates with and without the use of a tar cracking catalyst

4.4 Temperature Profile and Oxygen Sensor Readings

a) Temperature Profile

The time required for cypress mulch to reach the optimum temperature for gasification was half to that required by pine pellets. The low density of cypress mulch (Figure 4.4) was likely responsible for this behavior. The air flow was constant for both the feedstocks. This caused the cypress mulch to combust rather than to gasify. A probable cause of combustion of cypress mulch was due to inconsistent feeding. Figure 4.18 shows that Thermo # 5 and Thermo # 6 spiked to 450 ºC around the 2:00:00 hrs. As these two thermocouples are positioned above the air inlet point, high temperatures at this location is likely due to a partially empty gasifier chamber, which allowed the flames to go up into the upper sections of the gasifier. Low quantities of biomass in the chamber coupled with increased air flow rates (due to lowered resistance) likely caused the mulch to undergo combustion rather than gasification.

Figure 4.18 and 4.19 depict the internal temperature profile, which provides a better understanding of differences between gasification and combustion of feedstocks with different thermal and physical properties. In Figure 4.19 (pine pellets), the bottom two thermocouples (Thermo # 1 & 2) kept increasing until they reached steady state around 580 C. As the pellet consumption was slow, the manual feeding process was easy and did not cause any increases in Thermo # 3 and Thermo # 4 temperatures until the feeding was stopped at 3:15:00 hrs. Corn and

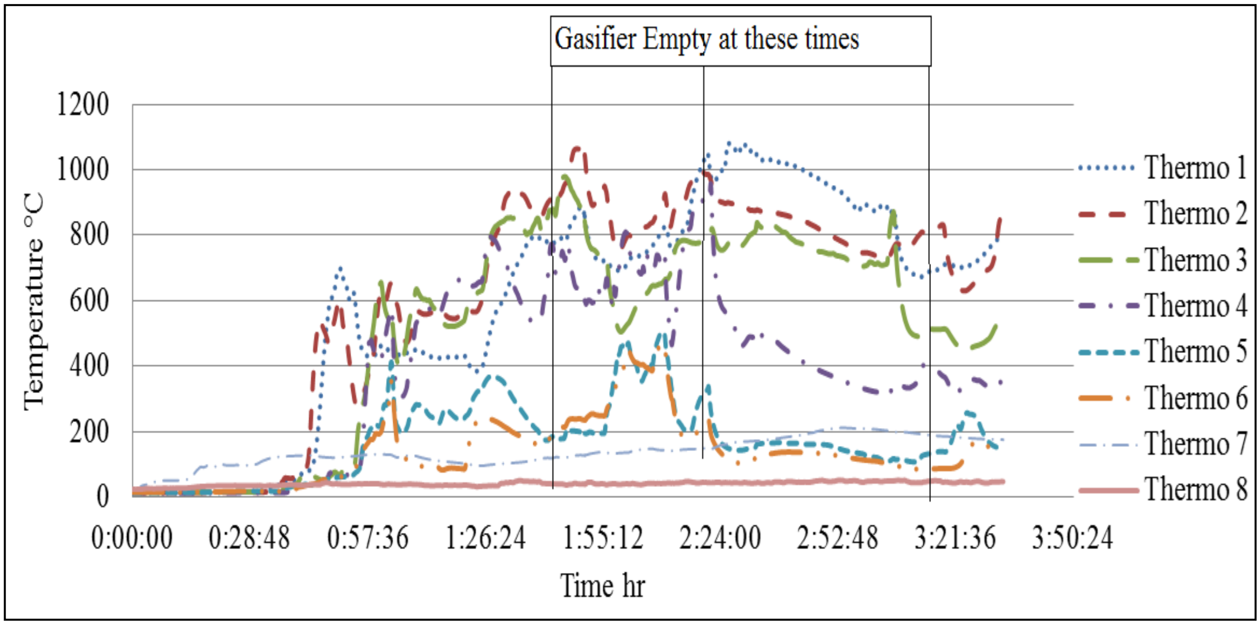


Figure 4.18: Cypress mulch gasification temperature profile. Quicker gasification than other feedstocks due to constant unmodified gasification agent (air) supply.

hardwood showed similar temperature profiles to that of pine pellets, which gasified successfully.

The decomposition of feedstocks between 350˚C and 500˚C initiated pyrolysis at temperatures above 450˚C. The sampling for gas composition was done at the time when thermo 2 (Figure 4.18 and 4.19) crossed 550˚C. The zone near Thermo # 2 physically represents the combustion section of the gasifier (Equation #1 and #2, Table 2.3). Wei and co-workers (2009) tested hardwood in a down-draft biomass gasifier. It was observed that pyrolysis of biomass took place between 200˚C and 500˚C[70]. A similar temperature profile was observed in feedstocks which were tested for gasification in LSU gasifier (Figure 4.18 and 4.19). A similar case was experienced by Wei and co-workers (2009) who explained that moisture content of a feedstock had a significant effect on the temperature profile of the feedstock. For the present research, the feedstocks with higher moisture contents and higher ash concentrations generally had an inconsistent temperature profile. Apparently, the changing temperature profile resulted in

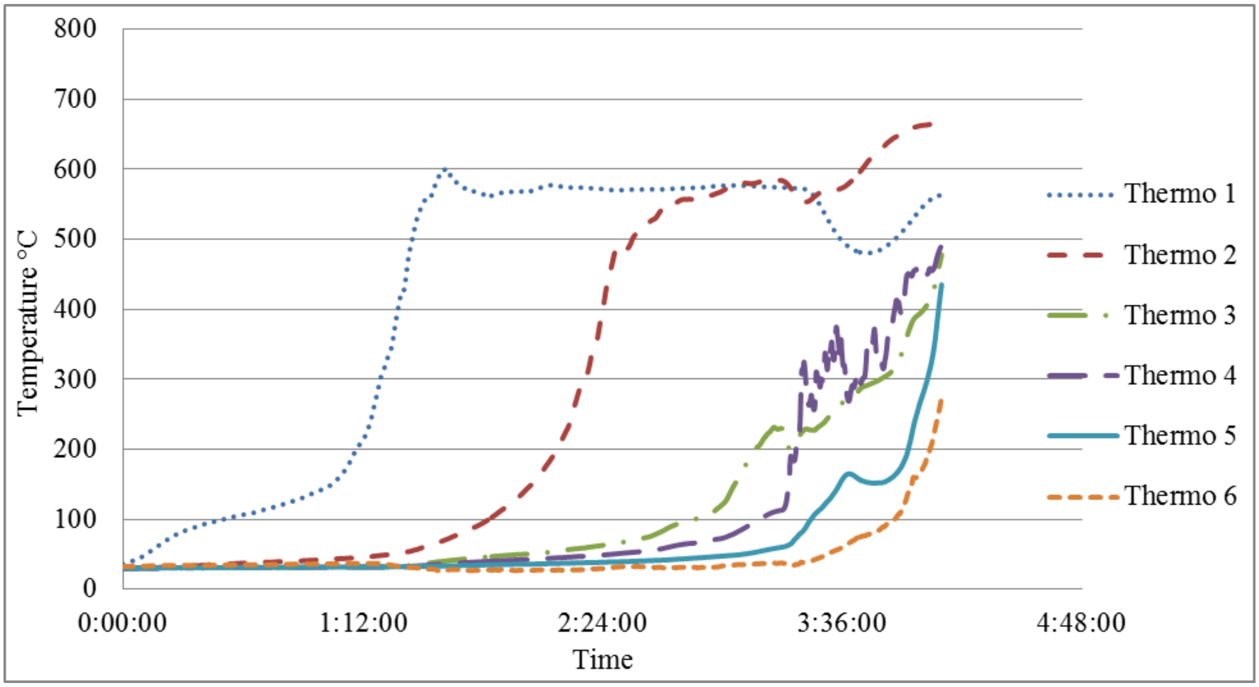


Figure 4.19: Temperature profile of pine pellets; 19 % CO and 17% H2 was observed after Thermo 2 reached 550˚C.

inconstant and altered reactions during gasification, and caused an increase or decrease of CO and H_2 concentrations inside the gasifier[70]. Kumar and co-workers (2009) quoted that at temperatures close to 600˚C, the endothermic nature of H_2 production reaction (Table 2.3 Equation # 5 to # 9) results in an increase in H_2 content[55]. The temperature profile resulted from gasification of pine pellets demonstrated a trend of constant gasification. Appendix 1.2 shows a temperature profile of bark nuggets which was affected due to the presence of moisture in the feedstock.

b) Oxygen Sensor

The Figures 4.20 and 4.21 depicts the oxygen concentrations: 1) inside the gasifier near the grate (Oxygen Sensor (i)), and 2) outside the gasifier and just before the flaring unit (Oxygen Sensor (O)). The oxygen inside the chamber depleted within 25 minutes of gasification experiment which led to generation of SYNGAS. When compared to the temperature profile

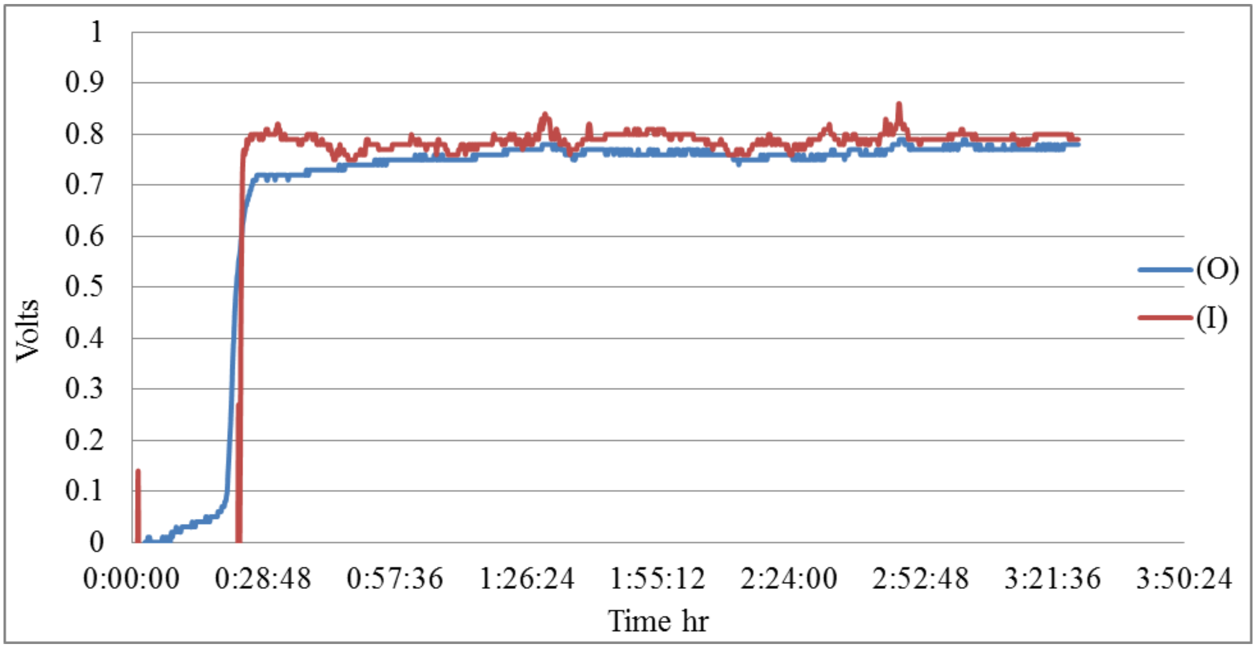


Figure 4.20: Bark nugget oxygen sensor profile. Oxygen present in substantial quantities inside and outside the gasification chamber represented by values less than 0.8 volts. This indicates that igniting the flame might result in combustion of feedstock.

(Figure 4.18), the depletion of oxygen (Figure 4.20) signifies the initiation of Equation # 1 and # 2 (Table 2.3). The gases which came out on the flaring end were rich in CO and H_2 (Figure 4.2). Oxygen profile of bark nuggets (Figure 4.21) shows the behavior of the oxygen sensor in case of excessive oxygen inside the gasification chamber. These low density feedstocks resulted in attaining gasification faster than pine, corn or hardwood pellets because the gasification agent (air) flow rates was not altered. The excess air volume resulted in low quality SYNGAS because of combustion and high CO_2 production.

The prime purpose of the two oxygen sensors was to monitor oxygen inside the gasification for safety reasons. The purpose of the second sensor was to serve as backup sensors. Both the oxygen sensors monitored the levels of oxygen and helped in detection of leaks or un-combusted oxygen. Oxygen at this point can cause a back flash, whereby, the flame from the flaring unit can travel back into the gasification chamber and combustion and ignite the

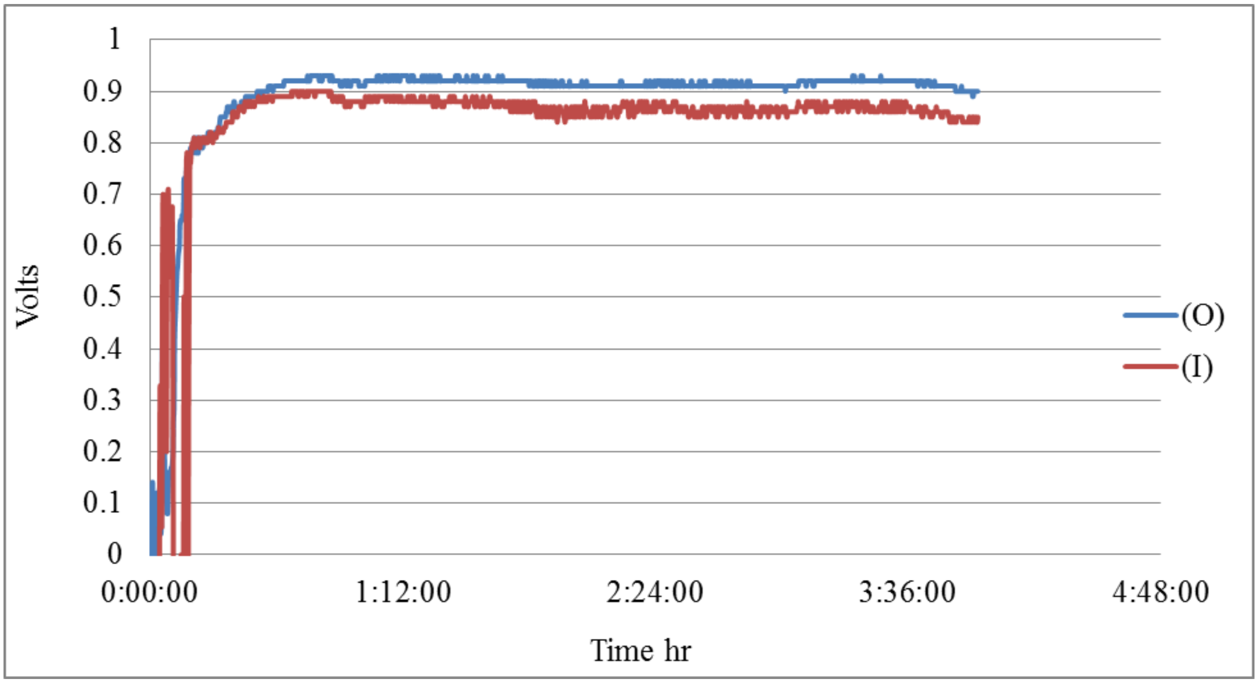


Figure 4.21: Oxygen sensor voltage readings for corn pellets. Depleted or zero oxygen concentration are indicated by a reading above 0.8 volts. This indicates the SNYGAS produced was safe to ignite.

combustible gasses in the pipes. Excessive oxygen concentrations can also indicate poor gasification or excess air flow rates. For the down-draft gasifier at LSU, a blower was used to push in the gasification agent. However, for certain designs, a blower is used to sucks the gasification agent. For the gasifiers that operate with negative pressure, high oxygen levels can also indicate leaks in the system, which can lead to explosions near the blower or during gas conditioning.

4.5 Ultimate and Proximate Analysis

The N, C and H analyses were performed to analyze the organic and nutrient constituents of feedstocks. The carbon content is a direct measure of suitability of a feedstock for gasification. Raveendran and co-researchers (1995) found 55 % of C and approximately 4% of H_2 in both corn and bagasse from ultimate analysis[56]. Similar results were noticed in corn and bagasse tested for this research at Agcenter's W.A. Callegari Environmental Center. Alfalfa on the other hand produced less than 43% C and less than 2% H. Timper (2000) found similar percentages of C and H (43% and 5.62%, respectively) when alfalfa was tested for ultimate analysis. Alfalfa had approximately 4.16% of sulfur which was in line with Timper's analysis[75]. High potassium and sulfur content, although generate ash with higher nutritive value, they made the feedstock difficult to gasify. Raveendran and co-workers (1995) stated that high inorganic material in biomass traps the carbon particles, making it unavailable for conversion[56]. The tested total P in alfalfa fly ash was higher than the reported 5 and 6 gm/kg for dairy and hog manure and was comparable with 14.5 gm/kg for boiler litter as reported by Eck and Stewart (1995), who also indicated that alfalfa ash was richer in these nutrients than the above organic fertilizer[76 77].

