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DEVELOPMENT OF COMPUTER CONTROL SYSTEM FOR THE PILOT SCALE FLUIDIZED BED BIOMASS GASIFICATION SYSTEM

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Abstract. *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. 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.*

Keywords. Gasification, fluidized bed, control system.

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) develop a process control program to properly operate the gasifier continuously (c) evaluate the performance of the gasification system in terms of synthesis gas production and gas quality.

Safety Emphasis

Once a gasification operation was completed, the gasifier was shut down following the prescribed shutdown procedure. The shut down procedure is normally done as follows:

- Use all biomass feedstock on the fuel bin
- The cold air blower is operated until the bed temperature is below combustion temperature of the biomass
- Opening all vents such that combustible gases are not trapped on hot areas within the gasifier system.

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 1).

Figure 1. Pilot scale fluidized bed gasification unit.

Figure 2 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.

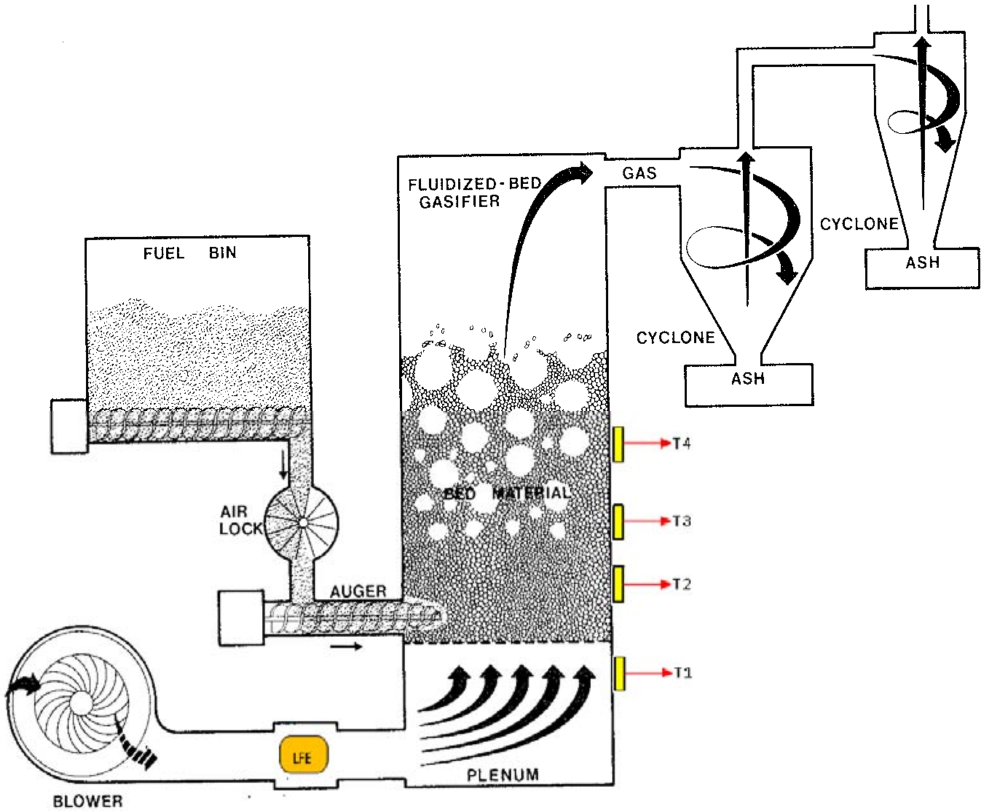


Figure 2. Operation of the fluidized bed gasifier (LePori and Soltes, 1985).

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.

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).

$$C_uH_wN_xO_yS_z + \text{a } O_2 \xrightarrow{yields} \text{b } H_2O + \text{c } CO_2 \qquad (2)$$

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.

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.

