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Assembly and Testing of an On-Farm Manure to Energy Conversion BMP for Animal Waste Pollution Control

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Texas Water Resources Institute
make every drop count

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Summary

Numerous gasification experiments were conducted and proved that with proper moisture content (usually near 10%) animal manure can be gasified using the TAMU fluidized bed gasifier. In summary the following has been established.

- The heating value of dairy manure on a dry basis was found to be 15.93 ± 0.26 MJ/kg (6,863 ± 112 Btu/lb), typical of most agricultural biomass. The heating value was around 14.09 MJ/kg (6,070 Btu/lb), on an "as received" basis (around 13% moisture).
- The heating value of synthesis gas from gasification of animal manure was estimated to be around 4.2 MJ/m^3 (113 Btu/ft^3). This value is very similar to most synthesis gas from agricultural residues.
- Synthesis gas production per unit weight of manure was estimated to be 2.11 m^3/kg. The gas production energy efficiency was estimated to be around 55.6% (i.e. 55.6% of the energy was contained in the synthesis gas).
- Char production was on the average around 20% of the feed input. The average heating value of manure char was around 19 MJ/kg (8,816 Btu/lb). Thus, the char energy conversion efficiency was approximately 24% (i.e. 24% of the energy was still contained in the char).
- Twenty percent (20%) of the energy from the biomass was used during the gasification to maintain the temperature of the reactor. Gasification is a continuous, endothermic process and thus, no external fuel is needed other than that used during startup. Natural gas was used during start-up and would last around 30 minutes. After the initial heating of the reactor, part of the biomass materials were used to maintain the operating temperature and the natural gas fuel source was shut off.
- The chemical formula for dairy manure during combustion is shown below. This formula was used only for stoichiometric calculation purposes only.

- Eutectic point analysis of the manure ash showed that the inorganic ash components will start to melt at around 600°C (1112°F). This was established using compressive strength as an indicator of fusion reactions.
- When used for power generation, it was expected to generate at least 25 kW of electrical power output for a 30 cm diameter pilot facility (i.e. at 1.6 tonnes/day (1.8 tons/day)) of feed input. The assumed conversion efficiency was roughly 15% (from synthesis gas to electrical power in a natural gas-type engine-generator).

Assembly and Testing of an On-Farm Manure to Energy Conversion BMP for Animal Water Pollution Control

INTRODUCTION

Gasification is a process of converting carbonaceous materials into combustible gases such as H_2, CO, CO_2, and CH_4 and char. In general, it involves the reaction of carbon in the biomass with limited air at high temperatures, typically in the range of between 800-900°C (1472-1652°F) to produce synthesis gas. Synthesis gas can be used as fuel to provide electric power and heat for industrial use or can serve as a raw material for the synthesis of chemicals or liquid fuels. As a process, gasification involves a number of steps and conditions that must be met to achieve the desired gaseous and solid products. A better understanding of these steps and conditions would provide the sound basis for further technology development. In this project, we have developed the procedures for the gasification of animal manure, particularly dairy manure, and how this gasification will be achieved using a fluidized bed gasifier.

Objectives

The main goal of the project was to evaluate the feasibility of converting animal manure by thermal means to generate heat, fuel, and power. The specific objectives are:

- Evaluate the physical and chemical properties of dairy manure,
- Perform gasification experiments and report on the performance characteristics,
- Evaluate the eutectic point behavior of dairy manure, and
- Estimate the energy produced during the conversion and the potential for heat and power production.

METHODOLOGY

Manure Characterization

Manure samples used in the experiments were taken from a cooperating dairy located near Comanche, Texas. The initial samples were air-dried before conducting the gasification experiments. Proximate analysis was performed following ASTM procedure (ASTM D 3172-07 a Standard Practice for Proximate Analysis of Coal and Coke). Proximate analysis includes the measurement of moisture content (MC), volatile combustible matter (VCM), fixed carbon (FC), and ash. Heating value analysis was also performed following the ASTM E 711-87 (Standard Method for Gross Calorific Value of Refuse-Derived Fuel by Bomb calorimeter). These analyses were performed at the Bio-Energy Testing and Analysis Laboratory (http://betalab.tamu.edu) of the Department of Biological and Agricultural Engineering (BAEN) at Texas A&M University (TAMU). Manure samples were also sent to Huffman Laboratories (Denver, CO) for complete inorganic ash analysis and ultimate analysis. Ultimate analysis includes determination of the elements contained in the manure samples such as carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O).