Whereas, pine pellets had almost 42% of C which was in line with Gil's (2010) discovery of 45% of C in pine sawdust[65]. It was concluded that that the very low inorganic content made it a better gasification fuel than alfalfa. Narvaez and researchers (1996) also found almost 50% of C and almost 6% of H_2 in pine sawdust, which was tested for its suitability in a fluidized bed biomass gasifier[43].

Animal waste feedstocks such as dairy manure and chicken litter had approximately 25% and 23% of C and approximately 3.2% and 0.7% of H. Eck and researchers (1995) reported a range of 15 to 22, 14 to 20, and 3 to 6% respectively for K, Ca and Mg for hog, dairy, and boiler manure[77].

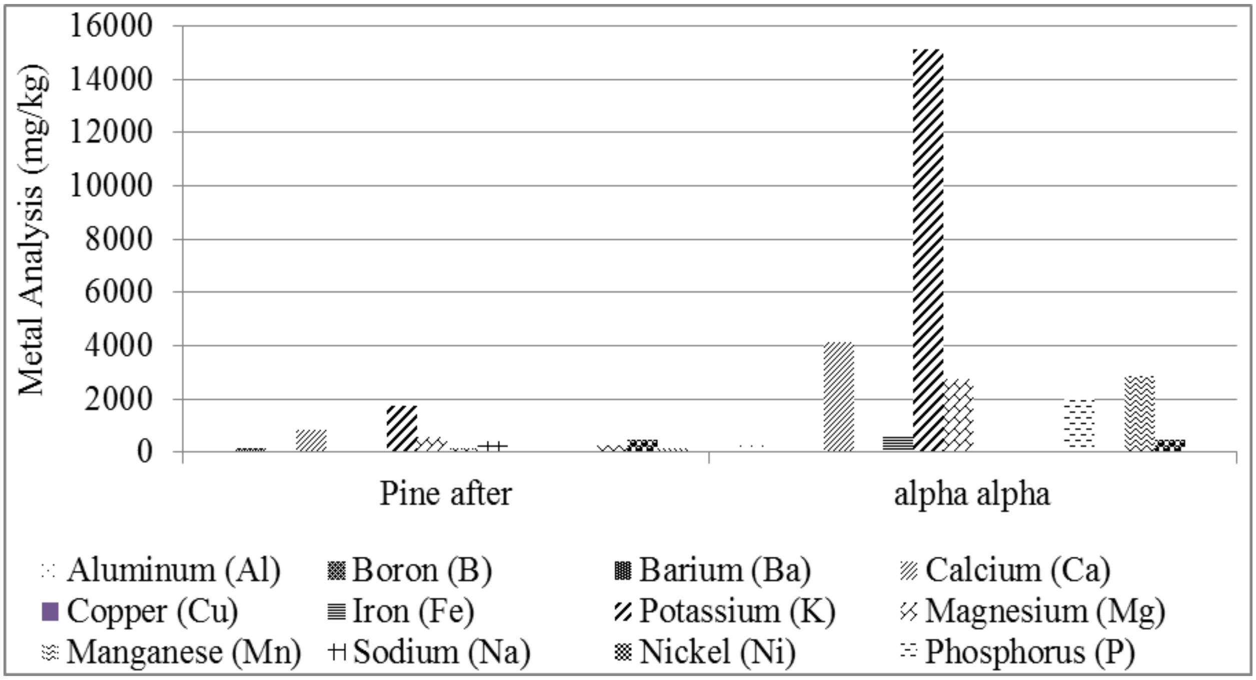


Figure 4. 22: Comparison of different metals present between a gasifying and a non-gasifying feedstock. The excess amount of inorganic compounds present in alfalfa made it a non-gasifying feedstock for gasification.

Similarly, alfalfa had high inorganic content. Figure 4.22 shows the metal concentrations in two feedstocks, out of which alfalfa did not qualify for gasification. On the hand, pine pellets contained low inorganic content. This resulted in low ash percentage and high calorific value of pine pellets. The metal concentrations all feedstocks tested in this research are presented in appendix 1.5.

The Figure 4.23 shows the presence of organic C along with percentage of nitrogen, which has been reported as a fertilizer for crops. This plot shows the CHN values of all the feedstocks before and after gasification. Pine pellets, corn stover pellets, bark nugget and hardwood pellets had high organic carbon than "potential fertilizer feedstocks" such as alfalfa, dairy manure and chicken litter, which have higher nitrogen content.

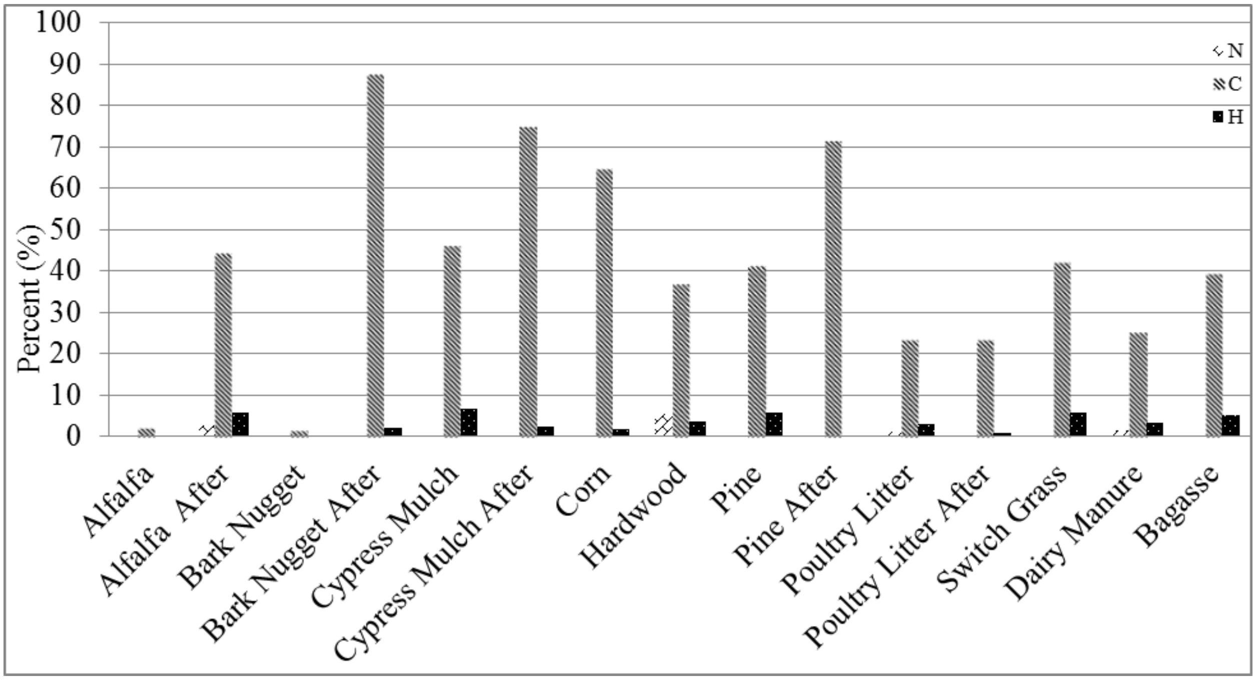


Figure 4.23: Comparison of Ultimate Analysis of different feedstocks and their ashes. Higher Carbon content (C) implied better heating value. ("After" = after gasification).

CHAPTER 5: CONCLUSION

5.1 Summary of Results

Gasification of biomass has been an old and proven technology. Clean SYNGAS can be used in numerous applications. DeGroot (1990) stated that gasification is the direct thermochemical conversion of biomass to a hot fuel gas in a gasifier unit[78]. Brushwood and co-workers (1998) stated that the fuel gas can be used to generate steam, which runs a turbine that generates electricity[79]. Williams and co-authors (1996) studied that electricity generation by the "new combined cycle gasification method" and indicated that gasification was more efficient than the traditional combustion method of energy generation[80].

Currently in the United States only 2.7 quadrillion Btu's of installed biomass capacity is available[9]. In order to reduce the dependence on foreign oil, many different technologies will have to be employed together across the nation. Gasification has the potential to offset the need for fossil fuels and provide the nation with cleaner "alternative fuel".

The objectives of this research have been met through a series of experiments designed to analyze Louisiana biomass-based feedstocks for their thermal and physical properties. A down-draft biomass gasifier was used to analyze the suitability of six different feedstocks for gasification. Temperature was an important parameter in the process of biomass gasification. It was concluded that temperatures nearing 250˚C started the process of pyrolysis (Equation #1 and #2, Table 2.3) and gasification was initiated at approximately 650˚C (Equation #5 to #10, Table 2.3). The initiation of gasification meant the production of SYNGAS. Sampling unit shown in Figure 3.2 was used to collect the samples for quantification of tars and particulates in SYNGAS. The gas was also tested for composition using a gas chromatographer.

Ten different feedstocks were tested for physical and thermal properties, amongst which six were tested in the gasifier. Four feedstocks were either not suitable or was not available in pelletized form in large enough quantities for conducting a full gasification run. It was noted that pine and hardwood pellets demonstrated optimum results in the laboratory tests conducted for thermal and physical properties. Both these feedstocks had approximately 6% moisture and approximately 1% ash. The heating value of pine was found to be 8000 btu/lb. Calorific value of hardwood pellets, cypress mulch and switchgrass pellets was found to be 6000 btu/lb. It was observed and noted from previous studies that moisture content of a feedstock had a major bearing on the on the calorific value of the feedstock and the temperature profile within the gasifier.

Corn and bark nugget initially contained 13% moisture and had to be dried to 5% ~ 6% for successful gasification. Moisture content of cypress mulch was close to 7%. Alfalfa was dried to 5 % moisture for gasification, but high percentage of minerals (for example P, K and Ca) in the feedstock it made unsuitable for gasification.

Corn yielded lowest tars and particulates concentration (0.040 g/Nm^3 tars and 0.613 g/Nm^3 particulates) in the group. It was difficult to understand why concentration of tars collected from sampling pine pellets was significantly high (4.063 g/Nm^3 of particulates and .8039 g/Nm^3 of tars). The ideal physical and chemical properties of pine pellets do not support the high tar and particulate concentrations noticed in resulting SYNGAS. Numerous factors such as design of the gasifier, pellet moisture content, gasifier temperature profile, ambient temperature and relative humidity could affect the generation of tars and particulates. Alfalfa had large quantities of nutrients such as phosphorous and potassium present in the feedstock which explained the high ash percentage and tar formation on gasification.

When a tar cracking catalyst was used in the sampling unit, the concentration of tars generated from pine pellets dropped from 0.8039 g/Nm^3 to 0.2676 g/Nm^3. These gasifier results, coupled with ideal physical, chemical and thermal properties of pine pellets (such as low ash content, high heating value, low mineral content, high volatile solids content) and the abundance of pine in the state of Louisiana, make pine pellets an ideal source of alternate energy in Louisiana.

5.2 Future Opportunities and Suggestions

Gasification can be a sustainable source of alternate energy for mega corporations such as paper and pulp industries, furniture stores and petroleum industries. It can also create opportunities for experimenting new mixtures such as glycerol mixed with pine or corn pellets. Glycerol, produced as a side product while converting used vegetable oil to bio-diesel at LSU Agcenter's W.A. Callegari Environmental Center, was mixed with pine pellets and tested in the gasifier as demonstration project. Although, this experiment was outside the scope of this thesis, results from this demo run indicated a high quality SYNGAS (not discussed in this thesis).

The fuel (SYNGAS) can be either used in turbines or liquefied for producing biodiesel. These options give us infinite opportunities to study biomass gasification and make the best use of technology available to us. The use of other products such as pine cones, municipal waste, furniture debris and dairy waste are also being studied at different locations in the world for gasification, resulting rich carbon-hydrogen chains, able to reproduce simple carbon-hydrogen chains to be used as different fuels.

With the quantity of biomass available today, there are infinite opportunities for gasification to succeed as an alternate source of energy

REFERENCE

[1] Tavasoli A., Ahangari G. M., Soni C., Dalai K. A., 2009. Production of hydrogen and syngas via gasification of the corn and wheat dry distiller grains (DDGS) in a fixed-bed micro reactor. Fuel Processing Technology 90 (2009) 472–482.

[2] Energy Information Administration, 2007.

[3] Dincer I. Environmental issues: I-energy utilization. Energy Source 2001; 23:69–81.

[4] Goudie A. S., 2006. Global warming and fluvial geomorphology. Geomorphology 79 (2006) 384–394

[5] Isoard S., 2010. The European Environment, State and Outlook 2010: Adapting to Climate Change**.** Luxembourg: Publications Office of the European Union, European Environmental Agency. 2010 ISBN 978-92-9213-159-3 doi: 10.2800/58998.

[6] Stevens D. J., 2001. Hot Gas Conditioning: Recent Progress with Larger-Scale Biomass Gasification Systems. Pacific Northwest National Laboratory NERL/SR 510-29952.

[7] Rezaiyan J., Cheremisinoff N. P., 2005. Gasification Technologies: A Primer for Engineers and Scientists

[8] McKendry P., 2002. Energy production from biomass (part 1): overview of biomass Applied Environmental Research Centre Ltd, Tey Grove, Elm Lane, Feering, Colchester CO5 9ES, UK.

[9] Jason Midget J., 2008; Assessing Hydrothermal Liquefaction Process Using Biomass Feedstocks: Louisiana State University; Thesis

[10] Babu S. P, Thomas P., 1992. Biomass Thermal Gasification Project Biomass and Bioenergy; IEA Vol 2, Nos 1 – 6m pp, 299 – 306

[11] Hall D. O., 1991. Biomass Energy, Energy Policy, 19 (8) pg: 71 l – 737.

[12] Wang, C., Wang, F., Yang, Q., Liang, R., 2009. Thermo-gravimetric studies of the behavior of wheat straw with added coal during combustion. Biomass Bioenerg. 33, 50–56.

[13] Rhen, C., Ohman, M., Gref, R., Wasterlund, I., 2007. Effect of raw material composition in woody biomass pellets on combustion characteristics. Biomass Bioenerg. 31, 66–72.

[14] Gasification.org, 2008. Gasification: Redefining Clean Energy. Gasification Technology Council.

[15] Jackson S. W., 2003. Louisiana Biomass and Bioenergy Overview, Southeastern Sun Grant Center Chyrel Mayfield, Texas A&M University

[16] LSU AgCenter. (2006). Biomass Energy Resources in Louisiana. RIS-102, Updated Nov, 2006. LSU AgCenter

[17] Souza-Santos M. L., 2004. Solid Fuels Combustion and Gasification – Modeling, Simulation, and Equipment Operation, Marcel Dekker Inc, New – York.

[18] Pinto F., Andre R. N., Gulyurtlu I., 2009; Innovation on Biomass Waste Utilization Through Gasification And Co-Gasificaiton Stage of Development and Needs for Further R&D. Biomass Gasification: Chemistry, Processes and Application ISBN: 978 – 1 – 60741 – 461 – 2. Nova Science Publisher, Inc. Ineti, Estrada do Paco do Lumiar, 22, 1649 – 038 Lisboa, Portugal.

[19] Lewis M. F., Ablow C. M., 1980. Thermodynamics of Pyrolysis and Activation in the Production of Waste or Biomass – Derived Activated Carbon. Thermal Conversion of Solid Wastes and Biomass; Chapter 23 pp 301 – 314.

[20] Wei, L. (2005). Experimental study on the effects of operational parameters of a downdraft gasifier

[21] Zainal Z. A., Ali R., Quadir G .A., Seetharamu K .N., 2002. Experimental Investigation of a Downdraft Biomass Gasifier. Biomass And Bioenergy; 23, 283 – 289

[22] Brown,R.C.(1994). Conversion Technology, In the Potential for Biomass Production and Conversion in Iowa-Final Report to Iowa Energy Center, Chp 4,209-260. Department of Mechanical and Chemical Engineering, Iowa State University, Ames, Ia.

[23] Graham, R. L., Downing M., Walsh M. E., 1996. A Framework to assess regional environmental impacts of dedicated energy crop production. Environment Management, 20: 475-485.

[24] Douglas S. D, Smith, P. J., 1985 Coal Combustion and Gasification, Plenum Press New – York, USA.

[25] United States Department of Energy. 1999; Program Plan: Clean Energy Plants for the 21st Century. Vision 21.

[26] Gasification: Robust Growth Forecast, 2004; Current Industry Perspective- World Survey Results; U.S Department of Energy- Office of Fossil Energy; National Energy Technology Laboratory Pg 4;

[29] Zainal Z. A., Ali R., Lean C. H., Seetharamu K. N., 2001. Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. Energy Conversion and Management Volume 42, Issue 12, Pages 1499-1515

[30] Narvaez I, Orio A, Aznar M. P., Corella J. 1996. Biomass gasification with air in an atmosphere bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. Industrial and Engineering Chemistry Research; 35(7): 2110–20.

