INSTRUMENTATION AND EVALUATION OF A PILOT SCALE

FLUIDIZED BED BIOMASS GASIFICATION SYSTEM

A Thesis

by

AMADO LATAYAN MAGLINAO, JR.

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2009

Major Subject: Biological and Agricultural Engineering

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Approved by:

Chair of Committee,	Sergio C. Capareda
Committee Members,	Calvin B. Parnell, Jr.
	Wei Zhan
Head of Department,	Gerald L. Riskowsky

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ABSTRACT

Instrumentation and Evaluation of a Pilot Scale Fluidized Bed Biomass

Gasification System. (December 2009)

Amado Latayan Maglinao Jr., B.S., University of the Philippines at Los Baños, Philippines

Chair of Advisory Committee: Dr. Sergio C. Capareda

A pilot scale fluidized bed biomass gasifier developed at Texas A&M University in College Station, Texas was instrumented with thermocouples, pressure transducers and motor controllers for monitoring gasification temperature and pressure, air flow and biomass feeding rates. A process control program was also developed and employed for easier measurement and control. The gasifier was then evaluated in the gasification of sorghum, cotton gin trash (CGT) and manure and predicting the slagging and fouling tendencies of CGT and manure.

The expected start-up time, operating temperature and desired fluidization were achieved without any trouble in the instrumented gasifier. The air flow rate was maintained at 1.99 kg/min and the fuel flow rate at 0.95 kg/min. The process control program considerably facilitated its operation which can now be remotely done.

The gasification of sorghum, CGT and manure showed that they contained high amounts of volatile component matter and comparable yields of hydrogen, carbon monoxide and methane. Manure showed higher ash content while sorghum yielded lower amount of hydrogen. Their heating values and gas yields did not vary but were considered

low ranging from only 4.09 to 4.19 MJ/m^3 and from 1.8 to 2.5 m^3/kg, respectively. The production of hydrogen and gas calorific values were significantly affected by biomass type but not by the operating temperature.

The high values of the alkali index and base-to acid ratio indicated fouling and slagging tendencies of manure and CGT during gasification. The compressive strength profile of pelleted CGT and manure ash showed that the melting (or eutectic point) of these feedstock were around 800°C for CGT and 600°C for manure. Scanning electron microscopy (SEM) images showed relatively uniform bonding behavior and structure of the manure ash while CGT showed agglomeration in its structure as the temperature increased.

The instrumentation of the fluidized bed gasifier and employing a process control program made its operation more convenient and safe. Further evaluation showed its application in quantifying the gasification products and predicting the slagging and fouling tendencies of selected biomass. With further development, a full automation of the operation of the gasifier may soon be realized.

DEDICATION

To my fiancée, Joan Hernandez, who supported and encouraged me in every step of the way. To my family, my father, Amado R. Maglinao, my mother, Erlinda L. Maglinao, and my two brothers, Ryan and Randy Maglinao, and also to my soon to be official family, Jose Hernandez, Julie Hernandez and Jonalyn Hernandez, who have always been supportive to me since the beginning of my studies.

ACKNOWLEDGEMENTS

NOMENCLATURE

AI- Alkali Index

ANOVA- Analysis of Variance

ASTM- American Society for Testing and Materials

BAI- Bed Agglomeration Index

BTU-British Thermal Unit

CGT- Cotton Gin Trash

daf.b- Dry Ash Free Basis

d.b- Dry Basis

df- Degrees of Freedom

ER- Equivalence Ratio

FC- Fixed Carbon

h- Hour

HHV- High Heating Value

hp- Horsepower

LabVIEW – Laboratory Virtual Instrumentation Engineering Workbench

LCV- Low Calorific Value

LFE- Laminar Flow Element

MMBtu- Thousand thousand BTU or one million BTU

mol- Moles

MWh- Megawatt hour

NI- National Instruments

PLC- Programmable Logic Controller

$R_{b/a}$- Base to acid ratio

R_f- Fouling ratio

R_s- Slagging ratio

SEM- Scanning Electron Microscopy

VM- Volatile Matter

vol%- Volume percent

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CHAPTER I

INTRODUCTION: IMPORTANCE OF THE RESEARCH

After decades of growth in energy consumption and a rapidly increasing energy demand, the fossil oil and gas reserves will continue to decline in a rapid pace (Johansson et al., 2006). The current sources of energy are obtained primarily from fossil fuels but they are non renewable and their supply will become limited (LePori and Soltes, 1985). According to the British Petroleum (BP) Global statistical review, the world primary energy consumption was 11,295 million tones oil equivalent (448 quadrillion BTU) in 2008, which is 1.4% higher than the last 10-year average. Energy consumption in the US fell by 2.8% at 2299 million tones oil equivalent (91 quadrillion BTU) in the year 2008 (BP, 2009).

In Texas, the rapid economic growth is driving increased demand for energy, especially in the electricity market, where demand is beginning to surpass supplies. The electric generating reserve margins are anticipated to fall below the minimum of 12.5% of the requirement in 2008. The serious need for new electricity generating capacity is coming at a time when prices for traditional fossil fuel resources are at unprecedented highs and concerns over the environmental impacts of energy production and use are mounting (Bullock et al., 2008).

Like fossil fuels, biomass contains high percentages of carbon and hydrogen and can be a good alternative source of energy (LePori and Soltes, 1985). Even though raw

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This thesis follows the style of the *Transactions of the ASAE*.

biomass has significantly less energy content than petroleum, its supply is renewable and with adequate reserves. The supply of heat and combined heat and power, as well as other energy forms such as electricity, liquid and gaseous fuels are some energy sources that can be satisfied partly by biomass. In order to address the most efficient transformation of biomass into other forms and fuels at the desired scale of operation, an understanding of the physical and chemical differences between biomass resources is needed (Overend and Wright, 2008).

Agricultural wastes, such as wastes produced during harvesting of crops or everyday wastes from animal industry, can be used as fuel for waste-to-energy facilities. In Texas, an estimated 3.9 million MWh of electrical energy can be produced from agricultural wastes each year using waste-to-energy plants (Bullock et al., 2008). The most suitable use of these biomass is by gasification on smaller scale (Mathieu and Dubuisson, 2002).

Thermochemical processes have the potential to convert biomass into a gas or liquid intermediate suitable for further refining to valuable products. Gasification is one of the thermochemical processes that can convert biomass into a useful product known as synthesis gas. Without complete combustion of the fuel, conversion occurs in an oxygen deficient (partial oxidation) condition at high temperatures. The partial oxidation process of the biomass takes place at temperatures of about 800°C (1400°F) and produces primarily combustible gases consisting of carbon monoxide (CO), hydrogen (H_2) and traces of methane and some other products like tar and char (Rajvanshi, 1986). In biomass gasification, the reactor types commonly used are the fixed bed and fluidized bed (Figure 1).
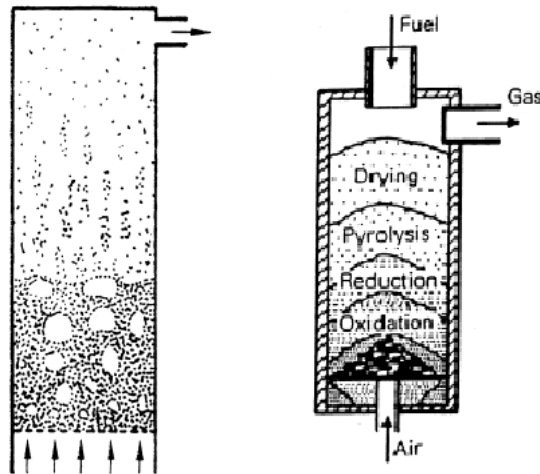
Figure 1. Fluidized bed (left) and fixed bed (right) reactors (Warnecke, 2000).

One significant advantage of the fluidized bed over the fixed bed reactor is the use of broad size particle distribution (Warnecke, 2000). In addition, fluidized bed reactors provide good mass and heat transfer rate between the fluid and the particles (Fu and Liu, 2007). The turbulent, fluidized state of inert particles in the bed creates a near isothermal zone and enables accurate control of reaction temperatures. Thermal energy stored in large mass of inert particles is rapidly transferred to solid fuel at stable temperatures. Violent agitation of solids provides efficient conversion reactions and allows introduction of fuels having wide variations in composition and particle size (LePori and Soltes, 1985).

Large scale projects for gasification have been envisioned to address alternative energy sources and yet many of those have remained in the proposal stage. Agricultural industries, such as the cotton gin, poultry and dairy industries, generate tons of wastes while consuming heat and power for their operation. Thus, the on-site conversion of the

generated wastes into useful products would be the most practical option as it will also minimize the transport cost of the biomass. Ultimately, this system will make these industries independent of their heat and power requirement thereby indirectly contributing to reduced dependency on foreign oil while generating new businesses in the farm.

The long term goal of this research project is to develop modular biomass thermal conversion systems for heat and power generation for the different agricultural industries in the region that generate residues and wastes. The specific objectives are to:

1. Develop an appropriate instrumentation for the process control system for an on-site gasification technology.
2. Evaluate the synthesis gas production of the skid-mounted fluidized bed gasifier using sorghum, manure and cotton gin trash as the biomass feedstock.
3. Determine the slagging and fouling behavior of ashes from beef cattle manure and cotton gin trash (CGT) and predict their deposit formation tendencies to identify possible solution to the problem.

CHAPTER II

INSTRUMENTATION AND PROCESS CONTROL PROGRAM FOR A

FLUIDIZED BED BIOMASS GASIFICATION SYSTEM

OVERVIEW

The conversion of biomass into energy (also called bioenergy) encompasses wide range of different types and sources of biomass, conversion options and end-use applications. These can be done through either thermochemical or bio-chemical/biological process technologies. Thermochemical conversion process options include direct combustion, pyrolysis, and gasification (McKendry, 2002a).

Gasification is a process for converting carbonaceous materials into a combustible or synthetic gas such as H_2, CO, and CH_4. In general, it involves the reaction of carbon with air, oxygen, steam, carbon dioxide, or a mixture of these gases at high temperatures, typically in the range between 800–900°C to produce synthesis gas. Synthesis gas can be used to provide electric power and heat for industries or can serve as a raw material for the synthesis of chemicals or liquid fuels. It may be used to generate gaseous fuels such as hydrogen and methane. As a process, gasification involves a number of steps and conditions to be met to achieve the desired product. A better understanding of these steps and conditions would provide the sound basis for further technology development.

INTRODUCTION

The conversion of biomass into a combustible gas mixture by the gasification process occurs through the partial oxidation of biomass at high temperatures. With air as gasifying medium, a low calorific value (LCV) gas of about $4 - 6$ MJ/m^3 (100 – 160 Btu/ft^3) may be produced (Lee, 2007). This gas can be burnt directly or used as a fuel for gas engines and gas turbines. Gasification is an ideal biomass thermal conversion process as many biomass fuels contained high amounts of ash with low melting points.

Gasification technologies have been commercially applied in the production of both fuels and chemicals for more than a century. Their application and further technology advancement are expected to continue considering the current trends in power generation industries. There are an increasing number of applications of synthesis gas in the basic manufacture of chemicals. In addition, the technology has the attractive feature of being able to produce a consistent product that can be used for the generation of electricity or as primary building blocks for the manufacture of transportation fuels. Moreover, it has the ability to process a wide range of feedstock including coal, heavy oils, petroleum coke, heavy refinery residuals, refinery wastes, hydrocarbon contaminated soils, biomass, and agricultural wastes.

The ability to reliably measure a variety of gasification input parameters including compositional analysis of the feedstock to control the gasifier would be most useful. Instrumentation and advanced control systems on a gasifier are considered key areas to further improve its development. A number of parameters can be controlled to differentiate the various feedstock conversion processes and obtain the desired end

product. These include heating rate, final temperature, residence time at certain temperature, presence or absence of air or oxygen, fuel particle size, and fuel moisture content.

In their study on the development of a low-density biomass gasification system for thermal applications using sugarcane leaves and bagasse, Jorapur and Rajvanshi (1997) employed a Programmable Logic Controller (PLC)-based control system designed to take automatic corrective actions under certain critical conditions. The biomass feeding and ash removal rates were fully controlled by this system. It also helped the operator in trouble-shooting by monitoring temperatures at various critical points in the gasification system. Automatic burner sequence controllers were provided for ignition of the producer gas.

The most basic feedback system measures the controlled variables, compare the actual measurements with the desired values and use the difference between them (error) to identify the appropriate corrective action. It is therefore necessary to first measure the variables that are to be maintained at the desired standard values (Anderson, 1997). According to LePori and Soltes (1985), the fuel to air ratio and operating temperature are probably the two most critical parameters to control during the biomass conversion.

This particular study explored the feasibility of an appropriate instrumentation for a fluidized bed biomass gasification system to facilitate measurement, operation and control. The specific objectives of the study include: (a) identify important operational parameters to monitor (b) install measuring and control devices (c) develop a process control program to properly operate the gasifier continuously.

MATERIALS AND METHODS

The Pilot Scale Gasification System

The pilot scale gasification system used was a fluidized bed gasifier developed at Texas A&M University at College Station, Texas and originally protected under US Patent No. 4848249 (LePori and Parnell, 1989). It is a 305mm (1-ft) diameter skid-mounted fluidized bed gasification unit with an average throughput of 70 kg/hr (150 lbs/hr) and can convert a variety of biomass residues (Figure 2).

Figure 2. Pilot scale fluidized bed gasification unit.

Figure 3 describes the stages of operation of the fluidized bed gasification system. The bed material at first heated in the reactor. The biomass is then placed in the fuel bin and fed into the fluidized bed gasifier through the screw conveyor system (auger). The gasification process occurs at the fluidized bed reactor where partial oxidation of biomass occurs. Here, the combustible gases are produced. The two-stage cyclones separate the char particulates from the combustible gas.
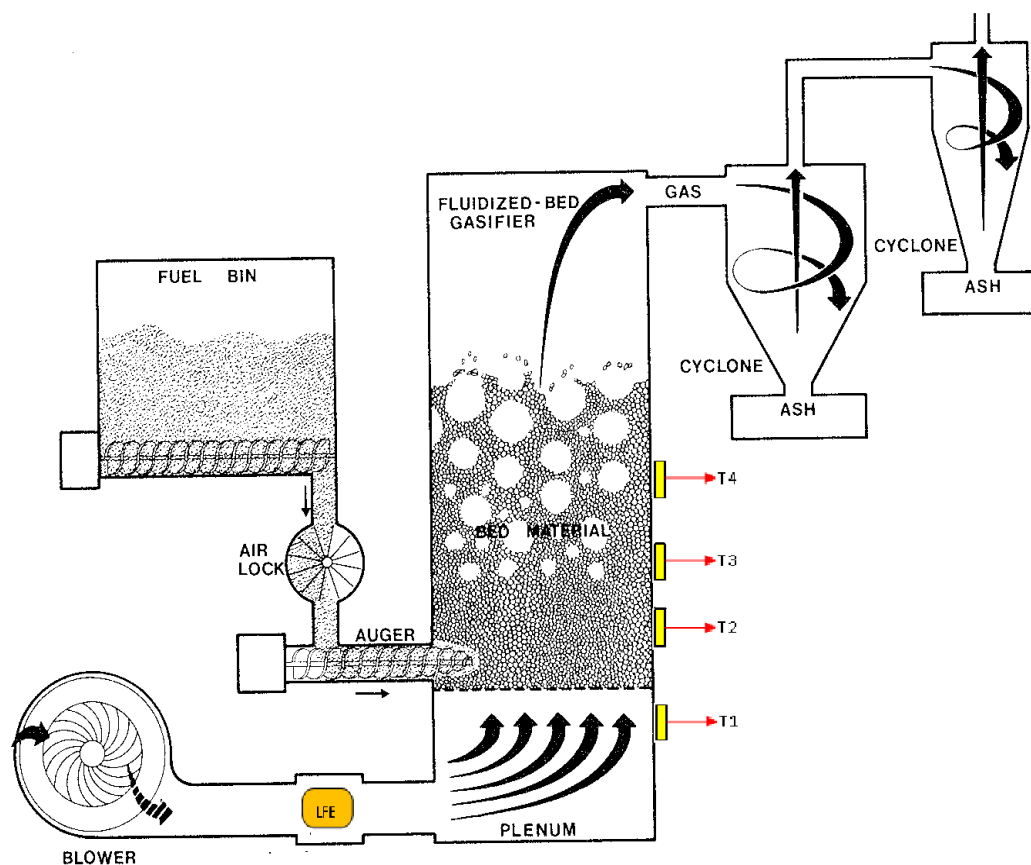
Figure 3. Operation of the fluidized bed gasifier (LePori and Soltes, 1985).

