Biomass Gasification Research
Research Blog

Started: September 24, 2014
Leaders: Chirag Pansuriya, Ernest Echefu, Dr. Jerry Cloward, Dr. Bai, Chengdong Hu, Seyedramin Khalilinejad, Dr. Peter Ping Liu

Syngas is a combustible gas derived from biomass feedstock which mostly consists of Carbon Monoxide, Hydrogen, Methane, Carbon Dioxide and Nitrogen. The Renewable Energy Center in Eastern Illinois University uses woodchips as the feedstock in syngas production for steam generation in order to supply the campuses. However, the feedstock is transported from Missouri to the center which means time and cost consideration for the center. In addition, feedstock transportation means more carbon footprint which has a significant impact on the overall carbon offset predicted for the center.

Therefore, finding a local source for the center has become a major issue to be considered for the future sources of feedstock. as a matter of the fact, the first step is to answer some questions such as: which of the local biomass resources in Charleston is the best feedstock for gasification? What infrastructure do we need for pre-processing the feedstock and how much does it cost per unit of mass production? How far can we improve carbon footprint as well as expenses of the project by switching to a local biomass feedstock? Thus, the research would provide experimental database for gasification of local and available biomass resources such as *Switchgrass* and *Miscanthus* in Charleston, IL.

Figure 1 shows the recent results which compares syngas composition derived from 100% woodchips with 50%woodchips + 50% switchgrass as feedstock.

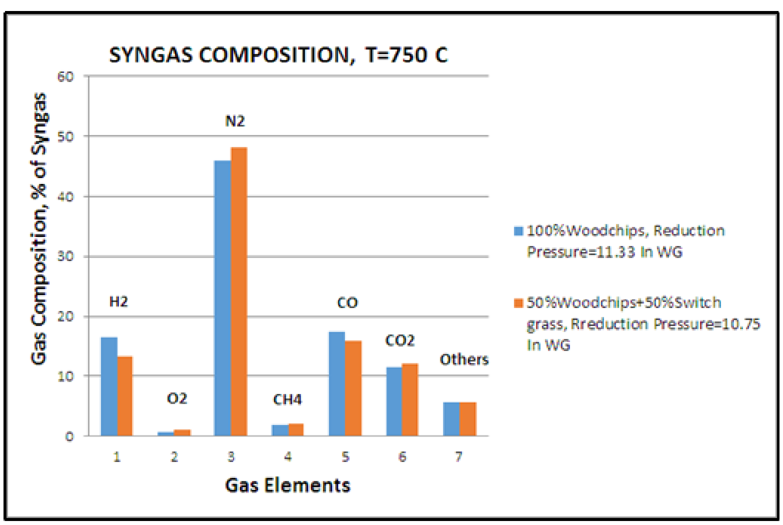


Figure 1. Syngas composition for woodchips-switchgrass pellet mixture

The experimental study in conducted in the gasification lab in EIU’s Technology Department. Figure 2 shows a lab scale downdraft gasifier produced by ALL Power Labs manufacturer (http://www.allpowerlabs.com/) considered as the pilot gasification setup in the experimentas study.

Figure 2. The pilot downdraft gasifier

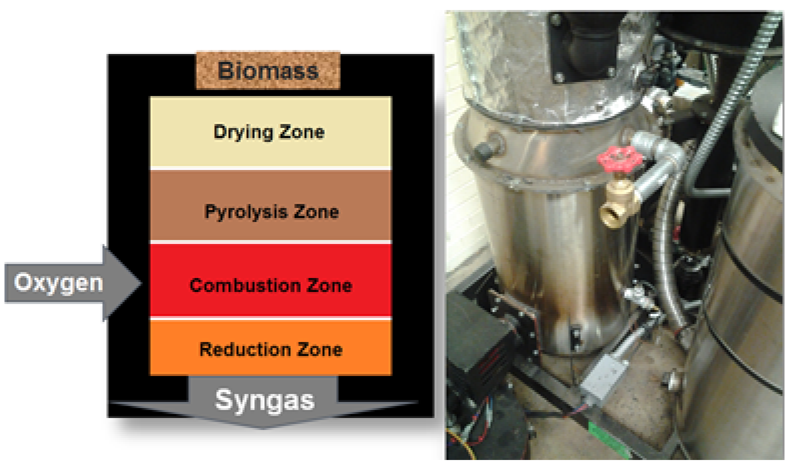


Figure 3. Left to right: gasification zones, reactor chamber

By providing a negative pressure inside the downdraft reactor caused by a venturi (figure4- left), the Air/Oxygen needed for the gasification is sucked through the gasifier and regulated with a globe valve (figure4-right).

Figure4. Left-venturi. right- air inlet valve

A copper pipe (figure 5-left) is used to cool and collect syngas samples with a hand-pump (figure 5-right) in different temperatures of combustion zone. The samples are collected in special bags and sent to a material lab in order to be analyzed by a Gas Chronograph (figure 6).

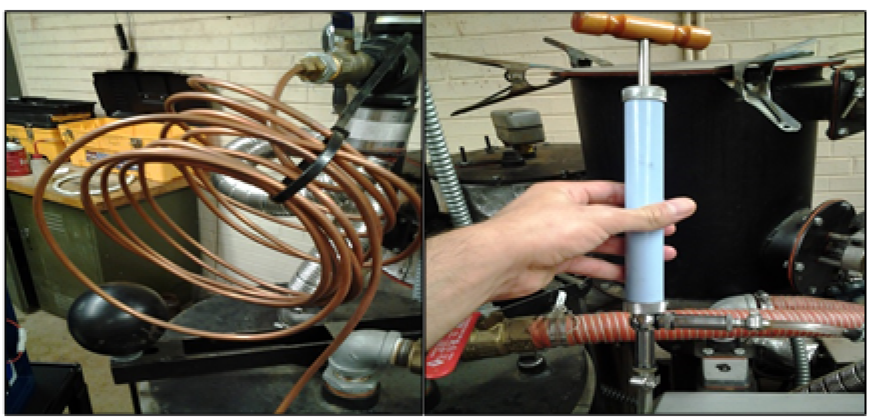


Figure 5. Left-copper pipe. right-hand-pump for syngas collection

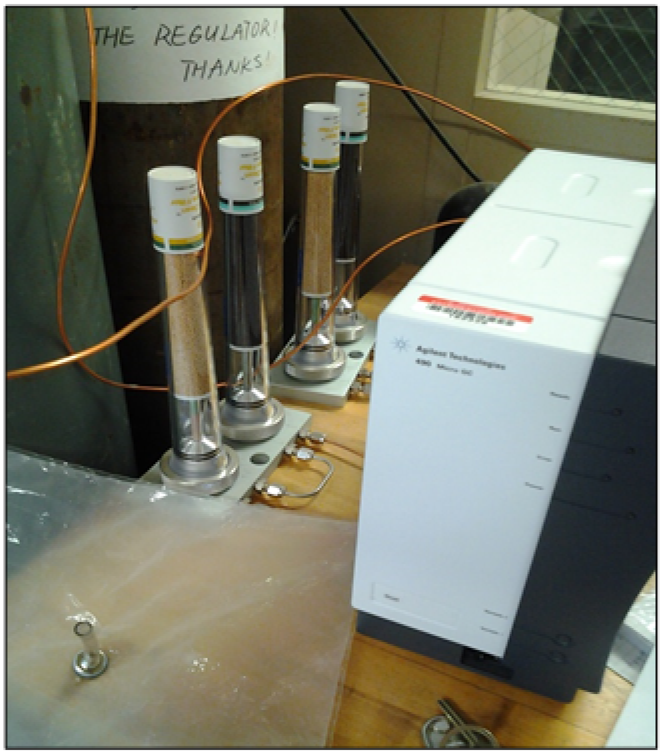


Figure 6. The Gas Chronograph (GC) with the sample bag

Recently, a portable gas analyzer (GASBOARD—3100P) is added to the experimental setup (figure 6- left) in order to simultaneously monitor the syngas composition during the experiments. Therefore, we are able to regulate the Air/Oxygen flow rate towards the best gas production by checking the syngas composition reported by the inline gas analyzer. Figure 7 shows the infrared measurement cell in the GASBOARD—3100P.

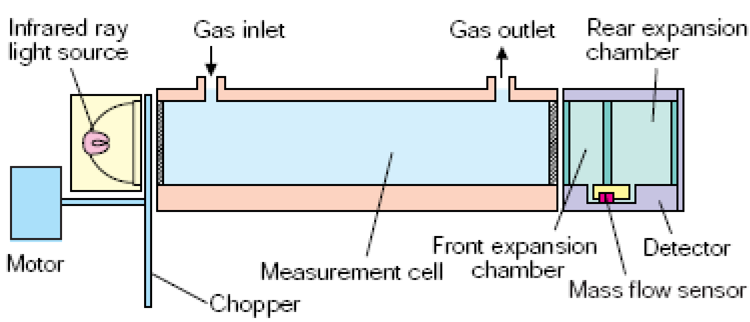


Figure 7. Measurement cell

GASBOARD—3100P Specification:

Components	Method	Range	Resolution	Precision	
CO2	NDIR	20%	0.01%	≤2%	
CO	NDIR	30%	0.01%	≤2%	
H2	TCD	30%	0.01%	≤3%	
O2	ECD	5%	0.01%	≤3%	
CH4	NDIR	10%	0.01%	≤2%	
CnHm	NDIR	10%	0.01%	≤2%	
Note: Measurement range can be customized by the requirement. Max: 6 components at the same time.					
Response Time (TD+T90)	<10s (NDIR)				
Response Time	15min				
I/O port	RS232				
Work temperature	0～50℃				
Relative humidity	5～85%				
Ambient air pressure	86～108kPa				
Power supply	AC 220±10%V 50Hz±1Hz				
Weight	About 3.5kg				

The analyzer is set to determine syngas compositions and related HHV simultaneously based on the NDIR and Thermal Conductivity detectors. Syngas is passed through a pre-filter (figure 7- right) in order to absorb tars and moisture before entering the analyzer.

Figure 7. The GASBOARD—3100P Portable Infrared Syngas Analyzer and the pre-filter setup

In order to connect the GASBOARD—3100P to the gasifier we considered a T-Connection (figure 8-left) after the copper pipe. Therefore, he can have both hand-pump sampling for GC and inline gas analyzing in a same time (figure 8-right).

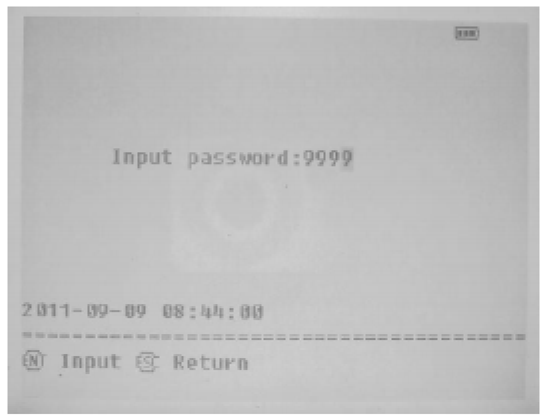
Figure 8. A separate line is considered for the GASBOARD—3100P

Figure 9. GASBOARD—3100P is added to the downdraft gasifier setup

System Zeroing and Calibration

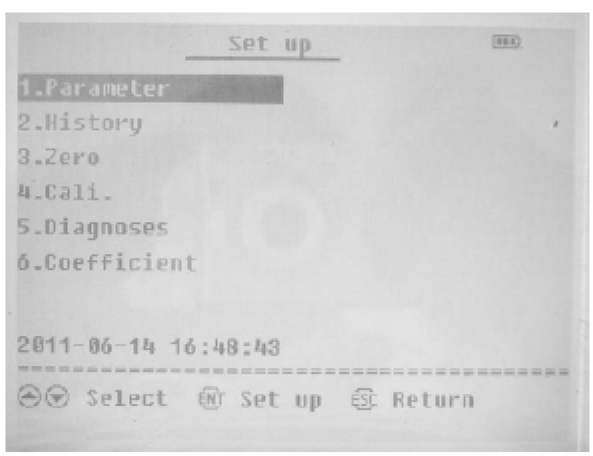
Menue:

1）Press “ENT” to input code.



2）Press “ENT”, alter number through up/down, value adds one by pressing “up” once, value reduces one by pressing “down” once.

3） Move cursor through left/right. Press “ENT” when you finish outputting. System will automatically enter into “system setting” interface if password is correctly entered.

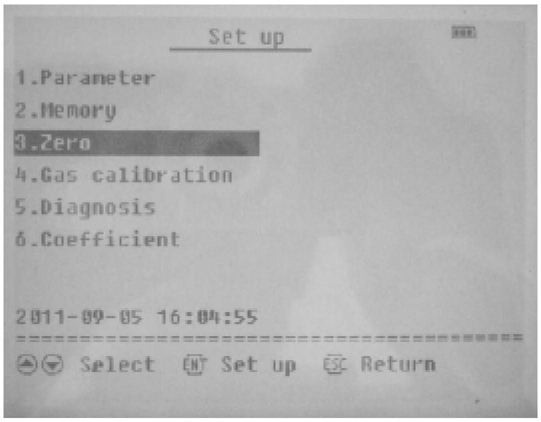


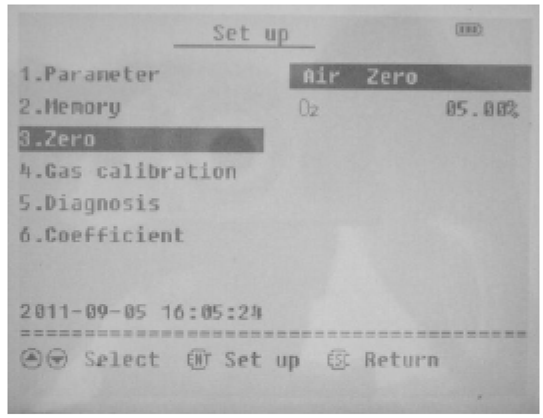
4）Select different system settings through up/down, press “ENT” to enter in related interface.

5）Press “ESC” to return to measuring interface.

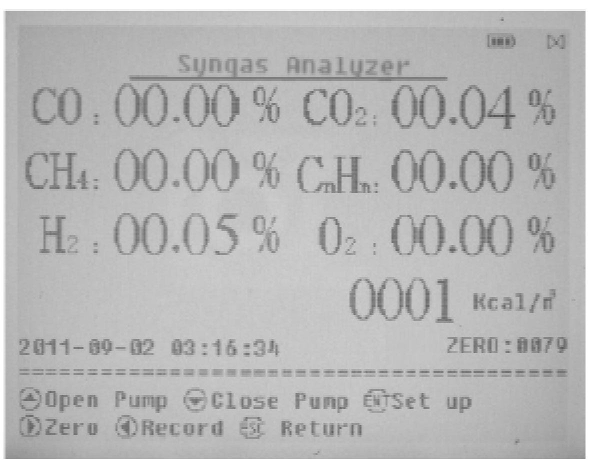
Zero Procedure:

When the cursor moves on the “Zero”, press “ENT” to enter it. There are two ways to do zero. One is pressing “→” button, the other is to do zero in software. Zero is recommended to do before you are using the gas analyzer.





This function allows the user to run a zeroing cycle for the NDIR and TCD detectors as well as separately for the oxygen sensor if the full measuring range of the oxygen sensor differs from the standard oxygen concentration in fresh ambient air (20,90%).
Put the cursor on Air zero and press ENTER: the analyser starts an automatic zeroing cycle for the NDIR and TCD detectors.



