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Exploratory Study on Gasification of Pelletized Grassy Biomass

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Abstract

Renewable energy offers a great potential for the world to reduce its dependency on fossil fuels, which can lead to a cleaner environment, better preservation of natural resources, and more economic opportunities for communities. Herbaceous biomass – such as switchgrass – is a major source of renewable energy available in the Midwest.

For this project, switchgrass pellets were successfully co-gasified with wood chips. Characteristics of solid fuel mix of 50% wood chips and 50% switchgrass pellets were examined in terms of their gasification behavior, in reference to wood chips and wood pellets. Chemical kinetic studies were conducted to investigate the effect of gasification temperature on the production of hydrogen, carbon monoxide, and carbon dioxide in syngas.

Within the operation temperature range studied (650-850°C), it was observed that hydrogen and carbon monoxide contents increased with gasification temperature (as gauged by the temperature at the top of the reaction zone).

The mix of 50% wood chips and 50% switchgrass pellets remained relatively uniform in the gasifier chamber, even though some segregation between the two fuels was observed at the top part of the gasifier. Degradation of switchgrass pellets was observed within the gasifier; feeding bucket; and the pyrolysis, combustion, and reduction zones.

A significant amount of clinkers were observed, especially toward the bottom of the reactor. Due to its chemical composition, switchgrass will inherently cause the formation of clinkers in the gasification and combustion process. Clinkers are a major technical challenge for extensive applications of grassy biomass as a renewable energy source. Further study on the ash fusion behavior for the purpose of clinker reduction is needed in order to effectively use herbaceous biomass as a renewable energy source.

I. Introduction

This exploratory project studied the characteristics of grassy biomass (switchgrass) pellets in terms of their gasification behavior and identified realistic operation conditions for those grasses, either native or readily available in the State of Illinois. The project examined parameters to successfully gasify pelletized grassy biomass as a source of renewable energy and obtained operational and experimental data to support further modeling of grassy biomass gasification.

This study will help Illinois embrace more and better uses of renewable biomass resources grown in the region. With the technical capability of utilizing grassy biomass as a source of renewable energy, the State will be positioned to help generate a market for biomass grown in the region. The market demand for more grassy biomass will lead to the creation of more job opportunities and, therefore, propel the economy of the State.

Specific objectives of the study were:

1. To identify operation conditions or parameters to successfully gasify pelletized grassy biomass.

2. To provide operational and experimental data to support further modeling of grassy biomass gasification.

3. To build a knowledge base in order for ISTC and EIU to collaboratively seek further funding opportunities from federal agencies such as National Science Foundation.

II. Materials and Setup

Figure 1 illustrates the down-draft gasification system used in this research project, whereas Figure 2 shows the system components and the flow of energy in the system. The copper coil tubing on the left corner of the system in Figure 1 was a part of the syngas sampling port.

Figure 1. Biomass gasification system.

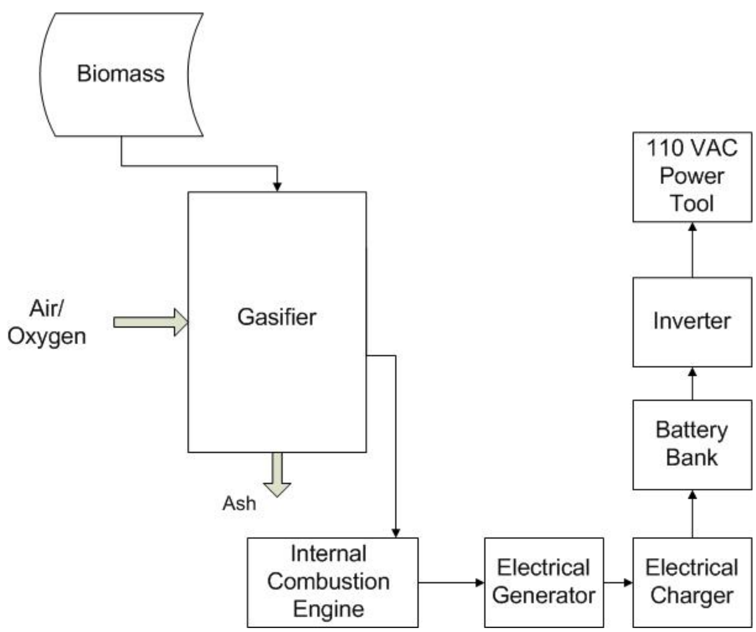

Figure 2. Flow of materials and energy in the biomass gasification system.

