Southeast Bioenergy Initiative – Auburn University

Systems Based Approaches for Thermochemical Conversion of Biomass to Bioenergy and Bioproducts

Award No. DE-FG36-08GO88024

FINAL REPORT

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Center for Bioenergy and Bioproducts

Point of Contact: Steven Taylor
taylost@auburn.edu

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Executive Summary

Systems Based Approaches for Thermochemical Conversion of Biomass to Bioenergy and Bioproducts

Auburn's Center for Bioenergy and Bioproducts and its Bioenergy and Bioproducts Laboratory were established to allow research, education, and outreach activities to occur in one location, ranging from feedstock production and processing through biofuel conversion to biofuel testing. The laboratory contains two gasification platforms suitable for conducting research on production of synthesis gas for use in power generation and the production of liquid fuels: 1) an air-blown downdraft gasifier with combined heat and power production modules, and 2) a pressurized, oxygen-blown bubbling-bed fluidized-bed gasifier (BFBG) with warm gas cleanup and a downstream gas-to-liquids conversion system for the production of liquid fuel products. These platforms provide researchers the ability to examine gasification of a wide variety of agricultural and forest biomass types.

Using systems approaches, Auburn scientists and engineers have performed integrated investigations of the entire thermochemical processing system. Researchers have studied the biomass supply chain by testing cropping systems for herbaceous and woody biomass and testing new methods for harvesting, transporting, and processing forest and agricultural biomass in preparation for gasification. The overall goal of our gasification research is to identify optimal processes for producing clean syngas to use in production of fuels and chemicals from underutilized agricultural and forest biomass feedstocks. Specific objectives of this project were as follows:

(1) Construct and commission a bubbling-bed fluidized-bed gasifier and associated facilities in a gasification laboratory.
(2) Perform shakedown of the gasification and gas cleanup system.

The result of this initial phase of our research is a fully commissioned gasification laboratory that is conducting testing on agricultural and forest biomass. Initial tests on forest biomass have served as the foundation for follow-up studies on gasification under a more extensive range of temperatures, pressures, and oxidant conditions. The laboratory gasification system consists of a biomass storage tank capable of holding up to 6 tons of biomass; a biomass feeding system, with loss-in-weight metering system, capable of feeding biomass at pressures up to 650 psig; a bubbling-bed fluidized-bed gasification reactor capable of operating at pressures up to 650 psig and temperatures of 1500^{o}F with biomass flowrates of 80 lb/hr and syngas production rates of 37 scfm; a warm-gas filtration system; fixed bed reactors for gas conditioning; and a final quench cooling system and activated carbon filtration system for gas conditioning prior to routing to Fischer-Tropsch reactors, or storage, or venting.

This completed laboratory enables research to help develop economically feasible technologies for production of biomass-derived synthesis gases that will be used for clean, renewable power generation and for production of liquid transportation fuels. Moreover, this research program provides the infrastructure to educate the next generation of engineers and scientists needed to implement these technologies.

Auburn University's fluidized bed gasification and gas conditioning system.

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A. Project Objectives

Auburn University's Center for Bioenergy and Bioproducts is investigating methods for conversion of biomass resources into biofuels and new products, thus creating new jobs and business opportunities that will revitalize local economies, while significantly benefitting Alabama farmers and forest landowners. The laboratory contains two gasification platforms suitable for conducting research on production of synthesis gas for use in power generation and the production of liquid fuels: 1) an air-blown downdraft gasifier with combined heat and power production modules, and 2) a pressurized, oxygen-blown bubbling-bed fluidized bed gasifier with warm gas cleanup and a downstream gas-to-liquids conversion system for the production of liquid fuel products. These platforms provide researchers the ability to examine gasification of a wide variety of agricultural and forest biomass types with results that are applicable to different scales and different industrial applications.

This research will examine the technical and economic feasibilities of thermochemical conversion platforms for agricultural and forest residues commonly available in the southeast U.S. Research on biomass gasification and subsequent gas-to-liquids conversion needs further experimental work to resolve questions on feedstock pretreatment and optimal feedstock form and condition; pressurized feeding; gasification parameters; warm gas cleanup to remove potential catalyst contaminants; and final gas-to-liquids conversion parameters.

The Gas Technology Institute (GTI) collaborated with Auburn University in developing a gasification laboratory at Auburn University where experimental studies are being conducted. In this research program, we propose to investigate the gasification of forest and agricultural biomass to produce clean syngas that can subsequently be used to produce fuels and chemicals. In this initial phase of the research, we completed construction of a bubbling-bed fluidized-bed gasification unit and conducted the initial testing and debugging of the system and the analytical procedures for measuring syngas properties. The overall goal of this gasification research is to identify optimal processes for producing clean syngas to use in synthesis of fuels and chemicals from underutilized agricultural and forest biomass feedstocks.

Specific objectives of the project were as follows:

(1) Construct and commission a fluidized bed gasifier and associated facilities in a gasification laboratory.
(2) Perform shakedown of the gasification and gas cleanup system.

B. Project Scope

This research is aligned with two primary areas in the Department of Energy's Biomass Energy Technology Office: Feedstocks and Thermochemical conversion. The work evaluates the use of woody and herbaceous biomass feedstocks (southern pine, hardwoods, and switchgrass) as well as investigating optimal gasification operational parameters to produce clean syngas from these feedstocks. The project will provide valuable information on the basic chemical composition and feedstock suitability of what are the most available sources of biomass in the southeastern U.S. A combination of field research and laboratory research has been conducted at Auburn whereby extensive testing of biomass has been conducted to determine physical and chemical properties. Laboratory research has then been conducted to determine optimal gasification conditions for production of clean syngas. Two gasification platforms have been utilized in this research: 1) an existing air-blown downdraft gasifier, and 2) a new pressurized, BFBG capable of being operated in oxygen-blown or air-blown modes. This project focused on the design and installation of the bubbling-bed fluidized-bed gasification reactor system.

C. Tasks Performed

Task 1 – Construct and commission a bubbling-bed fluidized-bed gasifier and associated facilities in a gasification laboratory.

Biomass gasification involves the partial oxidation of biomass feedstocks to produce a combustible medium to low calorific-value fuel called syngas or producer gas. The main components of the syngas are CO, H_2, CO_2, CH_4, N_2, and H_2O. This chemical transformation can take place in fixed, moving, or fluidized bed or entrained flow gasifiers at temperatures of 1400 to 1800°F with pressures from 1 to 30 atmospheres. Syngas can be utilized in catalytic synthesis to produce various biofuels, such as Fischer-Tropsch hydrocarbons, methanol, and hydrogen as illustrated in Figure 1.1. Liquid fuels and chemicals synthesis requires an optimal ratio of H_2:CO in syngas. For example, methanol synthesis is optimal at a syngas H_2:CO ratio of 3:1 while Fisher-Tropsch synthesis favors a H_2:CO ratio of 2.15. Therefore, it is necessary to maintain optimal ratio of H_2:CO for maximizing the conversion of syngas to desired fuels and chemicals. Although this thermochemical platform has been utilized for coal feedstocks as early as the 1930's, there are still many research questions for gasification or biomass and biomass fractions (such as lignin) and the resulting syngas H_2:CO ratio, volatile content, char reactivity, and mineral content. Significant research is needed to document the effects of operational parameters such as gasifier temperature, gasifier pressure, and feedstock form and condition (i.e. moisture content, etc.), and feedstock blends on syngas quality and the ratio of H_2:CO.