Air Zero function:

We recommend to use fresh ambient air, eventually through an external charcoal filter. If clean compressed air, synthetic air or Nitrogen from gas bottles is used, please control that the gas pressure is between 23 KPa (20 to 30 mbar) and the gas flow between 0.7 to 1.2L/min. When zeroing an analyzer with an oxygen measuring channel with galvanic fuel cell, the zero value will automatically be set to 20,90% O2 ,and other gases value will be “00.00”after 150S

Remark:

1. if O2 measurement range below 10% ,after finish zeroing ,”O2 **.**% will be displayed on the LCD due to it will not zeroing by the air
2. if CO2 measurement range below 5%,you should install NaOH filter or when you use Air to do the zeroing
3. if H2 measurement range below 15% ,it will not zeroing

Attention: Don't switch off the power source during zeroing the analyzer

Calibration Procedure:

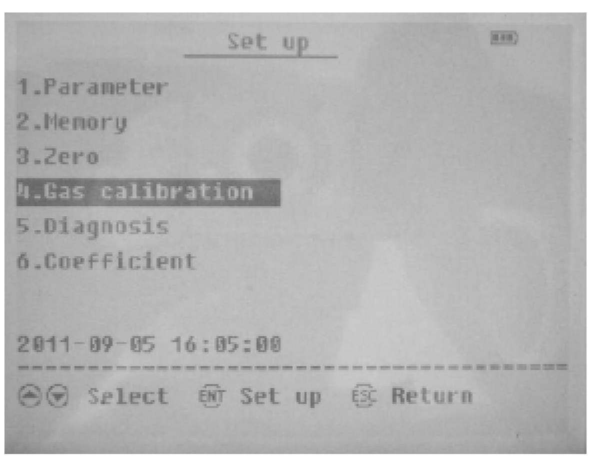
About calibration:

In order to ensure the precision of the instrument, we recommend warm up should be finished, and then implement the calibration operation.

- Calibration includes Zero calibration and Span calibration, which should be implemented continuously, then the result will be saved.
- The pressure of calibration gas should be controlled between 2 and 3 kPa, the gas flow should be controlled between 0.7 and 1.2L.min.

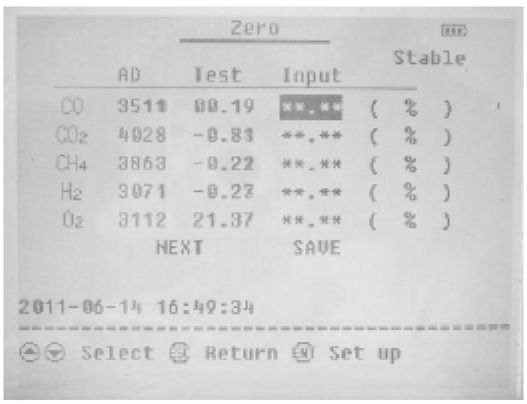
Operation Method:

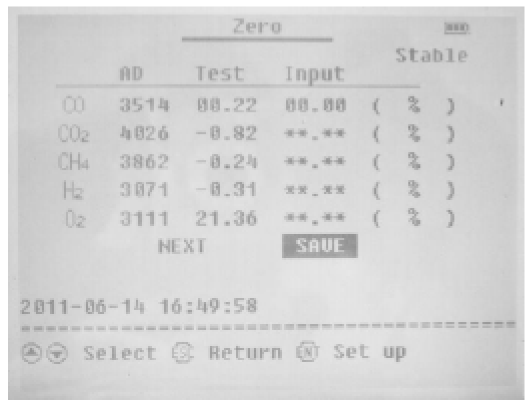
Under system setting interface, to move cursor to Calibration, then press ENT to enter into calibration interface.



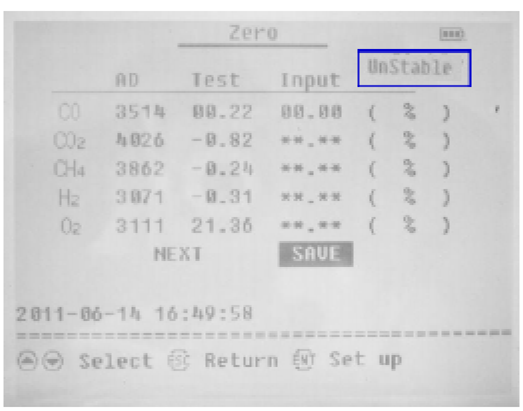
1) Zero Calibration(CO2 for example)

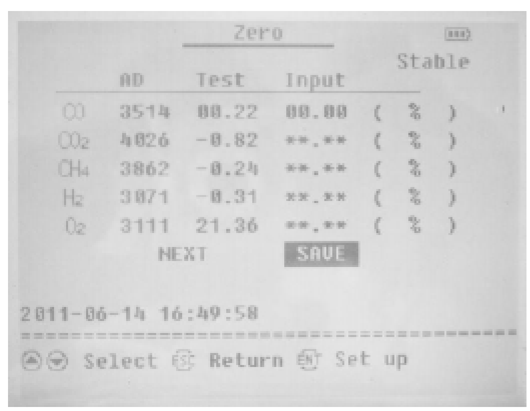
- ❑ Press ENTER to enter the Zero Calibration menu.
- ❑ Move the black cursor on the gas channel you want to calibrate using UP or DOWN buttons (in our example the CH4 channel)
- ❑ Press ENTER, the input value for the CH4 channel is **.**
- ❑ Press the UP button, the input value for the CH4 channel is now 00.00, then press ENTER again to confirm the value.
- ❑ Move the cursor on SAVE using the DOWN button





- ❑ Inject now pure nitrogen (N2) into the gas analyser. Attention: when you start injecting gas into the analyser, the indication will be on Stable but it will change into Unstable after a few seconds as soon as the gas fills the measuring chamber of the detector.

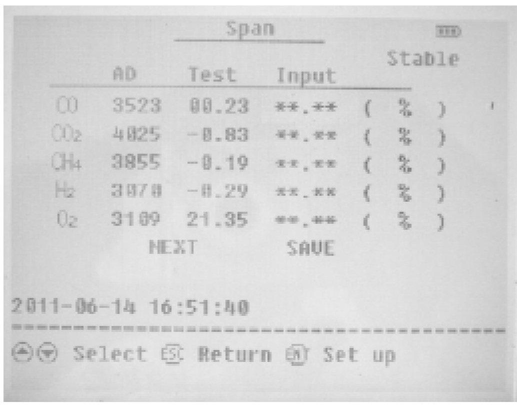


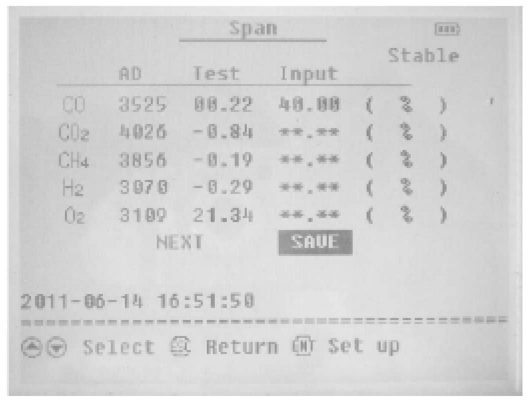


- ❑ Wait till the indication **Unstable** becomes **Stable**, then press ENTER to save the zero calibration. The display shows now the **SPAN** calibration screen.

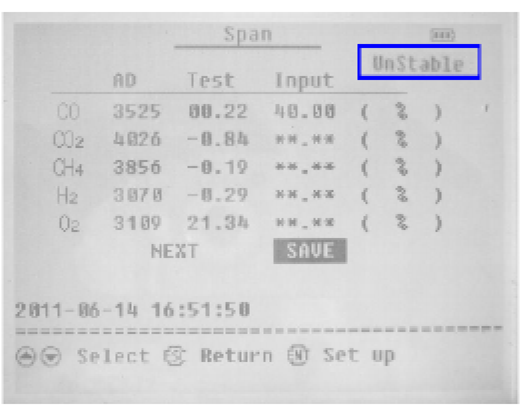
2）Span Calibration

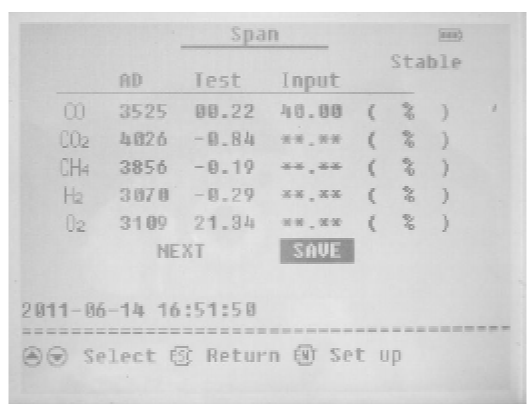
- ❑ Move the cursor on the channel you want to calibrate (in our example the CH4 channel) by using UP or DOWN buttons.
- ❑ Press ENTER.
- ❑ Press the UP button, the input value for the CH4 channel is now 00.00
- ❑ Input now the value indicated on the gas cylinder (in our example 40%) using UP or DOWN buttons to scroll the numbers from 0 to 9 and LEFT or RIGHT buttons for moving the cursor to another digit.
- ❑ Press ENTER to confirm the value
- ❑ Move the cursor on SAVE using the DOWN button





- ❑ Inject now pure methane (100% CH4) into the gas analyser. Attention: when you start injecting gas into the analyser, the indication will be on Stable but it will change into Unstable after a few seconds as soon as the gas fills the measuring chamber of the detector.
- ❑ Wait till the indication Unstable becomes Stable, then press ENTER to save the span calibration. The display turns automatically back in the Set up screen.





➢ ***To perform the zero and span calibration of the other measuring channels, follow the same procedure for each other measuring channel***

Zero and Calibration #1
Date: 10/06/2014

- **Nitrogen for zeroing**
- **Standard Synas for Calibration**

Test Gas	**Purpose**	**Composition**
N_2	Zero	100%
Standard Syngas	Calibration	25% CO, 25%H_2, 10%CO_2, 5% CH_4, 1% O_2, 34% N_2

Notes:

1. Use very low pressure for pure nitrogen;

2. Zero the instrument with low pressure nitrogen running for about 5 minutes;

3. Calibration: a. Zero with low pressure nitrogen

4. Calibration: b: Calibration with syngas running, until the readings are stabble, then save the result;

Experiment #1
Date: 10/01/2014
Feedstock: Woodchips

Table 1. Properties of the wood chips used in the experiment

Feedstock	Density	Moisture	HHV
Wood Chips	**221 Kg/m^3**	**10.6 % of Wet**	**7971.35 Btu/lb**

Figure 1. wood chips

Note 1: After around 55 minutes the feeder auger stopped working. Therefore, we had the feeder hopper almost full of wood chips (figure 2-left) while the top of the reactor was empty (figure 2-right). In addition, the wood chips at the top of the reactor were tarry.

Figure 2. Wood chips at the top of feeder hopper and reactor

Note 2: Almost (30 ml) of tars and moisture (figure3-right) are drained in the collector jar installed at the bottom of the cyclone (figure 3- left) during the experiment.

Figure 3. the cyclone and the collector jar

Note 3: Almost (110 ml) of tars and moisture (figure4-right) are drained in the jar installed at the bottom of the charcoal filter (figure 4- left) during the experiment.

Figure 4. the secondary filter and the collector jar

Note 4: Almost (110 ml) of ash (figure3-right) are removed by the ash collector (figure 3- left) during the experiment.

Figure 5. the ash collector and the ash produced during the experiment

Figure 6. Ashes are compared to the wood chips collected at the bottom of the reactor

Note 5: The duration of the experiment was almost one hour and figure 7 shows the temperature and pressure profiles during the experiment.

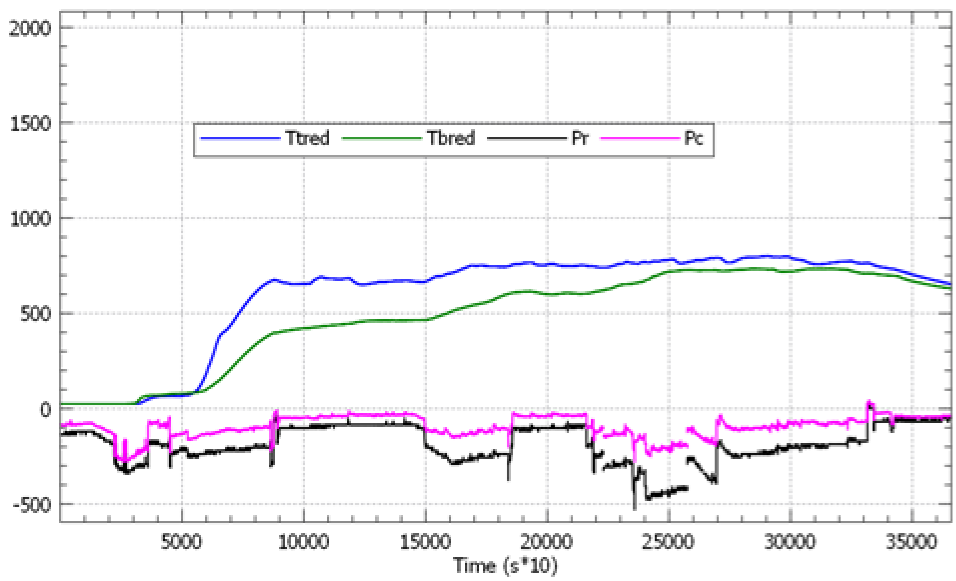


Figure 7. Temperature and pressure profile in top and bottom of the reduction zones

The gas analyzer was started to run for three combustion (top of the reduction zone) temperature points (stabilized points) including 666, 752 and 778 Celsius. In addition, the time interval between two detected points and the duration of the analyzing were set to 10 second and 5 minutes respectively. Figure 8, 9 and 10 show the results from the GASBOARD—3100P (the inline gas analyzer).