Figure 3 shows a gas sampling bag used to collect syngas samples from the gasifier system. The bags are used to carry the syngas to the next step of gas chromatography (GC) analysis. The micro-GC used to analyze the chemical composition of syngas is shown in Figure 4. Ultra high purity argon and helium gases were used as carrier gases for the GC.

Figure 3. Gas sampling bag (Fisher Scientific).

Figure 4. Micro GC used to measure the composition of syngas.

A solid fuel mix such as 50% wood chips and 50% swtichgrass pellets was loaded into the feeding bucket of the gasification system. The fuel mix was then fed into the gasifier chamber by an auger. Figure 5 shows the material condition in the feeding bucket. It was observed that the two solid fuels were mixed fairly uniformly during loading and fuel handling.

Figure 6 illustrates the fuel mix left in the top part of the gasifier chamber after a gasification experiment was completed and the gasifier was shut down and cooled. It was noted that while the solid fuel mix remained reasonably uniform in the gasifier chamber, the materials – especially the grass pellets – were changed. A significant amount of expansion was observed with the grass pellets.

Figure 5. Fuel mix (50% wood chips and 50% switchgrass pellets) in feeding bucket.

Figure 6. Solid fuel left on top of the gasifier chamber after the gasifier was shut down and cooled.

For this project, efforts were focused on a gasification study of wood chips, wood pellets, and switchgrass pellets. Wood pellets were used to establish a baseline to fully understand the gasification behavior of grassy biomass. Properties of the feedstock including the moisture content and higher heat value (HHV) were studied as a basis for a complete understanding. The following tasks were completed:

1. Gasification studies were performed at five stages of temperatures (650, 700, 750, 800, and 850°C) in order to understand the chemical kinetics of gasification, in terms of effect of temperature on syngas composition.

2. Syngas composition was measured using gas chromatography (GC) as a molar percentage of hydrogen, oxygen, nitrogen, carbon monoxide, and carbon dioxide.

3. The first series of experiments were conducted on gasification of wood pellets, intended as a baseline for studying gasification of grassy biomass pellets under the same experimental conditions as described in step 1.

4. A new source of supply for switchgrass pellets was identified and samples of switchgrass pellets were obtained.

5. An attempt was made to gasify the pellets of switchgrass. A major problem of biomass bridging was observed inside the gasifier, which was also reported in literature for grassy biomass gasification (Wei, Schnell, & Hein, 2005) and made it impractical to ignite the gasifier system. A decision was made to focus on co-gasification of 50% wood chips and 50% switchgrass pellets.

6. A mix of 50% wood chips and 50% wood pellets was used subsequently in this gasification study. This was conducted at the same five staged temperatures as described in step 1 (650, 700, 750, 800, and 850°C). The purpose was to establish a baseline for comparison with the co-gasification fuel mix of 50% wood chips and 50% switchgrass pellets.

7. An extensive experimental study was conducted on a mix of 50% wood chips and 50% switchgrass pellets in terms of the operating behavior, fuel characteristics inside the gasifier, and syngas composition. Those gasification experiments were performed under the same conditions as the fuel mix of 50% wood chips and 50% wood pellets and at same five staged temperatures (650, 700, 750, 800, and 850°C).

III. Methods and Results

A. Operation Characteristics and Mass Flow Rate of Biomass Gasification

The gasification process is controlled by multiple operation variables including the temperatures of the top and bottom of the reduction zone and pressures of the combustion and reaction zones. The process is also affected by the physical and chemical characteristics of fuel mix and its compositions. The pressures of the gasification chamber are directly related to the amount of air supplied to the gasification process, and this thus affect the gasification temperature. During a typical run of a gasification experiment, gasification temperatures are monitored while controlling the pressures in the gasifier chamber. The temperatures of the reduction zone dictate the chemical reaction for syngas production. During each experiment, the optimum gasification temperature based upon observation of syngas output was recorded.