This project focused on the design, fabrication, and installation of a pilot-scale laboratory gasification system. The overall laboratory houses a pressurized, bubbling-bed fluidized-bed gasifier, gas cleanup system, and multiple Fischer-Tropsch reactors. Auburn University worked collaboratively with the Gas Technology Institute to design and construct the gasification system.

The BFBG is designed to operate using oxygen, air, or steam as the oxidant. The oxidant requirement, in either case, is dictated by the heat balance, wherein the oxidant flow is controlled to maintain the desired bed temperature. In addition to fluidizing air or oxygen, steam can also be included to moderate the gasification chemistry of the reactor. The BFBG has much more flexibility in varying operating pressure and oxidant. Figure 1.2 shows a schematic of the BFBG designed by GTI for Auburn University.

The gasifier design of the facility is similar to that found in GTI's RENUGAS® technology.

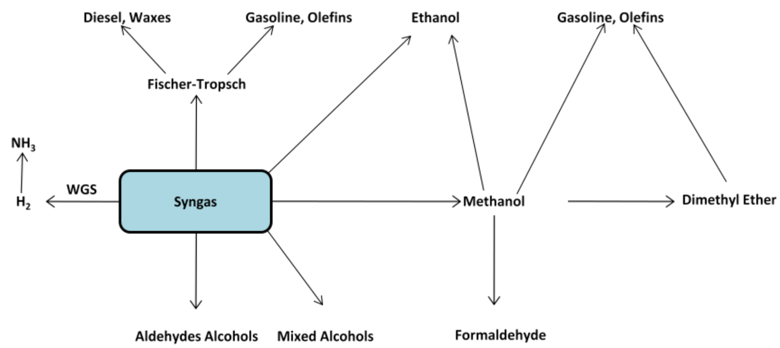

Figure 1.1. Various pathways for conversion of syngas to fuels and chemicals.

Overall specifications for the gasification system are listed in Table 1.1 and an initial overall schematic of the system is shown in Figure 1.1. The overall operating capacity of the reactor system is approximately 80 dry pounds per hour of biomass at 150 psig and 1500^{o}F under oxygen-blown conditions, which produces approximately 37 scfm of syngas. Table 1.2 contains a detailed description of possible operating conditions and biomass flow rates for the gasification system.

Table 1.1. Overall specifications for Auburn University's fluidized-bed gasifier and gas cleanup system.

System or subsystem	**Basic Specifications**	**Additional Comments**
Overall biomass throughput	Approximately 80 pounds per hour	At 1500^{o}F and 150 psig
Feeding system	Pressurized system controlled by loss-in-weight feeder	Designed for pelletized biomass
Gasification reactor	4 in. diameter bubbling bed reactor Operate at temperatures up to 1500^{o} F Operate at pressures up to 650 psig	Initial bed material - sand Fluidized bed – 50 in. Freeboard – 67 in.
Oxidant	Air Oxygen Steam	
Gas filtration	2 parallel banks of sintered metal filters Operate at temperatures up to 1000^{o} F	
Gas conditioning	3 fixed bed reactors suitable for sorbents to remove sulfur, halides, etc. or for water-gas-shift reactions	
Gas treatment before release	Quench cooler and activated carbon bed to remove remaining H_2S	Syngas can be vented, compressed and stored, or routed to Fischer-Tropsch reactors
Control system	Control system is based on National Instruments data acquisition and control hardware and custom designed software All data are stored on PI server which allows remote, real-time viewing of gasification operation	80 analog inputs are currently monitored 84 digital inputs are currently monitored 51 variables are currently controlled 113 thermocouples are currently monitored

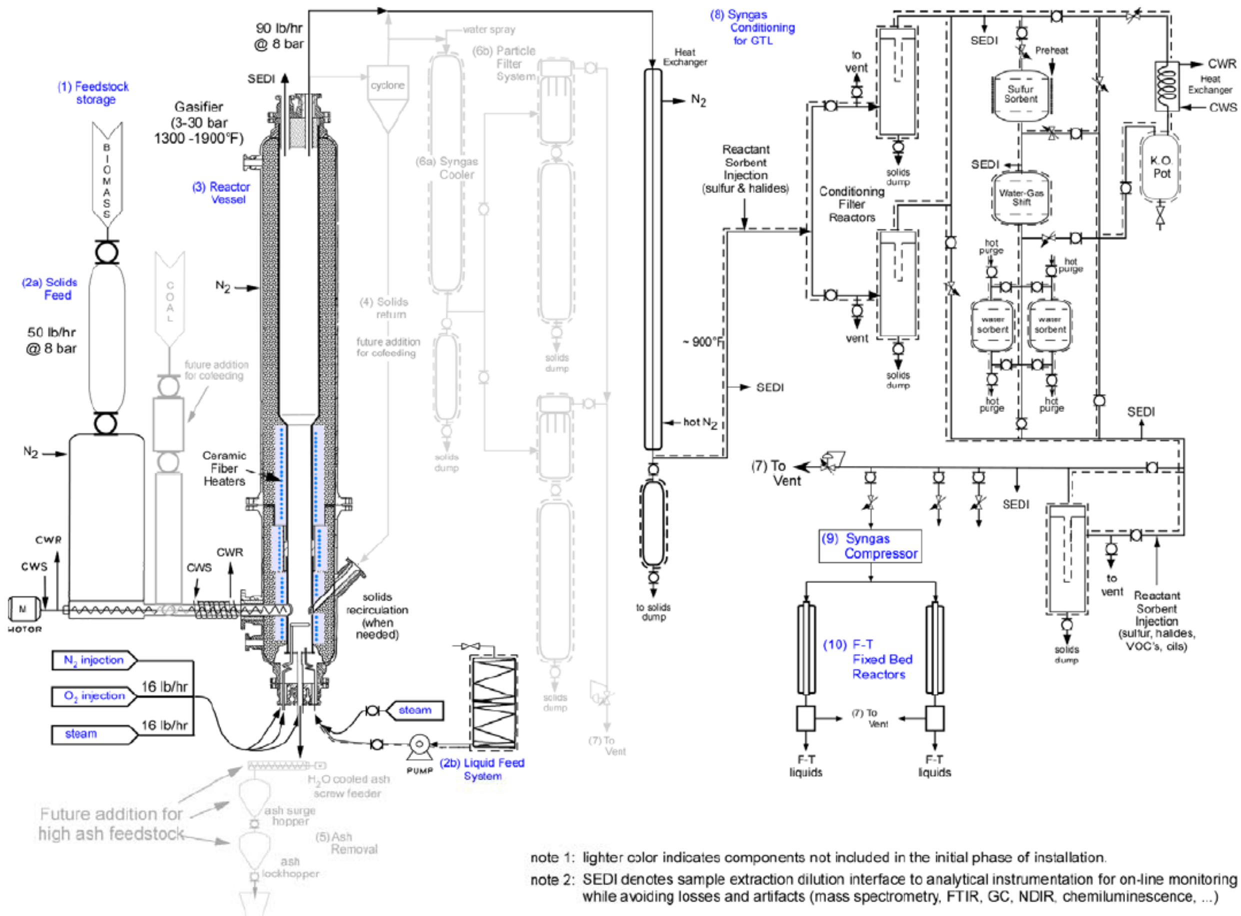

Figure 1.2. Schematic of Auburn University's fluidized-bed gasifier and gas cleanup system.