[31] Delgado J., Aznar M. P., Corella J., 1997. Biomass Gasification with Steam in Fluidized Bed: Effectiveness of CaO, MgO, and CaO–MgO for Hot Raw Gas Cleaning. Industrial and Engineering Chemistry Research. 36(5):1535–43.

[32] Goldman Y., Timnat Y. M., Arfi P., 1997. Moving Matrix Reactor for Biomass And Organic Waste Gasification. Proc. of the ASME Heat Transfer Division. HTD-Vol.352. p. 239 –48.

[33] Paisley M. A., Anson D., 1997. Biomass Gasification for Gas Turbine Based Power Generation. New York, NY: American Society of Mechanical Engineers. 97-GT-5.

[34] Overend, R. P. (1991). Biomass Electric Power Status and Five-Year Plan. Biomass Power Program. SERI, Golden, Colorado, U.S.A.

[35] Commission of the European Communities, Final Communication from the Commission, Biomass action plan, COM (2005) 628, SEC (2005) 1573, Brussels, 7 December 2005.

[36] Stiegel G. J., Maxwell R.C., 2001. Gasification Technologies: the path to clean, affordable energy in the 21st century. Fuel Processing Technology 71, 79 – 97

[37] Duret A., Friedli C., Marechal F., 2005. Ecole Polytechnique Fe´de´rale de Lausanne. Process Design of Synthetic Natural Gas (SNG) Production Using Wood Gasification, Switzerland. CH-1015 Lausanne

[38] Ferreira M. F., Ferreira M. C., 1994. Energetic Potentials Of Invited Cultures Of Plant Cells: Crude Oil Produced By Calli and Cell Of Euphorbia Characias. World Renewable Energy Conference, Reading.

[39] Sims R., 1994. Electricity Generation From Wood Biomass Fuels Compared With Other Renewable Energy Options. World Renewable Energy Congress, Reading.

[40] His C., Wang T. Y., Tsai C. H., Chang C. Y., Liu C. H., Chang Y. C., Kuo J. T., 2008. Characteristics of an Air- Blown Fixed – Bed Downdraft Biomass Gasifier. Energy & Fuels; 22, 4196–4205

[41] Bailey O., Worrell E., 2000. Clean Energy Technologies: A Preliminary Inventory of the Potential for Electricity Generation Energy Analysis Department. Environmental Energy

Technologies Division. Ernest Orlando Lawrence Berkeley National Laboratory. University of California Berkeley, CA 94720

[42] U.S. Department of Commerce/International Trade Administration, 2000. U.S. Industry & Trade Outlook 2000. U.S. Department of Commerce, McGraw-Hill.

[43] Narvaez I, Orio A, Aznar M. P., Corella J. 1996. Biomass gasification with air in an atmosphere bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. Industrial and Engineering Chemistry Research; 35(7): 2110–20.

[44] Texaco Gasification Process: Innovative Technology Evaluation Report, 1995. National Risk Management Research Laboratory; Office of Research and Development U. S Environmental Protection Agency Cincinnati OH 45268, EPA/540/R-94/514

[45] Hughes W., Larson E. D., 1997. Effect of Fuel Moisture Content on Biomass-IGCC Performance. American Society of Mechanical Engineers. New York, NY: 97-GT-4.

[46] Jorapur R, Rajvanshi A. K., 1997. Sugarcane Leaf-Bagasse Gasifiers for Industrial Heating Applications. Biomass and Bio-energy; 13(3):141–6.

[47] Skoulou V., Zabaniotou A., Stavropoulos G., Sakelarpoulos G., 2008. SYNGAS Production from Olive Tree Cuttings and Olive Kernels in a Downdraft Fixed – Bed Gasifier. International Journal of Hydrogen Energy. 33,1185 – 1194

[48] Olofsson I., Nordin A., Söderlind U., 2005. Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels. Energy Technology & Thermal Process Chemistry; ISSN 1653-0551 ETPC Report 05-02.

[49] Whatman Ltd., 2007 – 2009 Glass Fiber Filter. http://www.whatman.com/GlassMicrofiberBinderFree.aspx

[50] Sharma S.D., Dolan M., Park D., Morpeth L., Ilyushechkin A., McLennan K., Harris D. J., Thambimuthu K.V., 2007. A Critical Review of SYNGAS Cleaning Technologies — Fundamental Limitations and Practical Problems. Centre for Low Emission Technology, Queensland Centre for Advanced Technologies, PO Box 883, Kenmore, Queensland 4069, Australia

[51] Jin Q., Yang W., Yua A., Tlan X., Wang F., 1996. Helium Direct Current Discharge Ionization Detector for Gas Chromatography. Department of Chemistry, Jilin University, Changchun 130023, China School of Preventive Medicine, Bethune University of Medical Sciences, Changchun 130021, China

[52]Sheng C., Azevedo J.L.T., 2004. Estimating the higher heating value of biomass fuels from basic analysis data; Mechanical Engineering Department, Instituto Superior Te´cnico, Pavilha˜o de Meca˜nica I, 21 Andar, Av. Rovisco Pais, 1049-001 Lisbon, Portugal.

[53]Raveendran K., Ganesh A., 1996. Heating Value Of Biomass and Biomass Pyrolysis Products; Fuel Vol. 75, No. 15, pp. 1715-1720.

[54]Turare C., ARTES Institute, University of Flensburg, Flensburg, Germany http://cturare.tripod.com/fue.htm#moisture

[55]Kumar A., Jones D. D., Hanna M. A., 2009. Thermochemical Biomass Gasification: A Review of the Current Status of Technology. *Energies* 2, 556 – 581; doi: 10.3390/20300556. ISSN 1996-1073

[56]Raveendran K., Ganesh A., Khilart K. C., 1995. Influence of mineral matter on biomass pyrolysis characteristics. *Fuel* Vol. 74 No. 12, pp. 1812-1822.

[57]Lickacz J., 2002. Wood Ash: An Alternative Liming Material for Agricultural Soils. Pulse and Oilseed Unit, Alberta Agriculture, Food and Rural Development.

[58]McKendry P., 2001. Energy production from biomass (part 3): gasification technologies Bioresource Technology. 83 (2002) 55–63

[60]Banapurmath N. R., Tewari P. G., Yaliwal V. S., 2009. Producer Gas and Vegetable Oils Operated Compression Ignition Engines for Rural Applications. Biomass Gasification: Chemistry, Process and Applications. ISBN: 978 -1-60741-461-2. Nova Science Publishers, Inc.

[62]Chawdhury M. A., Mahkamov K., 2010. Development of a Small Downdraft Biomass Gasifier for Developing Countries. Journal of Scientific Research. J. Sci. Res. 3 (1), 51-64 (2011)

[63]Boateng A. A., Jung H. G., Adler P. R., 2006. Pyrolysis of energy crops including alfalfa stems, reed canarygrass, and eastern gamagrass. Fuel 85 (2006) 2450–2457

[64]Tavasoli A, Ahangari M.G., Soni C., Dalai A. K., 2009. Production of hydrogen and syngas via gasification of the corn and wheat dry distiller grains (DDGS) in a fixed-bed micro reactor. Fuel Processing Technology, 90(4): 472-482

[65]Gil M.V., Oulego P., Casal M.D., Pevida C., Pis J.J., Rubiera F., 2010. Mechanical durability and combustion characteristics of pellets from biomass blends. Bioresource Technology 101 8859–8867

[66]Kirubakarana V., Sivaramakrishnanb V., Nalinic R., Sekard T., Premalathae M., Subramaniane P., 2007. A review on gasification of biomass. Renewable and Sustainable Energy Reviews Vol 13 (2009) 179–186

[67] Demirbas A., 1997. Calculation of higher heating values of biomass fuels. *Fuel* Vol. 76, No. 5, pp. 431-434

[68] DeLong M. M., Onishak M., Schmid M., Wiant B., Oelke E., 1995. Alfalfa Stem feedstock for IGCC power system fuel. Symposium on biomass fuels (ACS Division of Fuel Chemistry) 40 (1995) 699.

[69] Boateng A. A., Mullen C. A., Glodberg N., Hicks K. B., 2008. Production of Bio-oil from Alfalfa Stems by Fluidized- Bed Fast Pyrolysis. Industrial and Engineering Chemistry Research, (2008) 47: 4115 – 4122.

[70] Wei L., Thomasson J. A., Brick R. M., Sui R., Wooten J. R., Columbus E. P., 2009. Syn – Gas Quality Evaluation for Biomass Gasification with a Down-draft Gasifier. American Society of Agricultural and Biological Engineers. Vol 52 (1): 21 – 37.

[71] Akudo C. O., Theegala C. S., 2007. Sampling and Analysis of Tars and Particulates from a Biomass Downdraft Gasifier. An ASABE Meeting Presentation. American Society of Agricultural and Biological Engineers. Paper # 074149.

[72] Carlson, C. L., Adriano D. C., 1993. Environmental impact of coal combustion residue. J. Environ. Qual. 22: 227-247

[73] Bowden R. D., Alexander L., Conroy A., 2008. Biomass, Nitrogen and Ash Content in Stands of Switchgrass and Big Blue Stem in Northwestern Pennsylvania. Allegheny College Center for Environmental and Economic Development Publication CEED-2008-4.

[74] Akudo C. O., 2008. A Thesis: Quantification of tars and particulates from a pilot scale, downdraft biomass gasifier. Department of Bioloagical and Agricultural Engineering. Louisiana State University and Agricultural and Mechanical College

[75] Timpe R.C., Mann M. D., Schmidt D. D., 2000. Gasification for distributed generation – task 3.5. AAD Document Control. National Energy Technology Laboratory.

[76] Mozaffari M., Rosen C. J., Russelle M. P., Nater E. A., 2000. Chemical characterization of ash from gasification of alfalfa stems: Implications for ash management. Journal of Environmental Quality. 29: 963 – 972.

[77] Eck, H. V., Stewart B. A., 1995. Soil amendments and water quality. In J. E. Rechcigal (ed.). Lewis Publication., Newyork. Manure. P. 169 0 199.

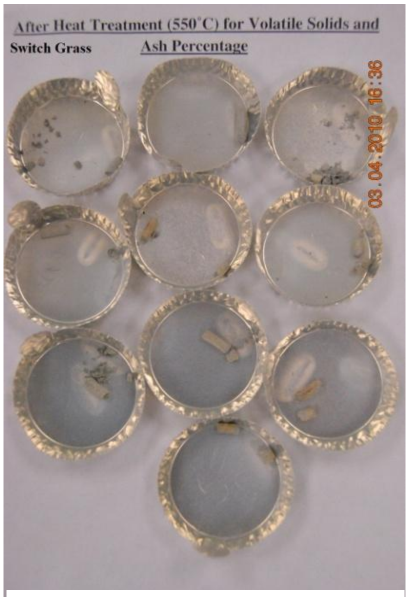
[78] DeGroot W.F., Kannan M. P., Richard G. N., Theander O., 1990. Gasification of agricultural residue (biomass): Influence of inorganic constituents. Journal of Agriculture Food Chemistry 38: 320-323.

[79] Brushwood J., Bachovchin D., 1998. Testing the multi annular swirl burner for the MAP project. Expanding Bioenergy Partnership, Madison, WI. 4 -8 Oct. 1998. Great Lakes Regional Biomass Energy Program, Chicago, IL. Bioenergy 98. P. 435-441

[80] William R., Larson E., 1996. Biomass gasifier gas turbine power generating technology. Biomass Bioenergy 10: 149 – 166.

APPENDIX

SectionA1.1: Volatile Solids and Ash Percentage Calculation



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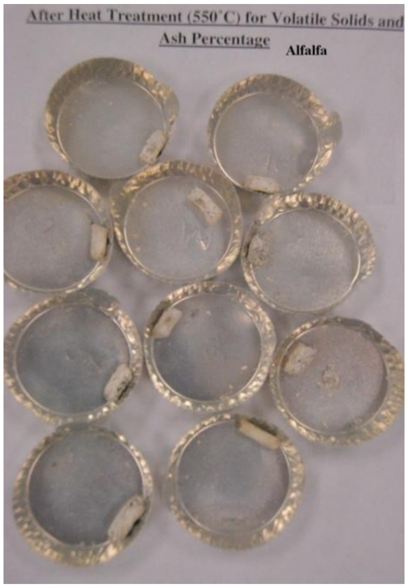

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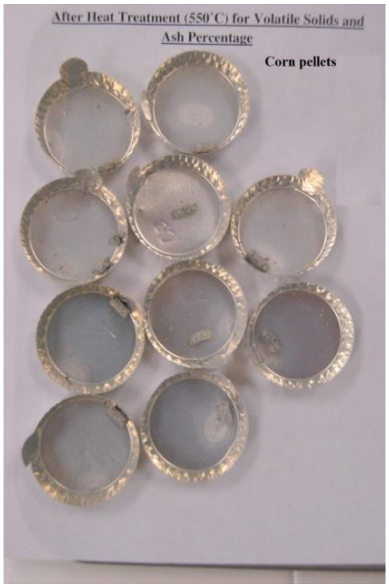

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Section A 1.1: Study of Volatile Solids and Ash Percentage of different feedstock (2) Cypress Mulch (3) Hardwood (4) Switch Grass (5) Alfalfa (6) Corn Pellet

Pinewood pellets

Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	6.49	18.07	597.77	590.70	0.99	555.20	1722.20	1167.00	6.49	18.07	597.77	0.93	6.39	1167.90	554.30	0.16	99.84
2.00	6.66	16.19	564.01	586.80	1.04	552.80	1715.20	1162.40	6.66	16.19	564.01	0.98	6.15	1164.00	551.20	0.29	99.71
3.00	6.52	16.37	546.55	628.40	1.15	590.20	1763.70	1173.50	6.52	16.37	546.55	1.08	6.47	1175.90	587.80	0.41	99.59
4.00	6.59	15.70	535.50	544.50	1.02	510.40	1681.90	1171.50	6.59	15.70	535.50	0.95	6.68	1173.30	508.60	0.35	99.65
5.00	6.50	15.92	528.27	611.20	1.16	573.00	1748.40	1175.40	6.50	15.92	528.27	1.08	6.67	1178.10	570.30	0.47	99.53
6.00	6.57	16.00	542.43	580.20	1.07	550.50	1723.60	1173.10	6.57	16.00	542.43	1.01	5.40	1175.40	548.20	0.42	99.58
7.00	6.47	16.17	531.63	532.40	1.00	504.40	1677.20	1172.80	6.47	16.17	531.63	0.95	5.55	1175.20	502.00	0.48	99.52
8.00	6.41	15.51	500.52	502.40	1.00	476.80	1640.70	1163.90	6.41	15.51	500.52	0.95	5.37	1166.20	474.50	0.48	99.52
9.00	6.42	15.21	492.37	415.50	0.84	393.20	1579.70	1186.50	6.42	15.21	492.37	0.80	5.67	1187.70	392.00	0.31	99.69
10.00	6.40	17.28	555.90	611.70	1.10	576.70	1755.30	1178.60	6.40	17.28	555.90	1.04	6.07	1180.90	574.40	0.40	99.60

Hardwood Pellets

Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	6.46	15.02	492.29	499.90	1.02	472.40	1630.30	1157.90	6.46	15.02	492.29	0.96	5.82	1162.10	468.20	0.89	99.11
2.00	6.59	16.32	556.65	506.30	0.91	480.60	1648.20	1167.60	6.59	16.32	556.65	0.86	5.35	1176.90	471.30	1.94	98.06
3.00	6.52	12.86	429.36	433.60	1.01	410.90	1584.00	1173.10	6.52	12.86	429.36	0.96	5.52	1171.60	412.40	-0.37	100.37
4.00	6.66	14.32	498.86	439.40	0.88	417.00	1592.90	1175.90	6.66	14.32	498.86	0.84	5.37	1178.50	414.40	0.62	99.38
5.00	6.60	12.72	435.18	423.10	0.97	401.40	1577.80	1176.40	6.60	12.72	435.18	0.92	5.41	1180.40	397.40	1.00	99.00
6.00	6.49	16.72	553.12	575.30	1.04	545.20	1724.60	1179.40	6.49	16.72	553.12	0.99	5.52	1183.90	540.70	0.83	99.17
7.00	6.60	14.23	486.84	484.90	1.00	460.30	1629.30	1169.00	6.60	14.23	486.84	0.95	5.34	1172.90	456.40	0.85	99.15
8.00	6.53	15.38	515.08	499.50	0.97	474.80	1654.80	1180.00	6.53	15.38	515.08	0.92	5.20	1183.80	471.00	0.80	99.20
9.00	6.67	14.02	489.88	438.40	0.89	417.10	1594.20	1177.10	6.67	14.02	489.88	0.85	5.11	1180.90	413.30	0.91	99.09
10.00	6.73	15.01	533.95	514.20	0.96	489.50	1651.30	1161.80	6.73	15.01	533.95	0.92	5.05	1167.30	484.00	1.12	98.88