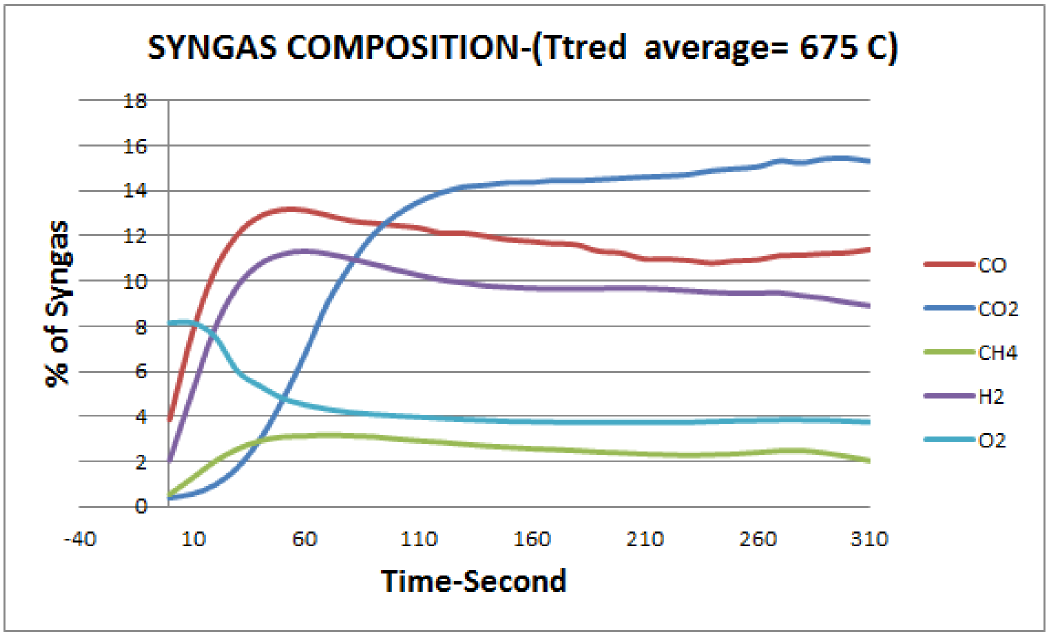


Figure 8. syngas composition

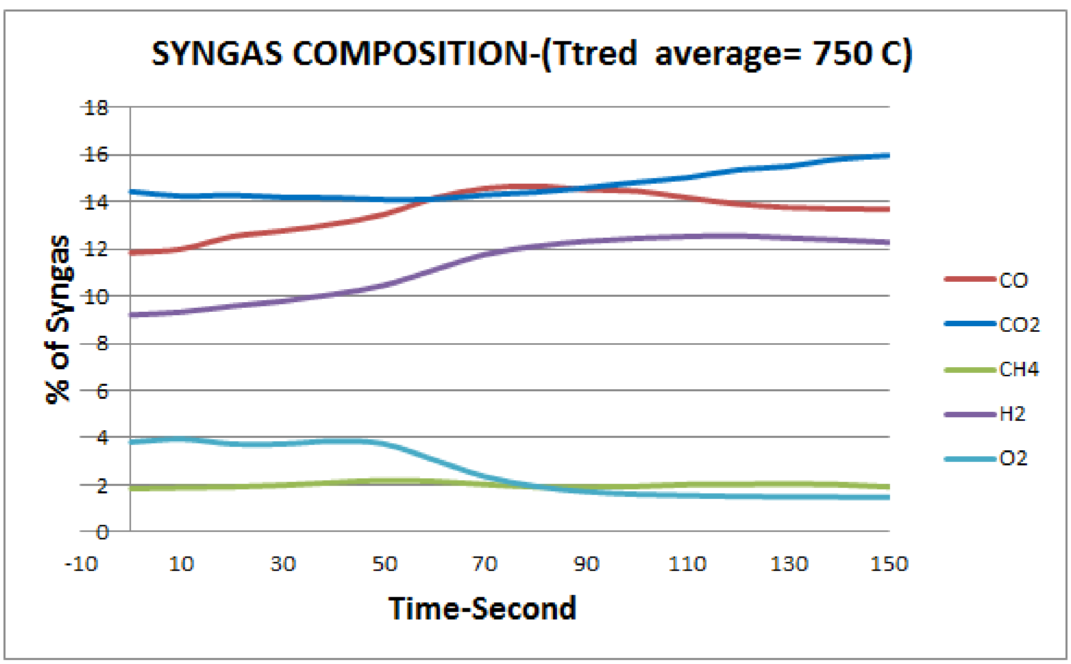


Figure 9. syngas composition

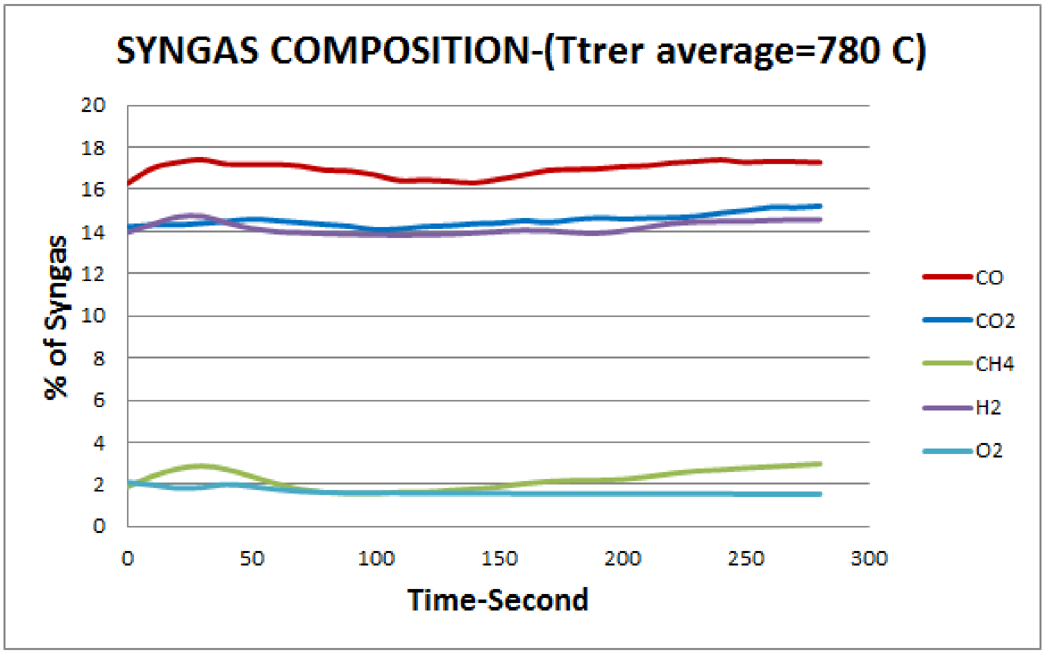


Figure 10. syngas composition

Experiment #2
Date: 10/08/2014
Feedstock: Woodchips

- The tar and moisture collected in cyclone and filter were almost 170 and 140 ml respectively (fig. 6 and 7)
- The auger was stopped working again (fig. 3)
- Due to the auger's problem and the gap appeared at the top of the reactor (fig. 4) , oxygen caused complete combustion at the top of the combustion zone (fig. 5)
- The average percentage of the gas elements in the syngas was lower than the previous experiment (table 1)

Table 1. Properties of the wood chips used in the experiment

Feedstock	Density	Moisture	HHV
Wood Chips	**221 Kg/m^3**	**10.6 % of Wet**	**7971.35 Btu/lb**

Figure 1. wood chips

Figure 2. wood chips at the top of the feeder hopper

Figure 3. the auger stopped working

Figure 4. the gap between fuel entrance and top of the reduction zone

Figure 5. complete combustion at the top of the reduction zone

Figure 6. tar and moisture collected by the cyclon

Figure 7. tar and moisture collected by the charcoal filter

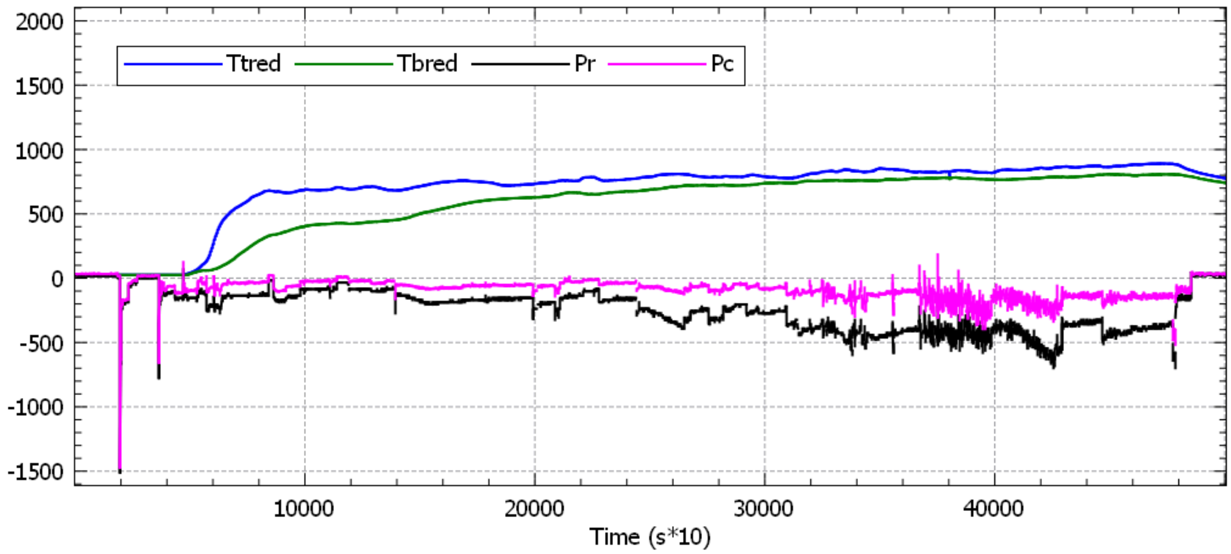


Figure 8. Temperature and pressure profiles in top and bottom of the reduction zone

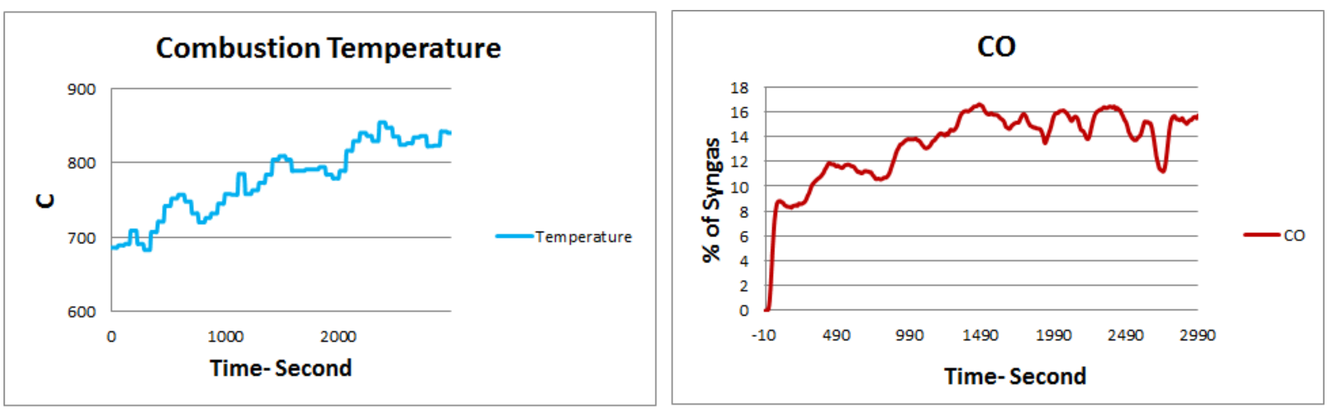


Figure 9. Ttred (left), CO concentration (right)

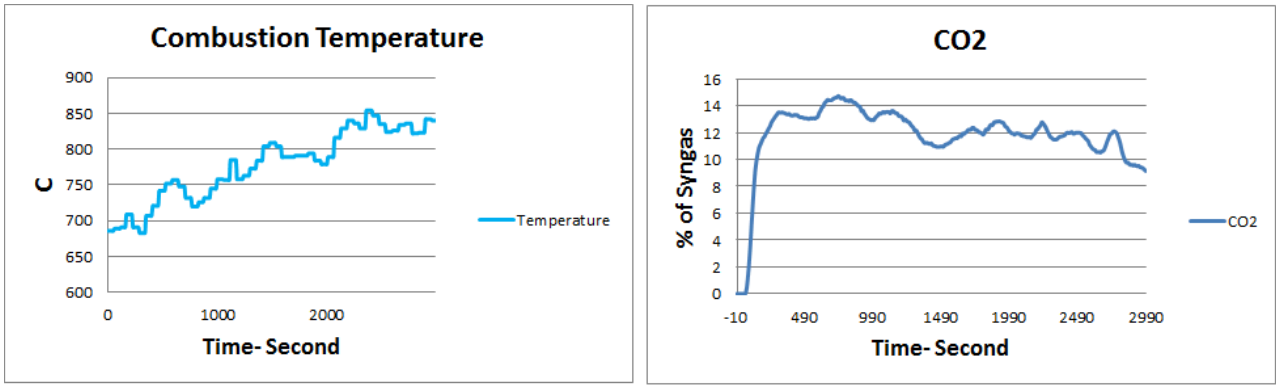


Figure 10. Ttred (left), CO2 concentration (right)

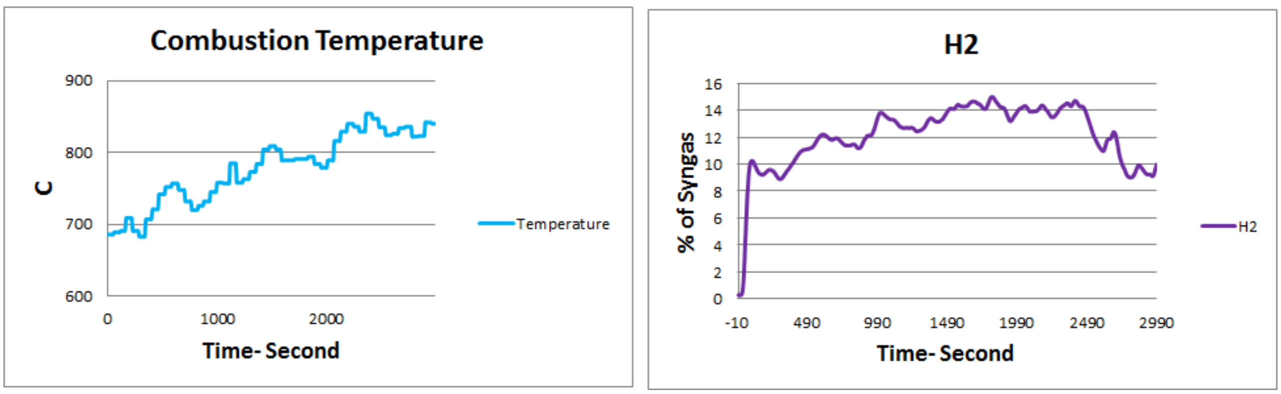


Figure 11. Ttred (left), H2 concentration (right)

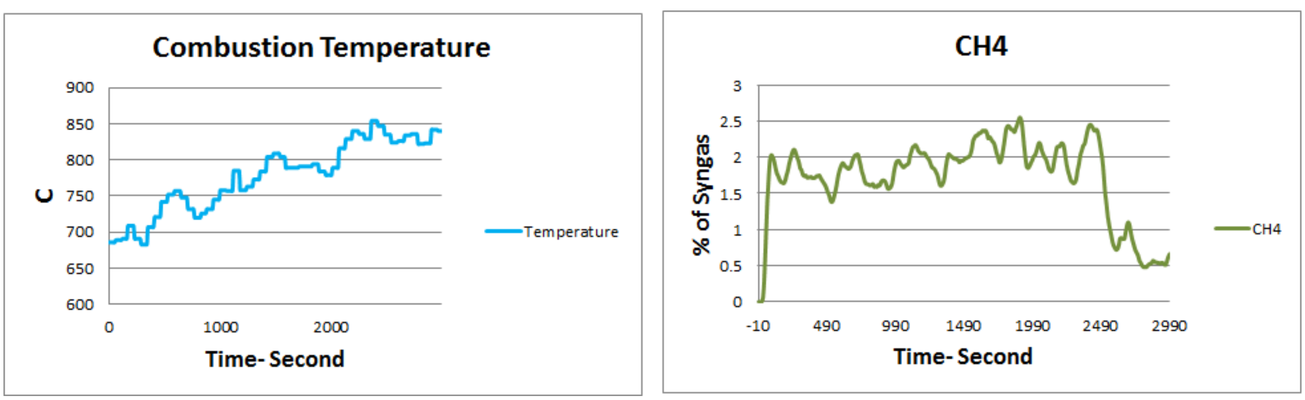


Figure 12. Ttred (left), CH4 concentration (right)

Experimental Results :

Table 1

	Ttred	**CO**	**CO2**	**CH4**	**H2**	**O2**
Ex. 10/01/14	667	11.43	11.05	2.53	9.52	4.49
	751	14.80	14.79	2.20	12.32	2.27
	792	16.88	14.32	2.04	14.10	1.76
Ex. 10/08/14	691	7.49	8.27	1.55	7.93	4.65
	748	12.63	13.33	1.79	12.08	2.05
	816	15.09	11.53	1.69	12.98	1.74

Cleaning and Maintenance #1
Date: 10/29/2014
Feedstock: Wood Chips

During the third experiment, we noticed that the pressure difference between top of the reduction zone and charcoal filter were significantly high. In addition, we could not able to increase the top of the reduction temperature higher than 700 C. therefore, we decided to stop the experiment and inspect the entire system in order to find the problem. Basically, two possible problems were suggested: block and leakage. Thus, we started to check the possible problems. First of all, we opened the reactor and we removed the feedstock inside the reactor. Then, we cleaned the reactor with a vacuum cleaner. figures 1 to 4 show the feedstock conditions during the cleaning process.