Table 1.2. Theoretical operating conditions and biomass flow rates for the gasification system.

	Biomass Feed Rate	Fluidized Bed Conditions		Syngas Output		
	(lbs/hr)	Temperature (°F)	Pressure (psig)	(lb/hr)	(scfm)	
Air blown	36	1500	100	98	24	Current gasifier configuration
O_2 blown	55	1500	100	96	25	
Air blown	52	1500	150	142	36	
O_2 blown	80	1500	150	139	37	
Air blown	70	1500	200	191	48	Future gasifier configuration
O_2 blown	100	1500	200	173	46	
Air blown	140	1500	425	382	96	
O_2 blown	210	1500	425	364	96	
Air blown	164	1500	500	447	112	
O_2 blown	250	1500	500	434	114	

System description

The gasification system consists of: 1) a set of external subsystems that supply biomass, compressed air, steam nitrogen, and oxygen; 2) gasification platform (with pressurized feeding system); 3) gas conditioning platform; and control room with data acquisition and control system. Photos of the gasification platform, gas conditioning platform, and control room are shown in the Appendix.

The external subsystems are installed on one of two concrete pads outside the gasification laboratory. One concrete pad, which is covered and located immediately adjacent to the laboratory, is equipped with a galvanized steel biomass storage tank capable of storing approximately 12,000 pounds of biomass, a steam generator, a screw-type air compressor and drier for instrument-grade air, and a reciprocating compressor for typical industrial-grade air. A backup electrical generator is also placed on this pad adjacent to the laboratory. A second external concrete pad is equipped with two 500 gallon tanks that are used to store liquid nitrogen and liquid oxygen with a 100 gallon backup liquid nitrogen tank for subsequent use in the gasification system.

The gasification platform consists of a pressurized biomass storage and feeding system, a water-cooled injector screw for biomass injection into the fluidized bed, the gasification reactor, and a heat exchanger to provide initial cooling of the syngas prior to releasing to the syngas conditioning platform. Biomass is conveyed from the external storage tank via a flexible screw auger. The system is intended primarily for pelletized biomass; however, other small particle sizes may be fed into the gasifier. Biomass is conveyed inside and dropped into a lock 24 in. tall by 24 in. diameter hopper on top of the main pressurized feed hopper, which is 65 in. tall and 30 in. diameter. Both feed hoppers are designed to operate at 650 psig and are purged with nitrogen during gasifier operations. To feed biomass, the lock hopper is depressurized and the top pneumatic knife valve is opened to allow biomass to feed into the lock hopper. After the lock hopper is full, feeding stops and the top pneumatic valve is closed and the vessel is pressurized to match the pressure in the lower feed hopper. Once pressures are equalized, the lower pneumatic knife valve is opened and biomass falls into a K-Tron gravimetric feeding system that is installed inside the lower feed hopper vessel. The K-Tron gravimetric feeding system activates to precisely feed the biomass out of the hopper, at the desired feeding rate, and drop it into an injector screw that then horizontally conveys the biomass and forces it inside the fluidized bed. Since the injector screw protrudes into the gasification reactor, it is water cooled to prevent damage.

The gasification reactor is 4 in. diameter with a fluidized bed height of roughly 54 in. A 67 in. high reactor freeboard section is provided above the fluidized bed. The fluidized bed is indirectly heated with ceramic electric resistance heaters. Insulation is installed between the outer pressure vessel shell and the ceramic heaters. In the initial configuration, sand has been used as the bed material. A diffuser plate at the bottom of the reactor allows the introduction of nitrogen, air, oxygen or steam as the oxidant and the mechanism to promote fluidization in the reactor. A refractory lined gas extraction module is positioned at the top of the reactor to redirect syngas into a horizontal shell-in-tube heat exchanger. This heat exchanger is a syngas-to-air cooler that reduces syngas temperature prior to entering the gas conditioning platform. In addition to controlling the ceramic heaters, nitrogen is used to moderate the conditions inside the reactor. In the initial configuration, the system is equipped with valves and components to allow operation up to pressures of 150 psig and temperatures of 1500^oF. Temperatures are cooled to approximately 1000^oF before leaving the heat exchanger and entering the gas conditioning platform.

Syngas is delivered to the gas conditioning platform and enters one of two char removal subsystems. These char removal subsystems rely on sintered metal, or candle type filters to remove particulates. Char is dropped into one of two bins for later removal. Filtered syngas then flows through up to three different fixed bed reactors that are 6 in. diameter by 47 in. tall. These fixed bed reactors may be equipped with chemical sorbents or configured to perform water gas shift reactions. Beyond the fixed bed reactors, syngas flows through a quench cooler and then through activated carbon filters to remove any remaining H_2S. At the exit of the activated carbon filter, the syngas is either vented, compressed and stored, or conveyed to the Fischer-Tropsch reactors in an adjacent laboratory. The design pressure for the major reactor vessels and associated feed system vessels was set at 650 psig so that increased syngas production and handling could be accommodated and so that direct gas-to-liquids (GTL) reactors could be operated at near to normal production levels without the syngas compressor. In subsequent phases of the facility, the larger syngas handling equipment illustrated by faded lines in Figure 1.2 may be added.

Control of the reactor system is accomplished through an extensive data acquisition and control system. The DAC system uses National Instruments hardware and LabView software to monitor and control hundreds of analog and digital inputs and outputs. Over 80 analog inputs and 84 digital inputs are monitored with an additional 51 control outputs. A custom developed control system provides semi-automated control of various subsystems, with significant ability to exert manual control over the reactor for research purposes and expand to suite future needs.

Assembly of the gasification system was completed in 2012. Subsequent shakedown and testing campaigns have been conducted in the years since 2013.

Task 2 – Shakedown of the gasification and gas cleanup system.

The following text describes one of the shakedown campaigns conducted in the gasification system. The text describes the biomass characteristics, experimental design, and resulting syngas quality.

Biomass Characteristics

Hardwood (oak) pellets were used as feedstock for gasification. The proximate and ultimate analysis results for this biomass is reported in Table 2.1 whereas the composition analysis of the biomass is reported in Table 2.2. Moisture content and energy content were 10.07% and 19.73 ±0.14 MJ/kg, respectively. It can be seen that all the biomass properties match well with those reported in literature for hardwood pellets [1-3].