Instrumentation for Measurement of Important Control Parameters

The gasification system was instrumented to conveniently measure and monitor the important parameters that may affect the operation of the gasification unit. These parameters include the gasification temperature, pressure in the gasifier, the air flow rate and the biomass feeding rate. The gasification temperature has to be maintained between 700 to 815°C (1300 to 1500°F) during its operation to produce the desired quality of the synthesis gas. Monitoring the pressure across the bed in the reactor is necessary during operation as this indicates the fluidization behavior of the bed material. The differential

pressure from the laminar flow element indicates the amount of air being supplied to the system. The air flow rate values are needed to set up the air to fuel ratio during the operation of the gasifier while the biomass feeding rate regulates the amount of feedstock introduced into the gasifier.

To measure and monitor the temperature in the gasifier, CAIN-14U K-type thermocouples (Omega, Stamford, CT) were installed at different locations. Differential pressure transducers were used to record the pressure readings taken at different points in the gasifier and displayed using Magnehelic differential pressure gages. The air flow rate was regulated using an AF-300 Mini AC motor controller (Grainger, Bryan, TX) for the 5 hp motor blower air system. To regulate the biomass feeding rate through the screw conveyor system driven by a 1 hp DC motor, a DART 251G controller was used. The speed of the screw conveyor was measured using a Monarch ROS-W optical sensor with 3 strips of reflective tape placed at the shaft of the screw conveyor.

Proper calibration tests were conducted for all the devices installed especially the pressure transducers. A set pressure was supplied to the digital manometer and the pressure transducer and the relationship of pressure (inches of water) to current (milliamperes) was obtained. Appropriate sensors were likewise connected to indicate numerical values or plots corresponding to the measured parameters. The appropriateness of the instrumentation and control devices installed in the gasifier was evaluated during the conduct of the preliminary tests for the process control program discussed in the subsequent sections.

Process Control Program Development

For easier measurement and control of the devices installed in the gasifier, a process control program was also developed. A National Instruments (NI) CompactDAQ was used for monitoring the sensor measurements in the gasification unit and for modular instrumentation. The NI CompactDAQ provides the plug-and-play simplicity of USB to sensor and electrical measurements on the bench top, in the field, and on the production line. It provides fast and accurate measurements in a small and simple system. Table 1 shows the different modules for the NI CompactDAQ used for this system. This system will be appropriate for research type pilot equipment. A dedicated programmable integrated system, programmed on a microchip may be appropriate for commercial systems.

Table 1. Modules used for CompactDAQ.

CompactDAQ Module	Function
NI 9211 Thermocouple Input Module	*-for K-type thermocouple readings*
NI 9203 ±20mA Analog Input Module	*-for pressure transducer readings*
NI 9205 ±200mV to ±10V Analog Input Module	*-for optical sensor reading*
NI 9263 ±10V Analog Voltage Output Module	*-for AC and DC motor controller*
	-for optical sensor supply

A LabVIEW (short for Laboratory Virtual Instrumentation Engineering Workbench) program was developed for the NI CompactDAQ to process all the electrical signals into readable values which were then used to control the factors that might influence the operation of the system. LabVIEW uses graphical programming to develop the measurement, test and control for the operation of the gasification system.

Feasibility of the Instrumentation and Control Process Program

Preliminary tests were conducted to determine the feasibility of the measurement and control system installed in the gasifier using the program developed. Sorghum was used as the feedstock to maintain a constant operating temperature while attempting to vary the air to fuel ratios. The effect of continuously switching the feedstock was also evaluated using wood chips, switchgrass and manure fed into the gasifier one after the other. The operating temperature was maintained with proper adjustments in the fuel feed rate and air flow rate. Performance was analyzed based on the resulting operating temperature profiles.

RESULTS AND DISCUSSION

Control Process Program Development

The process control program was developed for the proper operation of the fluidized bed gasifier after the installation of the monitoring and control devices. A user interface was designed and a software program was developed for measurement and control of the parameters during the gasification process.

Interface Development

The interface design for the program indicates quick control of the processes, displays all important information and indicates faulty operation. Figure 4 shows the main interface of the program indicating the gasification system and the important parameters during operation. The gasifier temperature, air flow rate, fuel feed rate and the air to fuel ratio which are the fundamental information needed in monitoring the gasification system

are all indicated in the interface. A main control panel was included to control the blower

and feeding system and put the fundamental parameters to the desired settings.

Maintaining a constant gasification temperature is very complex and with these controls,
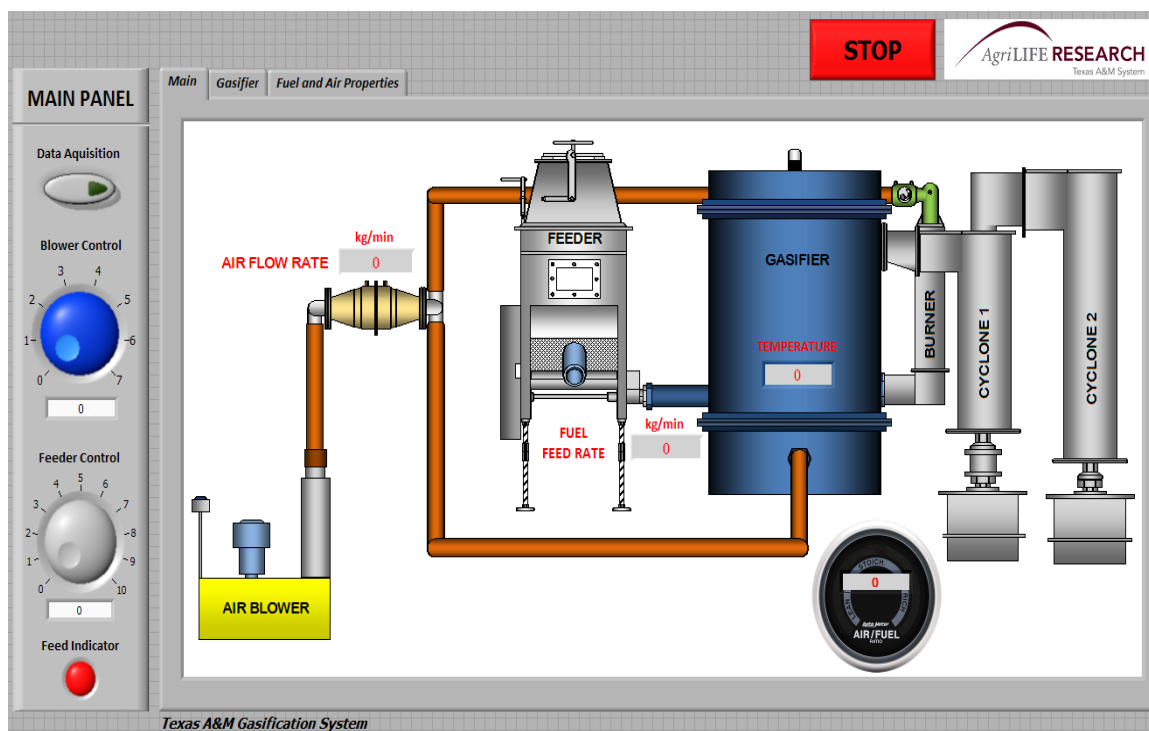
Figure 4. Main interface of the gasification process control program.

an operator can easily achieve this goal. In addition, a feed indicator is added to warn the

operator of unexpected clogging in the screw conveyor and decide on the necessary

actions. An emergency button is also included to shutdown the whole system when serious

problem occurs.

The gasifier interface displays the detailed information on the measured parameters

in the gasifier (Figure 5). This includes temperature and pressure readings at different

points in the system. With the limited number of input channels for the existing system, an

option to add exhaust temperature (see Figure 3) was included.
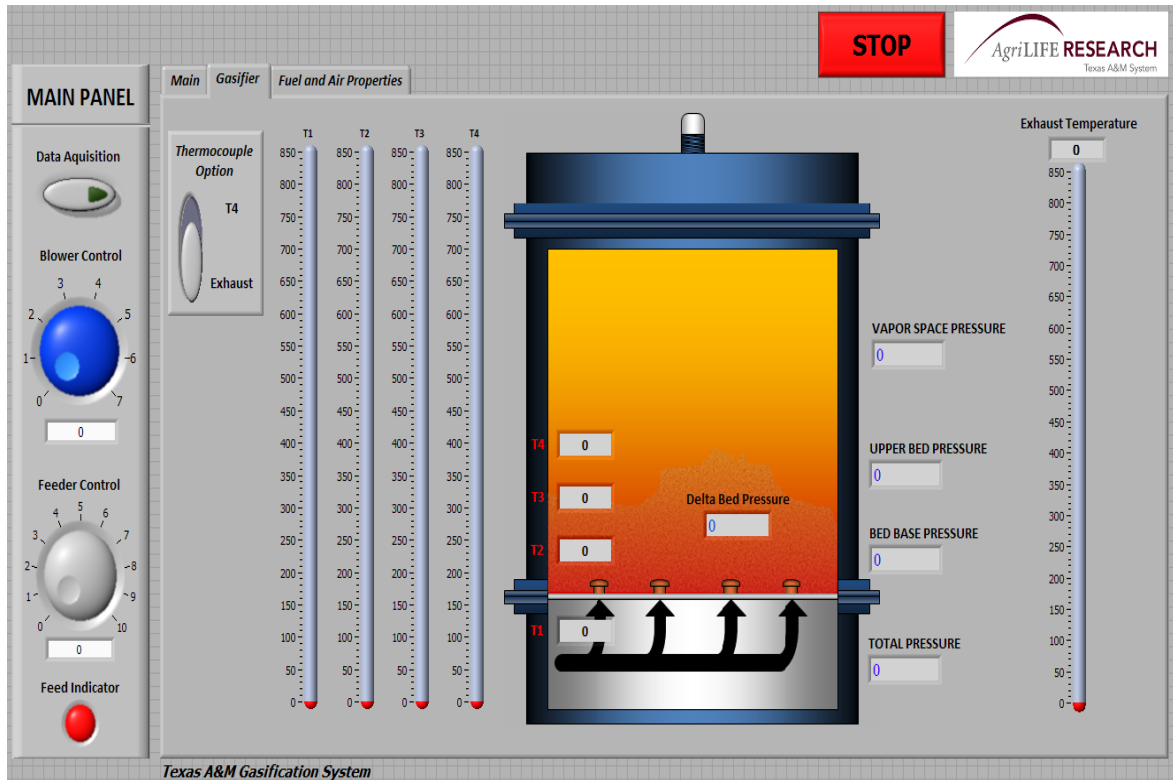
Figure 5. Detailed gasification system interface.

The last part of the interface is the display of air and fuel properties (Figure 6). The

interface provides a list of the solid biomass fuel that may be used in this research. It

specifies the bulk density and loading factor for each of the biomass. This interface also

includes the screw conveyor dimensions and its measured speed during operation.

Calculated mass flow rates are indicated and the amount of air supplied into the system and

the instantaneous air to fuel ratio are also shown.
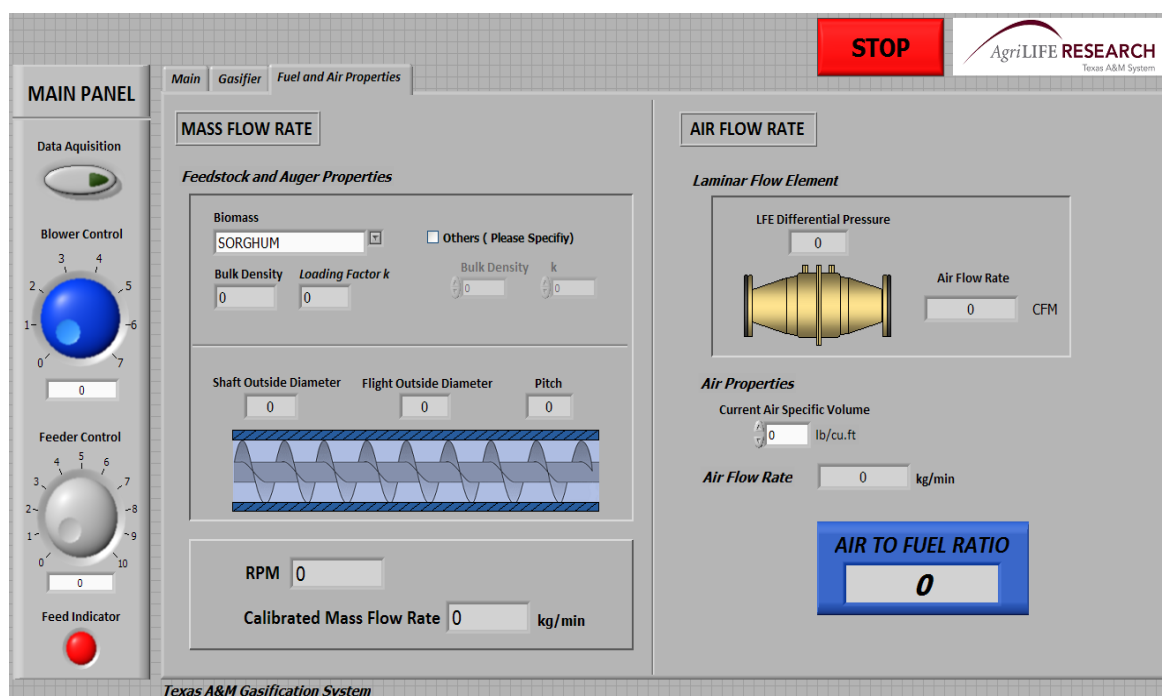
Figure 6. Air and solid fuel properties interface.