It was observed that gasification temperature (measured at top of the reduction zone) was limited to approximately 800°C when 100% wood pellets were gasified. This temperature is much lower than the gasification temperature for 100% wood chips (normally around 900-950°C). Using a gasification temperature higher than 800°C was attempted, but could not be stabilized for the gasification process of wood pellets. The gasification temperature for a fuel mix of 50% wood chips and 50% switchgrass pellets was around 800-850°C.

Fuel consumption or mass flow rate is dependent upon the chemical reactions in the gasification chamber, which is controlled by the previously mentioned variables such as pressure, temperature, and fuel characteristics. The average mass flow rate was 12 pounds per hour for the fuel mix of 50% wood chips and 50% switchgrass pellets, as well as for the fuel mix of 50% wood chips and 50% wood pellets.

B. Chemical Kinetics of Gasification of Wood Pellets and Wood Chips with Wood Pellets or Switchgrass Pellets

Figure 7 illustrates the effect of temperature on the hydrogen gas composition in the syngas output from the gasification of three feedstocks studied in this project - 100% wood pellets; 50/50 wood chips and wood pellets; and 50/50 wood chips and switchgrass pellets. In general, the hydrogen production increased with increasing temperature. However, the hydrogen production reached a peak at around 800°C.

The effect of gasification temperature on composition of carbon monoxide (CO) in syngas for the three feedstocks studied is shown in Figure 8. A similar trend to hydrogen production was observed with regard to the CO production with an increase in production with increase in temperature. But, the temperature effect seems to be more pronounced with the 50/50 mix of wood chips and pellets than 100% wood pellets. And, the CO production still increased for the 100% wood pellets above 800°C.

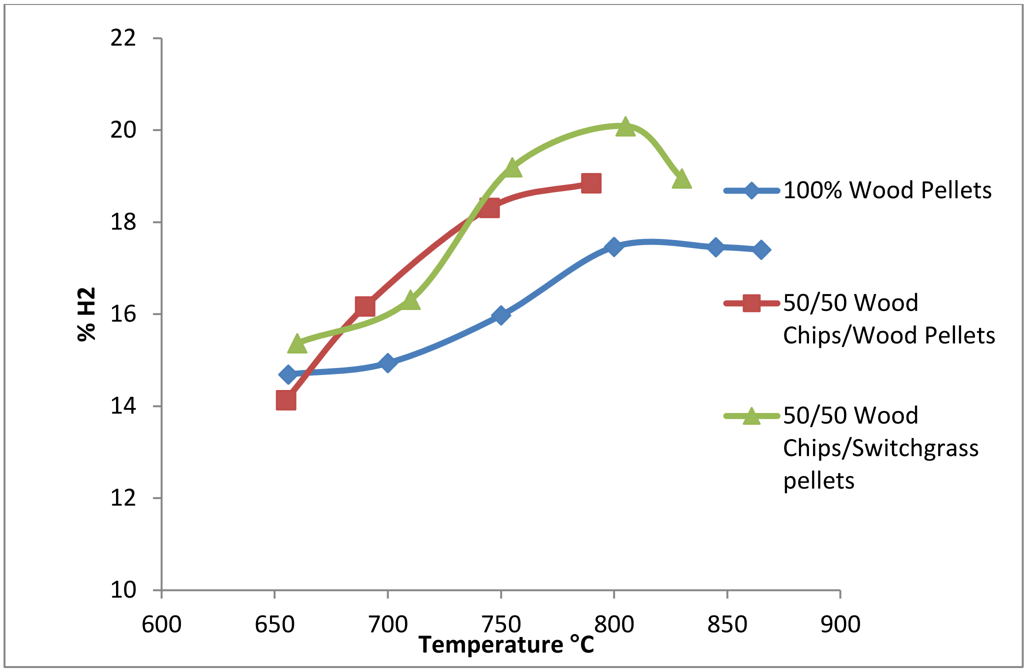

Figure 7. Effect of temperature on the hydrogen composition in syngas.