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 3 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,

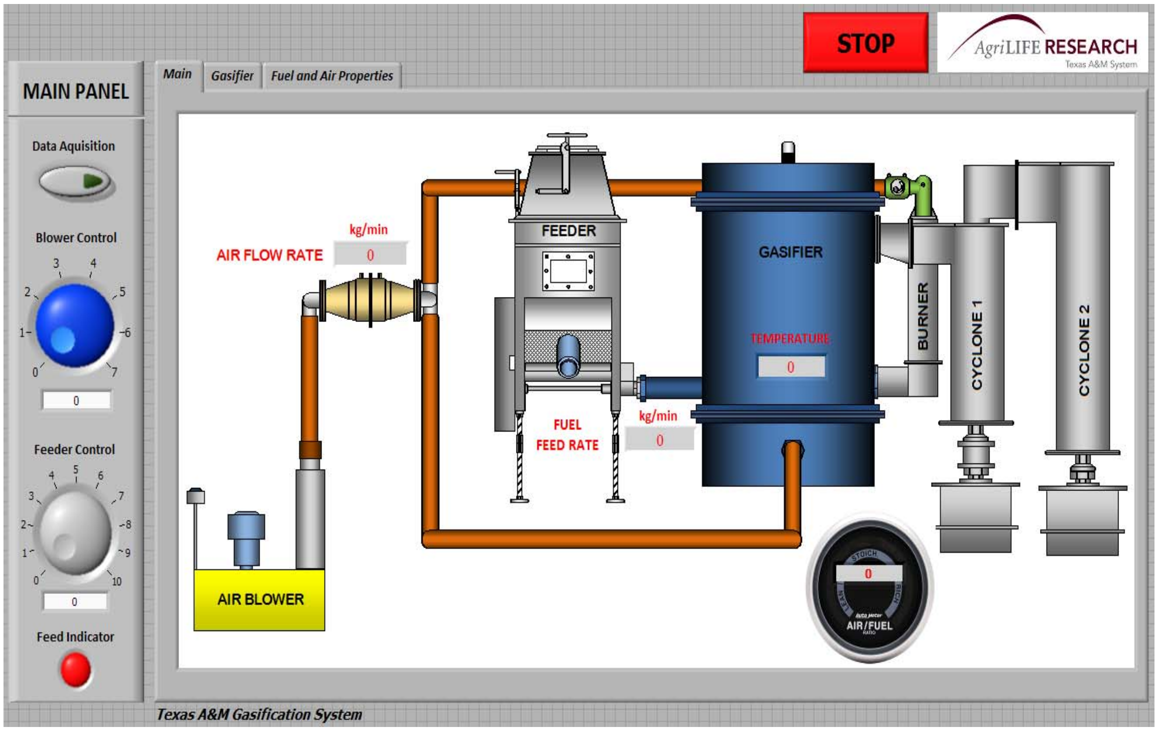


Figure 3. Main interface of the gasification process control program.

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 4). 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 2) was included.