Alfalfa

Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	7.11	16.28	646.37	612.40	0.95	553.40	1719.00	1165.60	7.11	16.28	646.37	0.86	10.66	1236.30	482.70	12.78	87.22
2.00	7.01	15.76	608.25	496.00	0.82	447.40	1630.00	1182.60	7.01	15.76	608.25	0.74	10.86	1238.20	391.80	12.43	87.57

3.00	6.87	15.41	571.22	612.40	1.07	550.20	1723.50	1173.30	6.87	15.41	571.22	0.96	11.30	1255.20	468.30	14.89	85.11
4.00	6.91	17.82	668.27	679.40	1.02	611.10	1781.50	1170.40	6.91	17.82	668.27	0.91	11.18	1242.70	538.80	11.83	88.17
5.00	6.96	17.25	656.29	591.30	0.90	533.40	1690.90	1157.50	6.96	17.25	656.29	0.81	10.85	1219.80	471.10	11.68	88.32
6.00	6.93	17.21	649.14	631.20	0.97	569.90	1740.20	1170.30	6.93	17.21	649.14	0.88	10.76	1234.90	505.30	11.34	88.66
7.00	7.17	20.25	817.62	706.30	0.86	639.50	1825.50	1186.00	7.17	20.25	817.62	0.78	10.45	1261.80	563.70	11.85	88.15
8.00	6.10	22.06	644.70	756.80	1.17	705.80	1875.20	1169.40	6.10	22.06	644.70	1.09	7.23	1252.60	622.60	11.79	88.21
9.00	7.45	16.13	703.13	591.90	0.84	536.10	1711.20	1175.10	7.45	16.13	703.13	0.76	10.41	1237.60	473.60	11.66	88.34
10.00	7.47	15.91	697.27	520.00	0.75	473.60	1636.60	1163.00	7.47	15.91	697.27	0.68	9.80	1217.00	419.60	11.40	88.60
Switch Grass																	
Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	6.06	16.41	473.31	559.20	1.18	517.20	1688.50	1171.30	6.06	16.41	473.31	1.09	8.12	1189.70	498.80	3.56	96.44
2.00	5.91	23.25	637.80	767.90	1.20	713.80	1888.00	1174.20	5.91	23.25	637.80	1.12	7.58	1199.70	688.30	3.57	96.43
3.00	6.14	17.94	531.19	547.20	1.03	510.30	1682.40	1172.10	6.14	17.94	531.19	0.96	7.23	1186.30	496.10	2.78	97.22
4.00	5.92	18.76	516.38	612.40	1.19	571.50	1742.70	1171.20	5.92	18.76	516.38	1.11	7.16	1188.20	554.50	2.97	97.03
5.00	6.20	20.01	604.12	656.30	1.09	608.20	1775.00	1166.80	6.20	20.01	604.12	1.01	7.91	1188.80	586.20	3.62	96.38
6.00	5.72	19.06	489.78	510.00	1.04	477.20	1644.20	1167.00	5.72	19.06	489.78	0.97	6.87	1182.30	461.90	3.21	96.79
7.00	6.01	25.42	721.13	872.50	1.21	809.70	1986.90	1177.20	6.01	25.42	721.13	1.12	7.76	1204.50	782.40	3.37	96.63
8.00	6.02	22.46	639.28	746.10	1.17	689.90	1866.10	1176.20	6.02	22.46	639.28	1.08	8.15	1198.00	668.10	3.16	96.84
9.00	5.86	25.08	676.41	786.10	1.16	734.50	1907.40	1172.90	5.86	25.08	676.41	1.09	7.03	1202.60	704.80	4.04	95.96
10.00	5.86	22.80	614.92	691.00	1.12	645.20	1809.90	1164.70	5.86	22.80	614.92	1.05	7.10	1181.40	628.50	2.59	97.41
Bagasse																	
Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	6.15	17.25	512.42	529.10	1.03	483.90	1645.80	1161.90	6.15	17.25	512.42	0.94	9.34	1201.00	444.80	8.08	91.92
2.00	5.90	23.87	652.60	756.10	1.16	691.00	1869.10	1178.10	5.90	23.87	652.60	1.06	9.42	1234.40	634.70	8.15	91.85
3.00	5.97	19.38	542.49	637.50	1.18	586.40	1754.10	1167.70	5.97	19.38	542.49	1.08	8.71	1215.80	538.30	8.20	91.80
4.00	5.96	20.20	563.55	602.80	1.07	552.20	1729.00	1176.80	5.96	20.20	563.55	0.98	9.16	1220.10	508.90	7.84	92.16
5.00	6.05	20.53	590.19	668.20	1.13	612.80	1789.70	1176.90	6.05	20.53	590.19	1.04	9.04	1216.90	572.80	6.53	93.47
6.00	5.91	18.34	503.11	628.50	1.25	576.60	1734.60	1158.00	5.91	18.34	503.11	1.15	9.00	1203.40	531.20	7.87	92.13

7.00	5.94	18.92	524.30	582.90	1.11	533.70	1705.60	1171.90	5.94	18.92	524.30	1.02	9.22	1215.90	489.70	8.24	91.76
8.00	6.01	17.67	501.27	581.60	1.16	537.70	1701.30	1163.60	6.01	17.67	501.27	1.07	8.16	1207.70	493.60	8.20	91.80
9.00	6.07	21.92	634.32	731.10	1.15	672.20	1837.10	1164.90	6.07	21.92	634.32	1.06	8.76	1219.40	617.70	8.11	91.89
10.00	6.02	21.60	614.80	732.40	1.19	675.80	1855.70	1179.90	6.02	21.60	614.80	1.10	8.38	1232.90	622.80	7.84	92.16
Corn																	
Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	6.33	13.55	426.42	436.80	1.02	384.20	1554.80	1170.60	6.33	13.55	426.42	0.90	13.69	1199.30	355.50	7.47	92.53
2.00	6.34	14.86	469.12	447.10	0.95	393.30	1568.10	1174.80	6.34	14.86	469.12	0.84	13.68	1203.40	364.70	7.27	92.73
3.00	6.42	14.77	478.12	488.90	1.02	429.70	1606.20	1176.50	6.42	14.77	478.12	0.90	13.78	1206.80	399.40	7.05	92.95
4.00	6.32	17.21	539.89	580.50	1.08	509.90	1688.00	1178.10	6.32	17.21	539.89	0.94	13.85	1216.50	471.50	7.53	92.47
5.00	6.19	17.52	527.24	517.10	0.98	457.40	1629.40	1172.00	6.19	17.52	527.24	0.87	13.05	1207.80	421.60	7.83	92.17
6.00	6.17	14.16	423.37	435.80	1.03	385.60	1554.30	1168.70	6.17	14.16	423.37	0.91	13.02	1196.90	357.40	7.31	92.69
7.00	6.29	14.20	441.24	457.50	1.04	404.40	1585.10	1180.70	6.29	14.20	441.24	0.92	13.13	1210.30	374.80	7.32	92.68
8.00	6.21	15.04	455.53	479.50	1.05	425.30	1605.70	1180.40	6.21	15.04	455.53	0.93	12.74	1208.90	396.80	6.70	93.30
9.00	6.18	16.24	487.14	472.70	0.97	418.70	1610.70	1192.00	6.18	16.24	487.14	0.86	12.90	1222.30	388.40	7.24	92.76
10.00	6.49	15.17	501.84	440.00	0.88	388.70	1561.40	1172.70	6.49	15.17	501.84	0.77	13.20	1198.70	362.70	6.69	93.31
Dairy Manure																	
Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	5.98	21.35	599.64	850.70	1.42	769.50	1941.00	1171.50	5.98	21.35	599.64	1.28	10.55	1482.70	458.30	40.44	59.56
2.00	6.06	17.30	498.98	611.70	1.23	558.10	1721.40	1163.30	6.06	17.30	498.98	1.12	9.60	1405.50	315.90	43.40	56.60
3.00	5.95	21.66	602.26	781.00	1.30	711.80	1881.10	1169.30	5.95	21.66	602.26	1.18	9.72	1476.60	404.50	43.17	56.83
4.00	5.98	19.00	533.64	722.10	1.35	655.70	1821.00	1165.30	5.98	19.00	533.64	1.23	10.13	1446.60	374.40	42.90	57.10
5.00	5.88	23.68	643.02	947.20	1.47	859.20	2033.20	1174.00	5.88	23.68	643.02	1.34	10.24	1533.50	499.70	41.84	58.16
6.00	5.87	20.66	559.11	810.00	1.45	734.10	1893.70	1159.60	5.87	20.66	559.11	1.31	10.34	1462.90	430.80	41.32	58.68
7.00	6.01	19.41	550.64	705.40	1.28	749.20	1907.60	1158.40	6.01	19.41	550.64	1.36	-5.85	1461.80	445.80	40.50	59.50
8.00	5.92	21.10	580.79	822.10	1.42	651.40	1817.10	1165.70	5.92	21.10	580.79	1.12	26.21	1469.20	347.90	46.59	53.41
9.00	5.88	24.72	671.26	947.40	1.41	868.40	2041.30	1172.90	5.88	24.72	671.26	1.29	9.10	1555.10	486.20	44.01	55.99
10.00	5.99	18.41	518.80	732.20	1.41	670.90	1828.80	1157.90	5.99	18.41	518.80	1.29	9.14	1442.70	386.10	42.45	57.55

Poultry Litter

Sno	Dia	Height	Volume	Mass	Density	Mass After 105 C	Dry Pellet + Dish	Mass of Cups	Dia	Height	Volume	Density	% of Moisture	Ash + dish weight	Ash only	% Ash	%VS
1.00	4.65	25.79	437.97	651.10	1.49	578.40	1752.50	1174.10	4.65	25.79	437.97	1.32	12.57	1409.50	343.00	40.70	59.30
2.00	5.48	20.89	492.71	673.50	1.37	623.10	1780.10	1157.00	5.48	20.89	492.71	1.26	8.09	1402.00	378.10	39.32	60.68
3.00	5.70	21.82	556.79	697.60	1.25	617.70	1798.90	1181.20	5.70	21.82	556.79	1.11	12.94	1426.60	372.30	39.73	60.27
4.00	5.43	19.78	458.05	541.50	1.18	489.80	1659.70	1169.90	5.43	19.78	458.05	1.07	10.56	1363.40	296.30	39.51	60.49
5.00	5.04	22.49	448.68	684.80	1.53	619.30	1785.90	1166.60	5.04	22.49	448.68	1.38	10.58	1414.10	371.80	39.96	60.04
6.00	5.75	19.00	493.38	605.70	1.23	544.30	1703.00	1158.70	5.75	19.00	493.38	1.10	11.28	1370.80	332.20	38.97	61.03
7.00	5.07	18.91	381.77	546.70	1.43	494.00	1667.70	1173.70	5.07	18.91	381.77	1.29	10.67	1375.60	292.10	40.87	59.13
8.00	5.22	21.24	454.55	566.50	1.25	509.70	1674.50	1164.80	5.22	21.24	454.55	1.12	11.14	1373.80	300.70	41.00	59.00
9.00	5.42	17.91	413.22	496.70	1.20	441.70	1598.70	1157.00	5.42	17.91	413.22	1.07	12.45	1329.30	269.40	39.01	60.99
10.00	5.94	16.83	466.39	551.70	1.18	503.40	1662.20	1158.80	5.94	16.83	466.39	1.08	9.59	1354.40	307.80	38.86	61.14

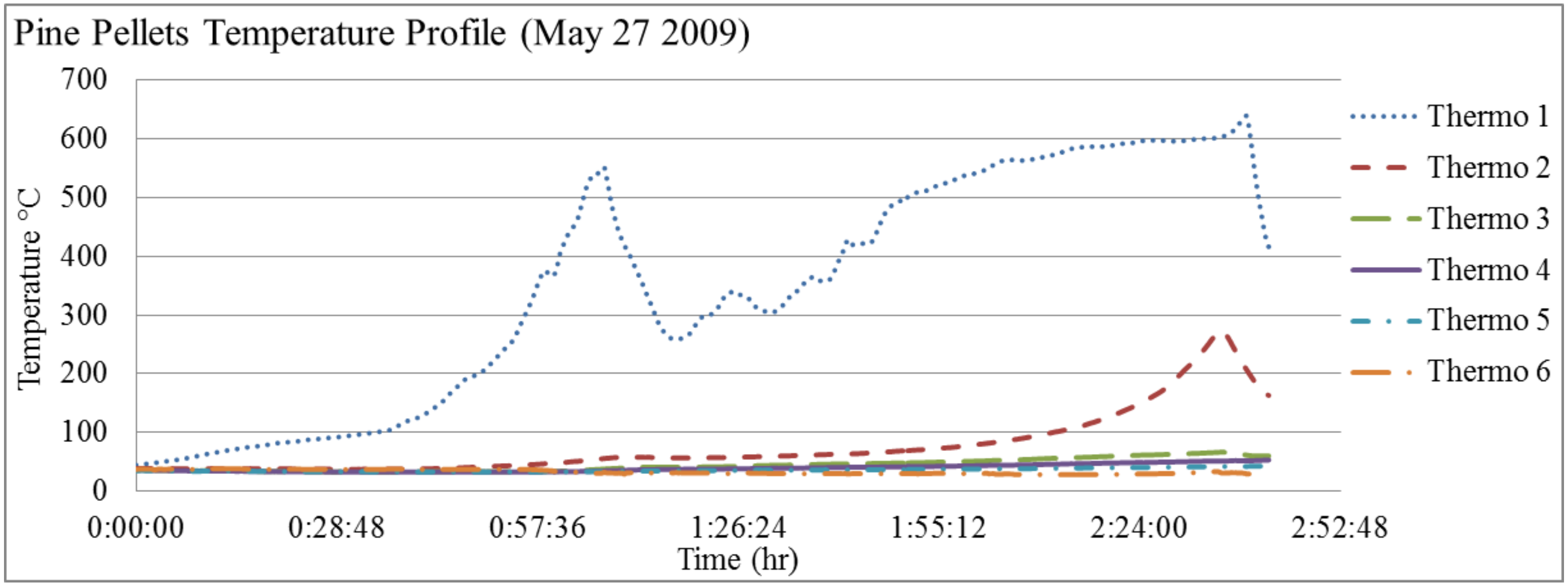
Cypress Mulch

S no	Length	Breath	Height	Volume	Mass	Density	Mass After 105	Dry Pellet + Dish	Mass of Cups	Length	Breath	Height	Volume	Density	% Moist	Ash + Dish	Ash	% Ash	%VS
1	43.79	7.59	6.16	2047.38	576.80	0.28	546.90	1698.80	1151.90	43.79	7.59	6.16	2047.38	0.27	5.47	1154.70	2.80	99.49	99.49
2	36.58	6.47	3.26	771.55	360.80	0.47	340.70	1503.30	1162.60	36.58	6.47	3.26	771.55	0.44	5.90	1164.20	1.60	99.89	99.53
3	32.74	12.77	7.55	3156.58	189.70	0.06	181.90	1347.70	1165.80	32.74	12.77	7.55	3156.58	0.06	4.29	1167.50	1.70	99.87	99.07
4	48.05	6.41	4.02	1238.16	478.90	0.39	453.10	1639.10	1186.00	48.05	6.41	4.02	1238.16	0.37	5.69	1190.60	4.60	99.72	98.98
5	40.14	13.66	6.57	3602.41	848.50	0.24	810.10	1976.70	1166.60	40.14	13.66	6.57	3602.41	0.22	4.74	1173.30	6.70	99.66	99.17
6	25.67	7.86	4.65	938.21	247.70	0.26	237.00	1403.10	1166.10	25.67	7.86	4.65	938.21	0.25	4.51	1168.10	2.00	99.86	99.16
7	25.35	11.78	5.49	1639.44	384.60	0.23	370.40	1550.80	1180.40	25.35	11.78	5.49	1639.44	0.23	3.83	1183.50	3.10	99.80	99.16
8	33.19	9.89	2.71	612.52	214.40	0.35	202.30	1374.50	1172.20	33.19	9.89	2.71	612.52	0.33	5.98	1174.30	2.10	99.85	98.96
9	34.92	6.81	4.78	1585.72	327.00	0.21	309.50	1470.70	1161.20	34.92	6.81	4.78	1585.72	0.20	5.65	1162.80	1.60	99.89	99.48
10	54.55	9.50	6.37	3301.09	833.60	0.25	787.90	1948.60	1160.70	54.55	9.50	6.37	3301.09	0.24	5.80	1163.50	2.80	99.86	99.64