Software Program Development

The software program was developed after the graphical user interface had been established using the LabVIEW. The program would make the computer interact with all the instruments installed in the gasification unit and allow the measurement and control of the identified parameters. With the LabVIEW, the program consisted of two sections using a timed loop: the Input Section and the Control Output Section (Figure 7). The input section includes all the data from the gasification system which are measured every 3 seconds. Different DAQmx tasks were made to gather these data readings. The gasifier profile task gathers the temperature and pressure readings from the thermocouples and pressure transducers, respectively. The air flow rate, in kg/min, was approximated using the ideal gas law and the volumetric flow rate obtained from the laminar flow element.
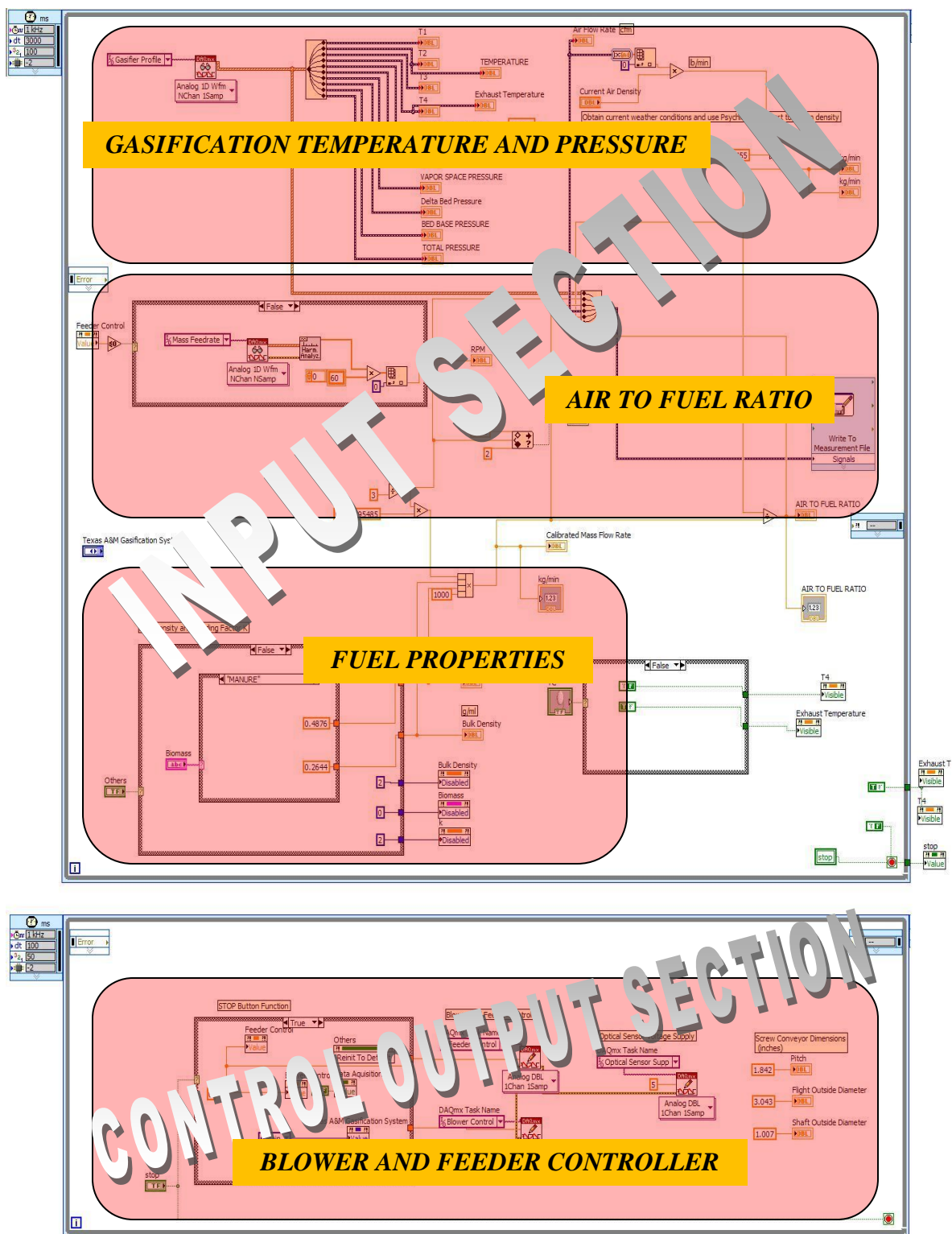
Figure 7. LabVIEW gasification system program.

The bulk density of the solid fuels, such as sorghum, cotton gin trash, manure and woodchips was obtained from earlier analyses using ASTM E873 (Test method for bulk density of densified particulate biomass fuels). The mass flow rate of solids in the feeding system using a regular helicoids flighting screw conveyor was determined following the equation of Woodcock and Mason (1987) shown in eq. (1) below.

$$\dot{m}_s = \rho_b \frac{1}{4} \pi (D_{sc}^2 - D_{sh}^2) k \lambda N \tag{1}$$

where ρ_b, bulk density

D_{sc}, trough of flight diameter

D_{sc}, shaft diameter

The measurements of the screw conveyor that are used in the equation are described in Figure 8. The loading factor, which should be generally between 0.15-0.45, depends upon the nature of the material to be conveyed (Woodcock and Mason, 1987). For this system, the loading factor
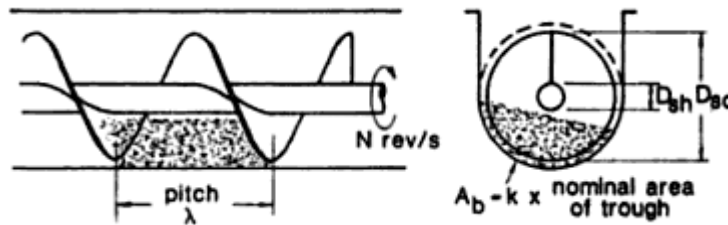
Figure 8. Capacity of a screw conveyor (Woodcock and Mason, 1987).

values for each of the biomass that would be used in the study are summarized in Table 2. For other solid fuels not included in the list, the operator can use an appropriate bulk density and a safe loading factor.

Table 2. Bulk density and loading factor.

Biomass	Bulk Density(kg/m^3)	Loading Factor
Sorghum	163	0.0942
Manure	264	0.4876
CGT	189	0.1621

A separate task and loop was made in the program to determine the speed of the screw conveyor. The optical sensor provides a negative output pulse signal each time the reflective tape passes and a waveform was produced. The fundamental frequency of the waveform was determined to obtain the number of revolutions per second of the screw conveyor.   An algorithm was developed to calculate the mass flow rate of the solid fuels through a screw conveyor. Calibration measurements were then made on each available feed stock.

The air volumetric flow rate, in cfm, was calculated using a calibration data sheet provided. The operator must specify the current air density, lb/ft^3 of the surrounding air to obtain the mass flow rate of air. In this research, psychometric chart was used to obtain this property based from the current temperature and relative humidity. The program also had an option to save all data measurements into a file for future analysis.

The output section of the program provides control for the blower and feeding systems. The motor controllers installed for the two systems have the capability of regulating the speed of the motor by an external 10V analog voltage. Tasks were created to vary the voltage supplied to the motor controllers. Also included in this section are the supply voltage for the optical sensor and a stop button to shutdown the gasification system and the computer program.

Feasibility of the Instrumentation and Process Control Program

The sample results of the preliminary test using sorghum as fuel are shown in Table 3. Clearly, the table shows all the parameter values that were measured at various stages of the gasification process. At a glance, the sample data readings derived from the gasification experiment seemed to show the feasibility of the instrumentation and the process control program for the fluidized bed gasifier used in the test.

A better picture of the functionality of the instrumentation and the process control program that were developed is shown in the succeeding figures derived from plotting the sample data from Table 3. Figure 9 describes the temperature and pressure profiles in the gasifier from start-up to the end of the operation. The expected start-up time and the
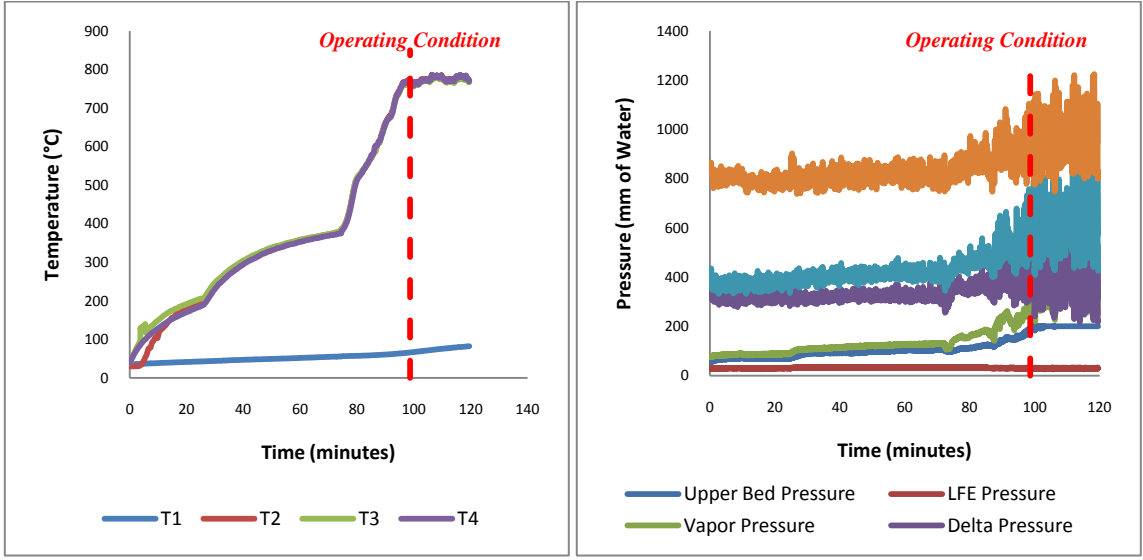
(a)   (b)

Figure 9. Temperature profile (a) and pressure profile (b) during the operation of the fluidized bed gasifier.

operating temperature was achieved without any trouble. The start-up time required about

100 minutes after which a more constant temperature was nearly maintained. Good

fluidization was also observed based on the pressure profile. Pressure fluctuation is an

inherent characteristics in a fluidized bed, especially with diverse sized biomass.

Once the gasification temperature was reached (eg. 775°C in Figure 10), it is being

maintained by the proper adjustments of the fuel feed rate and air flow rate using the

process control system. In this case, the air flow rate was maintained at an average of 1.99

kg/min while the fuel flow rate was maintained at an average of 0.95 kg/min. These flow

rates resulted in an air to fuel ratio of 2.10 kg/kg (Figure 11). In addition to help maintain

the operating temperature, the controlled air to fuel ratio also kept a good fluidization of

materials inside the gasifier as indicated by the pressure profiles. Continuously switching

feedstock using woodchips, switch grass and manure did not also show variation in the

operating temperature as shown in Figure 12.
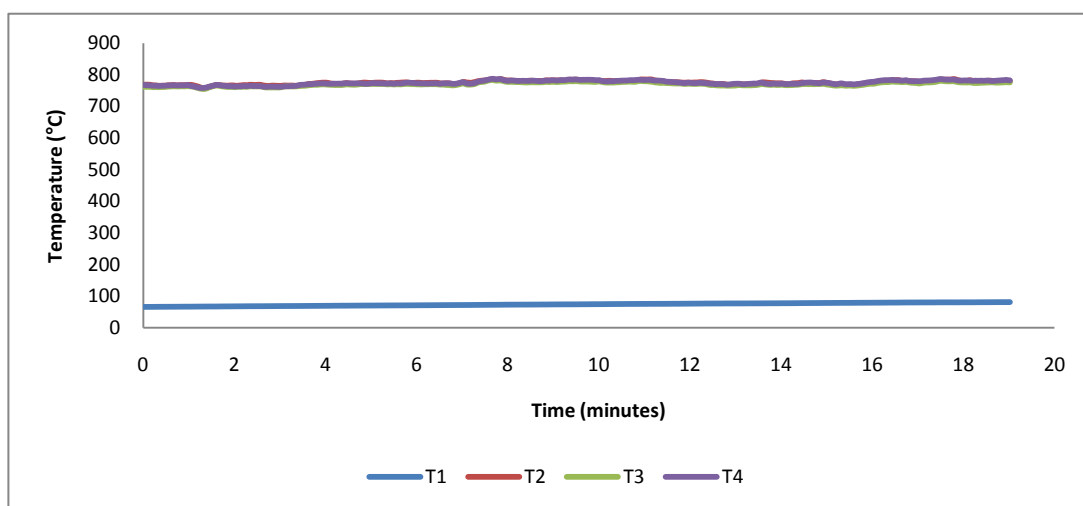
Figure 10. Temperature profile in the gasifier during its operation.
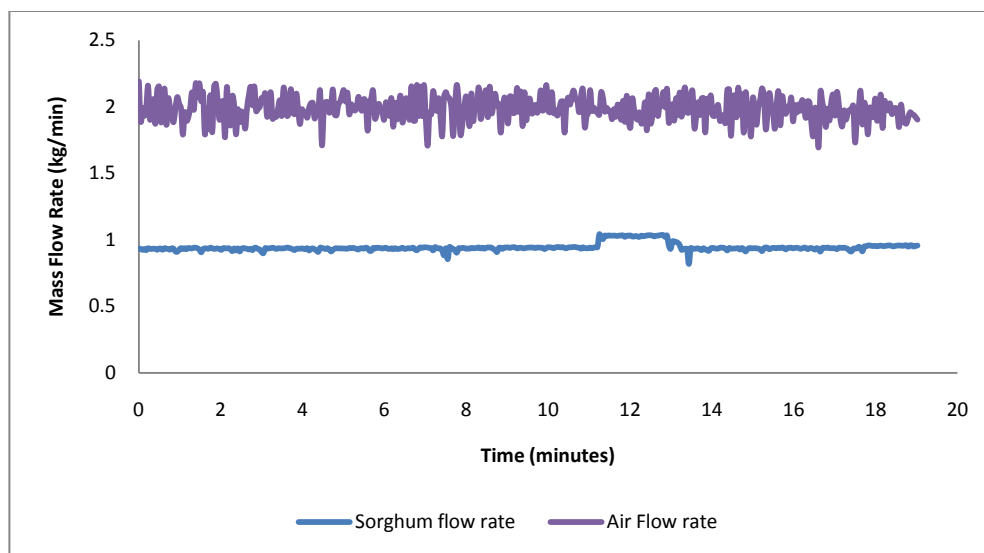
(a)
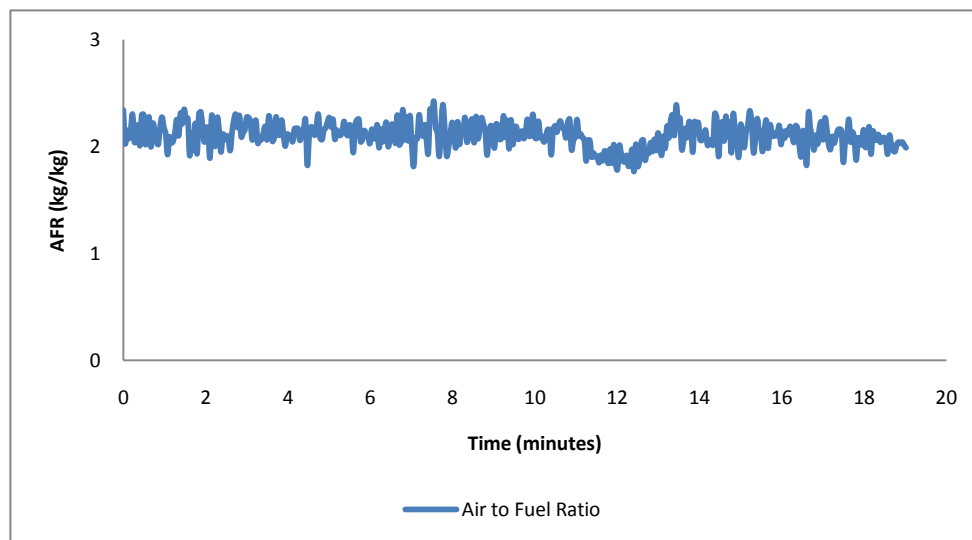
(b)

Figure 11. (a) Sorghum flow rate and air flow rate and the (b) resulting air to fuel ratio during the operation of the gasification.

Table 3. Sample gasification data readings.