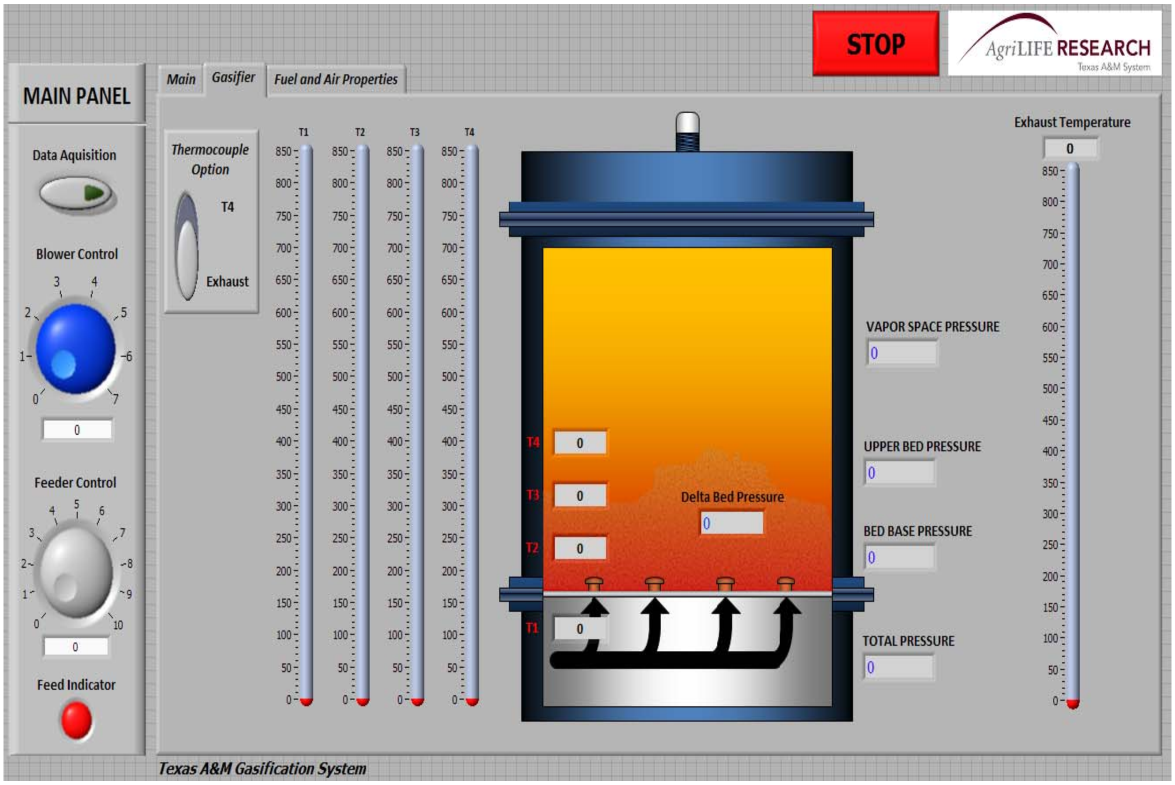


Figure 4. Detailed gasification system interface.

The last part of the interface is the display of air and fuel properties (Figure 5). 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.