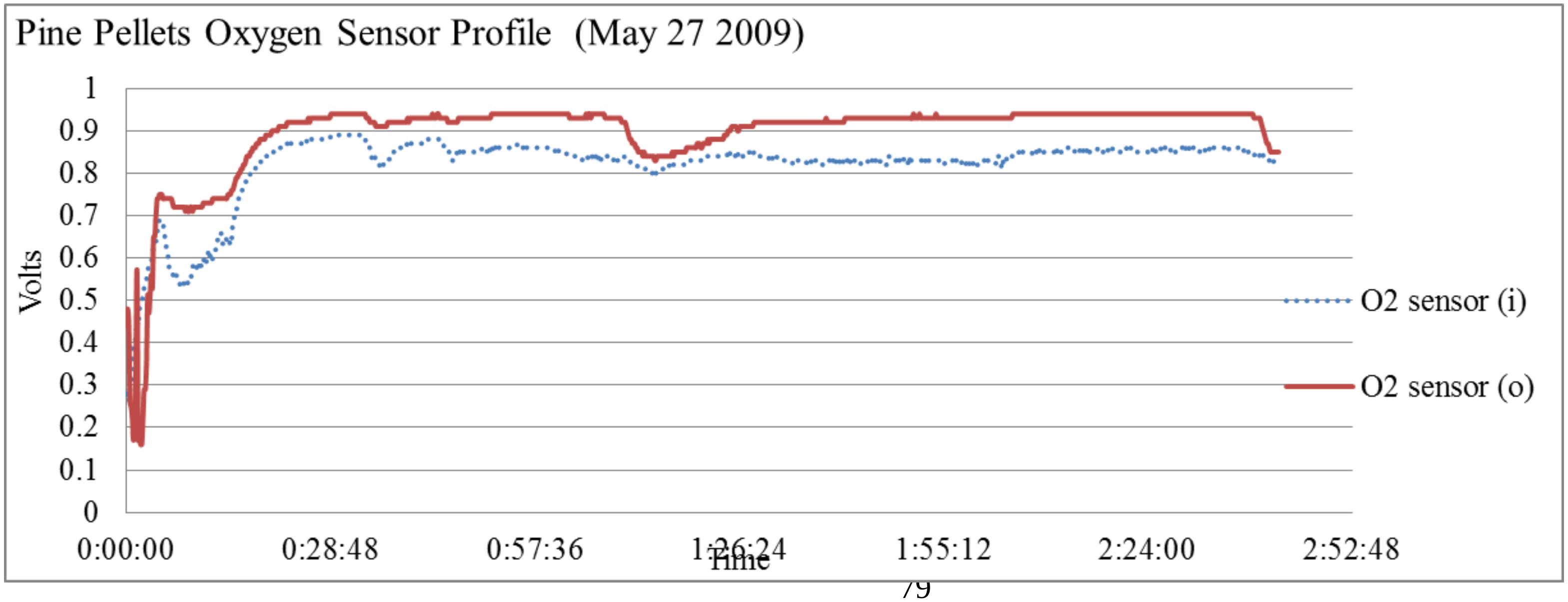
Bark Nugget

Sno	Length	Breath	Height	Volume	Mass	Density	Mass After 105	Dry Pellet + Dish	Mass of Cups	Length	Breath	Height	Volume	Density	% Moist	Ash + Dish	Ash	% Ash	%VS
1	27.55	21.43	4.19	2473.76	651.10	0.26	586.00	1760.50	1174.50	27.55	21.43	4.19	2473.76	0.24	11.11	1177.90	3.40	99.42	99.42
2	28.06	23.28	4.04	2639.08	664.90	0.25	599.20	1765.10	1165.90	28.06	23.28	4.04	2639.08	0.23	10.96	1169.30	3.40	99.43	99.43
3	33.52	28.82	4.36	4211.96	830.60	0.20	745.30	1903.40	1158.10	33.52	28.82	4.36	4211.96	0.18	11.45	1163.10	5.00	99.33	99.33
4	41.82	22.73	7.64	7262.34	1831.70	0.25	1646.20	2811.90	1165.70	41.82	22.73	7.64	7262.34	0.23	11.27	1175.10	9.40	99.43	99.43
5	32.88	32.61	6.08	6519.08	2011.50	0.31	1835.70	3000.70	1165.00	32.88	32.61	6.08	6519.08	0.28	9.58	1189.90	24.90	98.64	98.64
6	22.18	17.56	8.26	3217.11	961.80	0.30	874.90	2031.30	1156.40	22.18	17.56	8.26	3217.11	0.27	9.93	1162.00	5.60	99.36	99.36
7	29.66	21.86	5.87	3805.92	1035.50	0.27	911.10	2069.20	1158.10	29.66	21.86	5.87	3805.92	0.24	13.65	1164.40	6.30	99.31	99.31
8	26.86	30.64	19.10	12050.98	1423.50	0.12	1251.40	2418.00	1166.60	26.86	30.64	19.10	12050.98	0.10	13.75	1180.80	14.20	98.87	98.87
9	29.60	23.49	8.90	4078.05	1667.00	0.41	1493.10	2670.70	1177.60	29.60	23.49	8.90	4078.05	0.37	11.65	1186.10	8.50	99.43	99.43
10	18.71	15.48	6.66	1928.94	668.80	0.35	601.00	1761.70	1160.70	18.71	15.48	6.66	1928.94	0.31	11.28	1163.3	2.60	99.57	99.57

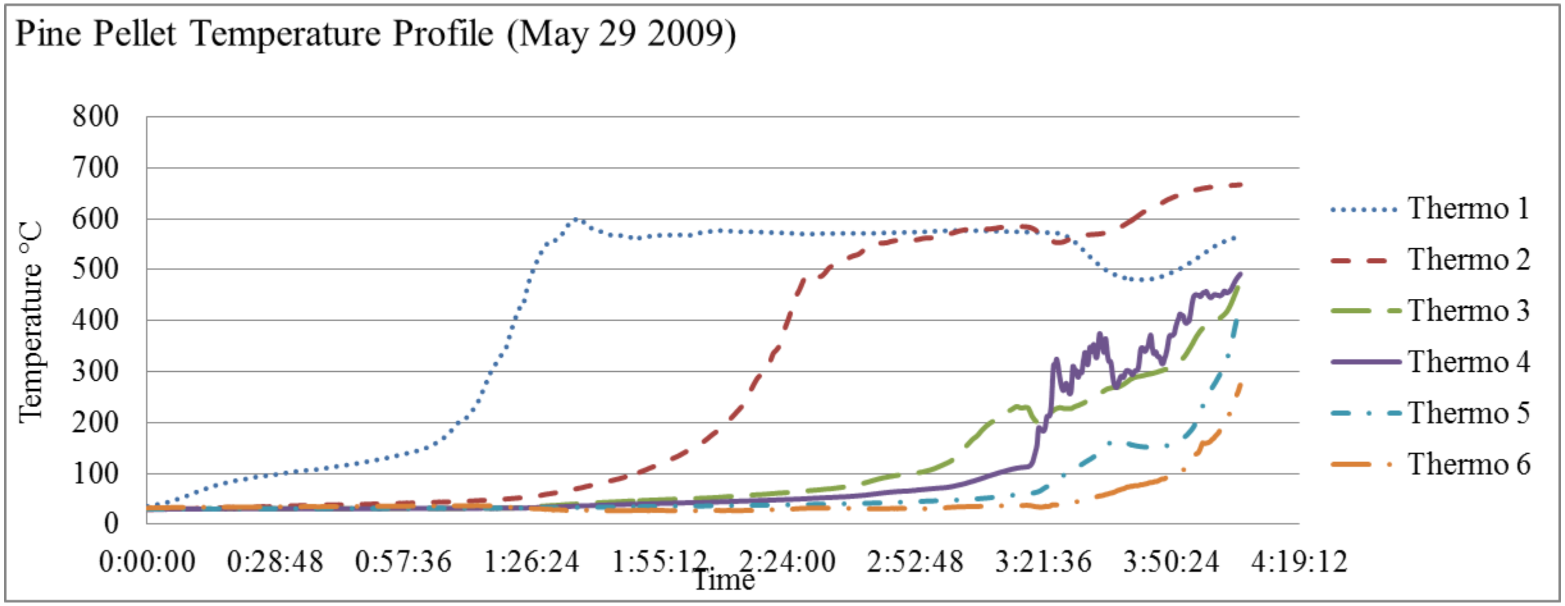
SectionA1.2: Temperature Profile and Oxygen Sensor Profiles

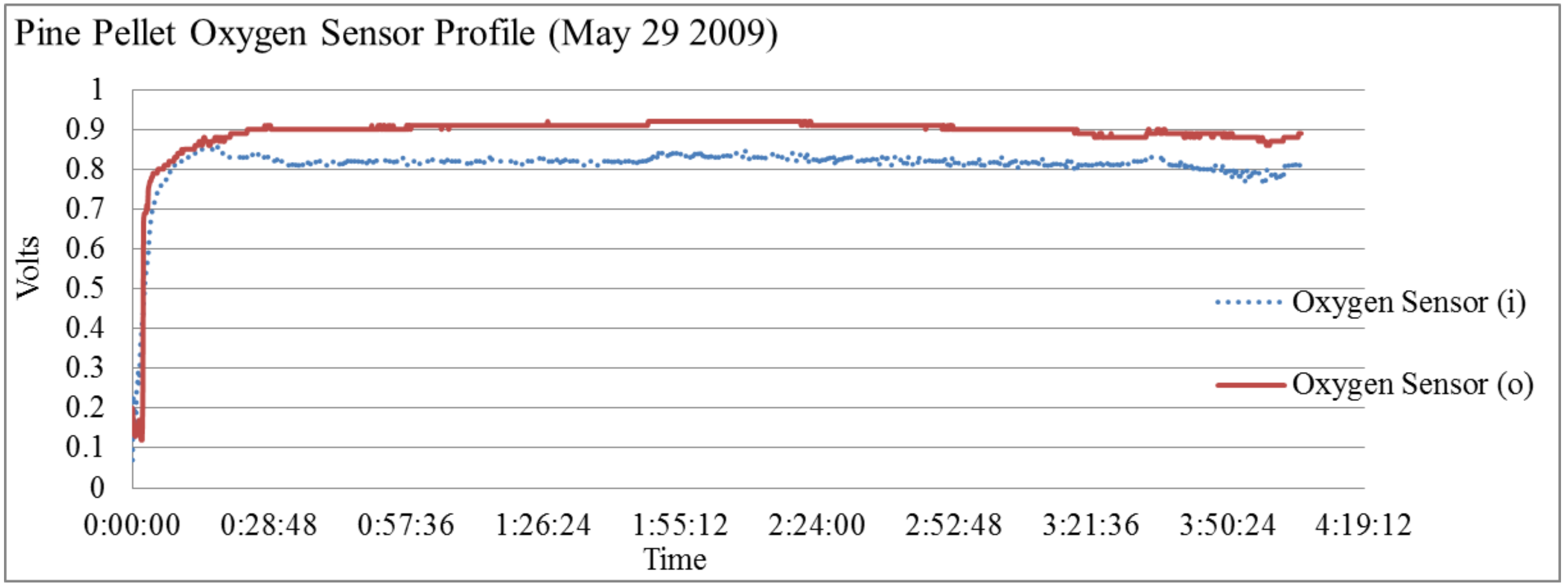


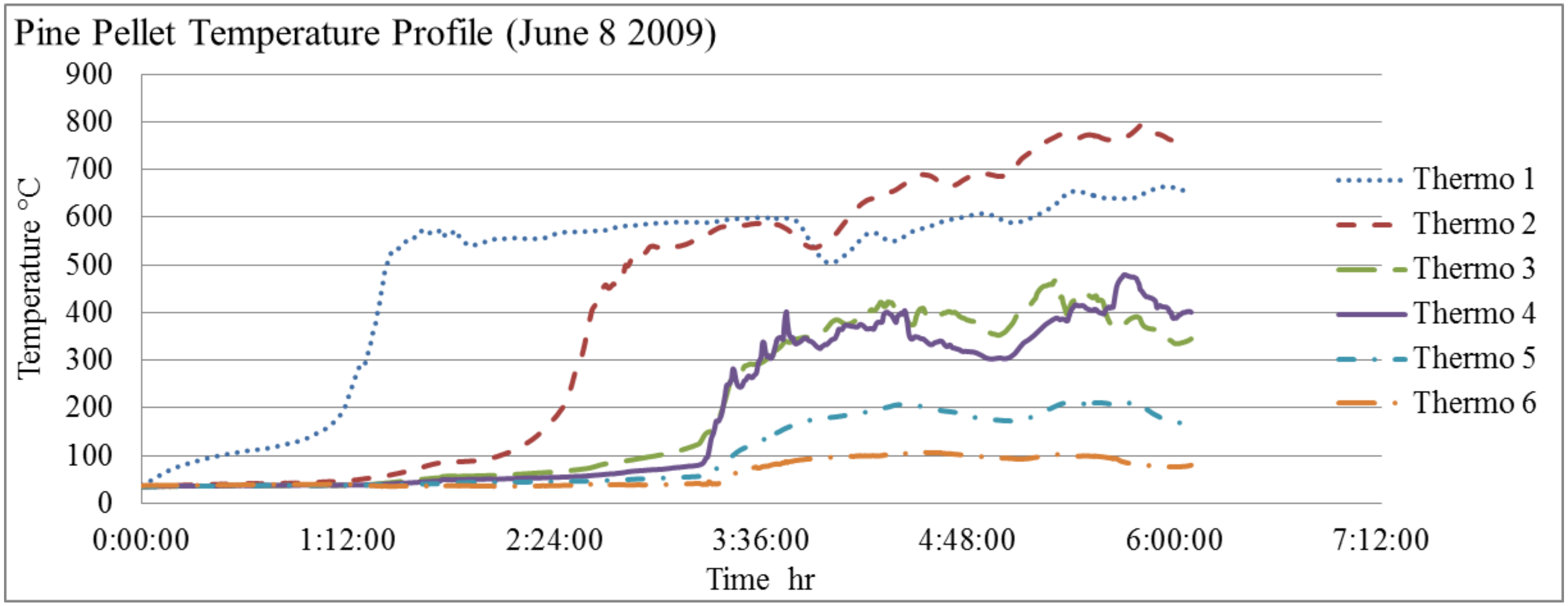
Pine Pellets Temperature Profile (May 27 2009)