Table 2.1. Biomass characteristics.

Ash	VM	FC	C	H	N	S	O
0.41 ±0.06	89.5 ±0.08	10.09 ±0.09	49.65 ±0.04	7.02 ±0.14	0.09 ±0.02	0.4 ±0.04	42.84 ±0.12

Table 2.2. Biomass composition.

Extractives	Cellulose	Hemicellulose	AIL	ASL
5.86	45.61 ±0.4	25.5 ±0.6	21.71 ±2.3	1.0 ±0.1

Experimental Design:

The aim of this particular gasification run was to study the effect of Equivalence Ratio (ER) on syngas composition and contaminants, and perform an initial study for air/steam gasification. A biomass feed rate of 20 lb/hr was selected based on previous initial runs. The ER was set at 0.30 and 0.40; these ER values are in the typical air gasification range reported in literature. The total flow rates were calculated from the Ergun equation . Table 2.3 reports the experimental results.

After approximately 20 hours of heating the gasifier to reach steady-state conditions, three different setpoints were evaluated. Setpoints 1 through 3 were maintained for 3 hours, while Condition 4 was maintained for 30 minutes. Previous runs had shown that tests of 3 hours allowed sufficient stabilization of the gasifier to provide meaningful results. Primary syngas composition was analyzed using California Analytical Instruments' gas analyzer and the contaminants were analyzed using IMAC FTIR. Tar was collected using impinger bottle set-up as described by Shrestha [1] and analyzed using GC FID. H_2S was analyzed using GC FPD as described in Abdoulmoumine et al. [4].

Table 2.3. Gasification Setpoint ID and parameters.

Setpoint	Parameters
Setpoint 1 Air gasification	Temp 850 °C, ER 0.40, Biomass feed rate 20 lb/ hr, Air 250 LPM, N_2 50 LPM
Setpoint 2 Air gasification	Temp 850 °C, ER 0.31, Biomass feed rate 20 lb/ hr, Air 200 LPM, N_2 100 LPM
Setpoint 3 Air/steam gasification	Temp 850 °C, ER 0.39, S/C = 1.2 feed rate 20 lb/ hr, Air 250 LPM, steam 12 lb.hr
Setpoint 4 Air/ steam gasification	Temp 850 °C, ER 0.28, S/C = 1.2, feed rate 20 lb/ hr, Air 200 LPM, steam 12 lb/hr

Gasification results

a. Equivalence ratio:

Syngas results for air gasification are reported in Table 2.4. Temperature for the experiments was kept constant at 850^{o}C. ERs of 0.30 and 0.39 were set as targets, which is within a typical range (0.20 to 0.40) reported for bubbling bed fluidized bed gasifiers[2]. The feed rate was set initially at 30 lb/hr, however, due to feeding issues, the feed rate was reduced to 20 lb/hr to ensure smooth operation. Air was used as an oxidizing agent, while nitrogen was used as a bubbling media.

Table 2.4. Experimental results for the ER study on the pilot scale bubbling fluidized bed gasifier.

Parameter	Setpoint 1	Setpoint 2
Temperature, ^{o}C	850	850
Pressure	50	50
ER[a]	0.39	0.31
Biomass Feed rate lb/hr, (kg/hr)	19.7 (8.0)	20.1 (8.1)
Air (lpm)	250	200
Nitrogen (lpm)	50	100
Syngas composition (Vol %)		
CO	11.8	8.9
CO_2	11.6	10.9
CH_4	2.1	2.5
H_2	7.5	6.9
C_2H_4	2.6	2.5
C_2H_2	0.01	0.02
N_2	64.4	68.3
Syngas yield Nm^3/ dry kg biomass	2.92	2.84
Syngas Energy MJ/Nm^3	4.7	4.4
Carbon balance	72.7	62.5
Syngas contaminants (ppmv)		
NH_3	72.2	44.08
HCN	37.8	29.8
HF	0.15	0.15
HCl	7.8	8.4
SO_2	60.18	67.73
H_2S	112.5	95.4
Tar (mg/ kg biomass)	18.8	11.1

The results in Table 2.4 indicate that the reduction in ER did not affect the syngas composition. This was largely due to dilution of syngas with nitrogen. Calculations were performed on nitrogen free basis and are shown in Figure 2.1. This figure shows that nitrogen free values agreed well with the literature for pilot scale gasification at similar temperatures [5, 6]. The syngas composition was better than that reported by Abdoulmoumine et al. and Kulkarni [7, 8] which reported studies on a bench-scale BFBG. Shrestha [1] used the same pellets in a gasification campaign in Auburn's downdraft gasifier air as the oxidant, temperatures of 800°C and ER 0.28. He found syngas composition of CO: 21%, CO_2: 11.60%, H_2: 16.77, CH_4: 1.94%. While Shrestha's results showed higher CO and H_2 yield with the downdraft gasifier, these results could be due to the BFBG gasifier using excess nitrogen for fluidization, which diluted the syngas, and also the high ER values. The syngas composition obtained using the pilot scale BFBG at ER 0.39 agrees well with that reported in Narvaez et al. at ER 0.37 and 800^{o}C in a pilot-scale fluidized bed gasifier[9].

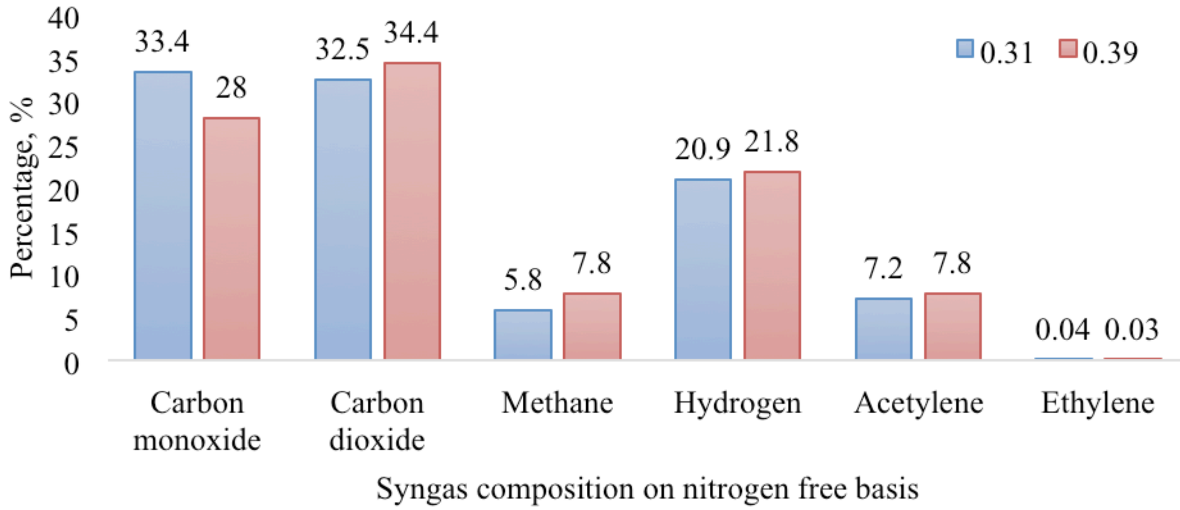

Figure 2.1. Effect of ER on syngas composition on nitrogen free basis.