Figure 1. Drying zone

Figure 2. Pyrolysis zone

Figure 3. top of the reduction zone

Figure 4. Reduction zone

Secondly, we opened the cyclone and related connections and we cleaned the cyclone and pipelines from the reactor to the cyclone and from the cyclone to the hopper. Then, we opened the bottom of the hopper in order to clean the second wall of the hopper in which syngas is cooled and tars are accumulated.

Figure 5. Inside the Cyclone

Figure 6. Cleaning the Cyclone

Figure 7. Bottom of the Fuel Hopper

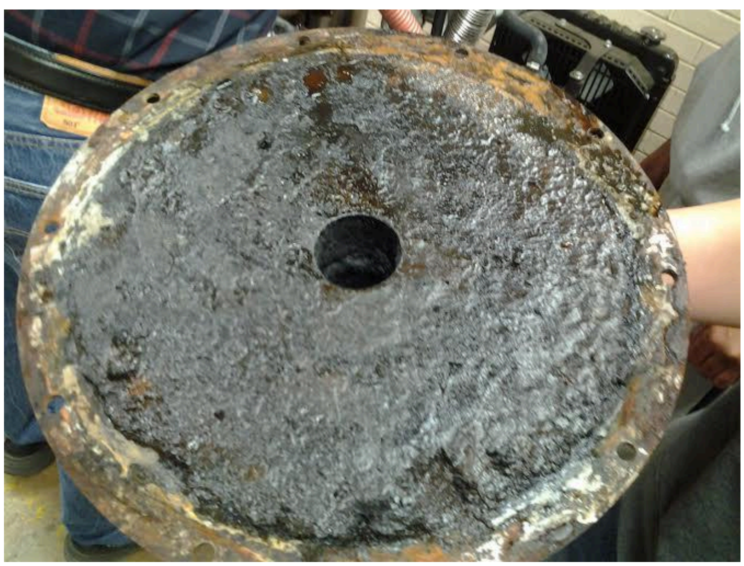


Figure 8. The connection plate between the Hopper and the Cyclone

At the end, we changed the gasket between the cyclone and the reactor. In addition, we added a new gasket between the cyclone and the hopper connection.

Experiment #3
Date: 11/14/2014
Feedstock: 50% Wood chips + 50% Switch grass

Notes

- The experiment was started on 1:40 pm and it did take almost one hour to see the flame in 270 C of combustion temperature.
- We could not reach the 800 C at top of the reduction zone

Experimental results:

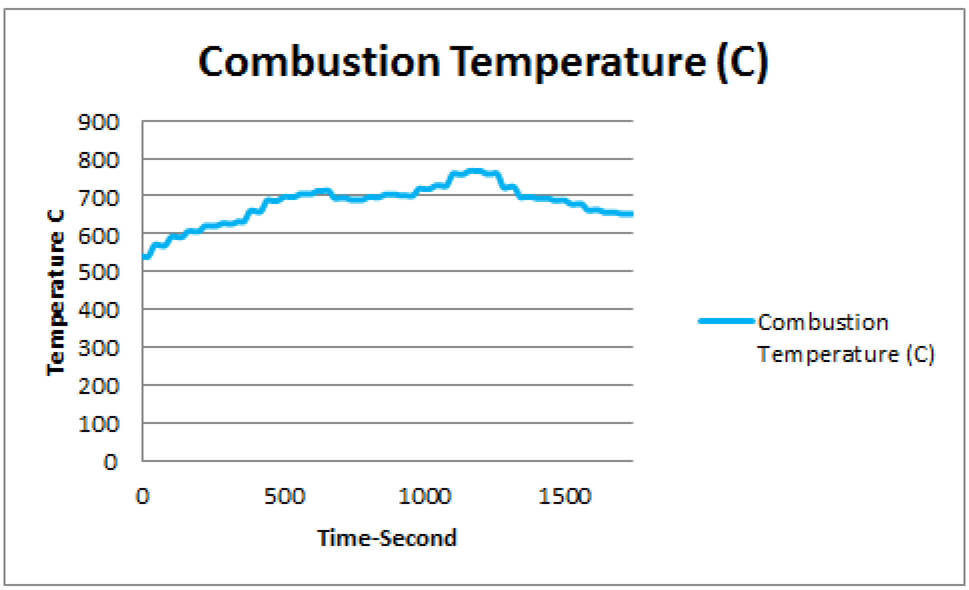


Figure 1. Ttred

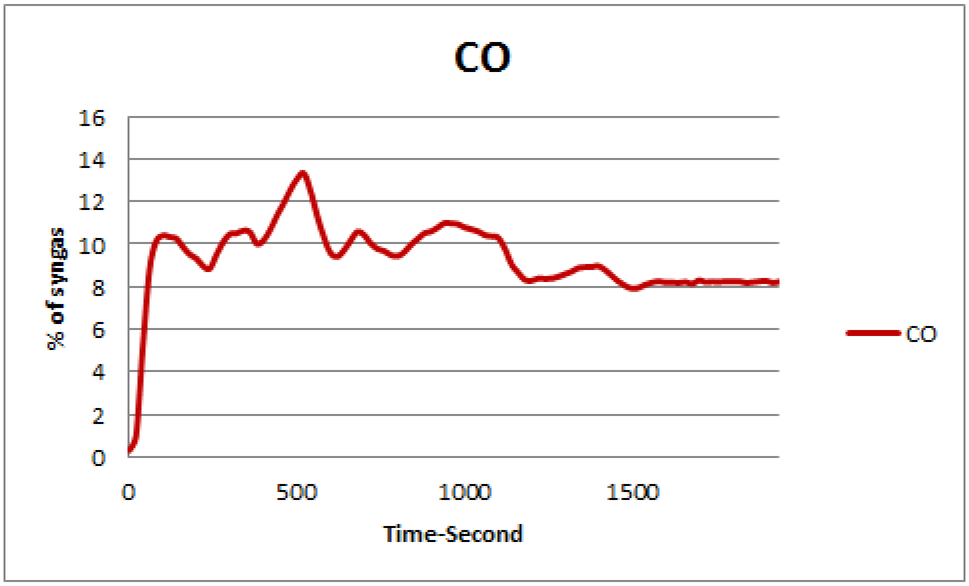


Figure 2. CO concentration

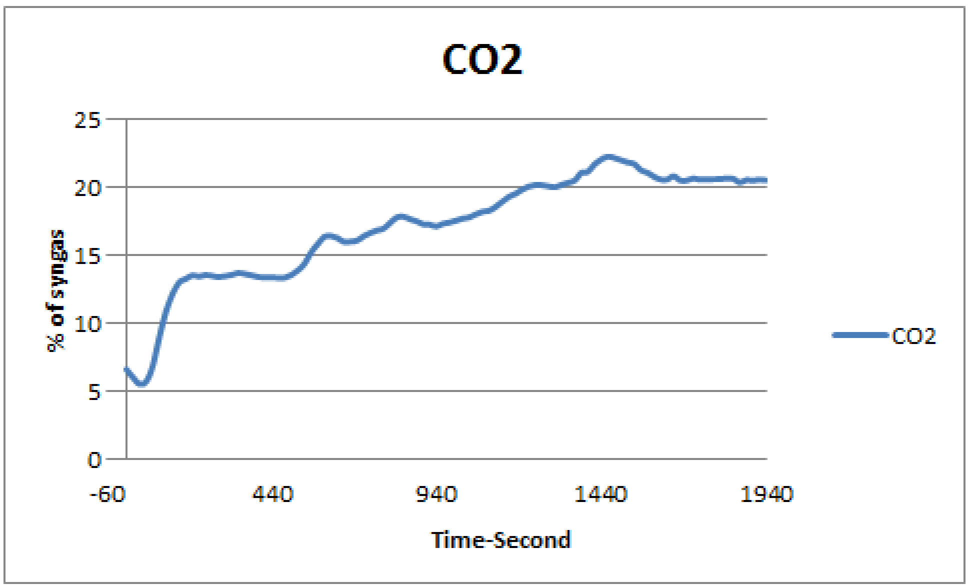


Figure 3. CO2 concentration

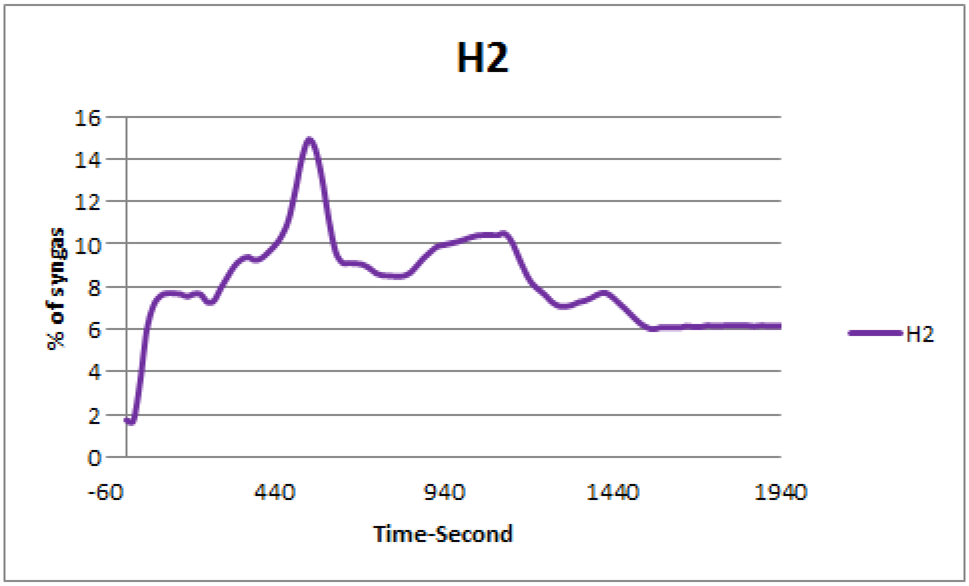


Figure 4. H2 concentration

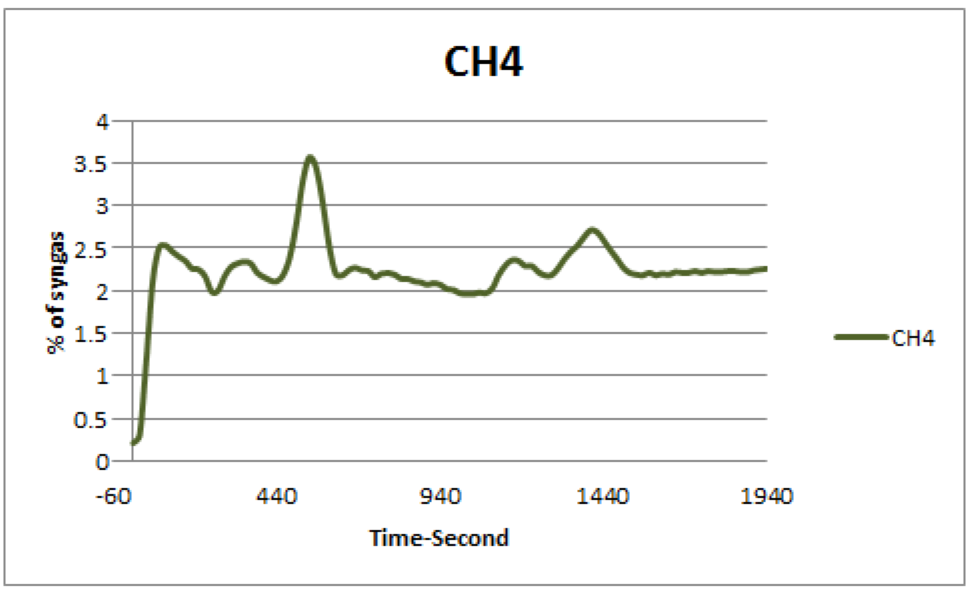


Figure 5. CH4 concentration

Experiment #4
Date: 12/03/2014
Feedstock: 50% Woodchips + 50% Switchgrass

At the beginning of the experiment the pressures in reduction zone and filter were checked. Figure 1 shows the results of the pressures.

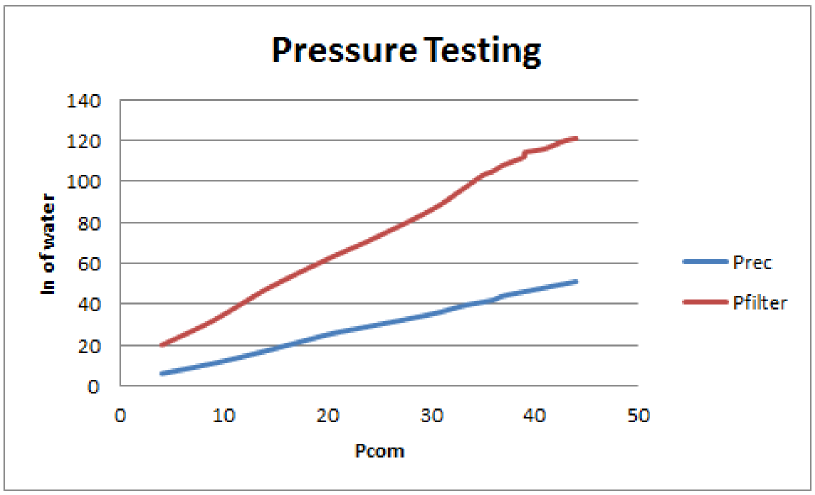


Figure 1

Figure 2 shows the Ttred (C) versus the time of the experiment.