LabVIEW Measurement GASIFICATION

BIOMASS	*Sorghum*
Date	*6/26/2009*
Start Time	*12:16:08 PM*

secs	mins	hh:mm	T1 Deg C	T2 Deg C	T3 Deg C	T4 Deg C	Upper Bed P inWC	LFE P inWC	Vapor P inWC	Delta Bed P inWC	Bed Base P inWC	Total P InWC	Auger Speed RPM	Mass Flow Rate kg/min	Air Flow Rate cfm	kg/min	Air to Fuel Ratio	Fuel to Air Ratio
0	0.00	12:16:08 PM	35.05	29.94	38.95	38.81	2.21	1.06	3.00	14.53	16.48	33.33	0.00	0.00	66.36	2.26	Inf	#VALUE!
3	0.05	12:16:11 PM	35.10	29.95	39.48	39.39	2.25	1.17	3.02	14.70	16.45	33.52	0.00	0.00	66.13	2.26	Inf	#VALUE!
6	0.10	12:16:14 PM	35.12	29.93	40.11	40.07	2.21	1.12	3.05	14.49	16.40	33.13	0.00	0.00	66.64	2.28	Inf	#VALUE!
9	0.15	12:16:17 PM	35.13	29.94	40.99	40.78	2.26	1.04	3.13	14.64	16.67	33.96	0.00	0.00	69.56	2.37	Inf	#VALUE!
12	0.20	12:16:20 PM	35.16	29.95	41.86	41.62	2.26	1.10	3.15	14.85	16.80	33.71	0.00	0.00	68.83	2.34	Inf	#VALUE!
15	0.25	12:16:23 PM	35.18	29.97	42.59	42.36	2.30	1.13	3.13	15.18	16.72	33.40	0.00	0.00	65.84	2.24	Inf	#VALUE!
18	0.30	12:16:26 PM	35.17	29.94	43.38	43.05	2.25	1.11	2.94	14.43	16.41	33.15	0.00	0.00	67.81	2.32	Inf	#VALUE!
									......									
4207	70.12	1:26:16 PM	66.18	768.97	762.09	766.48	7.16	1.15	11.75	13.85	20.73	34.59	485.21	0.93	57.59	1.99	2.15	0.46
4210	70.17	1:26:19 PM	66.20	768.83	762.23	766.40	7.60	1.10	11.65	18.90	26.13	40.35	488.78	0.93	55.20	1.93	2.07	0.48
4213	70.22	1:26:22 PM	66.25	767.86	761.61	765.46	7.57	1.14	12.25	18.23	25.60	35.62	484.13	0.92	57.42	1.99	2.15	0.46
4216	70.27	1:26:25 PM	66.28	766.66	761.14	765.00	7.19	1.24	11.37	13.68	20.63	33.72	491.79	0.94	62.57	2.16	2.30	0.43
4219	70.32	1:26:28 PM	66.36	766.69	761.37	765.05	7.70	1.08	11.65	19.95	27.39	42.66	489.69	0.93	54.31	1.91	2.04	0.49
4222	70.37	1:26:31 PM	66.41	765.93	761.14	764.40	7.53	1.13	11.89	17.30	24.64	34.75	488.97	0.93	56.83	1.97	2.11	0.47
4231	70.52	1:26:40 PM	66.45	765.40	761.19	764.41	7.27	1.18	11.36	14.11	21.45	34.67	490.05	0.93	59.50	2.06	2.20	0.45
4234	70.57	1:26:43 PM	66.48	765.61	761.51	764.88	7.62	1.07	11.47	18.36	25.46	39.21	489.20	0.93	53.66	1.87	2.01	0.50
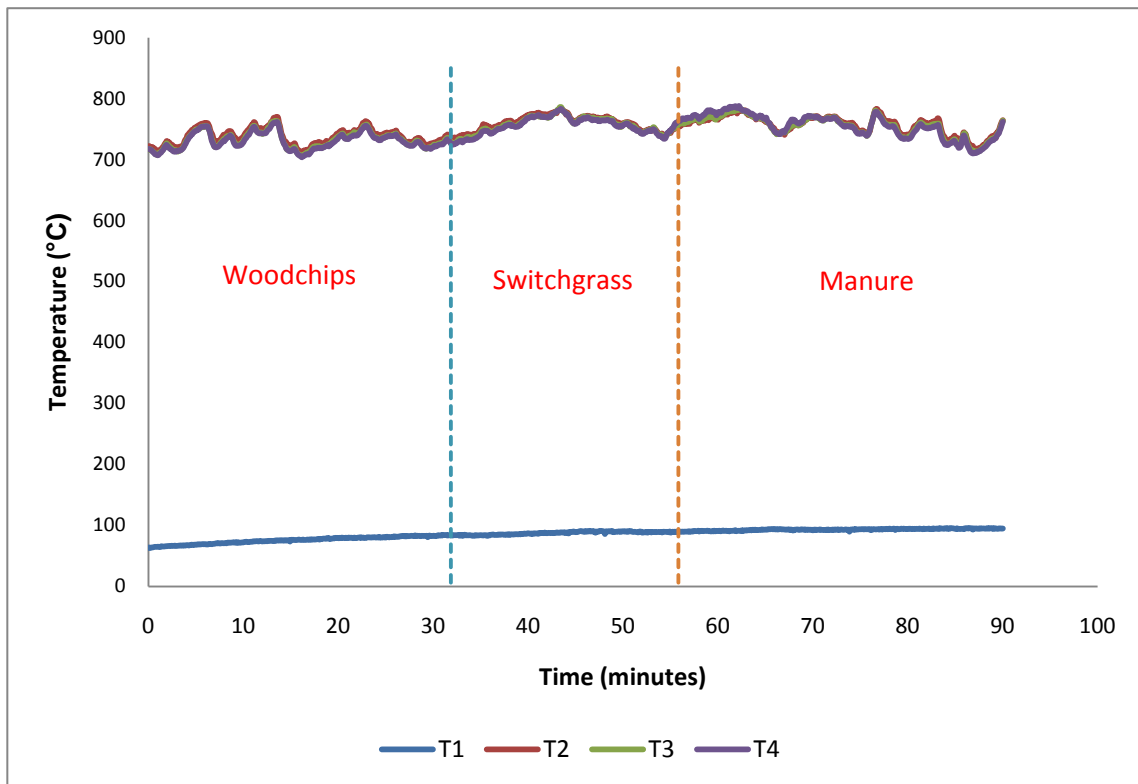
Figure 12. Gasification temperature with multiple feedstock.

The results shown in Figure 12 were comparable with the observations from similar tests conducted using manually controlled gasification system of poultry litter and wood chips as biomass (Maglinao et al., 2008). The start-up timed required 25 and 50 minutes to reach the operating temperature of about 760°C (1400°F) using poultry litter and wood chips, respectively as shown in Figures 13 and 14. The pressure and temperature profiles in the gasifier using poultry litter and wood chips are also shown.
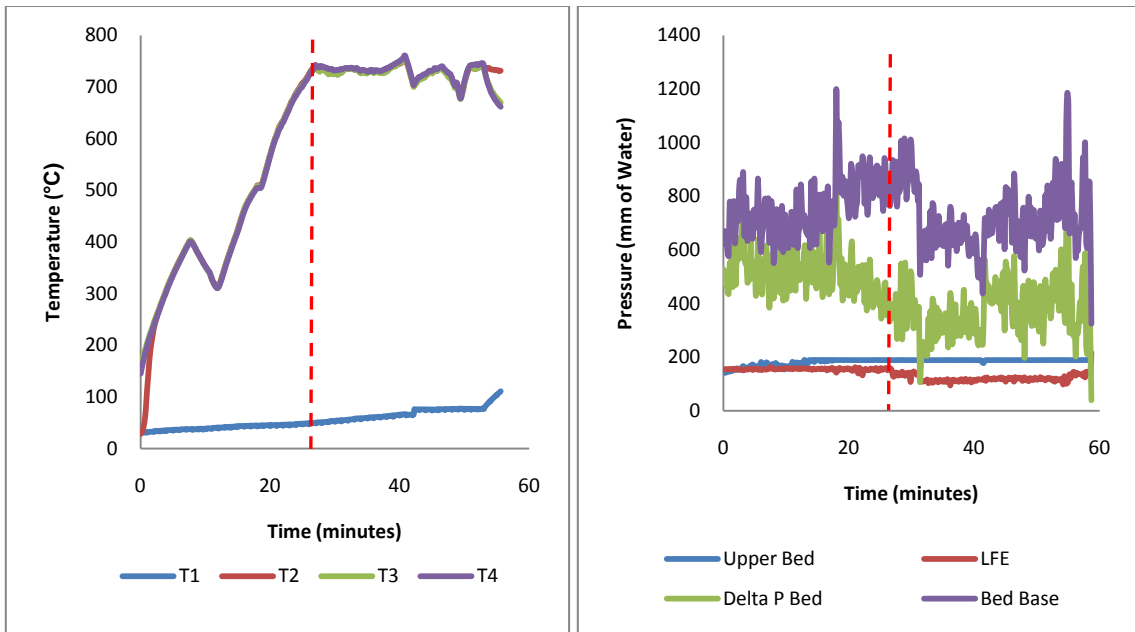
(a)   (b)

Figure 13. Poultry litter (a) temperature and (b) pressure profile.
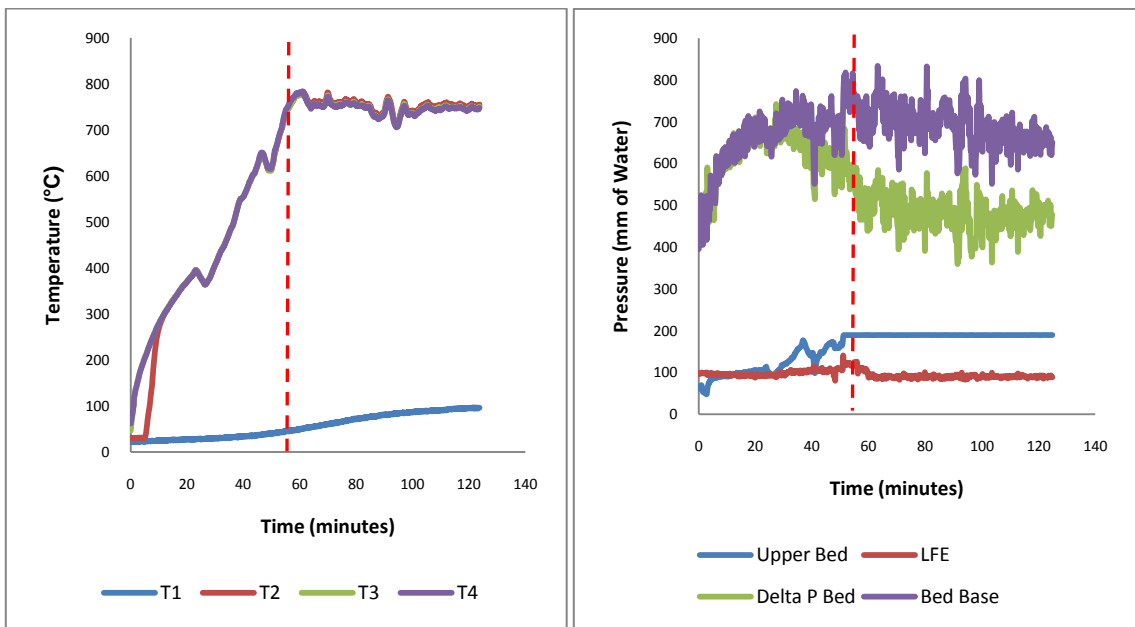
(a)   (b)

Figure 14. Woodchips (a) temperature and (b) pressure profile.

CONCLUSIONS

Instrumenting and developing a process control program for the operation of a fluidized bed gasification system was implemented in this research. A National Instrument (NI) data acquisition and control system (DAQs) was used in conjunction with a LabVIEW Control Program. Temperature, pressure, flow rate and feed rate monitoring system were installed with electronic output signal that is fed to the DAQs. A computer program was developed to display the parameters that may be monitored and controlled and an appropriate control system was activated. The measurement and control devices installed in the gasifier were able to provide the desired output data for easy monitoring. Coupled with the developed process control program, the operation of the gasifier has become more convenient and precise. The gasification unit can now be remotely operated which provides safety and comfort to the operator.

While the study contributed additional knowledge and practical applications, there are other areas that have to be addressed. The study also evaluated the quality of the char and the synthesis gas produced. Full automation of the operation of the gasifier should be implemented in succeeding studies.

CHAPTER III

SYNTHESIS GAS PRODUCTION OF A PILOT SCALE FLUIDIZED BED BIOMASS GASIFICATION SYSTEM

OVERVIEW

Biomass is widely considered a major potential fuel and renewable energy resource for the future (Bridgwater, 1995). Biomass can be classified as plant, animal manure or municipal solid waste. Biomass resources are abundant in most parts of the world and various commercially available conversion technologies could transform the current traditional technology into modern applications as energy source (Johansson et al., 2006). Biomass used as energy source can reduce CO_2 gases emitted by fossil fuel systems as well as and SO_2 and NO_x atmospheric pollution due to having neutral carbon contribution to the atmosphere (Cao et al., 2005).

Gasification is one of the thermochemical conversion routes which has an excellent future. (Sipila, 1995). Biomass gasification is the incomplete combustion of biomass resulting in the production of combustible gases consisting of carbon monoxide (CO), hydrogen (H_2) and traces of methane (CH_4). This mixture is called producer gas, synthesis gas or syngas. Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can generate the fuel. The combustible gases produced from gasification can be used to run internal combustion engines (both compression and spark ignition). It can also be used as a substitute for furnace oil in direct heat applications and

can be used to produce methanol. Methanol is an extremely attractive chemical which is useful both as fuel for heat engines as well as chemical feedstock for industries. In many situations where the price of petroleum fuels is high or where supplies are unreliable, the biomass gasification can provide an economically viable system especially if the suitable biomass feedstock is readily available.

INTRODUCTION

The products from complete combustion of biomass generally contain nitrogen, water vapor, carbon dioxide and surplus of oxygen. However, in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are combustible gases like carbon monoxide (CO), hydrogen (H_2) and traces of methane and solid products like char. The technology of biomass air gasification has been developed actively for industrial applications. The gasification system has proven to be a reliable alternative for village electrification and industrial operations for their thermal and electrical needs. Measurements on the large capacity gasifier system at 650 kg/h, have resulted in cold conversion efficiencies in the range of 85% (Dasappa et al., 2004). Biomass gasification with air in a fluidized bed seems to have a feasible application in some scenarios (Katofsky, 1993). However this technology produces a gas with a low heating value (4–6 MJ/m^3) with a H_2 content of 8–14 vol.% (Delgado and Aznar, 1997).