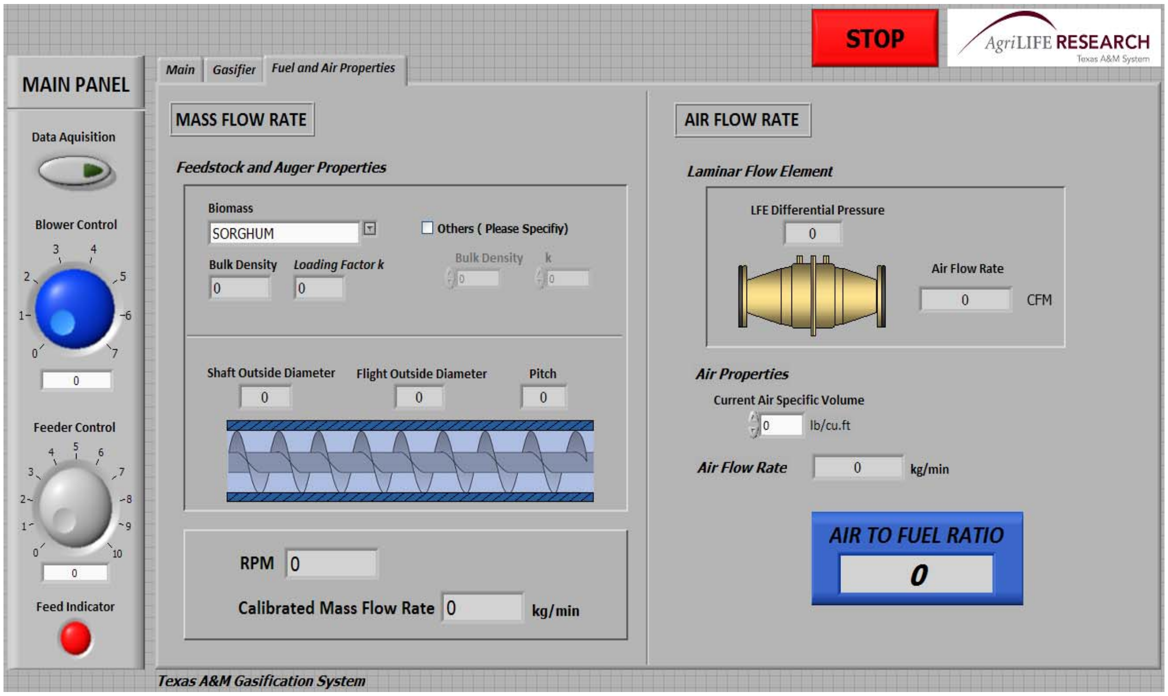
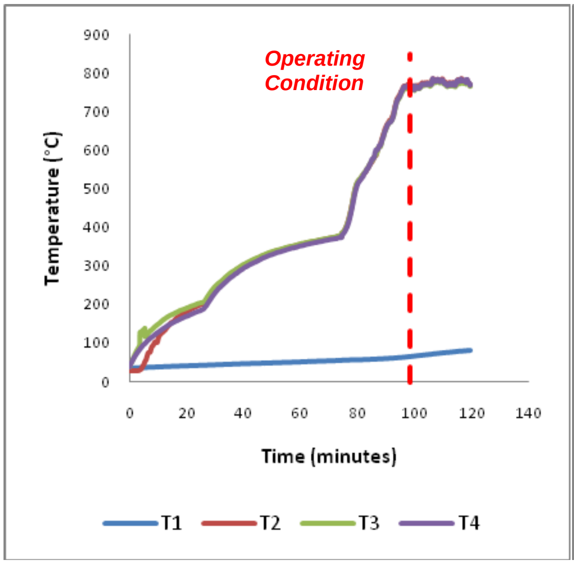


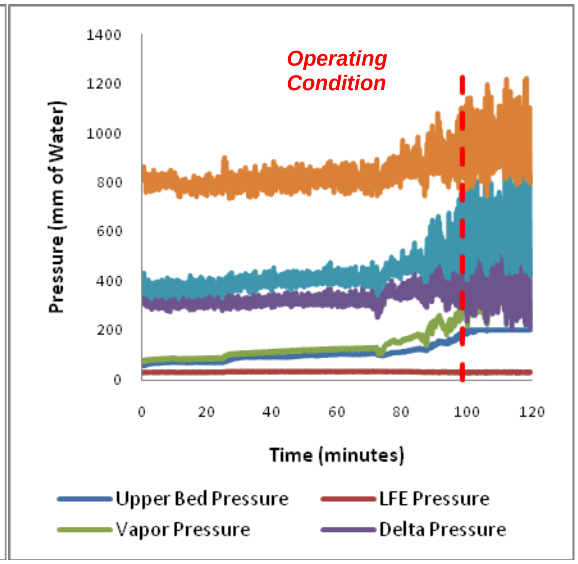
Figure 5. Air and solid fuel properties interface.

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. Figure 6 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 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 characteristic in a fluidized bed, especially with diverse sized biomass.





(a) (b)

Figure 6. Temperature profile (a) and pressure profile (b) during the operation of the fluidized bed gasifier.

Once the gasification temperature was reached (eg. 775°C in Figure 7), 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 8). 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 9.