Actual values of ER obtained during the gasification campaign were in the higher range of ER used for gasification. These higher values of ER most likely resulted in higher CO_2 (440 to 470 g/ kg of biomass) yield than CO (228 to 330 g/ kg of biomass). Comparable yields and concentrations of acetylene were observed when compared to gasification carried out on the bench-scale BFBG, while methane yield was lower[7, 8]. These methane and acetylene yields could be due to the longer bed area which helped the methane decompose to CO and H_2. The yields are reported in Figure 2.2.

Although it is expected that lower ER will result in a higher CO production, it was observed that the CO concentrations were lower at the ER of 0.31 compared to ER of 0.39. These low CO concentrations could be due to lower reactivity of the biomass with lower oxygen present in the gasifier at lower ER in the presence of high amounts of nitrogen. The carbon conversion values obtained (72% at ER of 0.39, while 68% at ER of 0.31) support the idea that lower oxygen levels and higher nitrogen levels resulted in lower CO production. Carbon conversion rates of approximately 80% were reported with same pellets in a downdraft gasifier[1]. To reduce the dilution effect, we have recommended that the use of nitrogen should be minimized for future runs. Air-blown gasification without use of additional nitrogen (for fluidization) in the system should be studied to understand the full potential of the gasifier under air-blown gasification conditions.

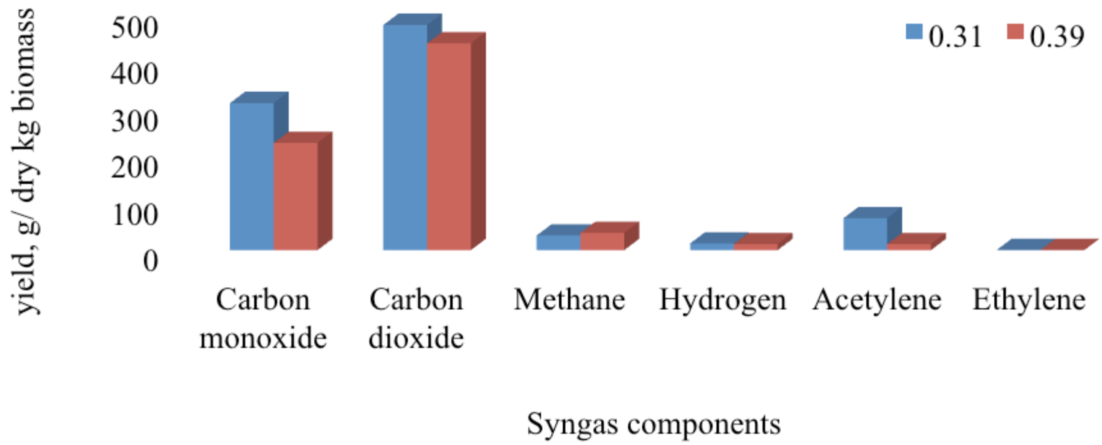

Figure 2.2. Effect of ER on syngas component yield.

The syngas energy content was observed to be 4.4 to 4.7 MJ/Nm^3, which is comparable with the values reported in literature (4 to 7 MJ/ Nm^3) [1, 2, 4, 5, 8] for air gasification in bubbling fluidized bed gasifiers. The syngas yield obtained was between 2.92 and 2.84 Nm^3/dry kg biomass and did not appear to be affected by ER. The heating value of syngas from pellets in a downdraft gasifier[1] (5.57 MJ/ Nm^3) was slightly higher than what was obtained in the current experiments in the BFBG.

The ammonia concentration was 72 ppm and 44 ppm at ER 0.39 and 0.31, respectively. These concentrations were lower than those reported for pine, switchgrass and torrefied pine[4, 8]. These lower values could be due to lower N_2 (volumetrically) used for gasification when compared to this set of experiments. The concentration of HCN was around 28 to 35 ppm. The HCN values agreed well with the earlier studies with a bench scale bubbling bed gasifier[4, 8]. While the hydrogen halides were below the 10 ppm range, they were much higher than those reported for pine, switchgrass and torrefied pine [4, 8]. Sulfur contaminants namely H_2S and SO_2 were measured at 60 to 65 ppm. While H_2S was found to be 109 ppm for an ER of 0.39 and 95 ppm for an ER of 0.31 ppm, this was slightly higher than that reported with the downdraft gasifier (80 ppm) [1].

Tar composition is shown in Figure 2.3. Total yield was 18.8 and 11.1 g per dry kg biomass for ER 0.39 and 0.31, respectively. These tar yields were higher than that reported for downdraft gasification of the same hardwood pellets, which is basically due to the nature of the downdraft gasifier, which helps thermal decomposition of tar. We observed that benzene, toluene and naphthalene were present in higher concentration compared with other compounds. With an increase in ER, the tar yield increased, which does not agree with literature [2, 4, 9]. Additional gasification campaigns must be performed to verify that this trend really exists.

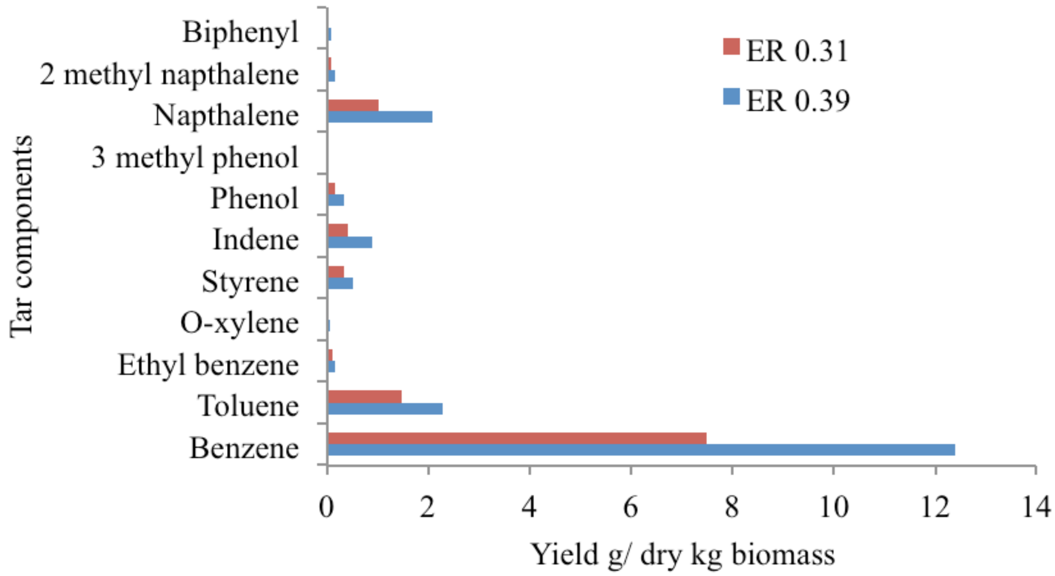

Figure 2.3. Tar component yield.

b. Steam Gasification

Steam gasification was carried out at S/C ratio of 1.2. The steam in the gasifier is expected to promote higher CO and H_2 production. The results from this set of experiments are presented in Table 2.5.