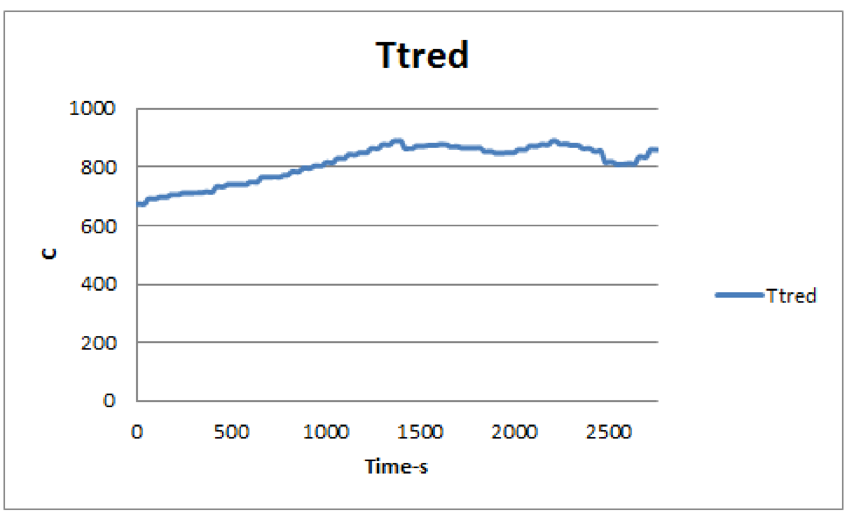


Figure 2

Figure 3 shows the syngas composition versus the Ttred.

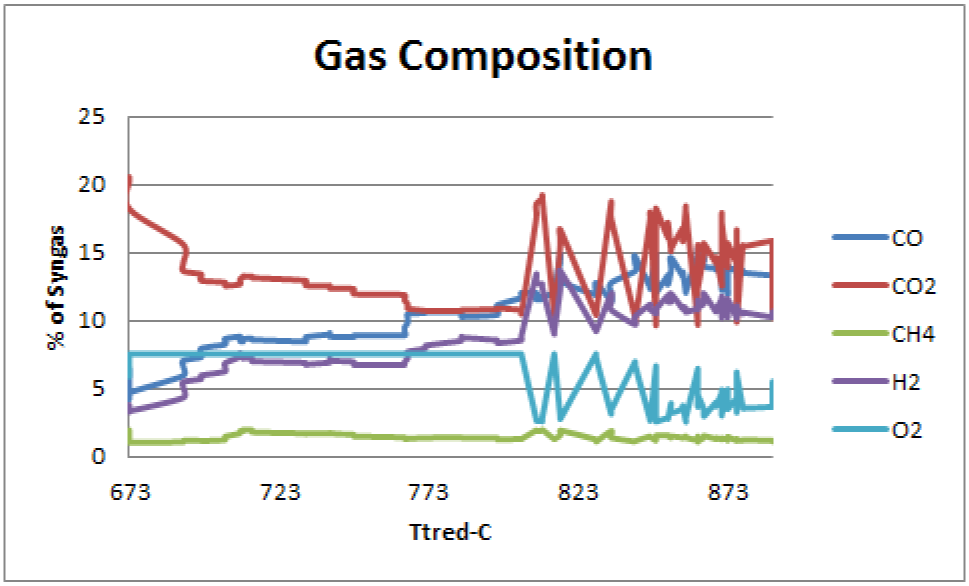


Figure 3

Table 1 shows the average gas composition for two runs of 50%woodchips+50%switchgrass

50%woodchips+50%switchgrass	**%CO**	**%CO2**	**%CH4**	**%H2**	**%O2**
Run 1 (11/14/14)-(Ttred=680 c)	9.3	17	2.2	8.2	5.0
Run 2 (12/3/14)-(Ttred=815 C)	11.8	14	1.4	9.5	5.4

12/8/14
During the break, organize the experimnetal data on 50% wood chips and 50% switchgrass, run on Spring 2014 and Fall 2014;
Table and graph;

For Spring 2015:
1. Clean the ash handling and grate area in the gasifier; (to see if we can reduce the pressure difference between P (filer) and P (react);
2. Use GC and GasBoard at the same time for our next experiment;

Experiment #5
Date: 1/30/2015
Feedstock: 100% Woodchips

Notes:

- The gasifier was not cleaned after the last experiment (50%woodchips+50%switchgrass)
- The gas composition shows almost low values in the third run of 100% woodchips

Figure 1 shows the gas composition reported by the inline analyzer.

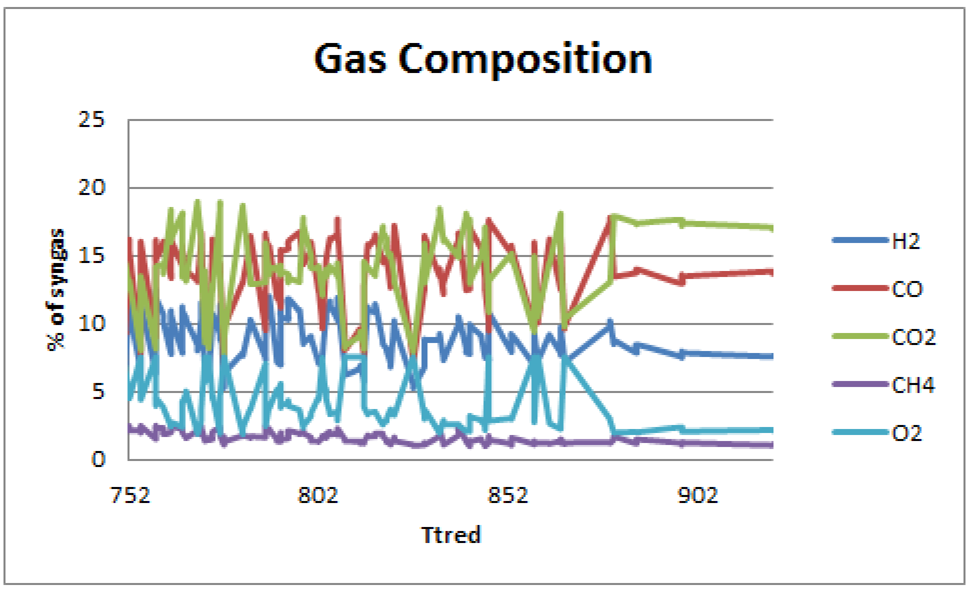


Fig.1

Table 1 and figures 2 to 4 compare the gas composition (inline analyzer) in stables pints with the previous experiments.

Table 1

	100% WOODCHIPS					
	Tred (C)	**CO**	**CO2**	**CH4**	**H2**	**O2**
Run1 (10/1/14)	650	11.43	11.05	2.53	9.49	4.49

	750	14.80	14.79	2.20	12.32	2.27
	800	16.88	14.32	2.04	14.10	1.76
Run 2 (10/8/14)	700	7.49	8.27	1.55	7.93	4.65
	750	12.63	13.33	1.79	12.08	2.05
	800	15.09	11.53	1.69	12.98	1.74
Run3 (1/30/2015)	750	11.80	12.26	2.00	8.20	5.64
	800	13.58	13.49	1.76	9.04	4.53
	850	13.97	14.66	1.32	8.36	3.42

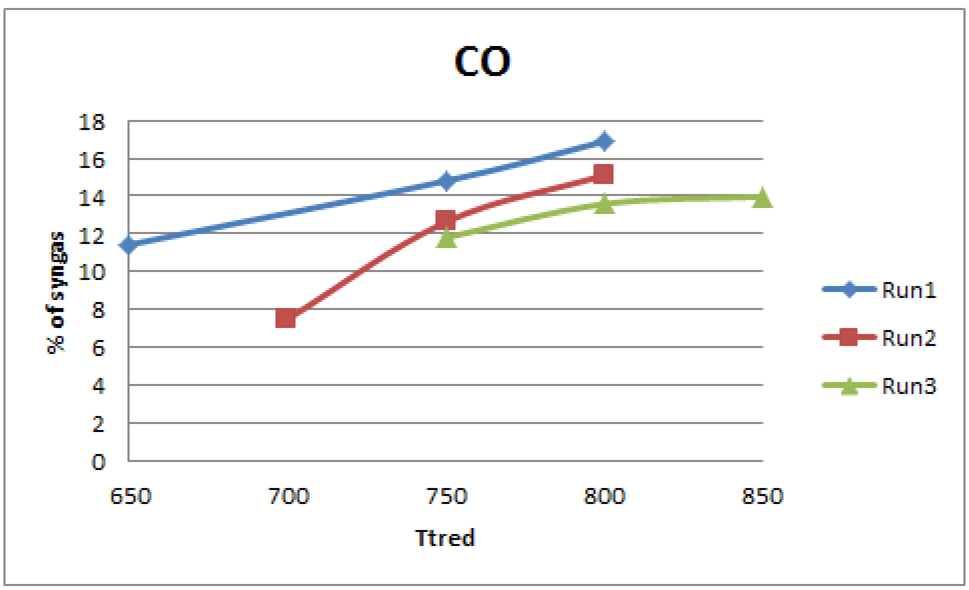


Fig.2

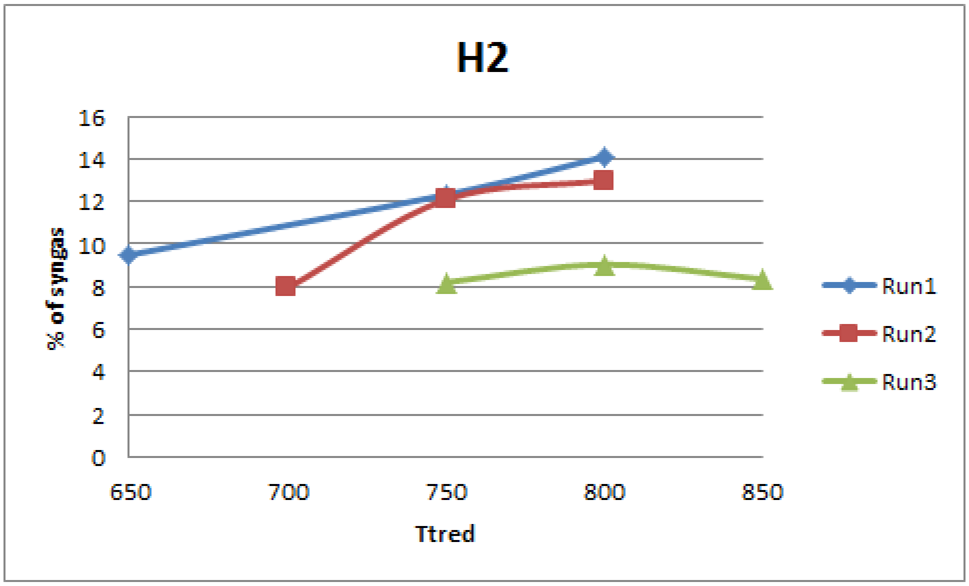

H2
16
14
12
10
8
6
4
2
0
% of syngas
650
700
750
800
850
Ttred
Run1
Run2
Run3

Fig.3

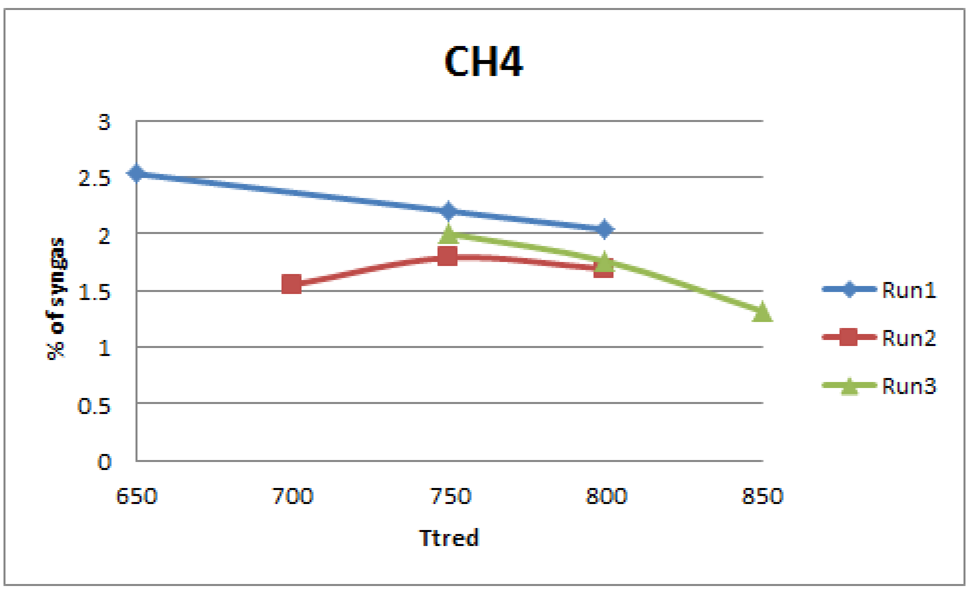

CH4
3
2.5
2
1.5
1
0.5
0
% of syngas
650
700
750
800
850
Ttred
Run1
Run2
Run3

Fig.4

Experiment #6
Date: 2/5/2015
Feedstock: 100% Woodchips

Before starting the experiment, the pressure sensors in top and bottom of the reduction zone reduction and charcoal-filter are checked and recorded as the following status:

Table 1

Pc	Pr	Pf	Pf-Pr
2	3	9	6
5	6	15	9
10	11	28	17
15	17	37	20
20	21	47	26
25	27	58	31
30	32	65	33

As it is shown in the table, the difference between reduction pressure and charcoal filter is significantly high.

Gas composition is recorded and related curves are shown in the figure 1:

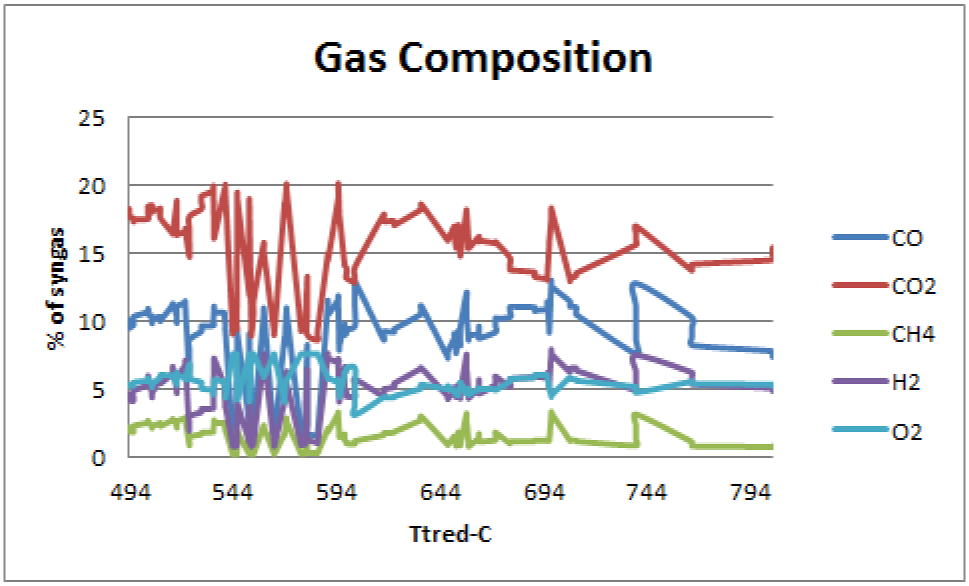


Fig.1

Table 1 compares the gas compositions for 100% woodchips gasifications:

Table 1

Run-Date	**100% WOODCHIPS**					
	Ttred (C)	**CO**	**CO2**	**CH4**	**H2**	**O2**
Run1-10/1/2014	650	11.43	11.05	2.53	9.49	4.49
	750	14.80	14.79	2.20	12.32	2.27
	800	16.88	14.32	2.04	14.10	1.76
Run 2-10/08/2014	700	7.49	8.27	1.55	7.93	4.65
	750	12.63	13.33	1.79	12.08	2.05
	800	15.09	11.53	1.69	12.98	1.74
Run 3- 1/30/2015	750	11.80	12.26	2.00	8.20	5.64
	800	13.58	13.49	1.76	9.04	4.53

	850	13.97	14.66	1.32	8.36	3.42
Run 4- 2/5/2015	600	8.60	15.51	1.53	4.62	5.59

Cleaning and Maintenance #2
Date: 2/10/2015

The pressure difference between reduction zone and charcoal filter was high during the previous experiments especially in high temperature points (high pressures as well). Therefore, the team decided to check the overall conditions of the gasifier in order to find the problem. First of all, a pressure test was conducted to record the current status of pressures in reduction zone and charcoal filter as well as combustion zone (top of the reduction zone). the table 1 shows the result of the initial test.