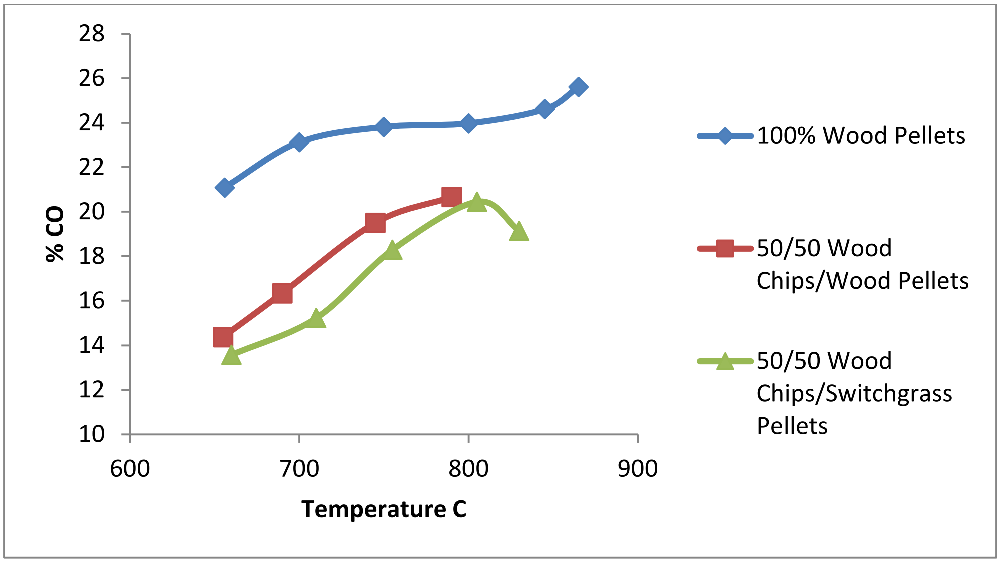

Figure 8. Effect of temperature on the carbon monoxide composition in syngas.

Figure 9 shows the effect of temperature on the ratio of carbon monoxide and hydrogen gas. This ratio provides insights on the balance of the chemical production during gasification. It was observed that the ratio remained relatively constant as the gasification temperature increased.

The effect of gasification temperature on the production of carbon dioxide is illustrated in Figure 10. Generally, the amount of carbon dioxide decreased with increasing gasification temperature within the temperature range studied. From the energy production point of view, we like to have a lower concentration of CO_2 from the syngas since CO_2 does not carry any energy value. However, the gasification temperature is limited by the gasification system utilized.

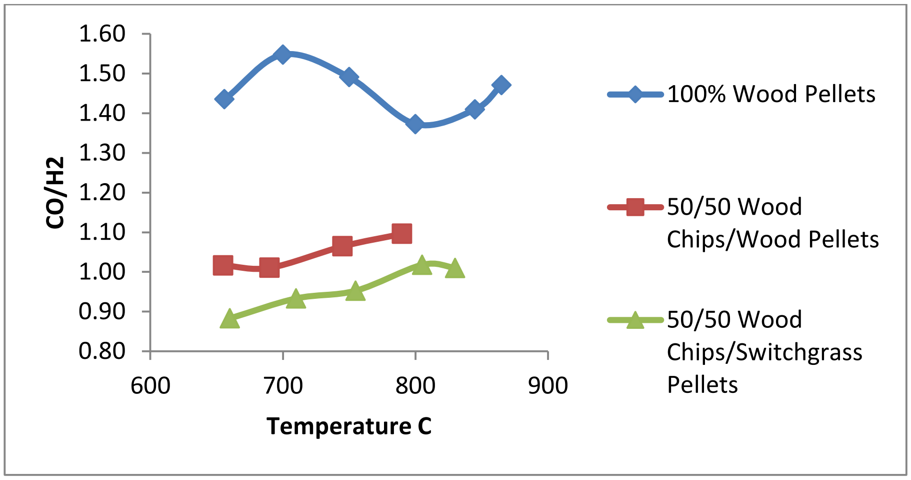

Figure 9. Effect of temperature on the ratio of carbon monoxide to hydrogen gas in syngas.