Table 2.5. Experimental results for steam gasification at S/C 1.2.

Parameter	Run 3	Run 4
Temperature, ^{o}C	850	850
Pressure (PSI)	50	50
ER	0.39	0.28
Biomass Feed rate lb/hr, (kg/hr)	19.7 (8.0)	20.1 (8.1)
Air (l/min)	250	200
Steam (lb/hr)	12	12
Syngas composition (Vol %)		
CO	9.8	8.18
CO_2	16.1	18.6
CH_4	2.7	3.5
H_2	10.5	16.2
C_2H_4	2.5	2.6
C_2H_2	0.01	0.001
H_2O	2.5	1.5
N_2	57.32	49.3
Syngas yield Nm^3/ dry kg biomass	2.6	2.2
Syngas Energy MJ/Nm^3	5.1	5.9
Carbon balance	70.2	63.4
Syngas contaminants (ppmv)		
NH_3	41.5	18.14
HCN	33.1	29.1
HF	0.14	0.15
HCl	10	17.6
SO_2	58.4	67.8
H_2S	125.4	na*
Tar (g/ kg biomass)	16.6	na*

*na not available

As seen in Table 2.5, CO_2 production, rather than CO production, was encouraged with the addition of steam. This prefential CO_2 production could be due to the higher ERs at which gasification was carried out or it could be due to the promotion of the water-gas-shift reaction. Nitrogen-free syngas composition is shown in Figure 2.4. The trends in Figure 2.4 indicate that that lower ER helped produce more hydrogen, and also reduced CO concentration, while CO_2 concentration is not influenced. Figure 2.5 shows the component yield in g per dry kg of biomass. When compared with air-blown gasification, the CO_2 and hydrogen yields were higher, while CO yield was much lower. The presence of excess oxygen (high ER) has led to higher CO_2 production, while the presence of steam on the other hand increased hydrogen and methane production as compared to pure air-blown gasification. In order to reduce the combustion products, a reduction in use of air is suggested. When compared with the air/steam gasification study reported by Lv et al. [10] which reports studies at 800 ^{o}C, ER 0.20 to 0.27 and S/B 1.56, the CO concentration in this study was much lower (30% as compared to 23%) on N_2 free basis, while CO_2 was higher (38% as compared to 25%). This was due to the difference in ER used by authors in the Lv et al. [10] study and the current study. The syngas composition obtained in the current study agreed well with results reported in steam/O_2 gasification performed by Gil et al. [5] under similar operational conditions in a pilot scale BFBG.

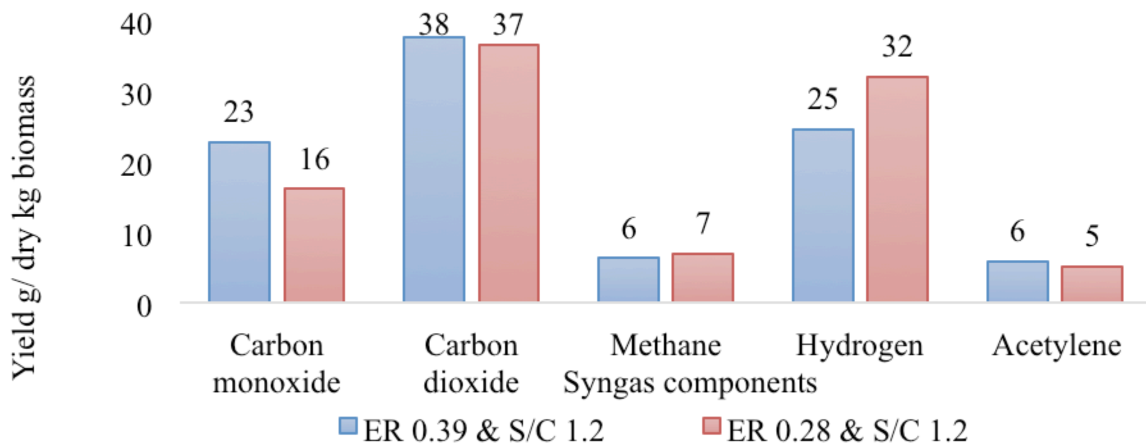

Figure 2.4. Syngas composition N_2 free basis.

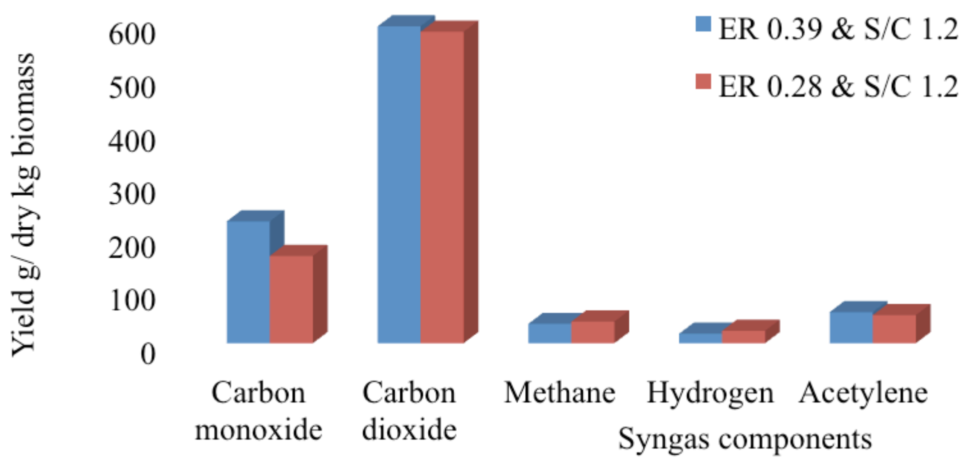

Figure 2.5. Syngas component yield.

Syngas yield ranged from 2.6 to 2.2 Nm^3/ dry kg of biomass, which was very similar to that with air gasification. These values agreed well with Lv et al. [10]. Steam helped improve the syngas energy content to around 5.7 to 5.9 MJ/ Nm^3. This increase was due to an increase in hydrogen production. If the parameters (ER and S/C ratio) are further adjusted, even higher energy contents in the syngas can be obtained by increasing CO production. The Lv et al. and Gil et al. reported higher heating values 7 to 13 MJ/Nm^3.