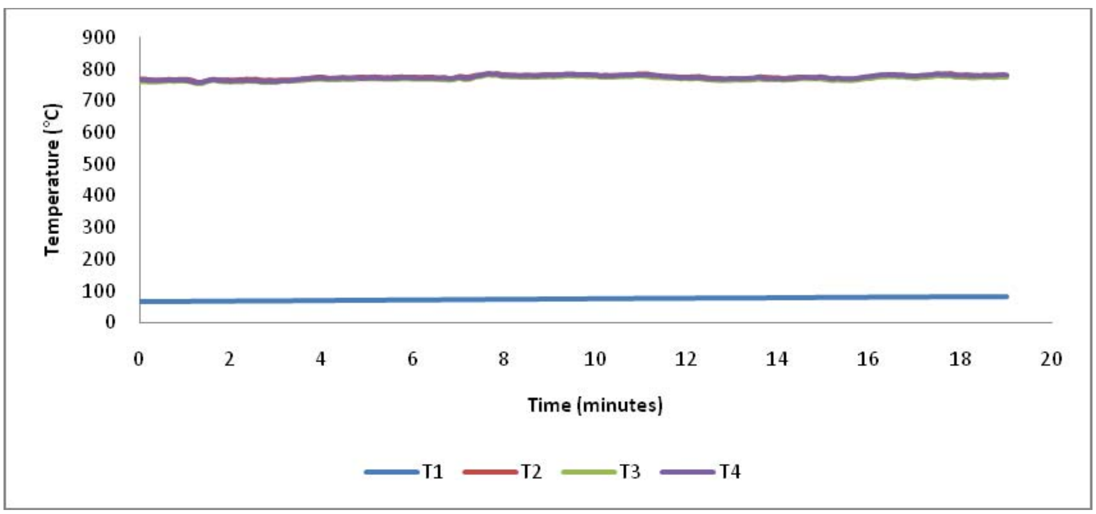
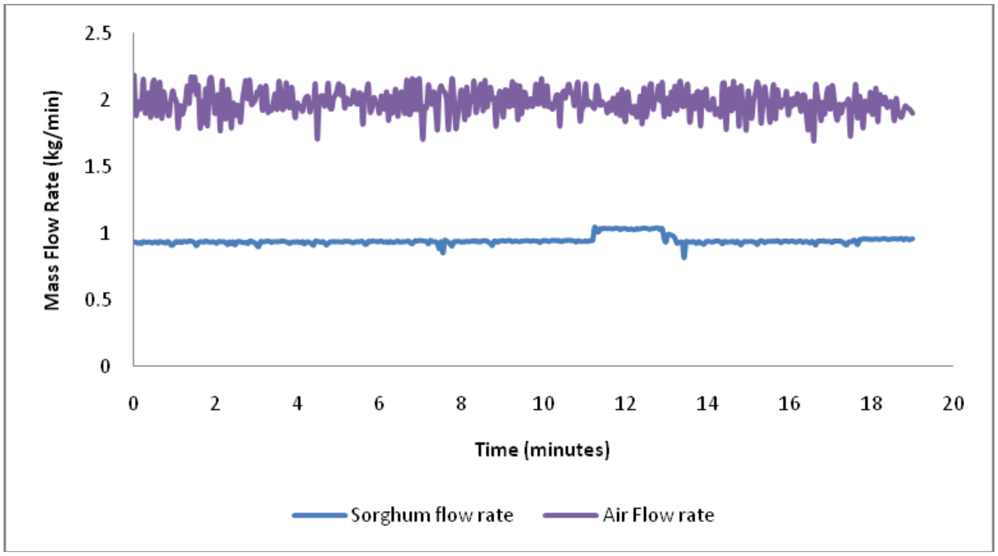
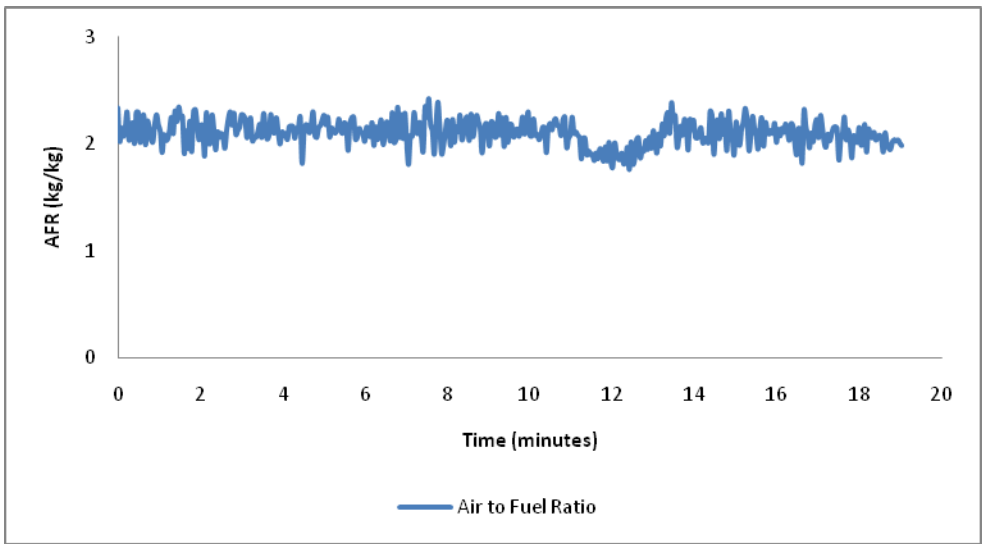