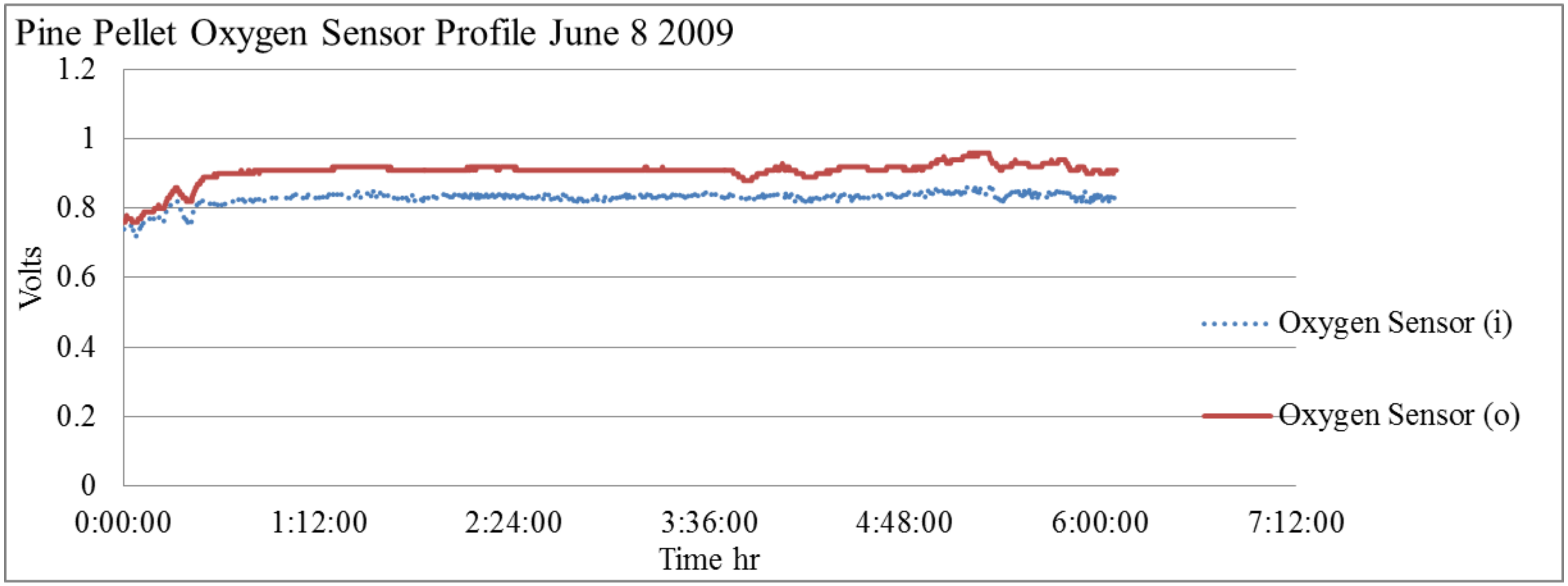


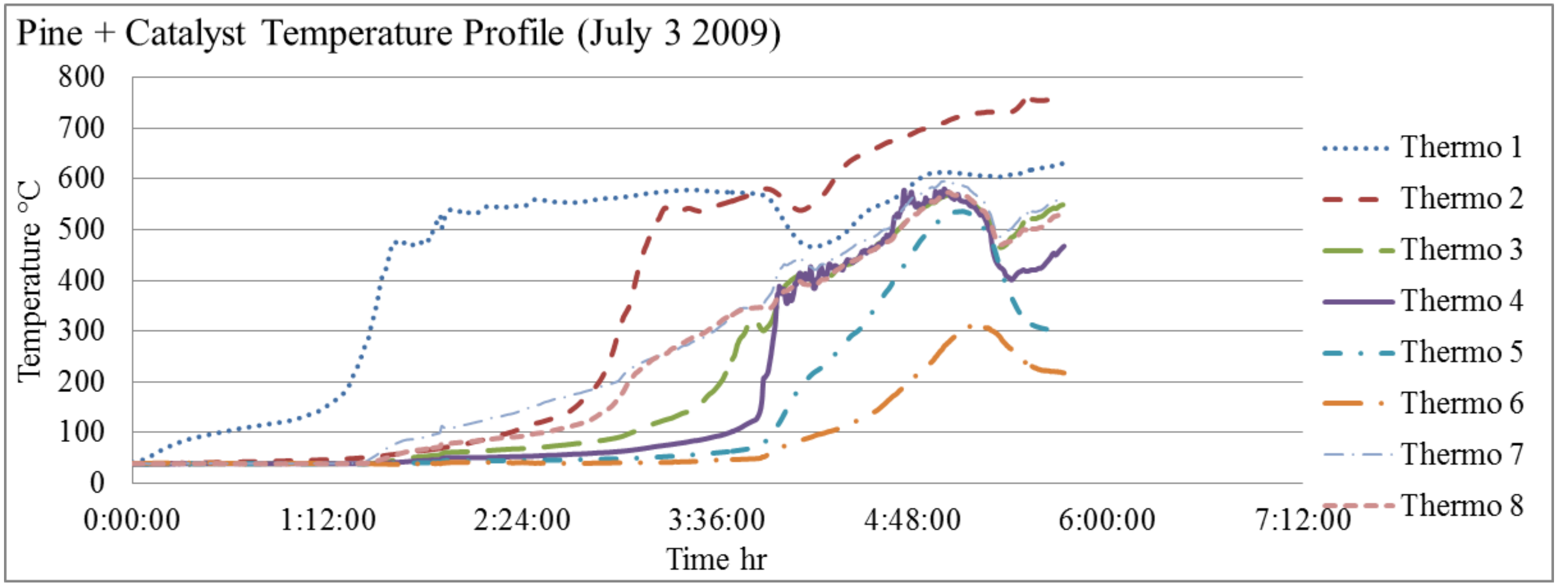
Pine Pellets Oxygen Sensor Profile (May 27 2009)

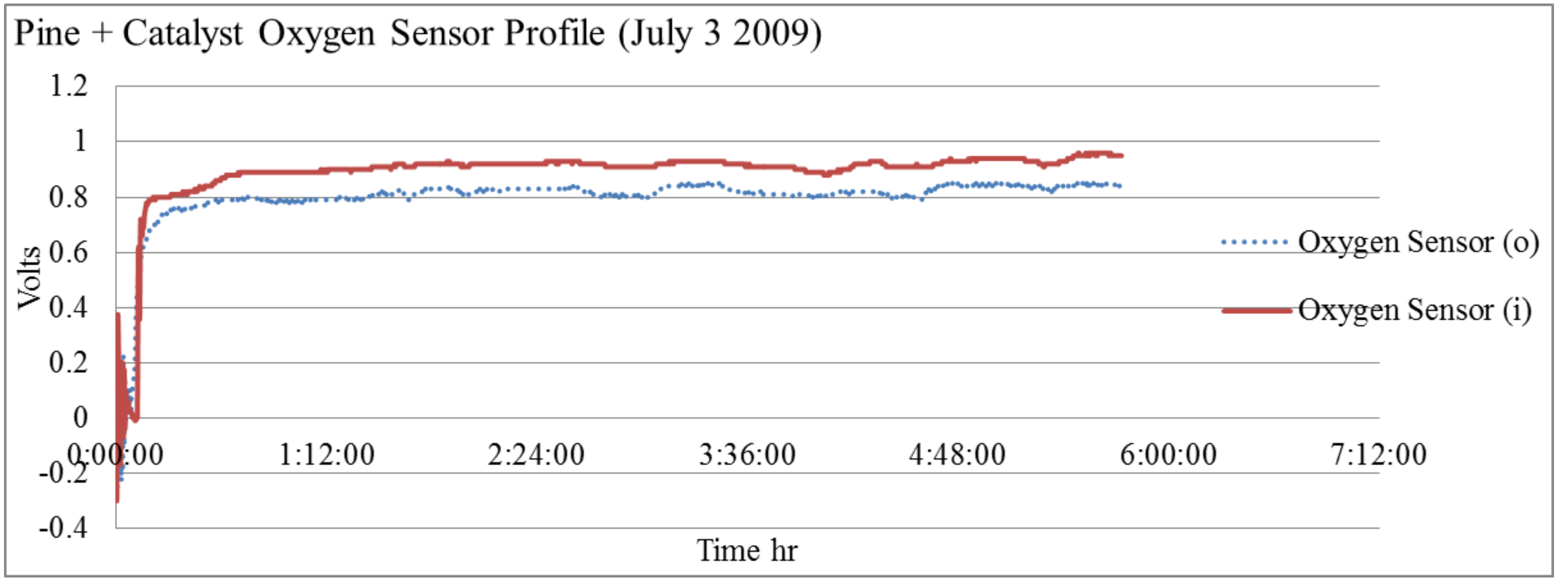

Pine Pellet Temperature Profile (May 29 2009)
Temperature °C
800
700
600
500
400
300
200
100
0
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
4:19:12
Time
Thermo 1
Thermo 2
Thermo 3
Thermo 4
Thermo 5
Thermo 6

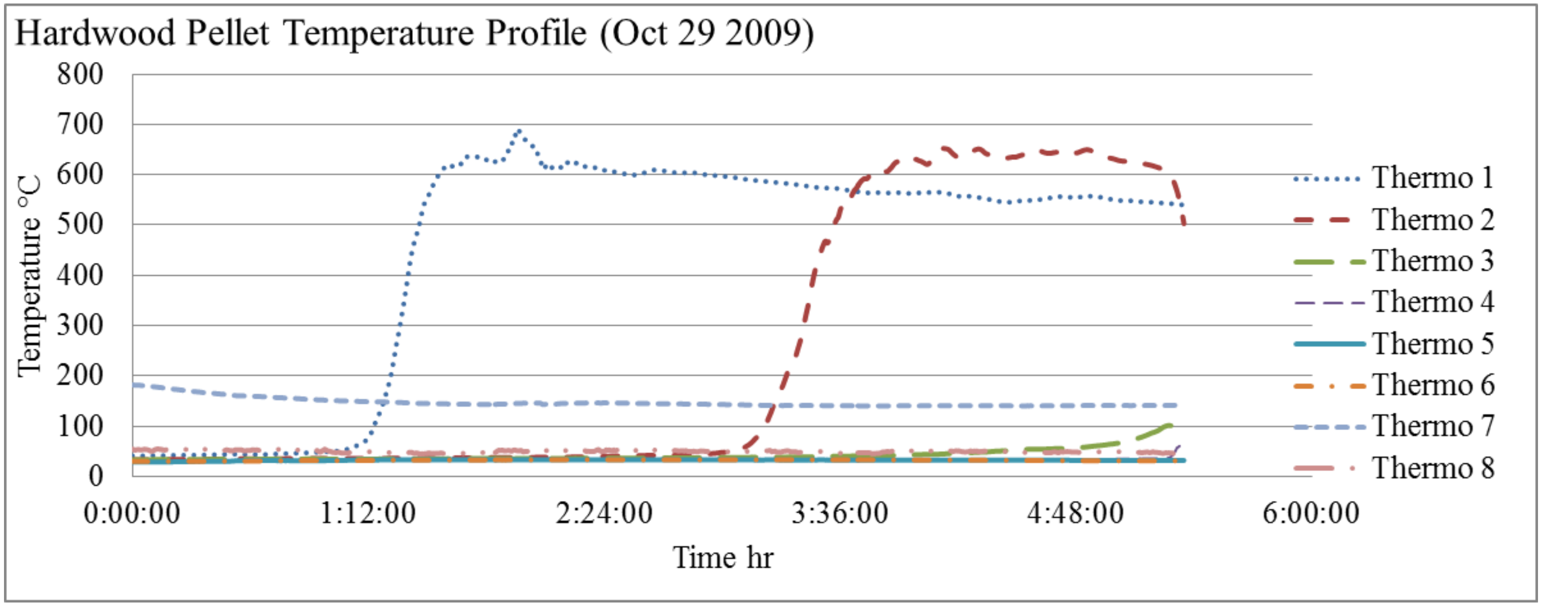

Pine Pellet Oxygen Sensor Profile (May 29 2009)
Volts
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
4:19:12
Time
Oxygen Sensor (i)
Oxygen Sensor (o)

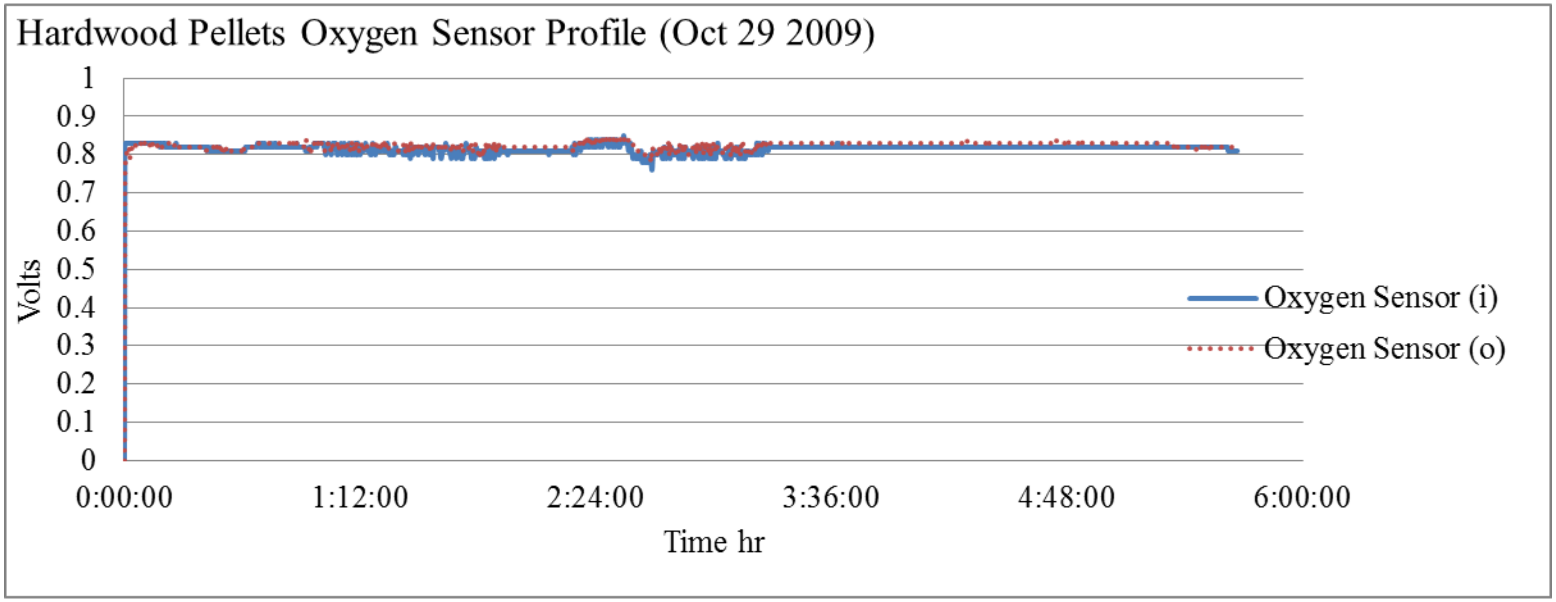

Pine Pellet Temperature Profile (June 8 2009)
Temperature °C
900
800
700
600
500
400
300
200
100
0
0:00:00
1:12:00
2:24:00
3:36:00
4:48:00
6:00:00
7:12:00
Time hr
Thermo 1
Thermo 2
Thermo 3
Thermo 4
Thermo 5
Thermo 6

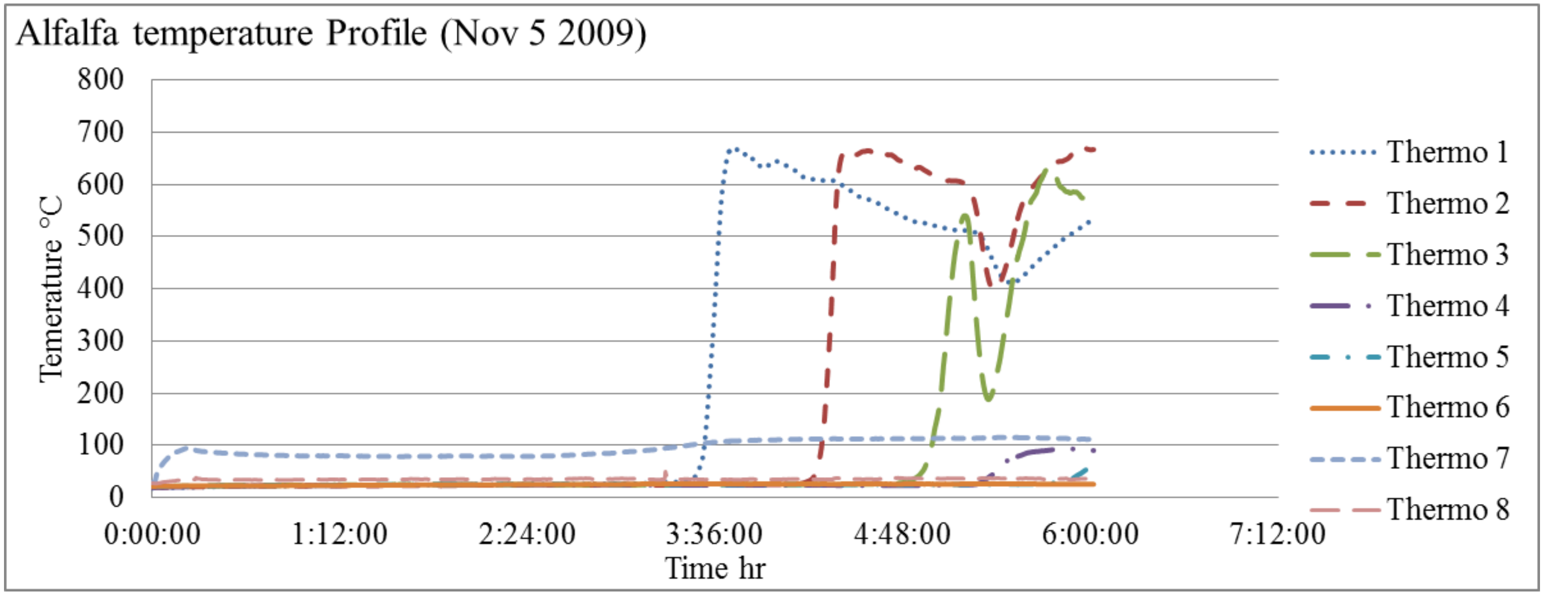

Pine Pellet Oxygen Sensor Profile June 8 2009
Volts
1.2
1
0.8
0.6
0.4
0.2
0
0:00:00
1:12:00
2:24:00
3:36:00
4:48:00
6:00:00
7:12:00
Time hr
Oxygen Sensor (i)
Oxygen Sensor (o)