Table 2.5 also shows the contaminants obtained during air/steam gasification. The concentrations of NH_3 (41 to 18ppm) and HCN (35 to 29 ppm) were much lower when compared to pure air gasification in spite of excess hydrogen present. The reduction in the nitrogen used for gasification could be a major factor in reduction of these contaminants. HCl concentration on the other hand was around 10 to 17ppm, much higher than in air-blown gasification reported in the previous section. This increase in HCl could be due to hydrogen in steam reacting with chlorine in biomass. These values are much higher than those obtained for pine, switchgrass or torrefied pine reported by Kulkarni[8] and are most likely the result of presence of steam. The SO_2 concentration (58 to 62ppm) was slightly lower than found in air-blown gasification, while H_2S concentration of approximately 125 ppm was slightly higher than that observed in air-blown gasification. The SO_2 concentrations were very similar to those reported for pine, switchgrass and torrefied pine [8], while the H_2S was higher than that reported for pine[4]. This increase in H_2S indicated that the presence of steam increased H_2S production over SO_2. H_2S was only collected for Setpoint 3.

Tar was collected for Setpoint 3 for 2 hours. Tar was not collected for Setpoint 4 due to its short duration. Total tar yield was around 16.6 g/ dry kg of biomass. Figure 2.6 shows the tar components and their respective yields. This tar yield value was similar to that obtained with air-blown gasification at ER 0.39. It could be seen that benzene, toluene and naphthalene are in higher concentration, similar to that observed with air gasification. The naphthalene concentrations were slightly higher than toluene, while benzene yield was highest. The total tar yield in g/ kg of biomass is much higher than that reported for air/steam gasification by Lv et al.[5] (2 to 4 g/ dry kg biomass), while it agrees well with that reported by Gil et al. [4]

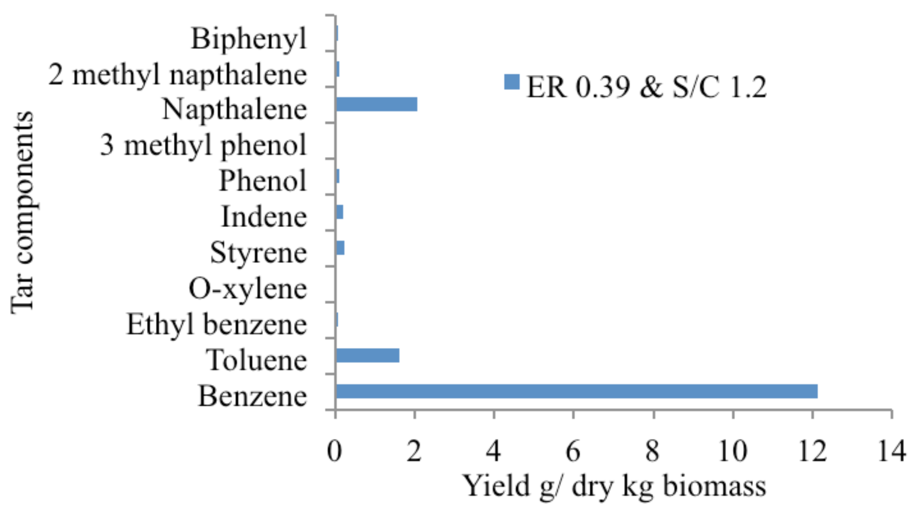

Figure 2.6. Tar components.

Task 2 Conclusion and recommendations

This set of gasification campaign data demonstrates that the reactor system is operational and capable of extensive use for gasification research. Apart from occasional issues with biomass feeding into to the reactor, the system functions well and is fully operational.

From these tests, we observe that syngas composition can be improved by reducing the nitrogen used for fluidization. For further air-blown gasification studies, lower ER around 0.20 to 0.28 should be targeted. Studies with pure air-blown gasification must be studied to understand the syngas composition that this particular pilot-scale BFBG can yield under pure air-blown gasification conditions. Additional studies are needed to further test techniques for catalytic tar/ contaminant removal. Further, when air/ steam gasification is to be carried out the ER should be maintained below 0.28 to reduce excess carbon dioxide formation and to increase CO production. S/B ratios from 0.5 to 2.5, ER 0.20 to 0.25 and higher temperature (around 900^{o}C) studies must be conducted to understand the optimum conditions for high CO to H_2 ratio.

D. Additional Collaborations Developed Through this Project

The project began with ongoing collaboration and excellent support from the Gas Technology Institute. During the project, additional collaborations were developed with numerous thermochemical conversion partners. These partners include Rentech, Inc.; RES Kaidi, Inc.; and Kior, Inc. As a result of the close collaboration with Rentech, this company made a significant donation to Auburn University. This donation included numerous catalytic reactors configured for Fischer-Tropsch Synthesis to be used in conjunction with the gasification reactors. The synergy that developed during this project has resulted in a significant infrastructure that allows research and education on gasification and gas-to-liquids technologies.

E. Summary

Auburn's Center for Bioenergy and Bioproducts contains two gasification platforms suitable for conducting research on production of synthesis gas for use in power generation and the production of liquid fuels: 1) an air-blown downdraft gasifier with combined heat and power production modules, and 2) a pressurized, oxygen-blown bubbling-bed fluidized-bed gasifier with warm gas cleanup and a downstream gas-to-liquids conversion system for the production of liquid fuel products. The overall goal of our gasification research is to identify optimal processes for producing clean syngas to use in production of fuels and chemicals from underutilized agricultural and forest biomass feedstocks. This project focused on construction and commissioning of a bubbling-bed fluidized-bed gasifier and subsequent shakedown of the gasification and gas cleanup system.

The result of this project is a fully commissioned gasification laboratory that is conducting testing on agricultural and forest biomass. Initial tests on forest biomass have served as the foundation for follow-up studies on gasification under a more extensive range of temperatures, pressures, and oxidant conditions. The laboratory gasification system consists of a biomass storage tank capable of holding up to 6 tons of biomass; a biomass feeding system, with loss-in-weight metering system, capable of feeding biomass at pressures up to 650 psig; a bubbling-bed fluidized-bed gasification reactor capable of operating at pressures up to 650 psig and temperatures of 1500^{o}F with biomass flowrates of 80 lb/hr and syngas production rates of 37 scfm; a warm-gas filtration system; fixed bed reactors for gas conditioning; and a final quench cooling system and activated carbon filtration system for gas conditioning prior to routing to Fischer-Tropsch reactors, or storage, or venting.

This completed laboratory enables research to help develop economically feasible technologies for production of biomass-derived synthesis gases that will be used for clean, renewable power generation and for production of liquid transportation fuels. Moreover, this research program provides the infrastructure to educate the next generation of engineers and scientists needed to implement these technologies.