Figure 7. Temperature profile in the gasifier during its operation.



(a)



(b)

Figure 8. (a) Sorghum flow rate and air flow rate and the (b) resulting air to fuel ratio during the operation of the gasification.

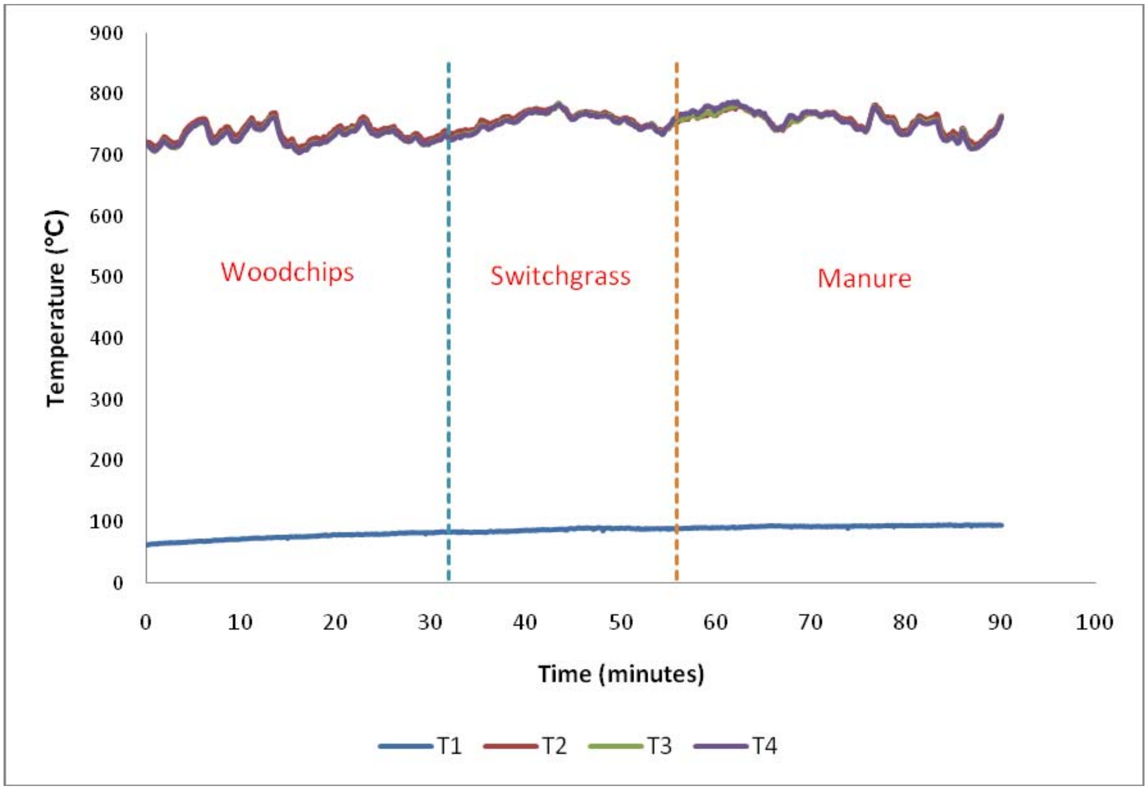


Figure 9. Gasification temperature with multiple feedstock.