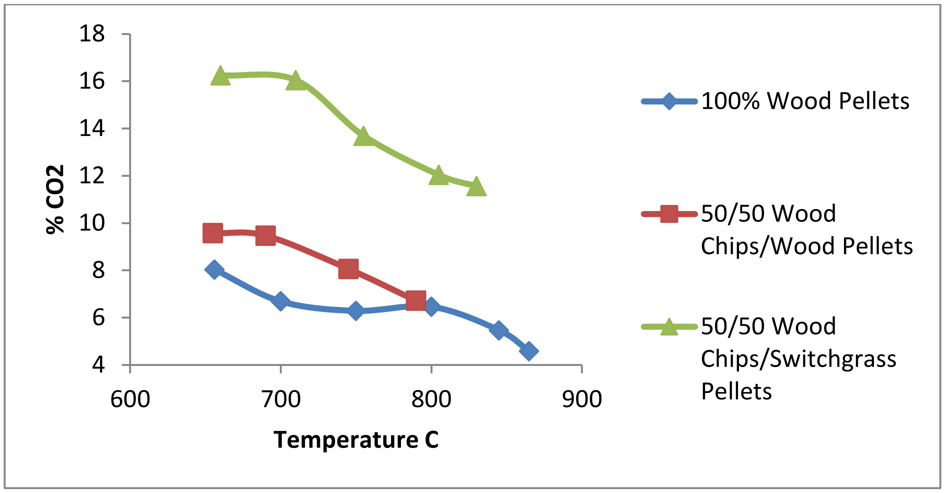

Figure 10. Effect of temperature on the carbon dioxide composition in syngas.

C. Observation of Characteristics for a Fuel Mix of 50% Wood Chips and 50% Switchgrass Pellets

Three experimental runs were conducted with 50% wood chips and 50% switchgrass pellets (supplied by FDC Enterprise) on September 5, September 19, and September 26, 2013. After the three runs, it was decided to open and clean the gasifier chamber. Careful observation was made while extracting left-over materials from the top to the bottom of the gasifier chamber.

Pellets were deteriorated in the feeding bucket after the run on September 26, 2013. Figure 11 shows a deteriorated pellet (top) and a pellet not affected (bottom) for comparison. A significant amount of expansion was observed after the gasifier was cooled down to room temperature. The expansion may be due to the effect of heat and moisture left inside the gasifier after the gasifier was shut down.

Figure 11. Pellets were deteriorated in feeding bucket after the previous run. Also shown is an unaffected pellet (bottom) for comparison.

Figure 12 shows a schematic of materials in the gasifier, relative to the auger position. There was a visible segregation between wood chips and switchgrass pellets in the gasifier chamber.

Figure 13 illustrates the materials exit from the feeding bucket to the gasifier chamber, pushed out by a screw auger. Some of the switchgrass pellets were seen ground into powder form in the feeding bucket before being dropped to the gasifier chamber.

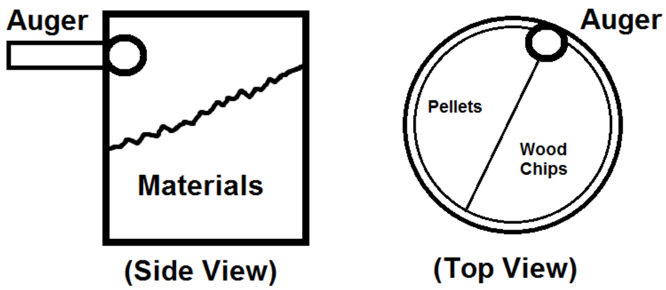

Figure 12. Schematic of materials left inside the top part of the gasifier chamber (approximately eight inches from the top).

Figure 13. The auger exit at the top of the gasifier. The auger was clogged due to large pieces of wood chips.

Figure 14 shows materials left inside the top part of the gasifier chamber (approximately eight inches from the top). It was observed that materials were tarry and somewhat wet. There were more switchgrass pellets on one side and the switchgrass pellets showed a significant amount of swelling or expansion. Further down – approximately 12 inches from the top – switchgrass pellets were still seen segregated from wood chips, more on one side than the other, as shown in Figure 15.