Mathieu and Dubuisson (2002) evaluated the efficiency of biomass gasifiers by conducting a performance analysis. They defined gasification efficiency as the ratio of the heat content of the fuel gas generated to the heat content of the fuel when it is totally burned. They observed that reaction temperature and amount of oxygen feed had

significant effects on the gasification efficiency (Figure 15). Gasification efficiency

increased with temperature but decreased as the amount oxygen fed increased.
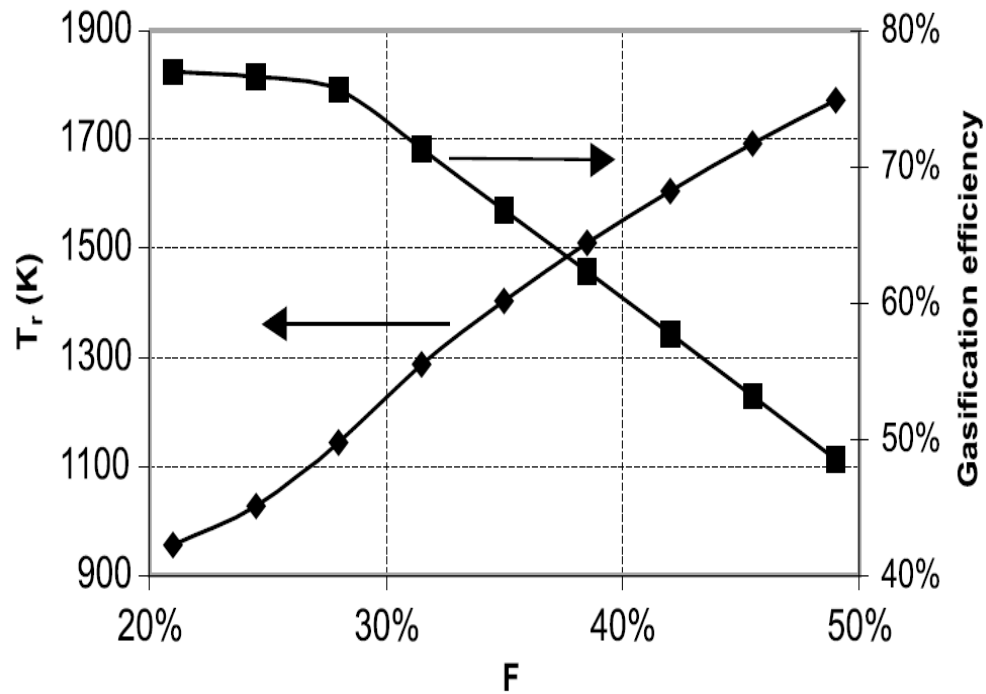
Figure 15. Gasification efficiency and reaction temperature, T_r vs the oxygen factor, F (Mathieu and Dubuisson, 2002).

This study evaluated the synthesis gas production of three biomass feedstock

using a pilot scale fluidized bed biomass gasification system. Specific objectives of the

study were to (a) conduct proximate and ultimate analyses of the different biomass

samples to describe their properties relevant to gasification, (b) evaluate the performance

of the gasification system in terms of synthesis gas production and gas quality, and (c)

apply a response surface methodology for optimizing the production of synthesis gas,

particularly H_2.

MATERIALS AND METHODS

Gasification System Facility

The gasification experiment was conducted using a pilot scale fluidized bed biomass gasifier developed at Texas A&M University at College Station, Texas and protected under US Patent No. 4848249 (Figure 16). The fluidized bed gasification reactor is 305mm (1-ft) in diameter and uses air as the gasifying agent. The feeding system uses a screw conveyor that was calibrated with different biomass fuels that were used in the test. Two stage cyclones were installed to capture the solid products (char) that were produced with the gas. Mulgrain 47- 10 x 18 (C E Minerals, Andersonville, GA) was used as the bed material. The gasification unit was equipped with monitoring and control instruments and a software program to facilitate the operation of the system.

Figure 16. Pilot scale fluidized bed gasification unit.

Solid Biomass Fuels Used and Their Properties

Sorghum, cotton gin trash (CGT) and dairy manure were used as the solid

biomass feedstock in the evaluation of gasification operation and performance.

The biomass samples were characterized by conducting proximate and ultimate

analyses. About 1 g sample of each biomass was used for proximate analysis. The

ash and volatile component matter (VM) contents were determined using the gravimetric

method according to ASTM standards E 1755 (Standard Test Method for Ash in

Biomass) for ash and D 3175 (Standard Test Method for Volatile Matter in the Analysis

Sample of Coal and Coke) for VM. The amount of fixed carbon (FC) was obtained by

difference (100 - % ash + % VM). In addition, the moisture content was determined

by oven drying in air approximately 1g of ground sample materials overnight at 105 °C

following the modified ASTM E871(Standard Method for Moisture Analysis of

Particulate Wood Fuels). The high heating value (HHV) was measured from the

combustion of the biomass using a Parr 6200 bomb calorimeter (Mukhtar and Capareda,

2006).

For ultimate analysis, ten (10)-g samples of each feedstock were sent to the

Huffman Laboratories Inc. in Denver, Colorado. The samples were ground to nominally

-200 mesh size particles using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). The

amounts of carbon, hydrogen and nitrogen were determined as per ASTM D5373

(Standard Test Methods for Instrumental Determination of Carbon, Hydrogen and

Nitrogen in Laboratory Samples of Coal) using approximately 2 to 8 mg of samples.

Sulfur analysis was performed with approximately 120 mg of samples per ASTM D4239

(Standard Test Methods for Sulfur in the Analysis Sample of Coal and Coke Using High Temperature Tube Furnace Combustion Methods). The percentage of oxygen was determined by difference assuming no halogens were present.

Gasification Operation and Performance

The gasification system was prepared for each test by first checking and calibrating instrument connections and readings. The bed material was sieved using Tyler sieves 12 and 20 to obtain a particle size of -1.70 mm to + 0.85 mm. Approximately 30 kg of sieved bed material was placed inside the reactor. The solid biomass fuels were prepared in 5 gallon buckets and weighed. The process control program was started to regulate the system and measure and store all instrument readings. The air blower system was turned on to effect fluidization inside the reactor. The desired operating temperature in the reactor was achieved by using a natural gas burner. As soon as the desired temperature was obtained, the supply of the hot gas from the burner was discontinued and feeding of the biomass was started. Typically, the operating temperature reaches its stable condition in only 3 minutes.

The desired air to fuel ratio was obtained by setting the speed of the screw conveyor of the feeding system and the air flow used. Since the desired air to fuel ratio varies with the feedstock, the speed of the conveyor was adjusted based on the stoichiometric air to fuel ratio of the biomass used. This represents the air to fuel ratio in an ideal combustion process when the fuel is burned completely. The stoichiometric air to fuel ratio is calculated by using the chemical equation for fuel as shown by equation (2).

$$C_vH_wN_xO_yS_z + \mathbf{a}\,O_2 \xrightarrow{\textit{yields}} \mathbf{b}\,H_2O + \mathbf{c}\,CO_2 \qquad\qquad (2)$$
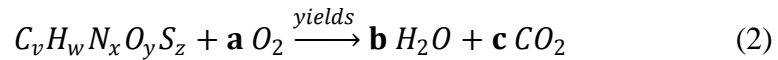
where a, b and c represent the number of moles of oxygen, water and carbon dioxide,

respectively, to effect complete combustion and the subscripts correspond to the mole

fraction values derived from the ultimate analysis of the different biomass. Gasification

operation normally operates between 20% - 40% of stoichiometric air to fuel ratio.

When the air to fuel ratio and the operating temperature has stabilized, 3 gas

samples were collected into a 1 L Tedlar bags (Restek, Bellefonte, PA) with the time of

collection noted. Gasification parameters for these gas samples were obtained from the

average data collected by the program within a 2 minute span from the time of

collection. In addition, the char produced during gasification was collected from the first

and second cyclones and weighed. Once this operation was completed, the gasifier was

shut down following the prescribed shutdown procedure. The shut down procedure is

normally done as follows:

(a) Use all biomass feedstock on the fuel bin

(b) The cold air blower is operated until the bed temperature is below

combustion temperature of the biomass

(c) Opening all vents such that combustible gases are not trapped on hot areas

within the gasifier system.

The performance of the gasification system using the three types of biomass was

evaluated based on the production and quality of the synthesis gas. Synthesis gas

production was obtained using the carbon mass balance assuming that tar production

was minimal and not included as by product since the gas produced was not condensed.

To evaluate the effect of biomass type and operating temperature, a completely randomized block design experiment was conducted using sorghum and CGT as fuel and operating temperatures of approximately 730, 760 and 790°C. Analysis of synthesis gas yield and its heating value was likewise conducted.

Optimization of Synthesis Gas Production

The production of synthesis gas was optimized in terms of combustible gas components, heating value, and gas yield. A response surface statistical design was used with gasification temperature and equivalence ratio (ER) as the numerical factors. Equivalence ratio is defined as the ratio between the actual air to fuel ratio used to the stoichiometric air to fuel ratio of the particular biomass feedstock. Stoichiometric combustion is the ideal combustion process when the fuel is burned completely. In this design, gasification temperature was set from 730 to 790°C while ER was set from 0.3 to 0.5.

The operating temperature is crucial in the overall biomass gasification process. Hydrogen production and gas yield were favored by higher temperature but gas heating was not. A very high temperature may lower the gas heating value from the biomass (Lv et al., 2004). The equivalence ratio (ER) is also considered important operational variables in biomass gasification (Narvaez et al., 1996). For any process, it represents the value of the air to fuel weight ratio used divided by the air to fuel weight ratio of stoichiometric combustion.

RESULTS AND DISCUSSION

Biomass Properties

      The inherent properties of the biomass resource determines both the choice of conversion process and any subsequent processing difficulties that may arise (McKendry, 2002b). In this study, the properties of sorghum, CGT and manure are summarized in Table 4. All three biomass fuels had sufficient calorific value and dry enough for gasification. The heating value of a biomass measures the amount of energy per mass or volume that results from its combustion (Mukhtar and Capareda, 2006).

Table 4. Properties of the three biomass fuels used in the experiment.

BIOMASS	*Sorghum*	*Cotton Gin Trash*	*Manure*
Moisture content, %	22.11 ± 1.44	9.01 ± 0.05	13.08 ± 0.54
Heating Value (d.b), MJ/kg	19.58 ± 0.13	16.67 ± 0.35	15.93 ± 0.26
Proximate Analysis (d.b), %			
Volatile Component Matter	71.40 ± 0.12	71.20 ± 2.10	59.05 ± 0.39
Ash	14.16 ± 0.90	13.02 ± 0.46	29.80 ± 2.80
Fixed Carbon	14.45 ± 0.80	15.78 ± 1.65	11.15 ± 2.92
Ultimate Analysis (daf.b), %			
C	44.92	44.58	43.5
H	6.37	6.15	6.19
N	0.47	1.63	2.19
O	46.17	47.25	47.63
S	0.08	0.38	0.49
Stoichiometric Air to Fuel Ratio (daf.b)			
mol/mol	19.31	17.96	17.49
kg/kg	5.52	5.13	5.00

Proximate analysis indicated high amounts of volatile component matter in all three biomass fuels used. The high ash content of manure indicates that fouling and slagging may occur during the gasification process.

The ultimate analysis did not show much variation among the three feedstock particularly in their contents of carbon, hydrogen and oxygen. Consequently, the calculated stoichiometric air to fuel ratio did not differ as well. This was calculated based from the chemical reactions as shown in equations (3), (4) and (5).

Sorghum: $\quad\quad\quad\quad\quad\quad C_{3.91}H_{6.32}O_{2.89} + 4.04O_2 \xrightarrow{yields} 3.16H_2O + 3.91CO_2 \quad\quad$ (3)

Cotton Gin Trash: $\quad C_{3.71}H_{6.11}O_{2.95} + 3.76O_2 \xrightarrow{yields} 3.06H_2O + 3.71CO_2 \quad\quad$ (4)

Manure: $\quad\quad\quad\quad\quad\quad C_{3.62}H_{6.14}O_{2.98} + 3.66O_2 \xrightarrow{yields} 3.07H_2O + 3.62CO_2 \quad\quad$ (5)
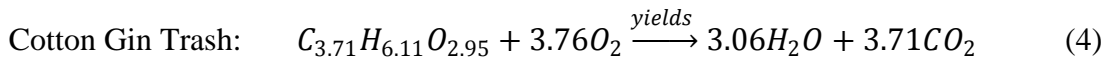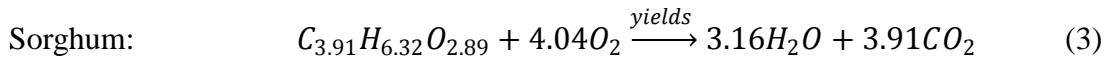
The stoichiometric air to fuel ratios for sorghum, cotton gin trash and manure were derived from the above equations indicating the amount of air needed to have a complete combustion. These are needed to determine the equivalence ratios for each biomass. If the raw gas is burned in downstream furnaces, without previously cooling it, the gasifier can be operated at the minimum ER of about 0.20 because the production of tar would not be a problem and the gas should have the maximum possible heating value (Narvaez et al., 1996).

Gasification Performance

Figure 17 shows a sample of carbon mass balance diagram for sorghum gasification to produce the synthesis gas. The production of tar was considered minimal and not included as a byproduct since the gas produced was not condensed. The same diagram and procedures were applied for cotton gin trash and manure.
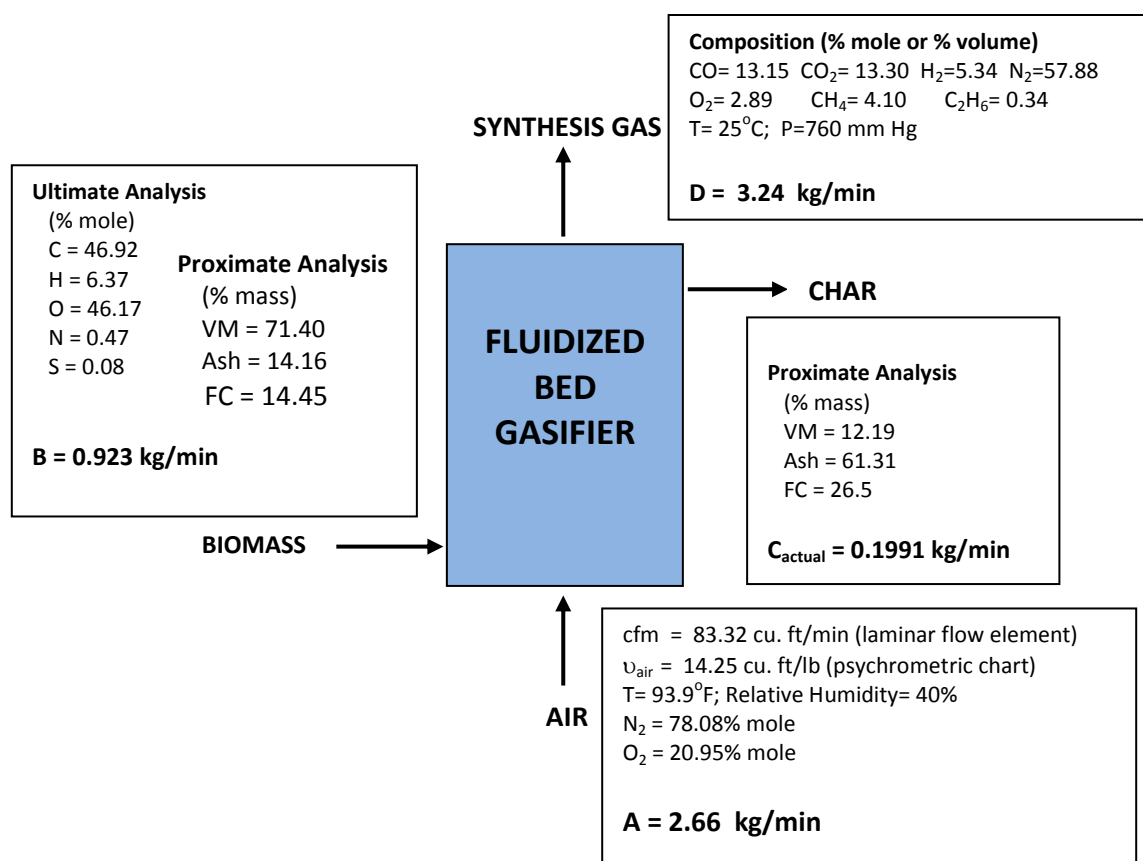
Figure 17. Carbon mass balance for sorghum gasification.