Gasification Experiments

Gasification experiments were conducted at the BioEnergy Testing and Analysis Laboratory on the TAMU campus. The TAMU gasifier is an atmospheric fluidized bed gasification system. The pilot scale gasifier was designed to convert up to 1.6 tonnes (1.8 tons) per day of biomass. The gasifier was instrumented to obtain information such as biomass feed rates, operating temperatures, and pressures and air flow rates. The reactor was 30 cm (1 ft) in diameter and measured about 1.5 m (5 ft) tall. The reactor was made up of 2 sections: the reactor bed and the free-board. Both sections are made of stainless steel and insulated with high temperature refractory to prevent heat loss. Fluidizing media was made of refractory sand with some metallic constituents. A nominal bed height of 45 cm (18 in) was used. The bed was heated by a natural gas burner to a temperature enough to convert the biomass into combustible gas, normally around 480°C (900°F). Biomass was then fed slowly to achieve the reaction temperature of between 700-760°C (1300-1400°F). The biomass will be converted into synthesis gas (mainly CO, H_2 and CH_4) and cleaned of char particulates using a set of series cyclones. The first stage low-efficiency cyclone removed the larger particulates and the second stage high-efficiency cyclones removed the smaller particulates. The particulate matter collection efficiency is normally higher than 80%. Upon leaving the cyclones, the synthesis gas was flared using propane pilot-igniter. A sample of gas exiting from the second cyclone was diverted into an online gas analyzer (Horiba Instruments, Irvine, CA). Another gas sampling port was available to collect samples from Tedlar bags for subsequent analysis using a gas chromatograph.

Eutectic Point Analysis of Animal Manure

The animal manure samples were converted into ash in a muffle furnace following ASTM D 1102-84 Standard (Standard Test method for Ash in Wood). Pellets measuring 2.54 cm in diameter and 1.65 cm in height were prepared using ten (10) grams of ash samples from dairy manure. Initially 16 samples were prepared for dairy manure and these were exposed to temperature settings of 550, 600, 700, and 800°C for four (4) hours using a completely randomized statistical experimental design. The compressive strength of the pellets was determined (after exposure) for three replicated samples using the same MTS Model 810 Material Stress Test System. The relationship between compressive strength of the pellets at various temperatures was plotted to determine the temperature at which the ash in the sample melted. This would indirectly indicate the slagging and fouling tendencies of dairy manure ash samples. When a mixture of material (in this case ash components) melts (called its eutectic point), the components crystallize exhibiting a brittle plastic range providing weak compressive strength. This behavior was then used to determine the melting point of the inorganic ash components in the biomass.

RESULTS AND DISCUSSIONS

In 2008-09, several manure gasification tests were conducted using the TAMU fluidized bed gasifier (Figure 1). Some of the tests were conducted during optimization of the control system that hindered the collection of other necessary technical data. Other tests were solely for generating consistent product synthesis gases and char. Figure 2 shows the corresponding display of the control system showing operational parameters.