Table 1

Pc (in water)	Pr (in water)	Pf (in water)	(Pf-Pr)
5	8	34	26
10	12	51	39
15	19	71	52
19	23	87	64
26	30	105	75

According to the system’s manual, the pressure difference should be less than 30 Inches of water during the operation. Thus, there should be either a leakage or a blockage in the system from reactor to the top of the filter. Basically, the system had been tested for any leakage before, thus, venturi system, cyclone and filter were opened for blockage inspection. The venturi connections and cyclone were cleaned and the upper pad of the filter was removed (covered by resin or tar). However, the filter media (sawdust) was in a good condition (figure 1 and 2).

fig1. venturi connections were opened and cleaned

fig2. sawdust (filter media)was in good condition

Then, the pressure values were checked again, however, there was not any difference between the pressure tests before and after the cleaning. Therefore, the last suspension was a blockage at the bottom of the reactor chamber. Thus, the ash collector was inspected and it was activated to remove ash from the bottom of the reactor. Based on the observation, there were significant amount of ash removed from the reactor. In fact, it turned out that the **ash remover had not been used since the last 3 or 4 experiments**. Finally, after removing the ash, the pressures were tested for the third time as it is recorded in the following table.

Pc (in water)	Pr (in water)	Pf (in water)	(Pf-Pr)
5	6	7	1
10	11	12	1

15	16	17	1
20	22	23	1
25	30	34	4
30	32	36	4
50	52	56	4
70	74	76	2
80	83	88	5

According to the last pressure test, the pressure differences between reduction zone and filter were dramatically reduced to a normal status. therefore, the ash was the major problem that had caused a blockage inside the system.

Experiment #7
Date: 2/12/2015
Feedstock: 100% Woodchips

After removing ash and regulating the pressures in reduction and charcoal filter, woodchips was used to check the temperature and gas composition in the present experiment. Basically, 8 stable pointes were observed during the syngas production. In addition, 3 samples were collected in order to analyze the gas composition by GC. Figure 1 shows the temperature and pressure profiles at the top and bottom of the reduction zone. In addition, Figure 2 shows the gas composition reported by the inline analyzer.

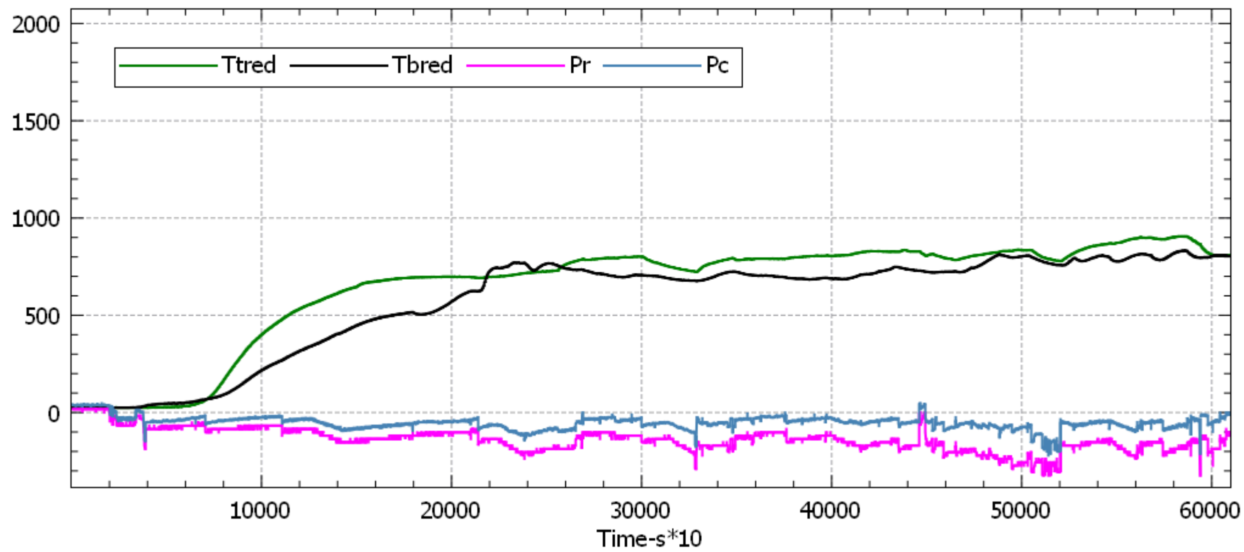


Fig.1

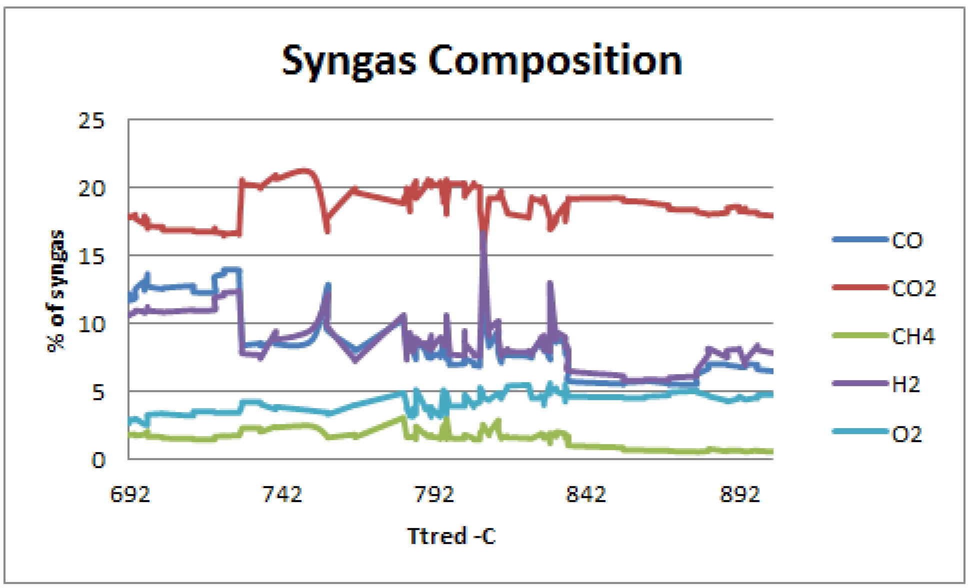


Fig.2

Table 1 compares the gas composition (inline analyzer) in stables pints with the preview experiments.

Table 1

	100% WOODCHIPS					
	Tred (C)	CO	CO2	CH4	H2	O2
Run1-10/1/2014	650	11.43	11.05	2.53	9.49	4.49
	750	14.80	14.79	2.20	12.32	2.27
	800	16.88	14.32	2.04	14.10	1.76
Run 2-10/08/2014	700	7.49	8.27	1.55	7.93	4.65
	750	12.63	13.33	1.79	12.08	2.05
	800	15.09	11.53	1.69	12.98	1.74
Run 3- 1/30/2014	750	11.80	12.26	2.00	8.20	5.64
	800	13.58	13.49	1.76	9.04	4.53
	850	13.97	14.66	1.32	8.36	3.42
Run 4- 2/5/2015	600	8.60	15.51	1.53	4.62	5.59
Run 5- 2/12/2015	700	13.4	17.20	1.85	10.87	2.56
	700	12.48	16.95	1.60	10.48	3.31
	800	7.43	20.37	1.48	8.57	3.30
	800	7.93	20.28	1.77	8.48	3.65
	800	7.17	20.22	1.52	7.78	3.84
	830	8.43	18.73	1.85	8.93	4.65
	815	8.02	18.56	7.93	8.09	5.21
	900	6.98	18.10	.56	7.55	4.28

Experiment #8
Date: 2/24/2015
Feedstock: 100% Woodchips

Before starting the new experiment, all the remained feedstock from preview experiments were removed from the reactor. Then, ash collector was disassembled and almost all the ashes accumulated at the bottom of the reactor were removed. Eventually, the result of the new pressure testing is reflected in the following Table 1.

Table 1

Pc	Pr	Pf
2	3	12
5	6	22
10	11	37
15	16	48
20	21	62
25	26	75
30	34	90

Temperature and Pressure curves show a normal condition during the experiment (Fig 1). In addition, figure 2 shows the gas composition versus the top of the reduction zone temperature.

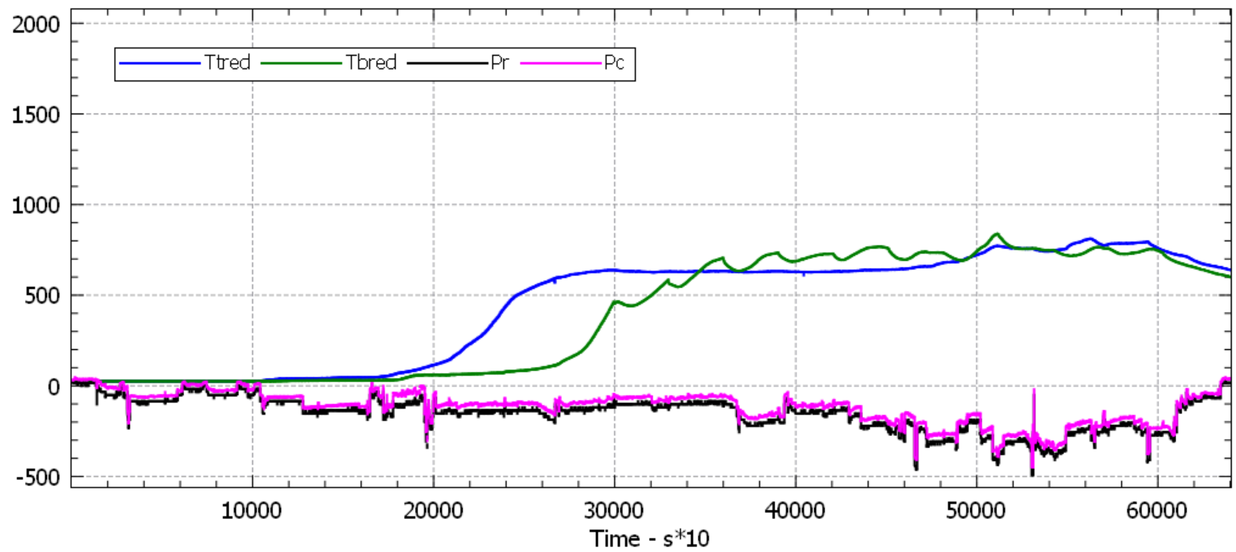


Fig.1

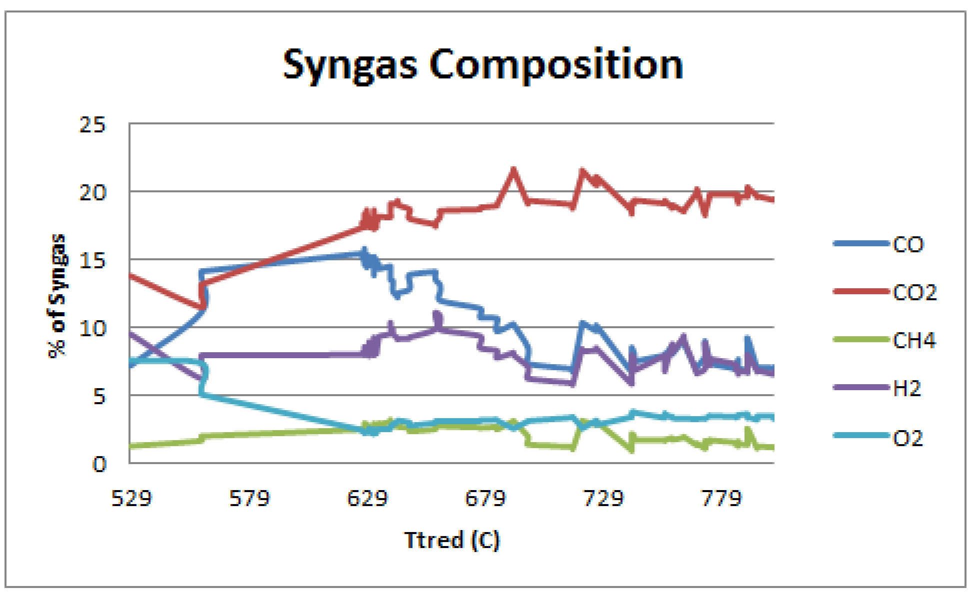


Fig.2

Table 2 shows the comparison between the results of the experiments using 100% wood chips as the feedstock.