Gasification Performance

Figure 10 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.

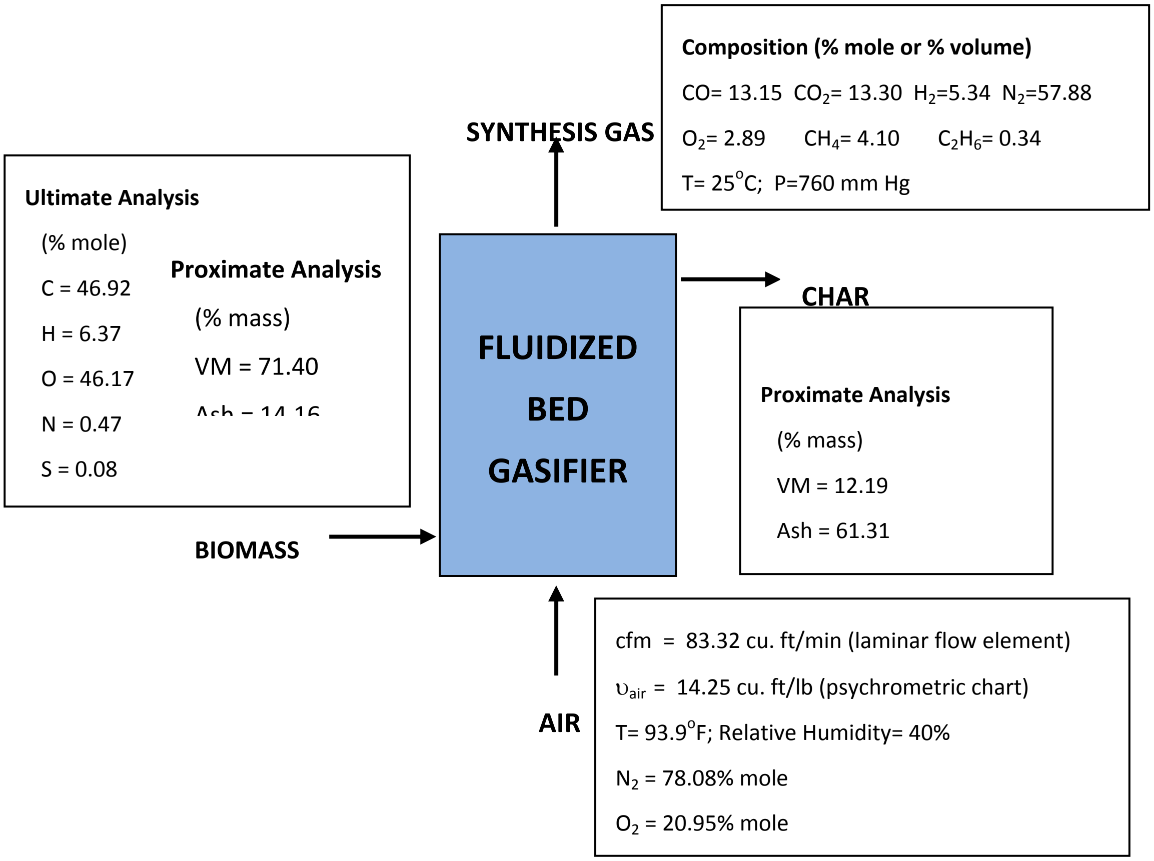


Figure 10. Carbon mass balance for sorghum gasification.

The quality and production of synthesis gas during the gasification of sorghum, cotton trash and manure as fuels is shown in Table 2. 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 2. 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

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.

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.

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