F. References

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Appendix

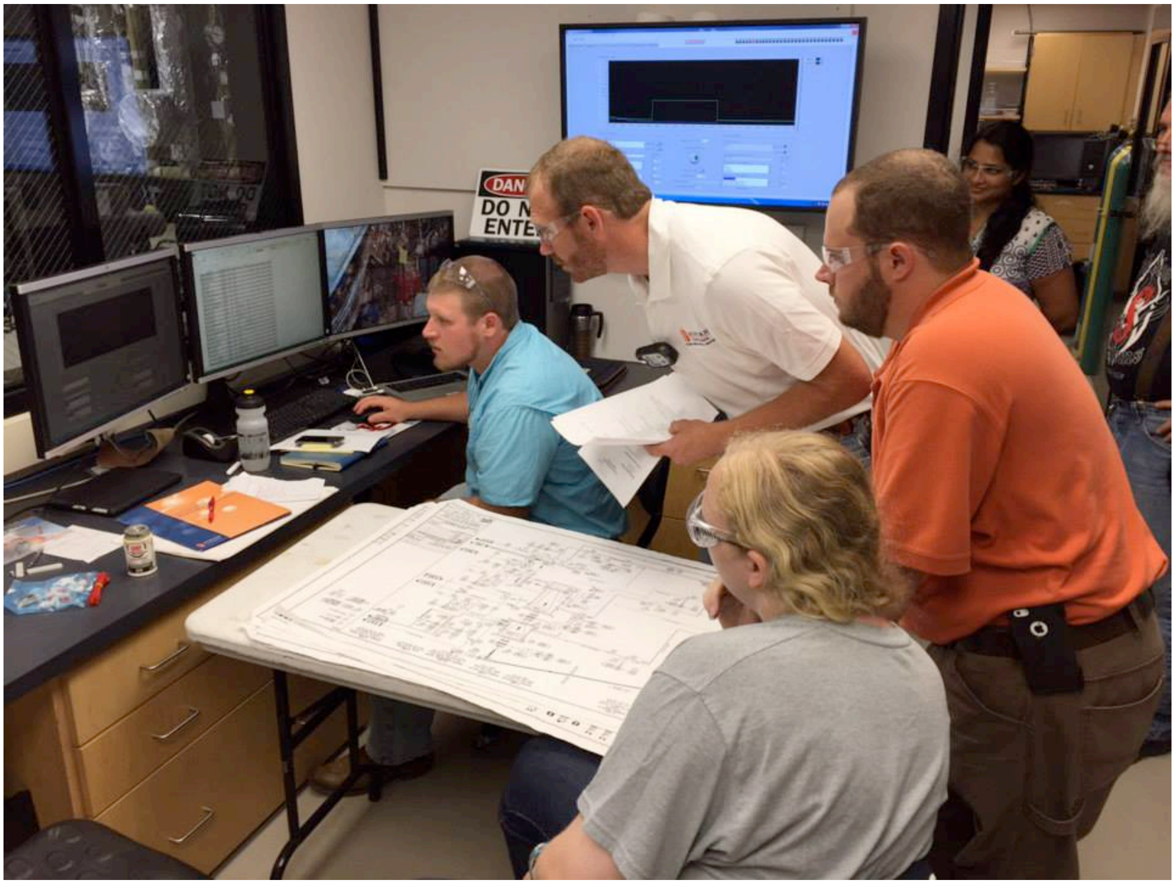
Photos of the Gasification System

Overall view of gasification platform (right) and gas conditioning platform (left).

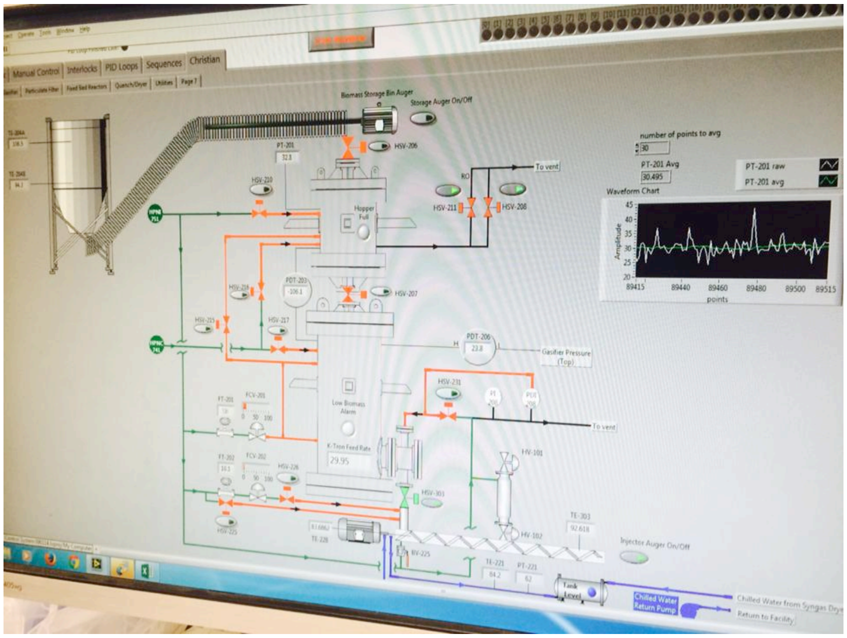
Gasification platform. Feed hoppers are shown on the right (white steel vessels) and gasifier is shown on the left (blue vessel).

Gas conditioning platform. Filters are shown on far right, fixed bed reactors are in the center, and quench cooler and activate carbon filter are on the left.

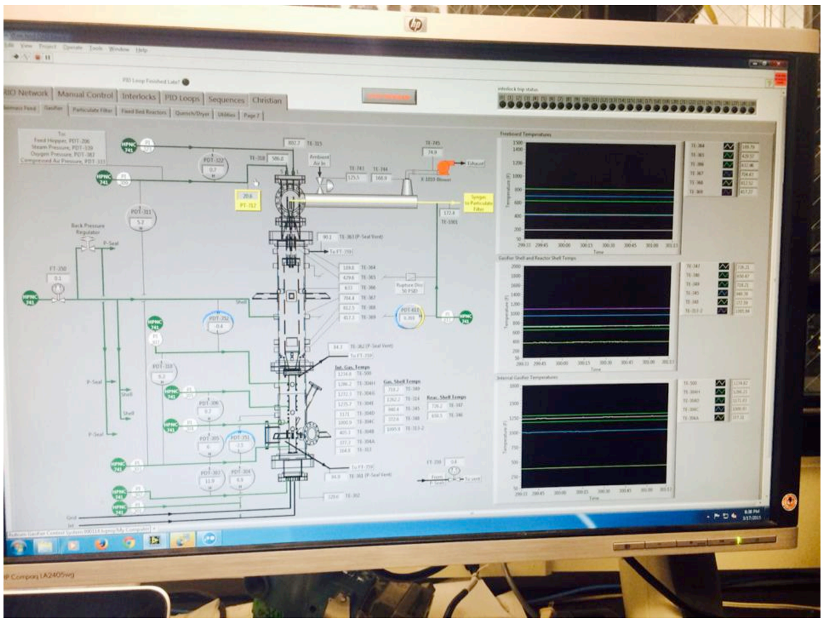
Performing pre-run check of gas conditioning system.



Control room during gasification campaign.



Control screen for the biomass feed system.



Control screen for the gasification reactor.