Table 2

	100% WOODCHIPS					
	Tred (C)	**CO**	**CO2**	**CH4**	**H2**	**O2**
Run1-10/1/2014	650	11.43	11.05	2.53	9.49	4.49
	750	14.80	14.79	2.20	12.32	2.27
	800	16.88	14.32	2.04	14.10	1.76
Run 2-10/08/2014	700	7.49	8.27	1.55	7.93	4.65
	750	12.63	13.33	1.79	12.08	2.05
	800	15.09	11.53	1.69	12.98	1.74
Run 3- 1/30/2014	750	11.80	12.26	2.00	8.20	5.64
	800	13.58	13.49	1.76	9.04	4.53
	850	13.97	14.66	1.32	8.36	3.42
Run 4- 2/5/2015	600	8.60	15.51	1.53	4.62	5.59
Run 5- 2/12/2015	700	13.4	17.20	1.85	10.87	2.56
	700	12.48	16.95	1.60	10.48	3.31
	800	7.43	20.37	1.48	8.57	3.30
	800	7.93	20.28	1.77	8.48	3.65
	800	7.17	20.22	1.52	7.78	3.84
	830	8.43	18.73	1.85	8.93	4.65
	815	8.02	18.56	7.93	8.09	5.21
	900	6.98	18.10	.56	7.55	4.28
Run 6- 2/24/2015	630	14.61	17.73	2.44	8.16	2.22
	640	13.45	19.06	2.99	9.9	2.75
	680	12.08	18.60	2.70	9.67	3.08
	755	8.67	18.76	1.83	8.57	3.40

	790	7.08	19.76	1.39	6.84	3.45
	660	10.21	21.57	3.12	8.06	2.52

Experiment #9
Date: 3/6/2015
Feedstock: 100% Woodchips

- Filter pressure was still high
- There was no flame in the flare
- The CO and H2 were significantly low in the syngas composition
- CO2 was so high (possibility of combustion caused by extra Oxygen)
- Fuel consumption was almost low

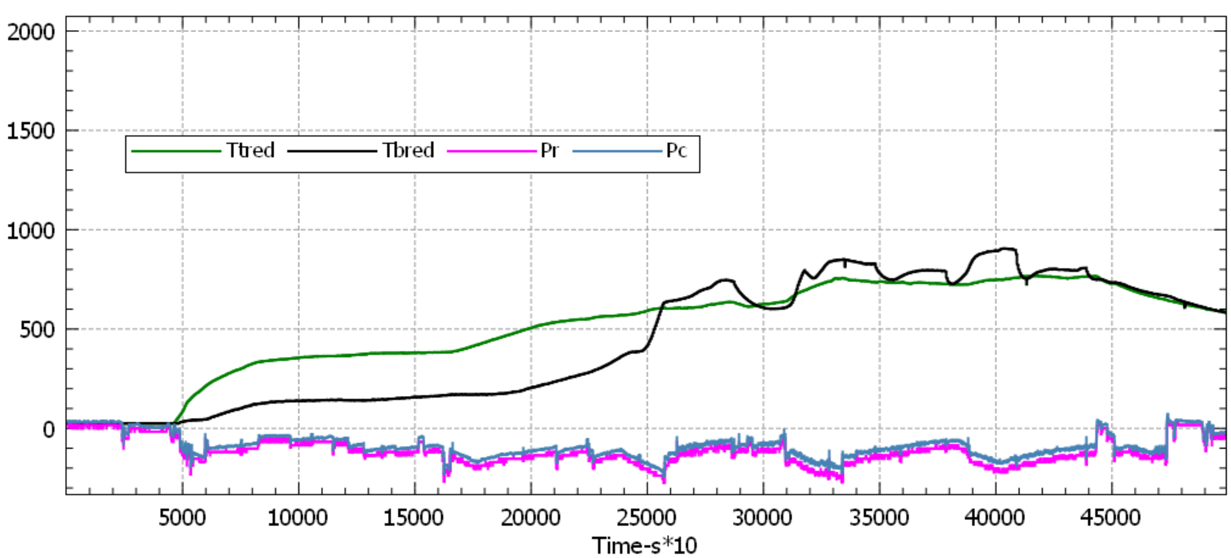


Fig.1

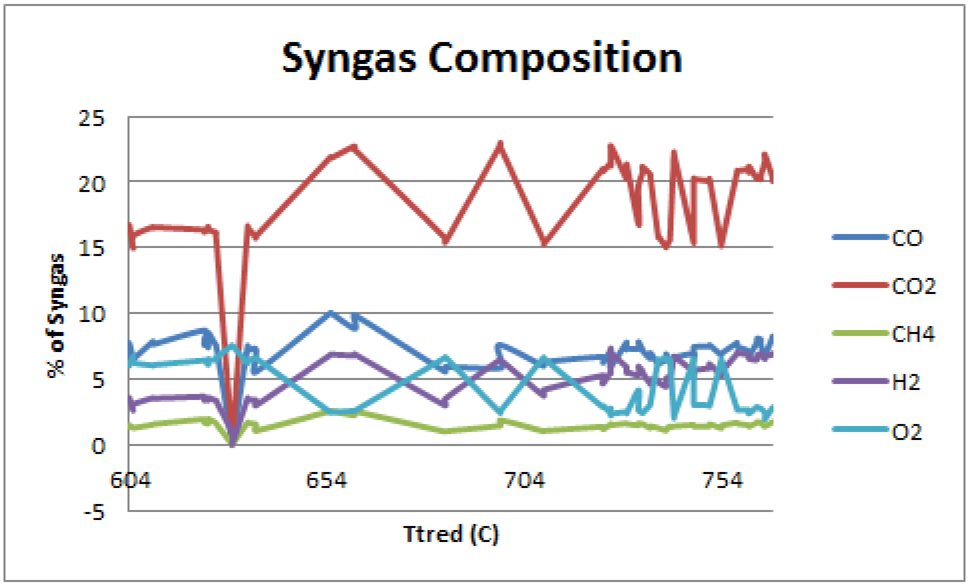


Fig.2

Table 1

	100% WOODCHIPS					
	Tred (C)	**CO**	**CO2**	**CH4**	**H2**	**O2**
Run1-10/1/2014	650	11.43	11.05	2.53	9.49	4.49
	750	14.80	14.79	2.20	12.32	2.27
	800	16.88	14.32	2.04	14.10	1.76
Run 2-10/08/2014	700	7.49	8.27	1.55	7.93	4.65
	750	12.63	13.33	1.79	12.08	2.05
	800	15.09	11.53	1.69	12.98	1.74
Run 3- 1/30/2014	750	11.80	12.26	2.00	8.20	5.64
	800	13.58	13.49	1.76	9.04	4.53
	850	13.97	14.66	1.32	8.36	3.42
Run 4- 2/5/2015	600	8.60	15.51	1.53	4.62	5.59

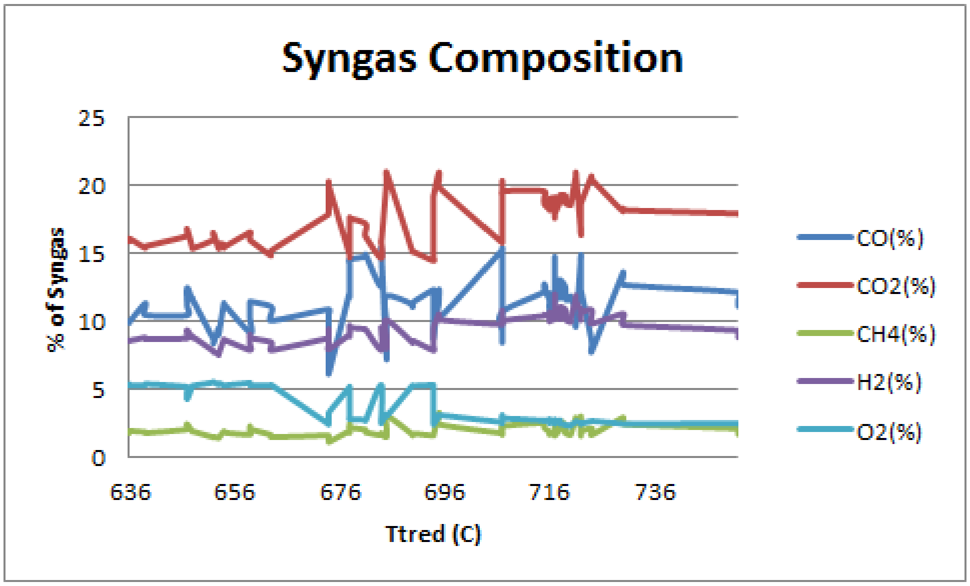
Run 5- 2/12/2015	700	13.4	17.20	1.85	10.87	2.56
	700	12.48	16.95	1.60	10.48	3.31
	800	7.43	20.37	1.48	8.57	3.30
	800	7.93	20.28	1.77	8.48	3.65
	800	7.17	20.22	1.52	7.78	3.84
	830	8.43	18.73	1.85	8.93	4.65
	815	8.02	18.56	7.93	8.09	5.21
	900	6.98	18.10	.56	7.55	4.28
Run 6- 2/24/2015	630	14.61	17.73	2.44	8.16	2.22
	640	13.45	19.06	2.99	9.9	2.75
	680	12.08	18.60	2.70	9.67	3.08
	755	8.67	18.76	1.83	8.57	3.40
	790	7.08	19.76	1.39	6.84	3.45
	660	10.21	21.57	3.12	8.06	2.52
Run 7- 3/6/2015	630	7.55	16.21	1.68	3.38	6.45
	730	7.66	20.54	1.62	5.81	2.47
	760	7.66	20.67	1.69	6.93	2.71
	650	7.93	22.63	2.11	6.68	2.58

Experiment #10
Date: 3/26/2015
Feedstock: 100% Woodchips

The following table shows the pressure test before starting the experiment:

P (com)	P (rec)	P (filter)
3	4	8
5	6	11
10	11	19
15	16	26
20	21	32
26	27	41
30	31	47
39	40	58
46	46	67

The results of the pressure test shows a normal condition inside the gasifier especially from the reaction chamber to the filter. Thus, it seemed that there was not any leakage or blockage inside the gasifier. the following figure shows the syngas composition:



The following table compares the syngas composition derived from 100% woodchips with the corresponded temperatures:

	100% WOODCHIPS					
	Tred (C)	**CO**	**CO2**	**CH4**	**H2**	**O2**
Run1-10/1/2014	650	11.43	11.05	2.53	9.49	4.49
	750	14.80	14.79	2.20	12.32	2.27
	800	16.88	14.32	2.04	14.10	1.76
Run 2-10/08/2014	700	7.49	8.27	1.55	7.93	4.65
	750	12.63	13.33	1.79	12.08	2.05
	800	15.09	11.53	1.69	12.98	1.74
Run 3- 1/30/2014	750	11.80	12.26	2.00	8.20	5.64
	800	13.58	13.49	1.76	9.04	4.53
	850	13.97	14.66	1.32	8.36	3.42

Run 4- 2/5/2015	600	8.60	15.51	1.53	4.62	5.59
Run 5- 2/12/2015	700	13.4	17.20	1.85	10.87	2.56
	700	12.48	16.95	1.60	10.48	3.31
	800	7.43	20.37	1.48	8.57	3.30
	800	7.93	20.28	1.77	8.48	3.65
	800	7.17	20.22	1.52	7.78	3.84
	830	8.43	18.73	1.85	8.93	4.65
	815	8.02	18.56	7.93	8.09	5.21
	900	6.98	18.10	.56	7.55	4.28
Run 6- 2/24/2015	630	14.61	17.73	2.44	8.16	2.22
	640	13.45	19.06	2.99	9.9	2.75
	680	12.08	18.60	2.70	9.67	3.08
	755	8.67	18.76	1.83	8.57	3.40
	790	7.08	19.76	1.39	6.84	3.45
	660	10.21	21.57	3.12	8.06	2.52
Run 7- 3/6/2015	630	7.55	16.21	1.68	3.38	6.45
	730	7.66	20.54	1.62	5.81	2.47
	760	7.66	20.67	1.69	6.93	2.71
	650	7.93	22.63	2.11	6.68	2.58
Run 8- 3/26/2015	680	12.44	14.42	1.57	7.82	5.29
	660	9.81	15.19	1.38	7.63	5.32
	660	11.38	15.89	1.96	8.68	5.25
	650	14.28	17.58	2.41	9.64	2.94
	730	12.18	17.84	2.00	9.12	2.43

	700	10.64	20.82	2.82	11.72	2.62
	710	12.11	19.12	2.17	9.20	2.63
	720	12.25	17.82	1.57	10.46	2.46

Experiment #10
Date: 3/31/2015
Feedstock: 100% paper-waste pellet

In the experiment, 100% paper-waste pellet was used as the feedstock. Initially, the previous feedstock (woodchips) is removed from the reactor unit. Due to the low bulk density of the paper-waste pellet, chars from woodchips were remained in the combustion zone. After loading the new feedstock, pressures inside the system were tested. Basically, the pressures in combustion zone, reduction zone and filter were normal. Thus, the system was ready and the ignition was started to initiate the gasification. However, after almost 30 minutes of the ignition, the temperature in the combustion zone did not change significantly (30 C~50 C). In fact, even by increasing the pressure in reduction zone (Prec) up to 10 (in), the temperature did not change remarkably.In addition, the pressure in the combustion zone (Pc) was almost zero that was not normal. Consequently, the experiment was stopped and the system was shutted shown. Then, the team decided to open the reactor unit and check the status of the feedstock inside the reactor in order to find the reason. the following pictures show the feedstock condition:

fig1. fuel hopper

fig2. drying zone

fig3. pyrolysis zone

fig4. combustion zone

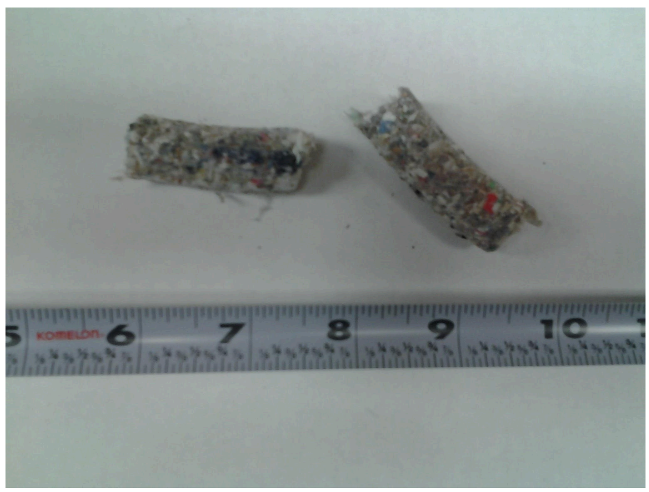


fig5. paper waste-pellet in drying zone

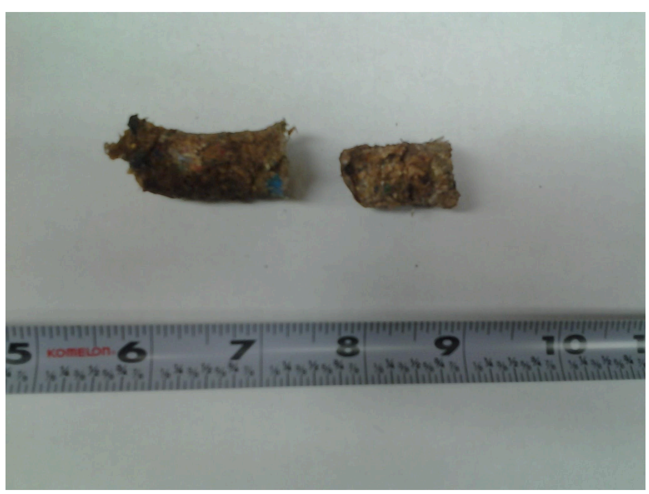


fig6. paper waste-pellet in pyrolysis zone

fig7. paper waste-pellet in combustion zone

Notes:

- Pellets were tarry in drying zone
- Some pellets were turned to small pieces in pyrolysis zone
- Melted plastics, as binders, had attached the pellets and pieces together in pyrolysis zone
- Combustion zone was attached to pyrolysis zone as a big piece of burned feedstock (see fig 4)
- It seems that the ignition port was blocked and the diesel could not reach the feedstock during the ignition process

Experiment #11
Date: 4/9/2015
Feedstock: 30% paper pellet-70% woodchips

Due to the problems with 100% paper waste pellets, 30% of the pellet was mixed with 70% of woodchips in weight as the feedstock for the experiment.