The quality and production of synthesis gas during the gasification of sorghum, cotton trash and manure as fuels is shown in Table 5. Comparable yields of methane, nitrogen and carbon dioxide were observed in the gasification of the three biomass, due

to the use of air as gasifying medium. Sorghum, however exhibited lower production of hydrogen than cotton gin trash and manure. The gas yields and their heating values were similar but were considered relatively low. The gasification system produced gas with calorific values of only 4.09 to 4.19 MJ/m^3 and yields ranging from 1.8 to 2.5 N m^3/kg. Gil et al. (1999) showed similar values of gas yield of 1.4 -2.4 N m^3/kg biomass in his gasification experiments with air. LePori and Soltes (1985) reported gas heating value as high as 8 MJ/m^3.

Table 5. Synthesis gas production using different biomass.

Synthesis Gas Production	Sorghum	CGT	Manure
Hydrogen	5.24	7.99	7.72
Methane	4.11	4.70	4.38
Carbon Monoxide	13.56	11.02	10.92
Ethane	0.42	0.33	0.43
Nitrogen	58.61	56.31	56.67
Oxygen	2.93	3.25	3.40
Carbon Dioxide	14.06	14.26	14.18
Heating Value, MJ/m^3	4.09	4.28	4.19
Gas Yield, m^3/kg biomass	2.04	1.81	2.11
Gas Production, kg/min	3.24	1.30	5.35
Carbon Conversion Efficiency,%	82.28	90.46	82.29
Cold Gasification Efficiency, %	49.99	44.68	51.05
Char Proximate Analysis			
VCM	12.19	14.25	16.20
ASH	61.31	59.11	81.18
FC	26.50	26.64	2.62

Effect of Operating Temperature and Biomass Type on Gasification

The effect of the operating temperature and biomass type on the production of

hydrogen and synthesis gas calorific values using sorghum and cotton gin trash are

summarized in Table 6. The analysis was focused only on hydrogen production as it

was the only gas that showed statistical significance ($\alpha = 0.05$).

Table 6. Hydrogen concentration and gas calorific values obtained from sorghum and cotton gin trash gasification.

STD	RUN	BIOMASS	Temperature °C	H2 vol %
1	5	Sorghum	730	*4.77*
2	11	Sorghum	730	*4.17*
3	3	CGT	730	*7.99*
4	12	CGT	730	*7.99*
5	2	Sorghum	760	*3.79*
6	9	Sorghum	760	*4.30*
7	4	CGT	760	*7.70*
8	10	CGT	760	*9.36*
9	6	Sorghum	790	*5.90*
10	8	Sorghum	790	*5.04*
11	1	CGT	790	*8.38*
12	7	CGT	790	*7.61*

Supportive of earlier results, the biomass type showed statistically significant

effect on hydrogen concentration but the operating temperature did not (Table 7).

Significant effects of temperature might have been observed if the experiment was

conducted with larger differences in gasification temperature. This experiment had been limited to maximum operating temperature of 820°C because of the gasification reactor capacity. According to Le Chatelier's principle, higher temperatures favor the reactants in exothermic reactions and favor the products in endothermic reactions. In gasification, hydrogen production involves endothermic reactions so it is expected to have an increase in H_2 concentration with temperature.

Table 7. Statistical analysis on the effect of biomass type and gasification temperature.

Response   Hydrogen Concentration
  Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Block	3.385E-004	1	3.385E-004			
Model	37.83	2	18.92	37.31	< 0.0001	**significant*
A-Biomass	*33.30*	*1*	*33.30*	*65.67*	*< 0.0001*	
B-Temperature	*0.84*	*1*	*0.84*	*1.65*	*0.2346*	
Residual	4.06	8	0.51			
Cor Total	41.89	11				

**The Model F-value of 37.31 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

As shown in Figure 18, the plot indicated that the temperature has no significant effect on the hydrogen concentration of the gas produced (p-value > 0.05). The nearly parallel lines of the plot may indicate similar responses of both sorghum and CGT to changes in operating temperature from 730°C to 790°C. Under all gasification temperatures, CGT was predicted to yield higher hydrogen concentration than sorghum (p-value< 0.0001).
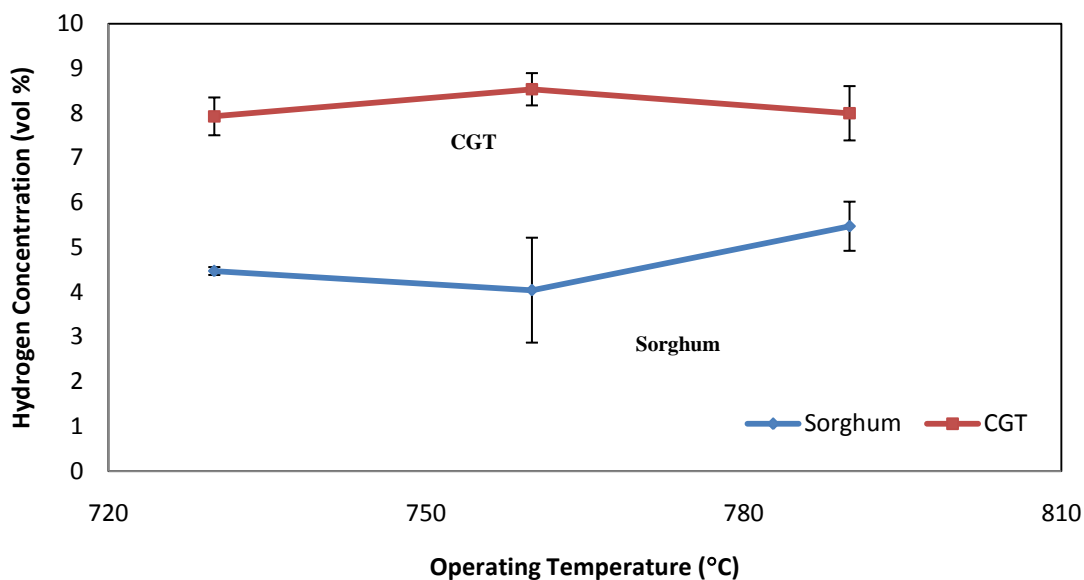
Figure 18. Hydrogen concentration at different temperatures.

Optimization of Synthesis Gas Production

Using sorghum for gasification, the experimental results did not show significant effect (p −value > 0.05) of temperature and equivalence ratio on the concentration of methane, carbon monoxide and ethane. This can be attributed to the limited range of gasification temperatures used in the experiment. However, the gasification temperature had significant effect on hydrogen concentration (Table 8).

Response surface methodology was used to explore the relationship between the gasification temperature and equivalence ratio with the hydrogen concentration. Hydrogen concentration increases with increasing temperature and decreasing equivalence ratio (Figure 19).

Table 8. Response surface statistical analysis.

Response	**1**		**H2**			
ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares - Type III]						

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	3.29	5	0.66	10.32	0.0114	**significant*
A-Gasifier Temperature	0.66	1	0.66	10.36	0.0235	
B-Equivalence Ratio	0.12	1	0.12	1.84	0.2332	
AB	0.18	1	0.18	2.84	0.1526	
A^2	0.31	1	0.31	4.92	0.0773	
B^2	0.57	1	0.57	9.00	0.0301	
Residual	0.32	5	0.064			
Cor Total	3.61	10				

The Model F-value of 10.32 implies the model is significant. There is only a 1.14% chance that a "Model F-Value" this large could occur due to noise.
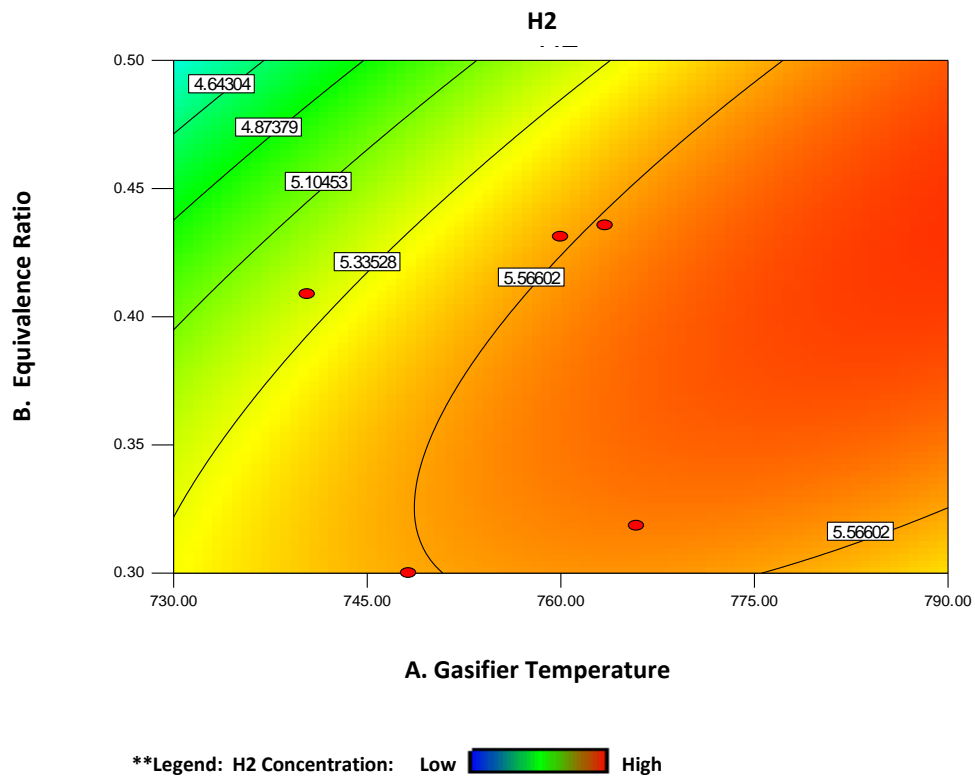
Figure 19. Response surface analysis plot for hydrogen concentration.

The equivalence ratio can be used to represent the amount of oxygen that was supplied into the gasification system. Higher ER can cause hydrogen concentration to decrease because of the occurrence of more oxidation reactions (Lv et al., 2004). Previous studies showed that values for ER lower than 0.18 are not practical because much tar is produced while ER higher than 0.45 produce a nonuseful gas (Narvaez et al., 1996). In addition, the figure suggests that high hydrogen concentration could be achieved from the gasification of sorghum within the region near the operating temperature of 780^0C with an equivalence ratio of 0.4.

CONCLUSIONS

The technology of biomass air gasification presents a reliable alternative for village electrification and industrial and agricultural operations. Further development of the technology would certainly provide a wider range of uses and applications. With sorghum, CGT and manure used as fuels, the production of synthesis gas and system performance were evaluated using a fluidized bed biomass gasification facility. While the biomass had calorific values and moisture contents enough for gasification, their gas yields and heating values were relatively low in this study. More studies may be conducted to raise their values and achieve more efficient gasification. With the high ash content found in manure, problems of fouling and slagging during gasification should already be anticipated such that timely corrective actions could be employed.

The production of the synthesis gas is affected by various processes and conditions. Its composition can be affected by the source of the biomass and the gasifier design. The same fuel may provide different calorific value when used in two different

gasifiers. Even though the biomass fuels used in the tests were all derived from agriculture, variation in terms of gas production and quality had been observed. Specifically, biomass type significantly affected the production of hydrogen. It was not however affected by the gasification temperature. These observations suggest that feedstock to be used for gasification should be carefully analyzed and evaluated. Adjustments in the gasifier design or parameter control is being recommended for future studies. In addition, further research on the effect of the operating temperature should be conducted employing a wider range of temperature to fully evaluate its effects. This may not be possible in the existing design.

The optimization test using sorghum for gasification did not show significant effect of temperature and equivalence ratio on the concentration of methane, carbon monoxide and ethane but temperature did have significant effect on hydrogen concentration. Again, these differences need to be addressed in future work. The response surface methodology for optimizing gas production should be done for all gases and the results applied in actual operation of gasifiers.

CHAPTER IV

PREDICTING FOULING AND SLAGGING BEHAVIOR OF MANURE AND COTTON GIN TRASH DURING THERMAL CONVERSION

OVERVIEW

Biomass, like fossil fuels, contains high percentages of carbon and hydrogen and can be a good alternative source of energy (LePori and Soltes, 1985). Even though raw biomass has significantly less energy content than petroleum, it has certain advantages compared to fossil fuels because it is renewable and has substantial reserves. Agricultural biomass resources are excellent feedstock for waste-to-energy conversion facilities such as the production of heat and electrical power (Maglinao et al., 2008). However, difficulties may be encountered in the thermal conversion of biomass residues especially in the complete combustion mode due to the high ash contents of most biomass (Nutalapati et al., 2007). The inorganic components of the biomass feedstock causes problems like slagging, fouling, bed agglomeration and corrosion (Bryers, 1996). The inorganic materials melt when they are exposed to high reaction temperatures and form slag. This slag will stick to heat transfer conveying surfaces upon cooling, thereby decreasing the cross sectional areas until fouling (or clogging) occurs. Very limited studies have been conducted to evaluate the slagging and fouling phenomena in most common agricultural wastes such as animal manure and crop residues.

Beef cattle manure and cotton gin trash (CGT) are abundant agricultural wastes and are excellent source of renewable energy in the farm. In the state of Texas, more

than 5 million tons/year of livestock manure are produced from 7.2 million heads that are fed each year. In addition, an estimated 2.3 million tons of poultry litter and 472,000 tons of swine are produced each year (Jackson and Mayfield, 2007). Approximately 2 million tons of cotton gin trash (CGT) are also available in Texas each year (Kennedy, 2006). Approximately 2 M tons of beef cattle manure is available for conversion (Bullock et al., 2008). This can provide a net recoverable heat of about 6 M MMBtu/year from cotton gin trash and 5 M MMBtu/year from manure. However, these feedstocks also contain relatively high percentages of ash which could pose problems during thermal conversion into combustible gas. Goodrich et al. (2008) reported that dairy manure (aged solids) could have an ash content of about 65.6% while LePori and Soltes (1985) showed an ash content of 14.5% in cotton gin trash. Ash is the mineral content in the fuel that remains in oxidized form after complete combustion. Ash basically interferes with the gasification process by forming slags which stop or inhibit the downward flow of biomass feed or lowering the fuel's reaction response to ignition.

INTRODUCTION

Formation of deposits on heat transfer surfaces, referred to as slagging and fouling, is one of the biggest problems for all solid fuel fired boilers, especially in biomass combustion (Tortosa-masia et al., 2005). Slagging occurs in the boiler sections that are directly exposed to flame irradiation and its formation involves stickiness, ash melting and sintering. Fouling deposits, on the other hand, form in the convective parts of the boiler and is mainly due to condensation of volatile species that have been vaporized in previous boiler sections and are loosely bonded. The slagging and

sintering behavior of different fuel ashes varies widely. Formation of deposits depends mainly on fuel quality, boiler design, and boiler operation. Although all biomass fuels exhibit fouling behavior, their rates differ depending on the content and composition of the ash. For instance, woods tend not to foul at a high rate as straws because at the same fuel firing rate, there is less ash entering the combustor and because woods have more favorable ash composition. Slagging also depends on the properties of the ash, which can be (but only approximately) described by the characteristic ash fusion temperatures: initial deformation temperature (IDT), softening temperature (ST), hemispherical temperature (HT) and flow temperature (FT). Over softening temperature ashes can be strongly adhesive, which results in slagging (Pronobis, 2005).

Predicting the ash behavior before a fuel is used would be desirable to avoid problems in the gasification operation (Zevenhoven-Onderwater et al., 2001 and Skrifvars et al., 1992). Reducing slagging and fouling will consequently reduce investment and operational costs and increase performance efficiency of gasifiers or any thermal conversion equipment. While a number of indices have been developed for coal and other fuels relating composition to fouling and slagging behavior, these have proved for most part to be of limited value as predictors for biomass (Jenkins et al., 1998). Despite their shortcomings, these empirical indices have been widely used to predict ash behavior and deposition tendencies for biomass type ashes.