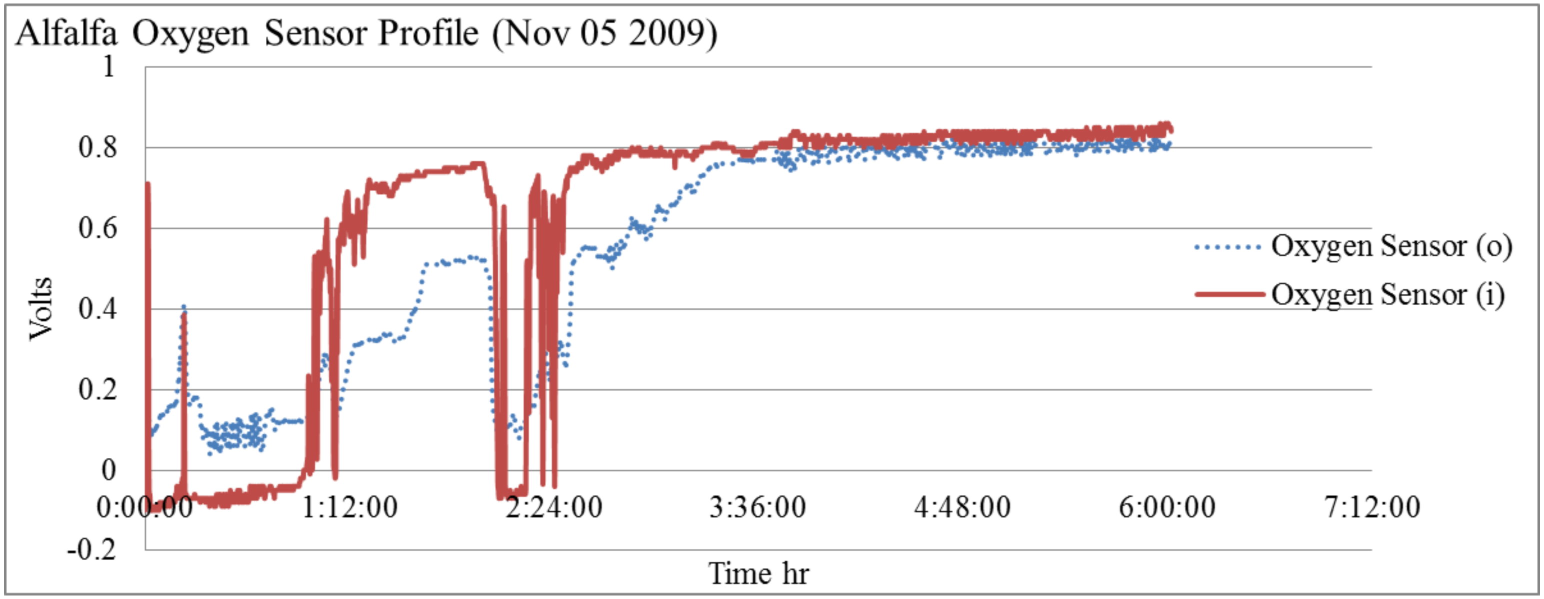

Pine + Catalyst Temperature Profile (July 3 2009)
Temperature °C
800
700
600
500
400
300
200
100
0
0:00:00
1:12:00
2:24:00
3:36:00
4:48:00
6:00:00
7:12:00
Time hr
Thermo 1
Thermo 2
Thermo 3
Thermo 4
Thermo 5
Thermo 6
Thermo 7
Thermo 8

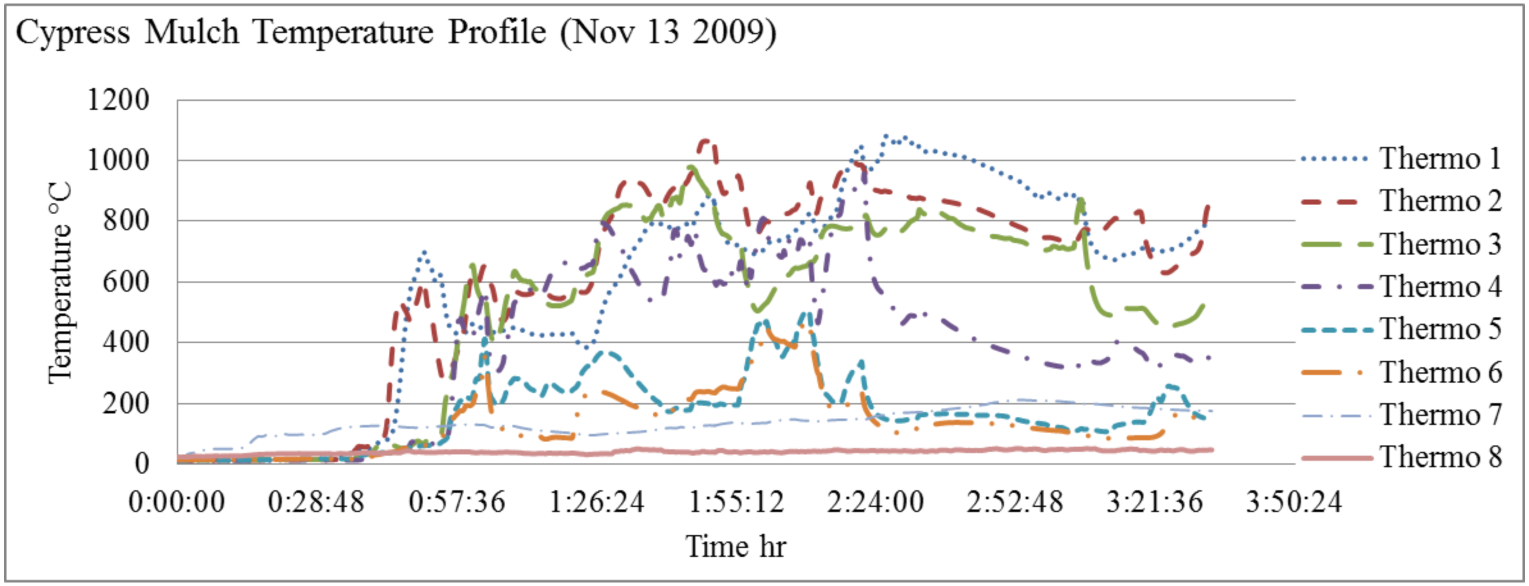

Pine + Catalyst Oxygen Sensor Profile (July 3 2009)
Volts
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0:00:00
1:12:00
2:24:00
3:36:00
4:48:00
6:00:00
7:12:00
Time hr
Oxygen Sensor (o)
Oxygen Sensor (i)

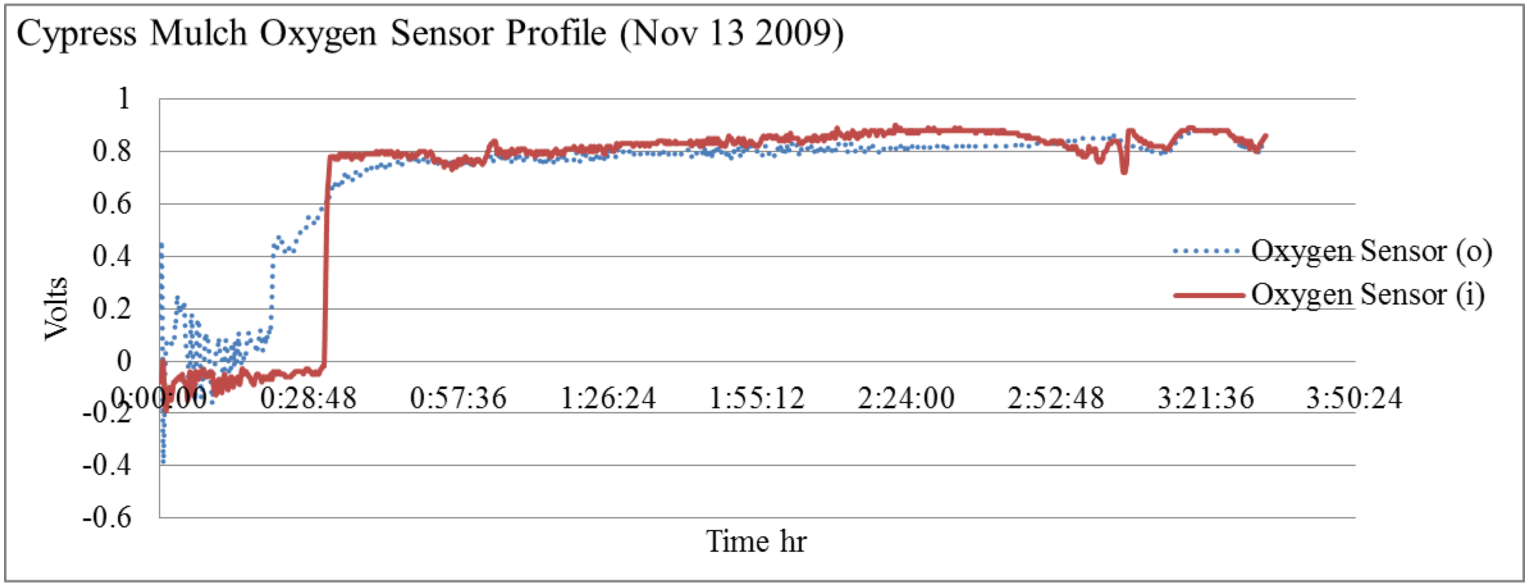

Hardwood Pellet Temperature Profile (Oct 29 2009)

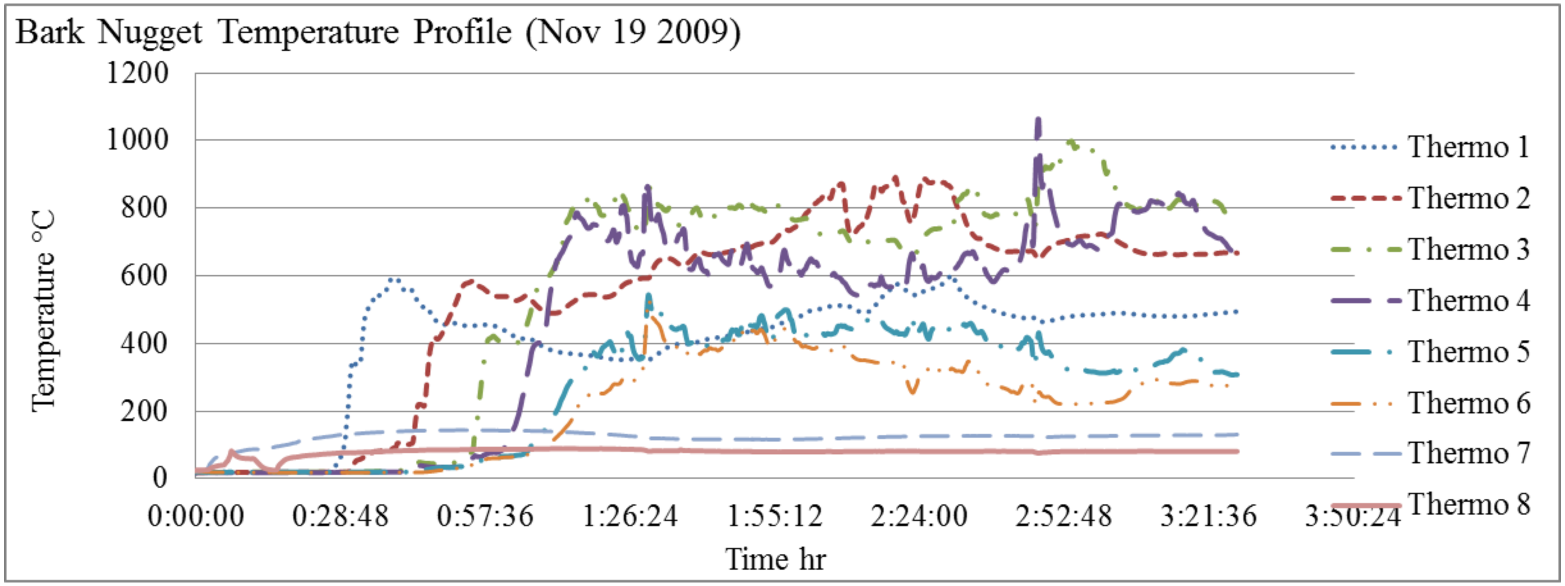

Hardwood Pellets Oxygen Sensor Profile (Oct 29 2009)

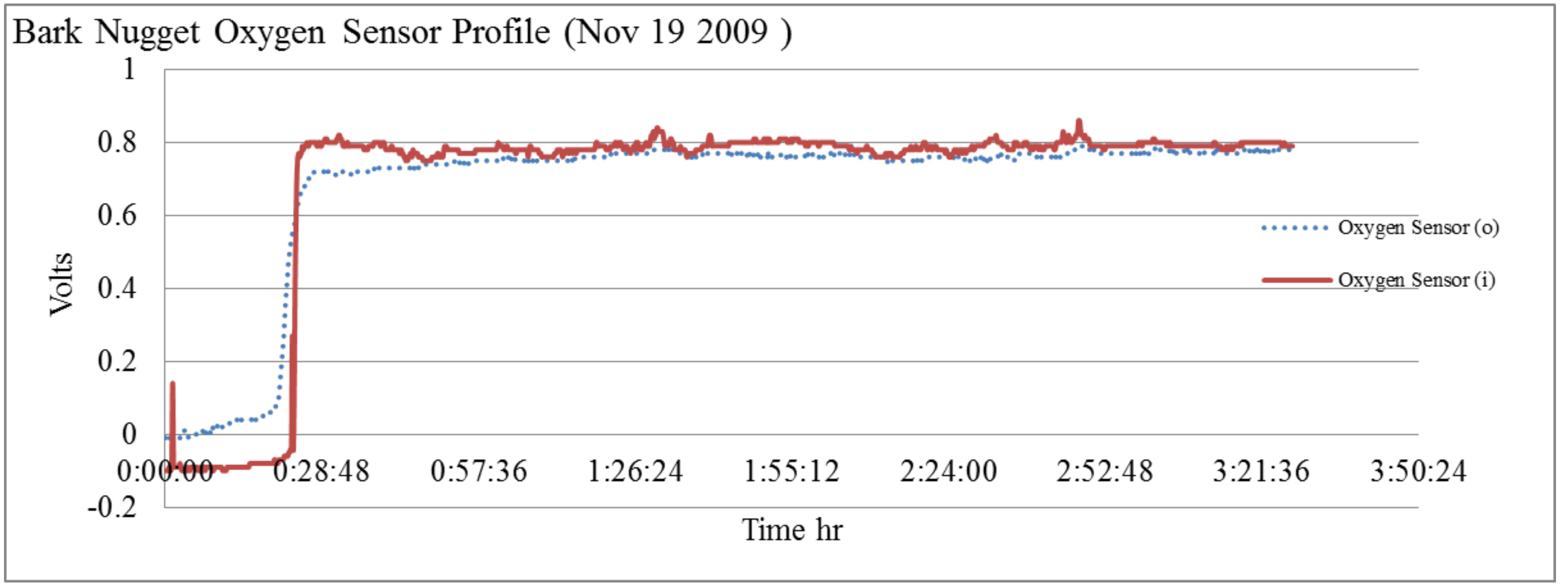

Alfalfa temperature Profile (Nov 5 2009)
Temerature °C
800
700
600
500
400
300
200
100
0
0:00:00
1:12:00
2:24:00
3:36:00
4:48:00
6:00:00
7:12:00
Time hr
Thermo 1
Thermo 2
Thermo 3
Thermo 4
Thermo 5
Thermo 6
Thermo 7
Thermo 8

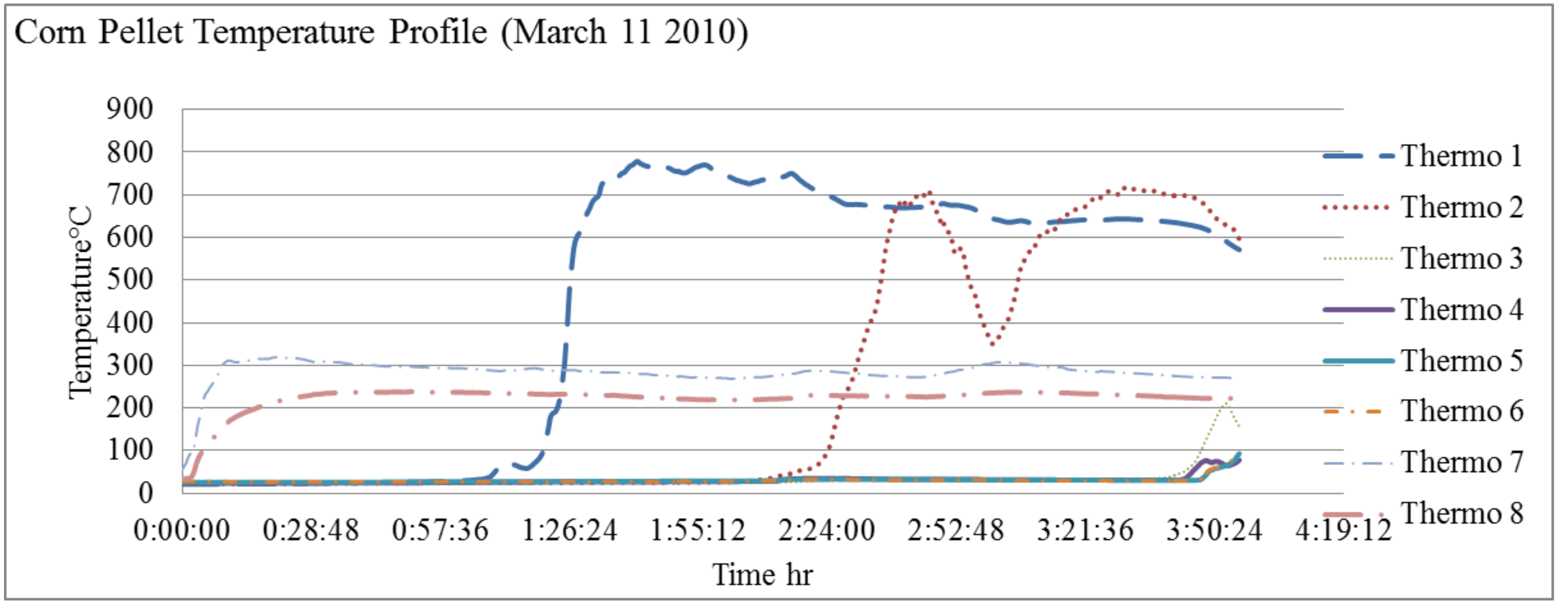

Alfalfa Oxygen Sensor Profile (Nov 05 2009)
Volts
1
0.8
0.6
0.4
0.2
0
-0.2
0:00:00
1:12:00
2:24:00
3:36:00
4:48:00
6:00:00
7:12:00
Time hr
Oxygen Sensor (o)
Oxygen Sensor (i)