Figure 14. Approximately eight inches from the top opening of the gasifier chamber. Materials were shown to be tarry and somewhat wet.

Figure 15. Switchgrass pellets were seen segregated from wood chips, approximately 12 inches from the top of the reactor.

In the combustion zone, a relatively uniform mix of fuel materials was observed. Some materials were found to be gasified incompletely as illustrated in Figure 16. A uniform mixture of pellet char and wood char was found at the bottom of the reactor. Switchgrass pellets were visible in the form of pellet char as seen in Figure 17. Small clinkers were found in the combustion zone as pictured in Figure 18. Clinkers are solids fused together from ash as a result of combustion or gasification, which pose a significant practical challenge for a long term operation of a biomass gasifier. Large clinkers found in the bottom of combustion zone or at the top of the reduction zone are shown in Figure 19. In the reduction zone, a good mix of pellet char and wood char was observed. There were switchgrass pellet chars that retained their original pellet size and shape.

Figure 16. A relatively uniform mix of wood chips and switchgrass pellets was found in the combustion zone.

Figure 17. A uniform mixture of pellet char and wood char was found at the bottom of the reactor. Switchgrass pellets were visible in the form of pellet char.

Figure 18. Small clinkers were found in the combustion zone.

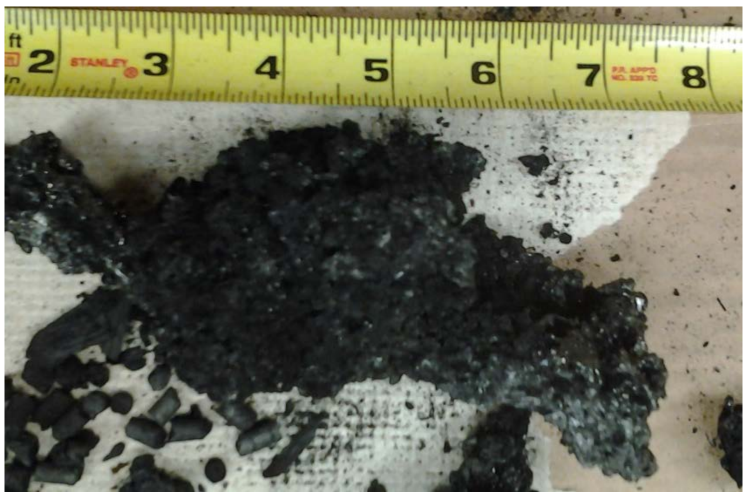

Figure 19. Large clinkers were found in bottom of reactor (reduction zone).

Clinker samples were sent for chemical analysis as the first attempt to understand the mechanism of clinker formation. They were found to contain 56% SiO_2, 12% CaO, 12% K_2O, 6% P_2O_5, 5% MgO, 3% C, 3% Fe_2O_3, 1% Al_2O_3, and the balance was oxides of other trace elements. Some oxides are known to lower ash melting temperature and thus aggravate sintering or fusion of ash (or slag) in a combustion or gasification process (Wei et al., 2005). Grassy biomass such as switchgrass inherently will cause the formation of clinkers in the gasification or combustion process due to its chemical composition (Wang et al., 2008). However, fusion behavior and its formation characteristics warrant further and more detailed study because the formation of clinkers can literally clog the materials flow in a gasifier and thus stop the gasification process completely.

D. Temperature Control of Gasification Process

In order to gain a solid understanding on the grass pellet gasification, two series of studies were conducted to observe the gasification behavior of 50% wood chips and 50% switchgrass pellets. The first series of gasification trials was conducted three times during a time span of approximately one month. After each run, the gasifier was shut down and reignited again for the following run, typically in a week.

Figure 20 illustrates the temperature response for the freshly cleaned and reloaded gasifier. It was observed that the temperature at the bottom of the reduction zone (black curve) was higher than that of the top of reduction zone (pink curve). It was also observed that both temperatures were very sensitive to the changes in air pressure in the reactor zone.