Vamvuka and Zografos (2004) used the alkali index, the base-to-acid ratio, and the bed agglomeration index to predict deposition tendencies in four types of agricultural residues, namely, olive kernel, olive tree wood, citrus tree wood and vine shoots. They

found that the removal of troublesome elements by leaching the biomass with water reduced slagging and fouling in furnaces. Leaching with water resulted in significant reductions in ash (up to 40%), problematic elements K (up to 93%), Na (up to 96%), P (up to 85%) and Cl (up to 97%) and heavy metals Co, U, Mo, Pb and As, and likewise improved fusibility behavior. A lower combustion temperature or water leaching substantially reduced the fouling potential due to alkali.

Ash pellet compressive strength measurements have likewise been used in earlier studies for predictions of ash agglomeration during pulverized coal combustion (Skrifvars et al., 1994) More recently, modeling techniques have also been applied to visualize slagging and fouling tendencies using mass and energy balances (Tortosia-Masia et al., 2005). They developed an on-line monitoring system which models heat transfer between the flue gases and the water/steam cycle and deposits formation on heat exchanger surfaces. Van der Drift et al. (2004) studied the slagging/melting tendencies of selected fuels using a thermodynamic equilibrium model (FACTSAGE), minimizing Gibbs free energy and applying it to hypothetical (pressurized) entrained-flow gasification system. The results showed that only 10-25% of the ash forming components of beech was liquid at typical operating temperatures of 1300-1500°C which was explained by the dominance of CaO, which melted at temperatures higher than 1700°C. The behavior of the slag was minimally affected at the high temperature region of 1300-2000°C.

This study evaluated the slagging and fouling behavior of ashes from beef cattle manure and cotton gin trash (CGT) and predicted their deposit formation tendencies to

identify possible solution to the problem. Specifically, it conducted a characterization of the biomass and their ash heated at different furnace temperatures, determined selected indices of slagging and fouling based on these characteristics, and predicted the ash and fouling tendencies of the ash based on these indices. Measurement of the compressive strengths of ash pellets was used to determine the maximum operating temperature during thermal conversion.

MATERIALS AND METHODS

Composition and Characteristics of the Biomass and Ash

Ten grams of biomass samples of manure and cotton gin trash (CGT) and 10 grams of the biomass ash samples were sent to the Huffman Laboratories Inc., Denver, Colorado, for ultimate and ash analyses. Samples were ground to nominally -200 mesh size particles using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) prior to all analyses. The loss on drying was determined by oven drying in air overnight at 105 °C of approximately 1g of ground sample materials as per the modified ASTM E871(Standard Method for Moisture Analysis of Particulate Wood Fuels).   The amounts of carbon, hydrogen and nitrogen were determined as per ASTM D5373 (Standard Test Methods for Instrumental Determination of Carbon, Hydrogen and Nitrogen in Laboratory Samples of Coal) using approximately 2 to 8 mg of samples. Sulfur analysis was performed with approximately 120 mg of samples per ASTM D4239 (Standard Test Methods for Sulfur in the Analysis Sample of Coal and Coke Using High Temperature Tube Furnace Combustion Methods). The ash content was determined by heating

approximately 1g sample at 750°C in air for 8 hours per modified ASTM E830

(Standard Test Methods for Ash in the Analysis Sample of Refuse-Derived Fuel). The

percentage of oxygen was determined by difference assuming no halogens were present.

Ash metal oxides were analyzed per ASTM D6349 (Standard Test Method for

Determination of Major and Minor Elements in Coal, Coke and Solid residues from

Combustion of Coal and Coke by Inductive Coupled Plasma – Atomic Emission

Spectrometry). All values were expressed as percentages of the total and reported as

averages of 2 replicates.

**Determination of Empirical Indices and Prediction of Ash Deposition and
Tendencies**

The results of the biomass and ash analyses were used to calculate the empirical

indices to predict ash deposition and tendencies.   The alkali index, the base-to-acid

ratio, and the bed agglomeration index used by Vamvuka and Zografos (2004) were also

used to characterize slagging and fouling behavior of the biomass ash of CGT and

manure. The alkali index expresses the quantity of alkali oxide in the fuel per unit of

fuel energy (kg alkali GJ^{-1} or lb alkali $MMBtu^{-1}$). It is computed as follows:

$$AI = \frac{kg(K_2O + Na_2O)}{GJ} \qquad (6)$$

When the alkali index values are within the range of 0.17-0.34 kg/GJ, fouling or

slagging may or may not occur but it is certain to happen when the values are above this

range.

The base-to-acid ratio in the ash takes the form

$$R_{b/a} = \frac{\%(Fe_2O_3 + CaO + MgO + K_2O + Na_2O)}{\%(SiO_2 + TiO_2 + Al_2O_3)} \tag{7}$$

where the label for each compound makes reference to its weight concentration in the ash. As $R_{b/a}$ increases, the fouling tendency of a fuel ash increases.

The third indicator, the bed agglomeration index relates ash composition to agglomerations in fluidized-bed reactors. It is calculated as

$$BAI = \frac{\%(Fe_2O_3)}{\%(K_2O + Na_2O)} \tag{8}$$

Bed agglomeration occurs when BAI values are lower than 0.15.

Using the calculated indices, the deposition tendencies of manure and CGT ash was predicted. Results of the evaluation were further discussed based on the measurement of the compressive strengths of the ash pellets and scanning electron microscopy of the ash as described below.

Slagging and Fouling Indices Used for Coal

For further evaluation of the slagging and fouling tendencies of cotton gin trash and manure, two slagging and fouling indices used for coal were also calculated. The slagging factor, R_s is defined as the ratio of base to acid constituents multiplied by the sulfur content while the fouling factor, R_f. represents the ratio of the base to acid constituents multiplied by the Na_2O components. These were calculated as shown in the following equations with the basic and acid constituents also enumerated after the equations.

$$R_s = \frac{Base}{Acid} x S \tag{9}$$

$$R_f = \frac{Base}{Acid} x Na_2O \tag{10}$$

Basic constituents: $Fe_2O_3 + CaO + MgO + Na_2O + K_2O$

Acid constituents: $SiO_2 + Al_2O_3 + TiO_2$

The R_s and R_f values were calculated based on the inorganic ash analysis of coal samples. The degree of slagging and fouling of the biomass was then referred to the slagging and fouling index values found in Table 9. The slagging and fouling type could be classified as low, medium, high or severe (Winegartner, 1974).

Table 9. Slagging and fouling index for coals.

Slagging/Fouling Type	Slagging	Fouling
Low	<0.6	<0.2
Medium	0.6 – 2.0	0.2 – 0.5
High	2.0 – 2.6	0.5 – 1.0
Severe	>2.6	>1.0

Compressive Strength of the Ash Pellets

Pellets measuring 2.54 cm in diameter and 1.65 cm in height were prepared using ten (10) grams of ash samples. Uniformity of the size and density of the pellets was ensured by using fabricated pellet press and the MTS Model 810 Material Stress Test System (Gray Machinery Company, Prospect Heights, Chicago, IL). Pellet samples were then treated by heating them at temperatures of 550, 600, 700 and 800°C for four (4) hours. Pellets of CGT ash were also heated at 900°C for the same length of time. The compressive strength of the pellets was determined using an MTS Model 810

Material Stress Test System. The relationship between compressive strength of the pellets and the heating temperature was determined and also used as indicator of the slagging and fouling tendencies of manure and CGT ash samples. When a mixture of material (in this case ash components) melts (called its eutectic point), the components crystallize exhibiting a brittle plastic range providing weak compressive strength (Stanzl-Tschegg, 2009). This material behavior was used to determine the melting point of the inorganic ash components in the biomass.

Scanning Electron Microscopy (SEM) of the Biomass Ash Samples

Ash samples of manure and CGT were heated at temperatures of 550, 600, 700 and 800°C for four (4) hours. Additional ash samples of CGT were also heated at 900°C for the same length of time. Ten (10) g of the treated samples were sent to the Microscopy and Imaging Center at Texas A&M University, College Station, Texas for scanning electron microscopy (SEM) evaluation. SEM specimens were prepared by spreading sample particles of each batch on carbon tape and subsequent coating with amorphous carbon film of ~ 30 nm thickness. The carbon tape and film were used for fixation of particles and removal of accumulated charges. Micrographs were taken using a JEOL JSM 6400 scanning electron microscope equipped with a tungsten electron gun. It was operated at a 15 kV acceleration voltage with a 15 mm working distance. These images were analyzed to determine the effects of exposure temperature on the compressive strength of the ash pellets and consequently used to supplement and/or complement the evaluation of fouling and slagging behavior of the ash based on the calculated indices.

RESULTS AND DISCUSSION

Composition of Manure and Cotton Gin Trash Biomass and Ash

The ultimate analysis of manure and CGT biomass are shown in Table 10. Both biomass samples contained relatively higher percentages of carbon and oxygen. The lowest value was for sulfur, followed by nitrogen. Compared to soft wood with ash contents of about 3% (Skrifvars et al., 1998), the ash contents of CGT and manure were rather high, 11.86% and 18.62%, respectively. Manure had higher ash content than CGT, but had lower carbon and oxygen content. The manure samples also had higher drying loss. Hydrogen, nitrogen and sulfur did not significantly differ between the two samples.

Table 10. Ultimate analysis of manure and cotton gin trash biomass.

Ultimate Analysis (%)	*Cotton gin trash*	*Manure*
Drying Loss	9.17	13.26
Carbon	39.30	35.40
Hydrogen	5.42	5.04
Nitrogen	1.44	1.78
Oxygen	41.65	38.76
Sulfur	0.34	0.4
Ash	11.86	18.62

Because of their high ash contents, fouling and slagging may be expected to occur during the combustion of manure and CGT. Having a higher content of ash, slagging would pose more of a problem with manure than with CGT. Rajvanshi (1986) stated that severe slagging can be expected for fuels having ash contents of 12 percent and above. In general, no slagging had been observed with fuels having ash contents below 5-6 percent. For fuels with ash contents between 6 and 12 percent, the slagging

behavior depends to a large extent on the ash melting temperature, which is influenced

by the presence of trace elements giving rise to the formation of low melting point

eutectic mixtures.

Both manure and CGT ash showed high amounts of SiO_2 and CaO but low

amounts of TiO_2 and MnO (Table 11). A striking difference in the K_2O content of the

biomass was observed with the CGT ash containing more than four times the K_2O

content in manure.

Table 11. Analysis of the ash from manure and cotton gin trash biomass.

Ash Analysis (%)	CGT Ash	Manure Ash
Al_2O_3	3.46	3.12
CaO	23.30	27.41
Fe_2O_3	1.11	1.84
MgO	5.69	10.90
MnO	0.06	0.14
P_2O_5	2.25	4.98
K_2O	24.62	5.28
SiO_2	21.70	32.46
Na_2O	0.76	1.82
SO_3	7.40	6.12
TiO_2	0.25	0.22
Total	90.60	94.29

The very high K_2O content of the CGT ash compared to its content in manure

tends to indicate that a more serious fouling and slagging problem would be expected to

occur with CGT. Miles et al. (1995) reported that potassium in particular is important to

indicate potential ash fusion or deposition through vaporization and condensation.

Potassium is transformed during combustion and combines with other elements such as

sulfur, chlorine and silica. Silica in combination with alkali and alkaline earth metals,

especially with the readily volatilized form of potassium present in biomass, can lead to the formation of low melting point compounds which readily slag and foul at normal biomass boiler furnace temperature of 800-900°C. The alkali earths, MgO and CaO are also important in slagging and deposit formation because their very high fusion temperatures tend to inhibit the eutectic effects of alkalis – especially in fluidized beds. The above observations clearly indicate that predicting fouling and slagging tendencies of biomass ash cannot simply be based on their composition and characteristics.

Indices of Slagging and Fouling

The calculated alkali index, the base-to-acid ratio and the bed agglomeration index of the CGT and manure ash are shown in Table 12. The high values of the alkali index and the base-to acid ratio indicate that fouling and slagging is surely to occur during combustion of both CGT and manure. Vamvuka and Zografos (2004) suggested that an alkali index of more than 0.34 kg/GJ would indicate certainty of fouling.

As the base-to-acid ratio increases, the slagging tendency also increases. The melting temperature of ash tends to be parabolic with respect to $R_{b/a}$, reaching a minimum at intermediate values. For coal, a minimum is frequently located in the vicinity of $R_{b/a} = 0.75$, but for biomass the minimum tends to appear at lower values (Jenkins et.al., 1998). This information suggests that CGT and manure would not be a good fuel for combustion. Obviously, the calculated values of the alkali index and the base-to-acid ratio indicate that ash deposition tendencies are certain to occur for both biomass with CGT having a higher degree. The low bed agglomeration index further supports the higher fouling tendency expected with the CGT ash.

The calculated slagging (Rs) and fouling (Rf) factors show that the CGT and
manure samples have very low fouling and slagging potential. Both have R_f of 0.02 and
R_s of less than 0.6. However, these values contradict with the indices discussed earlier.
One limitation on the use of Rs and Rf is the fact that these parameters should not be
applied to lignitic type ash which resembles much of the agricultural and biomass
residues. Rf is known to give incorrect results for lignite (Winegartner, 1974).

**Table 12. Calculated slagging and fouling indices of the ash from manure and
cotton gin trash.**

Slagging and Fouling Index	*CGT Ash*	*Manure Ash*	*Slagging and Fouling Potential/Degree*
Alkali Index	1.96	0.95	*> 0.34 certain to occur*
Base to Acid Ratio	2.18	1.32	
Rf (Fouling Factor)	0.02	0.02	*< 0.2 Low*
Rs (SlaggingFactor)	0.16	0.08	*< 0.6 Low*
Bed Agglomeration Index	0.04	0.26	*Bed agglomeration occurs when index < 0.15*

Compressive Strength of the Ash Pellets

No single index has so far been developed that reliably describes the behavior of
the ash under all combustion conditions, especially the operating temperature. One
method that was also used for ash behavior prediction is the measurement of the
compressive strength of ash pellets previously heated at different temperatures. The
method does not predict adequately the ash sintering behavior of woody fuels and other
biomasses with a lower content in alkaline elements. However, the compressive strength
measurement method seems to offer consistent results under the conditions tested when

compared to the disintegrating and fusibility methods for biomass with high alkaline

oxides content (Fernandez Llorente and Carrasco Garcia, 2005).

The compressive strengths of the treated manure and CGT ash pellets are

summarized in Table 13 and Figure 20. The compressive strength of CGT ash was

lowest at the lowest temperature of 550°C but continued to increase sharply until about

800°C after which its strength rapidly decreased. On the other hand, manure ash pellets

exhibited the highest compressive strength at 600°C. The analysis of variance indicates

significant differences in the compressive strengths of CGT and manure ash pellets (p-

value < 0.0001) subjected to different temperatures.

Table 13. Measured compressive strengths of treated ash pellets of manure and CGT.