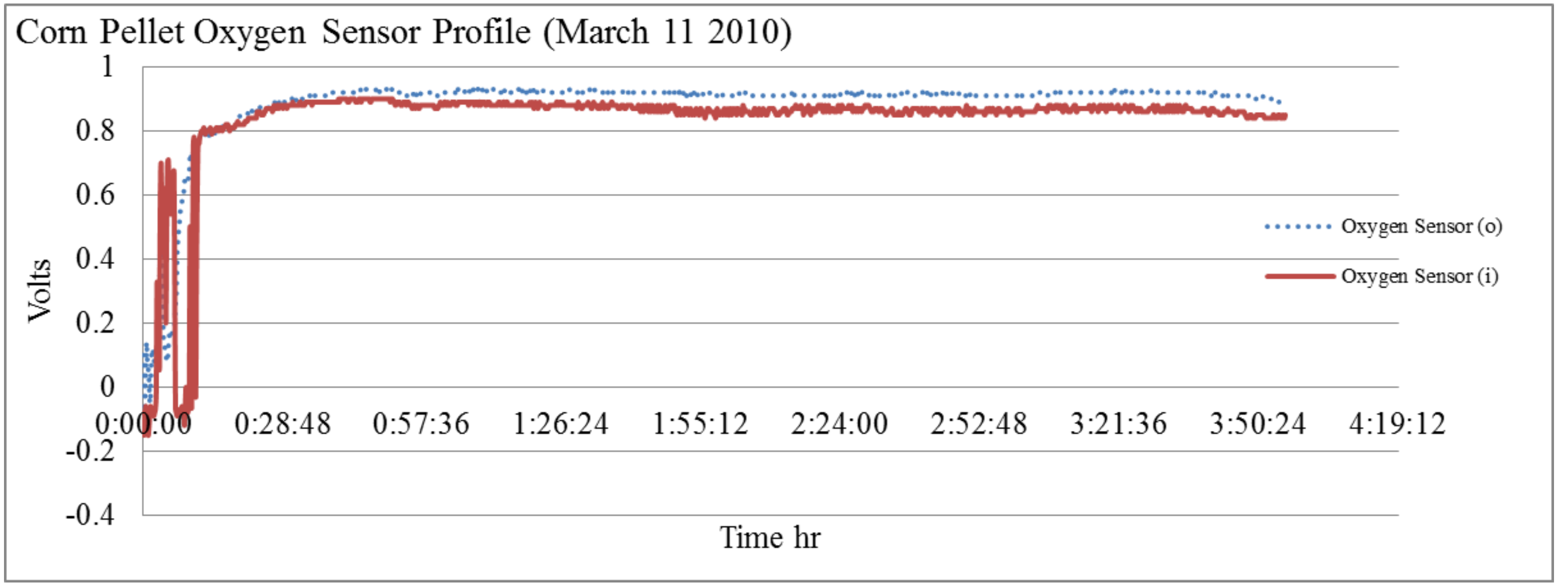

Cypress Mulch Temperature Profile (Nov 13 2009)
Temperature °C
1200
1000
800
600
400
200
0
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
Time hr
Thermo 1
Thermo 2
Thermo 3
Thermo 4
Thermo 5
Thermo 6
Thermo 7
Thermo 8


Cypress Mulch Oxygen Sensor Profile (Nov 13 2009)
Volts
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
Time hr
Oxygen Sensor (o)
Oxygen Sensor (i)


Bark Nugget Temperature Profile (Nov 19 2009)
Temperature °C
1200
1000
800
600
400
200
0
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
Time hr
Thermo 1
Thermo 2
Thermo 3
Thermo 4
Thermo 5
Thermo 6
Thermo 7
Thermo 8


Bark Nugget Oxygen Sensor Profile (Nov 19 2009)
Volts
1
0.8
0.6
0.4
0.2
0
-0.2
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
Time hr
Oxygen Sensor (o)
Oxygen Sensor (i)


Corn Pellet Temperature Profile (March 11 2010)
Temperature°C
900
800
700
600
500
400
300
200
100
0
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
4:19:12
Time hr
Thermo 1
Thermo 2
Thermo 3
Thermo 4
Thermo 5
Thermo 6
Thermo 7
Thermo 8


Corn Pellet Oxygen Sensor Profile (March 11 2010)
Volts
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0:00:00
0:28:48
0:57:36
1:26:24
1:55:12
2:24:00
2:52:48
3:21:36
3:50:24
4:19:12
Time hr
Oxygen Sensor (o)
Oxygen Sensor (i)

SectionA1.3: (i) Concentration of Particulates

For Glass Fiber Filter Paper: Particulates.

Sno No	Feedstock	Experiment Date	Initial (gm)	Final (gm)	Difference (gm)	SCFH	cfm ((.3048 m)^3/min)	Duration (min)	m^3	Deposition (g/Nm^3)
1	Pine pellets	5/27/2009	0.4711	1.0986	0.6275	10	0.004719474	30	0.141584	4.431990674
		5/29/2009	0.4614	1.1024	0.641	10	0.004719474	30	0.141584	4.527340274
		6/8/2009	0.4789	0.9365	0.4576	10	0.004719474	30	0.141584	3.231998298
2	pine+cat	7/3/2009	0.4661	0.4842	0.0181	10	0.004719474	30	0.141584	0.127839094
3	Hardwood	10/29/2009	0.4687	0.9439	0.4752	10	0.004719474	30	0.141584	3.356305925
		10/29/2009	0.4779	0.8051	0.3272	10	0.004719474	30	0.141584	2.31099179
		10/29/2009	0.4688	0.9056	0.4368	10	0.004719474	30	0.141584	3.085089285
4	Hardwood	2/18/2010	0.4036	0.7188	0.3152	10	0.004719474	30	0.141584	2.22623659
		2/18/2010	0.4864	0.627	0.1406	10	0.004719474	30	0.141584	0.993048428
		2/18/2010	0.4864	0.7805	0.2941	10	0.004719474	30	0.141584	2.077208697
5	Alfalfa	11/5/2009	0.4673	0.9076	0.4403	10	0.004719474	30	0.141584	3.109809551
		11/5/2009	0.478	0.9223	0.4443	10	0.004719474	30	0.141584	3.138061285
		11/5/2009	0.4689	1.2004	0.7315	10	0.004719474	30	0.141584	5.166535741
6	Cypress	11/13/2009	0.4636	0.5313	0.0677	10	0.004719474	30	0.141584	0.478160587
		11/13/2009	0.4677	0.4806	0.0129	10	0.004719474	30	0.141584	0.09111184
		11/13/2009	0.4684	0.8107	0.3423	10	0.004719474	30	0.141584	2.417642084
	Bark Nugget	11/17/2009	0.4732	0.5313	0.0581	10	0.004719474	30	0.141584	0.410356427
		11/17/2009	0.471	0.4806	0.0096	10	0.004719474	30	0.141584	0.06780416
		11/17/2009	0.4686	0.8107	0.3421	10	0.004719474	30	0.141584	2.416229497
8	Corn	3/11/2010	0.4714	0.5187	0.0473	10	0.004719474	30	0.141584	0.334076747
		3/11/2010	0.4691	0.5017	0.0326	10	0.004719474	30	0.141584	0.230251627
		3/11/2010	0.4673	0.6479	0.1806	10	0.004719474	30	0.141584	1.275565762

SectionA1.3: (ii) Concentration of Tars

For Acetone Bottles : Tars										
Sno No.	**Feedstock**	**Experiment Date**	**Initial (gm)**	**Final (gm)**	**Difference (gm)**	**SCFH**	**cfm ((.3048 m)^3/min)**	**Duration (min)**	**m^3**	**Deposition (g/Nm^3)**
1	pine	5/27/2009	4.0146	4.1555	0.1409	10	0.004719474	30	0.14158423	0.995167308
		5/29/2009	4.0412	4.1302	0.089	10	0.004719474	30	0.14158423	0.628601068
		6/8/2009	4.0182	4.1298	0.1116	10	0.004719474	30	0.14158423	0.788223361
2	pine+cat	7/3/2009	4.0187	4.0566	0.0379	10	0.004719474	30	0.14158423	0.267685174
3	Hardwood	10/29/2009	4.0616	4.1136	0.052	10	0.004719474	30	0.14158423	0.367272534
		10/29/2009	3.9722	3.998	0.0258	10	0.004719474	30	0.14158423	0.18222368
		10/29/2009	4.0639	4.085	0.0211	10	0.004719474	30	0.14158423	0.149027894
4	Hardwood	2/18/2010	4.0362	4.1106	0.0744	10	0.004719474	30	0.14158423	0.525482241
		2/18/2010	4.0684	4.1236	0.0552	10	0.004719474	30	0.14158423	0.389873921
		2/18/2010	4.1036	4.1194	0.0158	10	0.004719474	30	0.14158423	0.111594347
5	Alfalfa	11/5/2009	4.0505	4.0962	0.0457	10	0.004719474	30	0.14158423	0.322776054
		11/5/2009	4.0409	4.16	0.1191	10	0.004719474	30	0.14158423	0.841195361
		11/5/2009	4.033	4.075	0.042	10	0.004719474	30	0.14158423	0.2966432
6	Cypress	11/13/2009	4.5077	4.7032	0.1955	10	0.004719474	30	0.14158423	1.380803469
		11/13/2009	4.077	4.1036	0.0266	10	0.004719474	30	0.14158423	0.187874027
		11/13/2009	4.0362	4.1003	0.0641	10	0.004719474	30	0.14158423	0.452734027
7	Bark Nugget	11/17/2009	4.1198	4.1378	0.018	10	0.004719474	30	0.14158423	0.1271328
		11/17/2009	4.1112	4.1262	0.015	10	0.004719474	30	0.14158423	0.105944
		11/17/2009	4.1081	4.145	0.0369	10	0.004719474	30	0.14158423	0.26062224
8	Corn	3/11/2010	4.1173	4.1251	0.0078	10	0.004719474	30	0.14158423	0.05509088
		3/11/2010	4.0913	4.0971	0.0058	10	0.004719474	30	0.14158423	0.040965013
		3/11/2010	4.1121	4.1156	0.0035	10	0.004719474	30	0.14158423	0.024720267

SectionA1.4: Gas Chromatography Results

Alfalfa	
Component	
H2	7.880825
O2	1.919724
N2	60.55117
CO	11.36245
CH4	1.387682
CO2	16.89815
	100
Bark Nugget	
Component	
H2	9.755832
O2	3.679034
N2	66.69237
CO	5.596378
CH4	0.299128
CO2	13.97725
	100
Cypress Mulch	
Component	
H2	16.25293
O2	3.320185
N2	58.77528
CO	6.195482
CH4	0.998059
CO2	14.45806
	100
Corn	
Component	
H2	9.555212
O2	2.607696
N2	54.20146
CO	15.14757
CH4	2.413195
CO2	16.07486
	100
Hardwood	
Component	
H2	10.37458
O2	1.386127
N2	50.90602
CO	16.83399

CH4	4.084746
CO2	16.41453
	100
Pine	
Component	
H2	18.082
O2	1.124769
N2	42.56786
CO	18.26108
CH4	3.978105
CO2	15.98619
	100

SectionA1.5: Metal Analysis Results

Metals (EPA 200.7)	Result						
Sample Lab ID							
Sample Field ID	MDL	Chicken Before	Chicken after	Pine Before	Pine after	alfalfa	Switchgrass before
Unit:	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Aluminum (Al)	0.06	971.653	1525.223	41.137	223.295	405.470	92.220
Arsenic (As)	0.01	10.225	10.120	10.840	18.459	12.843	8.625
Boron (B)	0.02	23.706	132.741	8.445	146.781	65.152	12.779
Barium (Ba)	0.02	4.827	80.262	1.895	93.157	2.285	4.209
Beryllium (Be)	0.01	0.087	0.090	0.014	0.043	0.039	0.029
Calcium (Ca)	0.02	3670.368	4715.498	369.199	857.535	4166.398	762.006
Cadmium (Cd)	0.01	0.211	0.111	0.163	0.163	0.010	ND
Cobalt (Co)	0.01	1.121	1.552	0.106	ND	0.246	0.115
Chromium (Cr)	0.01	20.636	24.281	ND	0.606	1.388	1.066
Copper (Cu)	0.01	24.711	35.172	ND	ND	5.087	2.174
Iron (Fe)	0.01	4839.419	6210.515	17.869	103.425	618.465	357.960
Potassium (K)	0.032	1018.810	2287.504	350.758	1789.100	15124.208	5789.260
Magnesium (Mg)	0.01	2696.612	3712.410	260.971	593.886	2768.467	1249.964
Manganese (Mn)	0.01	73.596	129.995	110.697	154.331	53.243	64.024
Molybdenum (Mo)	0.038	ND	ND	ND	ND	ND	ND
Sodium (Na)	0.029	171.162	555.112	38.455	411.337	142.162	67.790
Nickel (Ni)	0.01	4.382	4.428	0.193	0.442	1.082	2.242
Phosphorus (P)	0.024	2234.483	3383.156	66.800	179.405	2017.062	690.634
Lead (Pb)	0.01	1.997	2.202	N/A	ND	0.345	0.834
Sulfur (S)	0.011	1738.105	887.080	140.898	269.475	2890.810	655.817
Antimony (Sb)	0.01	1.256	3.826	N/A	3.832	1.008	0.876
Selenium (Se)	0.01	0.298	0.900	0.444	1.342	0.529	0.463
Silicone (Si)	0.7	904.806	411.542	51.088	483.758	477.652	1231.951
Tin (Sn)	0.01	2.638	3.773	0.347	2.504	0.478	0.767
Strontium (Sr)	0.02	ND	ND	ND	ND	ND	ND
Thallium (Tl)	0.01	ND	ND	ND	ND	ND	ND
Vanadium (V)	0.01	4.335	5.344	ND	0.261	0.596	0.177
Yttrium (Y)	0.01	0.851	0.957	0.034	0.129	0.171	0.153
Zinc (Zn)	0.01	147.208	415.583	8.287	251.045	18.619	22.345
% C	%	29.360			71.260	39.840	
% N	%	1.360			0.255	2.856	
C/N		21.590			279.300	13.950	
%H	%	4.021			0.000	5.785	

SectionA1.6: Ultimate Analysis

	N	**C**	**H**
Alfalfa	N/A*	2.268	0.326
Alfalfa After	2.856	44.4	5.785
Bark Nugget	N/A*	1.553	0.207
Bark Nugget After	0.218	87.5	2.263
Cypress Mulch	0.23	46.15	6.682
Cypress Mulch After	0.164	74.87	2.541
Corn	0.569	64.59	1.838
Hardwood	5.461	37.02	3.683
Pine	0.536	41.12	5.724
Pine After	0.255	71.26	N/A
Poultry Litter	1.118	23.32	3.075
Poultry Litter After	0.692	23.46	0.792
Switch Grass	0.547	42.1	5.933
Dairy Manure	1.487	25.28	3.352
Bagasse	0.4	39.24	5.225

*N/A = Not Available

VITA

Akshya Sharma was born in 1983, in Rewa, Madhya Pradesh, India. He attended Rajiv Gandhi Technical University, India, and graduated May 2006 with a Bachelor of Science in Electrical Engineering.

In January 2008 he was admitted into the Master of Science program in the Department of Biological and Agricultural Engineering at Louisiana State University and Agricultural and Mechanical College and is currently pursuing the degree of Master of Science in Biological and Agricultural Engineering. The title of his thesis is “Assessing the Suitability of Various Feedstocks or Biomass Gasification”