As the gasification proceeded the second time (Figure 20B) and third time (Figure 20C), it was observed that the temperature at the bottom of reduction zone (black curve) shifted to be lower than that of the top of reduction zone (pink curve). Based upon the previous observation on gasification with other fuels, it was thought that the gasification run on September 26, 2013, (Figure 20C) indicated a stable gasification process.

After the series of experiments, the gasifier was opened, cleaned and reloaded. Observation of the inside of the gasifier chamber was made after the first series of gasification runs. Details on the fuel changes inside the gasifier (evidence on what happened during and after gasification) can be seen in section IV. C.

A more extensive study on the gasification of 50% wood chips and 50% switchgrass pellets was conducted, following the first series of experiments. The gasifier was completely emptied, cleaned and reloaded with new fuel mix before the second series. After each run, the gasifier was shut down, and reignited again for the following run.

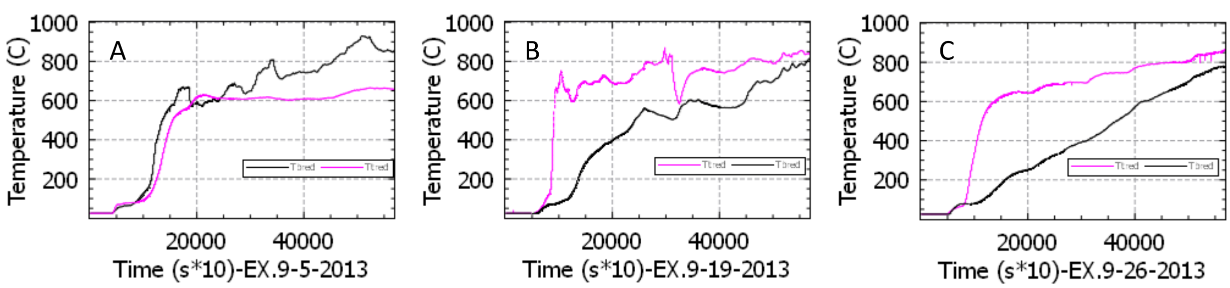

Figure 20. Top (pink) and bottom (black) of reduction zone temperatures as a function of time. Graphs A is the first ignition and B and C are subsequent ignitions.

Figure 21 illustrates the progression of the five experiments during an approximate span of one month. The data collection for the second run (October 17, 2013) was interrupted due to a computer problem; therefore, the graph for October 17 showed only the partial process data toward the later part of the gasification experiment. Similar to the previous series, for the first and second run, the temperature at the bottom of reduction zone (black curve) was generally higher than that at the top of the reduction zone (pink curve) for October 10, 2013, and October 17, 2013. As the series of experiment went further, the temperature at the bottom of reduction zone (black curve) gradually shifted and eventually became lower than that at the top of the reduction zone (pink curve) for October 24, 2013, and later cases. The gasifier behaved as a steady state for October 31, 2013, and November 7, 2013.

It was also observed that the air pressure in the reactor for the fuel mix of 50% wood chips and 50% switchgrass pellets ranged between 249 and 374 Pa (1.0 and 1.5 inches of water), compared with 4 inches of water for 100% wood chips. This fact suggested that the switchgrass pellets were more reactive in the gasifier than wood chips. It also indicated a lower thermal conversion efficiency for the mixed fuel than for wood chips, based upon a previous study conducted in the lab (Wang W. , 2013).