Treatment Temperature	Compressive Strength (kPa)	
°C	Cotton Gin Trash	Manure
550	808.58 ± 43.48	1428.61 ± 177.60
600	1365.22 ± 115.68	1778.10 ± 83.21
700	2785.68 ± 290.45	1159 ± 85.44
800	4129.58 ± 178.42	1037.42 ± 99.96
900	1967.95 ± 351.71	(not tested)

Previous studies suggest that ash pellet reduces its breakdown pressure as the

heating temperature increases due to the volatilization of CO_2 from the ash carbonates,

which produces an increase in the ash pellet porosity and fragility at higher heating

temperatures. The temperature at which the compressive strength is highest before any

decrease with increasing temperature is suggested to be the eutectic point of the ash at

which slagging and fouling of ash could be minimized or avoided. Based from the

results, it can be suggested that manure ash has a melting point (eutectic) at around 600°C while CGT ash has a higher melting temperature of 800°C. These temperatures indicate the melting point of the ash at which brittleness of the pellets were experienced. The results indicate that thermal conversion of manure does not provide any flexibility in terms of operating temperature. Because of the higher compressive strength values and higher melting temperature for the cotton gin trash, this feedstock is expected to present lesser problems than animal manure during thermal conversion. The normal operating temperature for gasification process is approximately 760°C (Maglinao et al., 2008). Thus, CGT may be gasified conveniently at this operating temperature with minimal slagging. Animal manure will be difficult to gasify at this operating temperature because of the production of slag at the operating temperature. Conventional atmospheric fluidized bed combustion temperatures are normally within the range from 800-900°C (Levy et al., 1981). CGT and animal manure feedstock are not suitable for atmospheric combustion because of this higher operating temperature requirement.
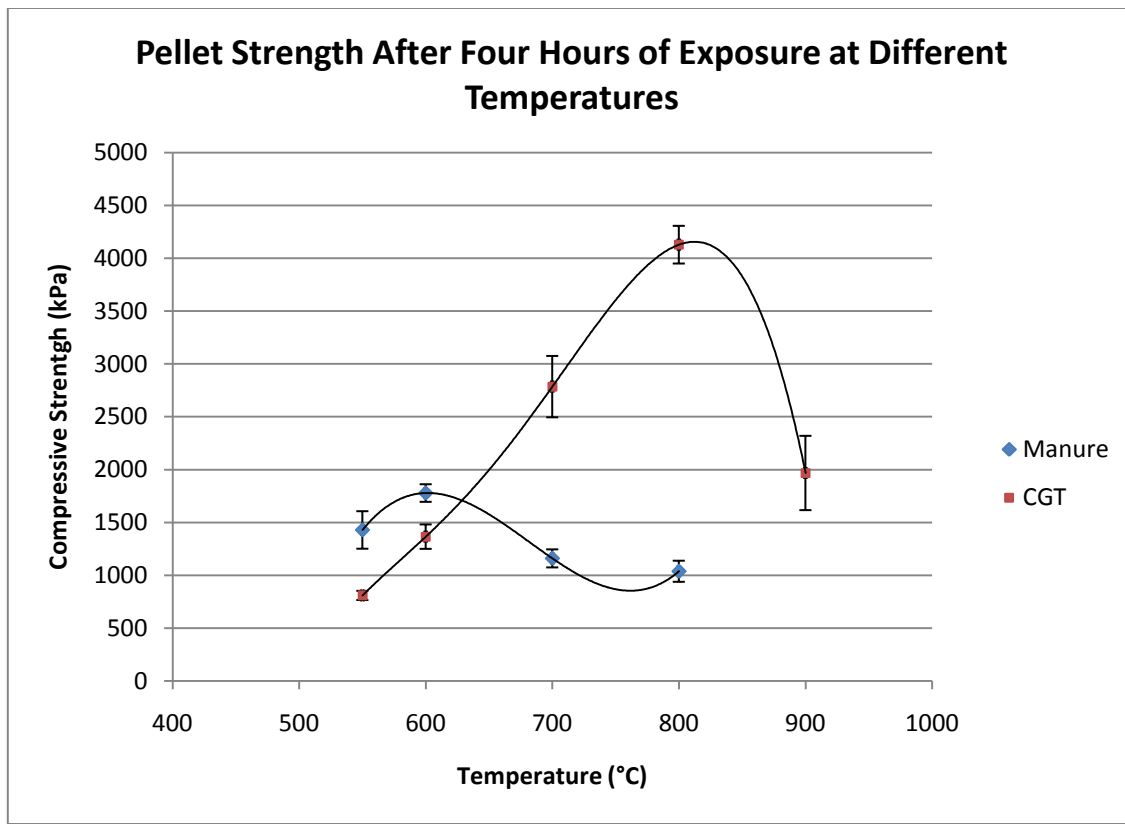
Figure 20. Compressive strength of manure and cotton gin trash ash pellets subjected to different temperatures.

Scanning Electron Microscopy (SEM) of the Biomass Ash Samples

The scanning electron micrographs of the different ash samples of manure and cotton gin trash subjected to different temperatures are shown in Figure 21 and Figure 22, respectively. The electron microscopy images indicate the bonding behavior and granular structure of the ash samples. As shown in Figure 21, the bonding behavior and structure of the manure ash remained relatively uniform at the different temperatures. On the other hand, the CGT images shown in Figure 22 indicate agglomeration in its structure as the temperature increased. This observation is consistent with the small

variation in the compressive strengths of the manure ash pellets and the wider range of

compressive strengths of the CGT ash pellets measured at different temperatures.
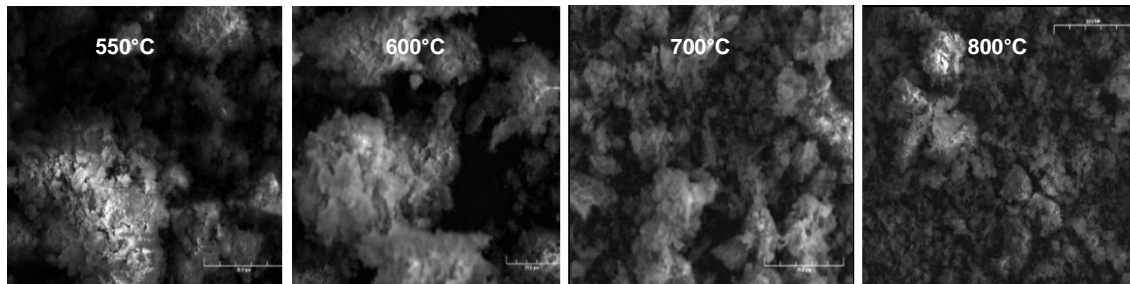
Figure 21. SEM pictures of manure ash at 1200x.
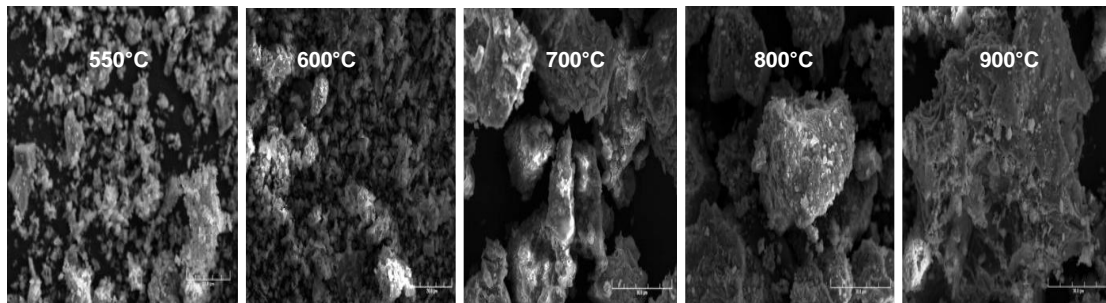
Figure 22. SEM pictures of CGT ash at 1200x.

CONCLUSIONS

Formation of deposits on heat transfer surfaces, referred to as slagging and

fouling, is one of the biggest problems in all solid fuel fired boilers, especially in

biomass combustion, and predicting the ash behavior and tendencies before a fuel is

used would be most desirable.   This study evaluated the slagging and fouling behavior

of ashes from dairy manure and cotton gin trash (CGT) using different indices and

measurements and predicted deposit formation tendencies to identify possible solution to

the problem. Initial evaluation was done based on the charactertistics and composition

of the biomass and ash samples. Because of their high ash contents, fouling and slagging is expected to occur during the combustion of manure and CGT. Having a higher content of ash, slagging would pose more of a problem with manure than with CGT. However, the very high content of K_2O in the CGT ash indicates otherwise. Fouling and slagging was also predicted to occur in both CGT and manure during combustion as shown by the high values of the alkali index and the base-to acid ratio. Moreover, the calculated values indicate that ash deposition tendencies would be higher with CGT. The low bed agglomeration index further supports the higher fouling tendency expected with the CGT ash. In a way, these three indices of slagging are in agreement with the inference made based on the high K_2O content of the CGT ash. The slagging and fouling indices used for coal are not suitable for agricultural residues and wastes. The R_s and R_f factors suggest that CGT and manure have low slagging and fouling potential contrary to the above conclusions. These factors are not used for lignites which have similar characteristics with most agricultural biomass.

The measured compressive strength of CGT ash was lowest at the lowest temperature of 550°C but continued to increase sharply until about 800°C after which its strength rapidly decreased. On the other hand, manure ash pellets exhibited little variation with the highest compressive strength measured at 550°C. The analysis of variance indicates significant differences in the compressive strengths of the ash pellets subjected to different temperatures. The temperature at which the compressive strength is highest before any decrease with increasing temperature is suggested to be melting (or eutectic) point of the ash at which slagging and fouling of ash could be avoided. Therefore, it can

be suggested that manure ash has a eutectic temperature of around 600°C while CGT has a eutectic temperature of around 800°C. These results indicate that the thermal conversion of manure does not provide any flexibility in terms of operating temperature.

The electron microscopy images indicate that the bonding behavior and granular structure of the manure ash samples remained relatively uniform at 550°C-800°C temperatures while agglomeration in its structure was observed in the CGT samples as the temperature was increased from at 550°C-900°C These observations are consistent with the small variation in the compressive strengths of the manure ash pellets and the wider range of compressive strengths of the CGT ash pellets.

The above observations clearly indicate that predicting fouling and slagging tendencies of biomass ash cannot simply be based on their composition and characteristics alone. While a number of indices have been used, no single index has so far been developed that reliably describes the behavior of the ash under all combustion conditions, especially the operating temperature. A careful analysis of a combination or combinations of indices and measurements appears to be the logical procedure to use. A clear prediction of the fouling and slagging tendencies of biomass during combustion will surely contribute to the reduction and costs of operation and increase in performance efficiency.

CHAPTER V

CONCLUSIONS

Large scale projects for gasification have been envisioned to develop alternative energy sources and yet many of them have remained in the infancy stage. Agricultural industries, such as the cotton gin, poultry and dairy industries, generate volumes of wastes while consuming considerable amounts of heat and power for their operation. The conversion of wastes generated onsite into useful products would be the most practical option for development. In addition to minimizing the transport cost of the biomass, this system will make these industries independent of their heat and power requirement from outside sources.

Further improvement in the operation and management of the pilot scale fluidized bed biomass gasification system developed at Texas A&M University in College Station, Texas provides support to the strategy outlined above. This research developed an appropriate instrumentation, measurement and control of the gasifier, evaluated its synthesis gas production using three common agricultural residues in the region and determined the slagging and fouling behavior of the biomass during gasification.

Instrumentation, measurement and control system for the TAMU fluidized bed gasifier has been developed to provide the desired operational conditions. The control program is based on NI DAQs and the use of LabVIEW program. With the process control program developed, the operation of the gasifier has become more convenient

and facilitated. The gasification unit can now be remotely operated which provides safety and comfort to the operator. However, future control system may be based on dedicated integrated circuits that will be program to do specific tasks. While the study contributed additional knowledge and practical applications, further refinement can possibly be achieved by regulating and measuring devices in the char removal and the synthesis gas collection, including loading of the biomass to the feedstock bin. This will demonstrate fully controlled operation for longer periods. Ultimately, a full automation of the operation of the gasifier will be made.

The analysis of sorghum, cotton gin trash and manure used in the evaluation of synthesis gas production and gasifier performance showed that they have calorific values and moisture contents suitable for gasification. However, the gas yields and their heating values were relatively low. Conducting studies to raise their values and achieve more efficient gasification may be the next goal. With the high ash content found in manure, problems of fouling and slagging during gasification should already be anticipated such that timely corrective actions could be employed.

Even though the biomass fuels used in the tests were all derived from agriculture, variation in terms of gas production and quality had been observed. Specifically, biomass type significantly affected the production of hydrogen. It was not however affected by the gasification temperature. These observations suggest that feedstock to be used for gasification should be carefully analyzed and evaluated. Adjustments in the gasifier design or parameter control may be investigated in the future. Further research

on the effect of the operating temperature should be conducted employing a broader range of temperature to fully evaluate its effects.

The optimization test using sorghum for gasification did not show significant effect of temperature and equivalence ratio on the concentration of methane, carbon monoxide and ethane but temperature did have significant effect on hydrogen concentration.   Again, these differences need to be addressed in future work. The response surface methodology for optimizing gas production should be done for all gases and the results practically applied in actual operation of gasifiers.

Initial evaluation of the slagging and fouling behavior of ashes from dairy manure and cotton gin trash based on the characteristics and composition of the biomass and their ash samples indicated that slagging and fouling would be expected to occur during gasification. Fouling and slagging was also predicted to occur in both biomass. The low bed agglomeration index further supports the higher fouling tendency expected with the cotton gin trash ash. In a way, these three indices of slagging are in agreement with the inference made based on the high K_2O content of the CGT ash. The slagging and fouling indices used for coal are not suitable for agricultural residues and wastes. The R_s and R_f factors suggest that CGT and manure have low slagging and fouling potential contrary to the above observatiions. These factors are not used for lignites which have similar characteristics as of most agricultural biomass.

The temperature at which the compressive strength is highest before any decrease with increasing temperature is suggested to be the melting (eutectic) temperature at which slagging and fouling of ash could be avoided. The measured compressive

strength of CGT ash was lowest at the lowest temperature of 550°C but continued to increase sharply until about 800°C after which its strength rapidly decreased. On the other hand, manure ash pellets exhibited little variation with the highest compressive strength measured at 550^0C. Therefore, it can be suggested that manure ash melting (eutectic) temperature was around 600°C while CGT ash has a higher melting (eutectic) temperature at around 800°C.

The electron microscopy images indicate that the bonding behavior and granular structure of the manure ash samples remained relatively uniform between 550°C-800°C temperatures while agglomeration in its structure was observed in the CGT samples as the temperature was increased from at 550°C-900°C These observations are consistent with the small variation in the compressive strengths of the manure ash pellets and the wider range of compressive strengths of the CGT ash pellets.

Ash composition and characteristics alone cannot clearly predict the fouling and slagging tendencies of biomass ash. While a number of indices have been used, no single index has so far been developed that reliably describes the behavior of the ash during thermal conversion process, especially the operating temperature. A careful analysis of a combination or combinations of indices and measurements appears to be the logical procedure to use. A clear prediction of the fouling and slagging tendencies of biomass during thermochemical process will surely contribute to the reduction on the costs of operation and increase in performance efficiency.

In summary, the research conducted has contributed additional information and practical applications to enhance the operation of a fluidized bed gasification system.

Further refinement in the instrumentation of the gasifier, additional researches on the

synthesis gas production and system performance and development of appropriate

indices for slagging and fouling for biomass are considered priority for future work.

Ultimately, the design and development of a full automation system for the operation

and management of the gasifier would be most appropriate.

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VITA

Name: **Amado Latayan Maglinao Jr.**

Office Address: **Biological and Agricultural Engineering Department**
201 Scoates Hall MS 2117
Texas A&M University
College Station, Texas 77843-2117

E-mail Address: amado_jr@tamu.edu, aoshi_madz@yahoo.com

Education: **M.S. Biological and Agricultural Engineering**, December 2009
Texas A&M University
College Station, Texas 77843

B.S. Electrical Engineering, April 2003
Minor in Electronics
University of the Philippines at Los Baños
College, Laguna. 4031. Philippines