Table1. Ultimate and proximate analysis

Ultimate Analysis

Biomass	C%	H%	O%	N%	S%
Woodchips (hard)	49.48%	5.3%	43.13%	0.35 %	0.01%
Paper waste pellet	54.19%	7.77%	27.74%	0.38 %	0.15%

Proximate Analysis (wt.% in d. basis)

Biomass	Volatile matter	Fixed Carbon	Ash
Woodchips (hard)	82.80%	16.40%	0.80%
Paper waste pellet	84.74%	9.04%	6.22%

Table2. Pressure test before the experiment

Pc	Pre	Pf
-5	-6	-13
-10	-11	-20
-15	-17	-32
-23	-24	-43
-30	-31	-56
-42	-43	-71

Figure 1. mixture

Figure 2. drying zone

Figure 3. pyrolysis zone

Figure 4. a hole between pyrolysis and combustion zones

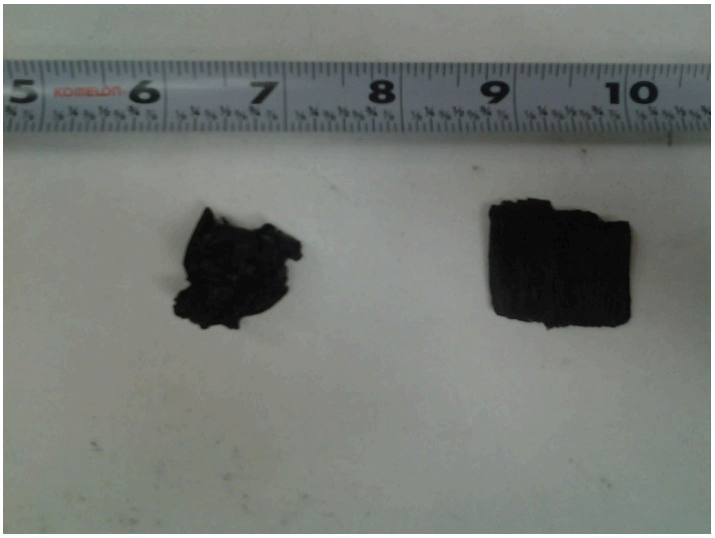


Figure 5. left: pellet char, right: woodchips char

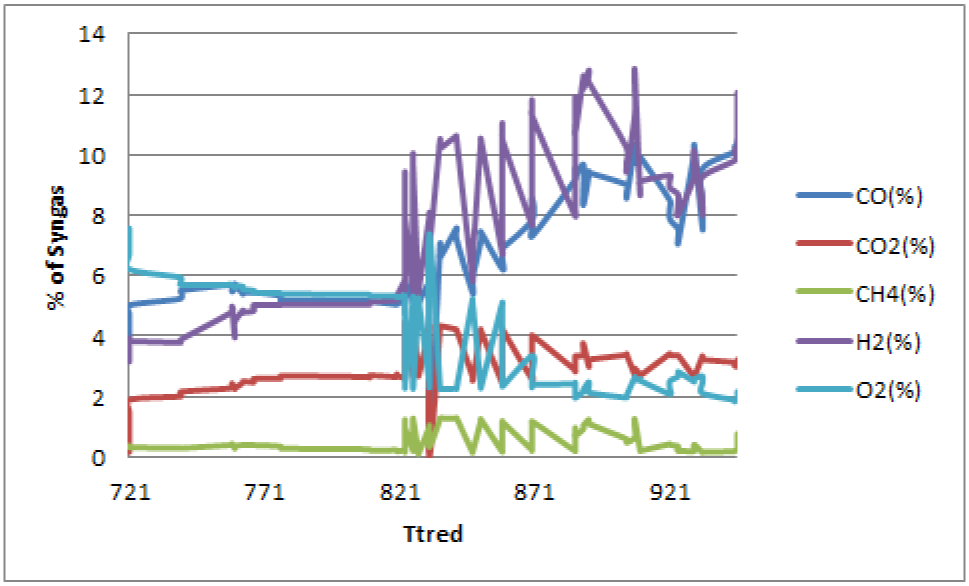


Figure 6. syngas composition

Table 3. Comparison between syngas composition

	Tred (C)	CO	CO2	CH4	H2	O2
100% woodchips-3/26/2015	680	12.44	14.42	1.57	7.82	5.29
	660	9.81	15.19	1.38	7.63	5.32
	660	11.38	15.89	1.96	8.68	5.25
	650	14.28	17.58	2.41	9.64	2.94
	730	12.18	17.84	2.00	9.12	2.43
	700	10.64	20.82	2.82	11.72	2.62
	710	12.11	19.12	2.17	9.20	2.63
	720	12.25	17.82	1.57	10.46	2.46
30% paper pellet-70% woodchips-4/9/2015	760	5.07	1.92	0.30	3.78	5.91
	767	5.73	2.28	0.39	4.75	5.70
	826	5.17	2.64	0.25	5.04	5.35
	848	5.21	2.61	0.22	5.81	5.35
	910	7.84	2.63	7.77	0.21	2.74
	905	9.34	3.01	1.23	12.66	2.31
	933	8.51	3.43	0.43	9.28	2.14
	889	10.26	3.06	0.20	10.15	1.89
	851	8.02	3.85	1.10	11.70	2.33
	826	7.26	4.22	1.30	10.57	2.24
	823	5.95	4.47	1.25	9.53	2.25
	830	5.82	4.25	0.97	7.93	2.39

Notes:

- The pressures were normal before and during the experiment
- The ignition process was slow and it took more than 30 minutes to reach 100 C from 25 C in Ttred
- Small and unstable flame was observed
- CO_2 concentration was remarkably low (See Table 3)
- Considering ultimate and proximate analysis, pellet has lower oxygen and fixed carbon. Thus, we can suggest that the lower concentrations of oxygen and fixed carbon in the mixture have caused the significant reduction in CO_2 comparison to pure wood chips.

Experiment #12
Date: 4/16/2015
Feedstock: 30% paper pellet-70% woodchips

Table1. Pressure test before the experiment

Pc	Pr	Pf
-3	-4	-9
-5	-6	-11
-10	-10	-21
-15	-17	-30
-20	-21	-38
-25	-27	-48
-30	-32	-54
-40	-43	-69

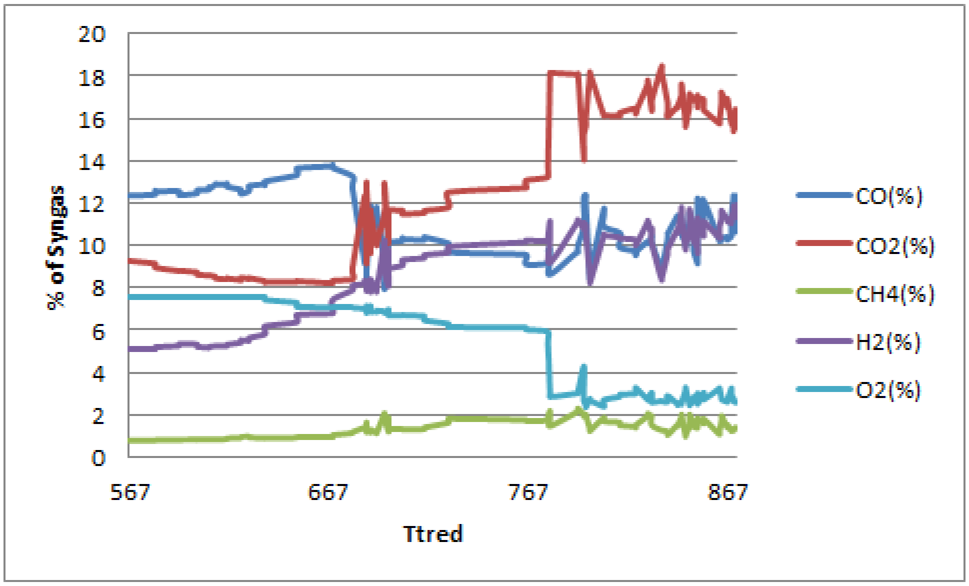


Figure 1. syngas composition

Table 2. Comparison between syngas composition

	Tred (C)	CO	CO2	CH4	H2	O2
100% woodchips-3/26/2015	680	12.44	14.42	1.57	7.82	5.29
	660	9.81	15.19	1.38	7.63	5.32
	660	11.38	15.89	1.96	8.68	5.25
	650	14.28	17.58	2.41	9.64	2.94
	730	12.18	17.84	2.00	9.12	2.43
	700	10.64	20.82	2.82	11.72	2.62
	710	12.11	19.12	2.17	9.20	2.63
	720	12.25	17.82	1.57	10.46	2.46
	760	5.07	1.92	0.30	3.78	5.91
	767	5.73	2.28	0.39	4.75	5.70
	826	5.17	2.64	0.25	5.04	5.35
	848	5.21	2.61	0.22	5.81	5.35
	910	7.84	2.63	7.77	0.21	2.74

30% paper pellet-70% woodchips-4/9/2015	905	9.34	3.01	1.23	12.66	2.31
	933	8.51	3.43	0.43	9.28	2.14
	889	10.26	3.06	0.20	10.15	1.89
	851	8.02	3.85	1.10	11.70	2.33
	826	7.26	4.22	1.30	10.57	2.24
	823	5.95	4.47	1.25	9.53	2.25
	830	5.82	4.25	0.97	7.93	2.39
30% paper pellet-70% woodchips-4/16/2015	567	5.16	14.09	0.76	4.08	7.57
	601	12.62	9.04	0.78	5.12	7.57
	616	12.66	8.50	0.82	5.15	7.57
	635	12.69	8.36	0.91	5.48	7.57
	679	13.10	8.27	0.91	6.39	7.26
	691	12.60	9.05	1.18	8.07	7.07
	686	11.62	10.09	1.24	8.23	6.97
	697	8.90	12.36	1.39	8.22	7.01
	727	10.09	11.53	1.30	9.25	6.71
	795	9.76	12.42	1.81	9.93	6.14
	805	12.41	15.53	1.98	11.01	2.42
	846	10.49	16.76	1.88	10.26	2.58
	869	10.31	15.74	1.24	11.55	2.81
	871	11.33	15.74	1.24	11.55	2.81
	844	10.57	16.47	1.38	11.20	2.60
	848	11.28	16.79	1.70	11.27	2.53
	852	9.06	16.96	1.37	9.65	3.00

	844	12.25	16.47	1.84	11.34	2.54
	792	11.47	17.25	2.00	11.78	2.48
	834	10.06	18.25	2.24	11.21	3.01
	857	8.76	18.41	1.26	8.39	2.64

Notes:

- The level of the water drained from the charcoal filter was almost higher than all the previous experiments (100% wood chips, 50%woodchips-50%switchgrass pellet)
- It took almost 15 minutes for Ttred to reach 100 C from 25 C (almost half of the time in previous experiment)
- Small flame was observed and the unstable flame was sensitive to filter pressure (Pf)
- It is observed that most of the time after shaking, Tbred is reduced, while, gas composition is increased
- Based on table 2, concentration of CO, H2 and CO2 are higher than the previous experiment.

Experiment #13
Date: 10/12/2015
Feedstock: 100% woodchips

FIRST RUN								
Date	**Feedstock**	**Ttred**	**Tbred**	**Pcomb**	**Preac**	**Pfilt**	**Prati**	**Notes**
10/12/2015	100% Woodchip	73	67	-8	-10	-51	75	
		98	65	-6	-9	-45	70	
		117	65	-6	-8	-43	68	
		153	72	0	-4	-50	-4	

		179	79	-2	-7	-60	34	
		283	92	-5	-9	-51	61	Air inlet was 1/4 opened
		345	109	-5	-9	-50	57	
		394	122	-5	-8	-48	60	
		666	228	-6	-10	-54	64	
		705	248	-5	-9	-52	59	
		702	267	-5	-8	-49	55	
		720	270	-4	-7	-44	60	
		722	288	-5	-8	-48	57	
		730	335	-5	-10	-56	60	
		723	469	-4	-13	-57	55	
		739	605	-7	-14	-54	53	
		760	810	-4	-10	-55	55	
		758	926	-5	-10	-52	53	
		760	947	-3	-5	-50	-41	Auger was turned on
		690	807	-2	-8	-62	31	
		692	826	-2	-8	-58	36	
		624	819	0	-6	-55	9	
		619	801	-1	-7	-60	16	
		648	782	-2	-8	-67	22	
		680	779	-2	-10	-75	28	
		720	798	-3	-10	-75	32	

Experiment #14
Date: 10/19/2015
Feedstock: 100% woodchips

SECOND RUN								
Date	**Feedstock**	**Tred**	**Tbred**	**Pcomb**	**Prec**	**Pfilt**	**Prati**	**Notes**
10/19/2015	100% Woodchip	552	126	-7	-10	-54	69	
		578	141	-6	-9	-51	68	
		595	154	-6	-10	-50	71	
		642	177	-6	-9	-50	71	
		663	196	-6	-8	-46	73	Negative Pressure was reduced
		674	201	-5	-9	-51	73	
		679	208	-6	-8	-71	71	
		703	276	-8	-11	-57	72	
		713	254	-6	-10	-52	71	
		722	290	-7	-9	-57	66	
		721	297	-6	-9	-47	73	
		701	313	-6	-8	-45	72	
		701	320	-6	-8	-46	67	
		691	329	-6	-10	-43	69	
		683	335	-6	-10	-42	71	
		686	346	-8	-10	-43	64	
		722	359	-7	-10	-54	65	
		713	370	-6	-8	-54	65	

		709	391	-5	-8	-52	60	
		694	376	-5	-9	-50	62	
		695	420	-6	-8	-45	65	
		719	426	-5	-8	-44	65	
		710	430	-5	-9	-43	67	Negative pressure increased
		711	434	-4	-13	-41	65	
		708	509	-6	-12	-52	65	
		708	652	-9	-12	-65	64	
		773	666	-8	-11	-60	65	
		730	697	-8	-11	-59	63	
		729	699	-7	-11	-56	66	
		729	808	-7	-10	-55	65	
		729	804	-5	-10	-65	51	
		723	742	-5	-9	-64	50	
		741	758	-4	-8	-60	49	
		751	853	-4	-12	-98	51	
		751	894	-4	-12	-95	49	
		752	903	-5	-11	-71	46	
		749	832	-5	-12	-78	43	

Experiment #15
Date: 10/22/2015
Feedstock: 100% woodchips

THIRD RUN									
Date	**Feedstock**	**Tred**	**Tbred**	**Pcomb**	**Prec**	**Pfilt**	**Prati**	**Notes**	
10/22/2015	100% Woodchip	664	714	-4	-8	-65	44		
		667	766	-4	-10	-72	46		
		654	832	-6	-12	-82	48		
		654	829	-6	-10	-80	44		
		672	819	-4	-10	-73	41	Not given out much gas	
		679	828	-3	-9	-71	43		
		683	859	-3	-8	-69	43	Tbred is too high reason it could be bridging	
		674	863	-3	-9	-65	42		
		667	801	-3	-10	-71	45		
		667	814	-4	-11	-81	40		
		689	844	-4	-10	-84	38		
		703	855	-4	-10	-79	36		
		702	926	-3	-8	-73	28	Tbred too hot	
		695	910	-2	-8	-61	31		
		696	803	-2	-8	-71	33	engine started but not running	
		680	809	-2	-10	-72	39		

		660	847	-2	-10	-86	37		
		667	829	-3	-10	-88	39		
		661	840	-4	-10	-87	39		
		628	942	-3	-10	-79	36	shutting down	

Experiment #16
Troubleshooting the Gasifier

At the end of the spring semester 2016, the issue with the proper combustion in the gasifier was identified. After disassembling the gasifier unit, it was proved that the part of the problem was associated with the stainless spiral tubing outside of the combustion chamber which was partially burned out. The spiral tubing is used to collect the syngas from the gasifier unit and transmit it to the collector. After brainstorming, it turned out that there may be two possibilities as the reason for the problem: 1) The extremely high temperature of the gasifier unit especially outside the combustion chamber would have caused the spiral tubing to be burned out. 2) Operating span of the gasifier unit is already about five years. Due to wear and tear, spiral tubing might have been damaged.

The below figures are showing the combustion chamber of the gasifier before the cleaning. The inner body was full of ash and tar which was removed after the removal of the spiral tubing.