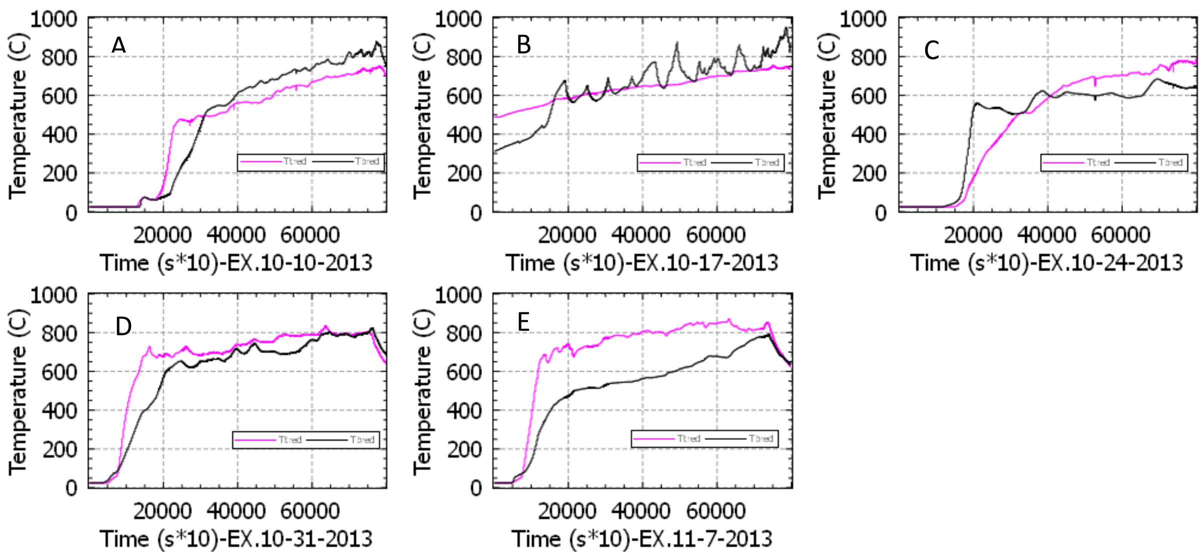

Figure 21. Gasification temperatures as a function of time during the second series of gasification experiments with 50% wood chips and 50% switchgrass pellets. Graphs A is the first ignition and B-E are subsequent ignitions.

IV. Summary of the Preliminary Findings

1. This project systematically studied the gasification characteristics and operational conditions for a mix of 50% wood chips and 50% switchgrass pellets utilized as a fuel source. Future study should be directed toward evaluating more fuel combinations such as using a higher percentage of switchgrass pellets with the wood chips and using other grasses such as *Miscanthus* instead of switchgrass.

2. The mix of 50% wood chips and 50% switchgrass pellets remained relatively uniform in the gasifier chamber, even though some segregation between the two fuels was observed at the top part of the gasifier. (Gasification experiments were also conducted with 100% wood pellets, which served as a base line.)

3. Degradation of switchgrass pellets was observed within the gasifier; the feeding bucket; and the pyrolysis, combustion, and reduction zones.

4. Within the operation temperature range (650-850°C) for the fuels studied, it was generally observed that hydrogen and carbon monoxide contents increased with increasing gasification temperature (as gauged by the temperature at the top of the reaction zone).

5. A significant amount of clinkers was observed, especially toward the bottom of the reactor. Due to its chemical composition, grassy biomass such as switchgrass will inherently cause the formation of clinkers in the gasification and combustion process. Clinkers are a major technical challenge for extensive applications of grassy biomass as a renewable energy source. Further study on the ash fusion behavior for the purpose of clinker reduction is needed.

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Wei, X., Schnell, U., & Hein, K. R. (2005). Behavior of gaseous chlorine and alkali metals during biomass thermal utilisation. *Fuel*, 841-848.

Appendix A. Presentations Based Upon the Current Project:

The financial support for this project from ISTC was acknowledged at the following presentations:

1. P. Lyons, P. P. Liu, and I. Slaven, "Study of regional biomass feedstock as resources for renewable bio-energy," Association of Technology, Management and Applied Engineering (ATMAE), New Orleans, LA, Nov. 13-15, 2013.

2. C. Hu, J. Cloward, and P. P. Liu, "Investigation of the local biomass resources for sustainable energy," Association of Technology, Management and Applied Engineering (ATMAE), New Orleans, LA, Nov. 13-15, 2013.

3. P. P. Liu, “CENCERE: Moving Forward,” Revolution in Science and Technology Paradigms, Eastern Illinois University, Oct. 23, 2013.

4. W. Wang, P. Lyons, P. P. Liu, and J. Cloward, “Thermal efficiency comparison model for different biomass fuels on a laboratory scale gasification system,” 246th American Chemical Society (ACS) National Conference, Indianapolis, Indiana, September 8-12, 2013.