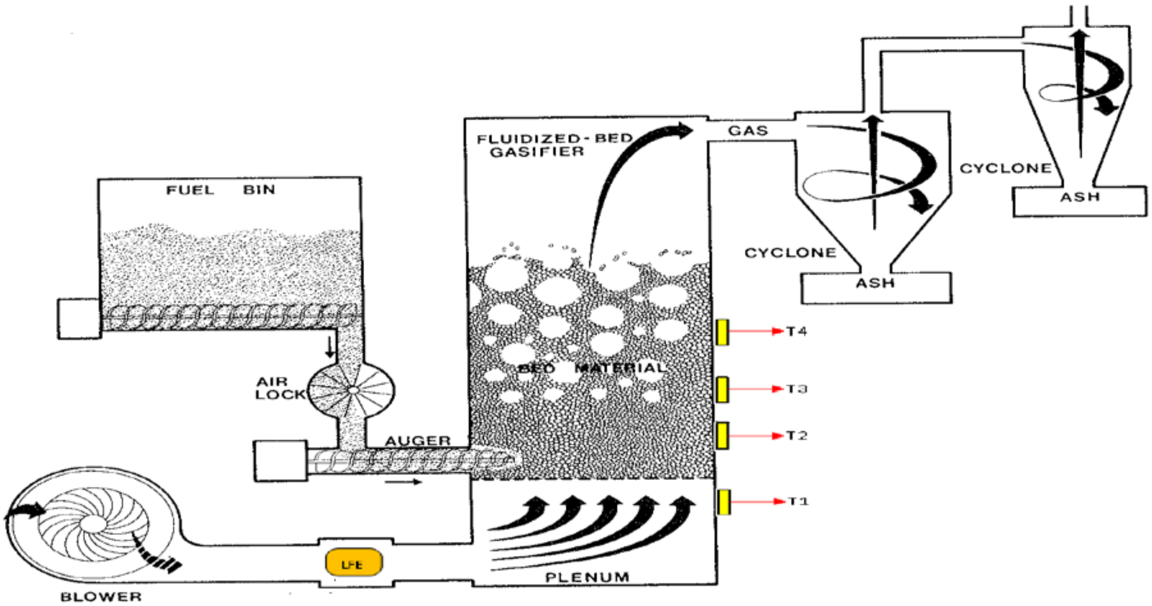

Figure 1. Schematic of the TAMU fluidized bed gasifier showing location of temperature sensors.

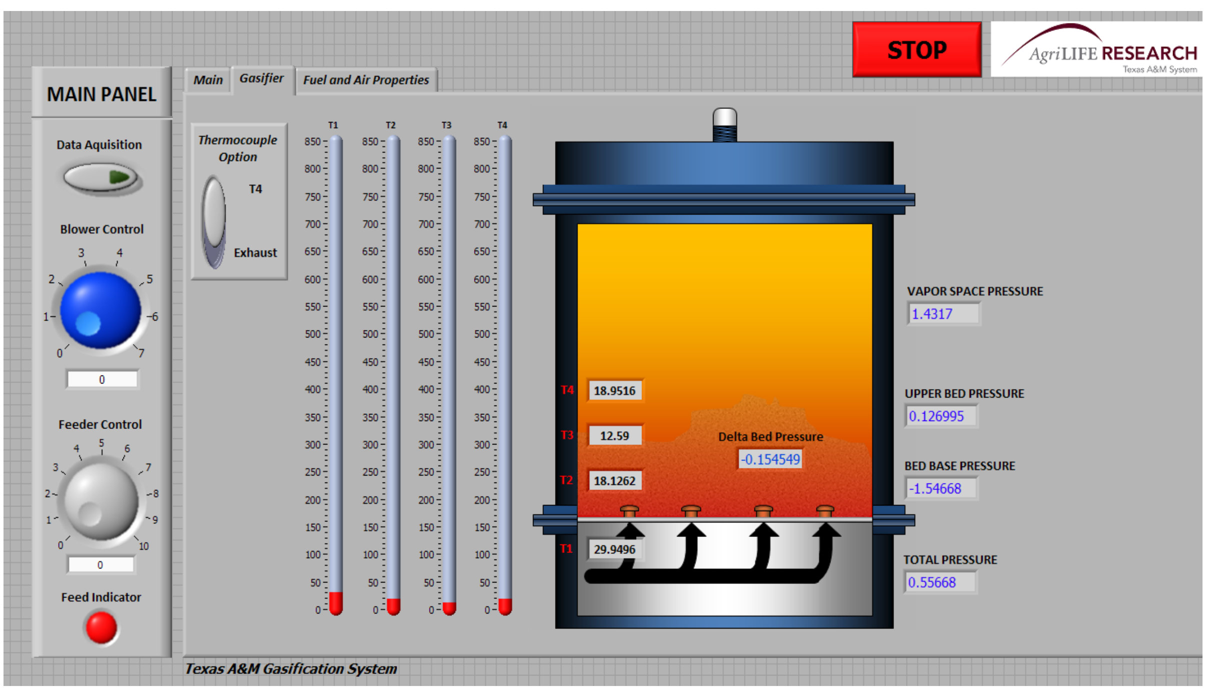

Figure 2. Schematic of the display for the control system showing operational parameters.

Manure Characterization

Table 1 shows the properties of dairy manure used in the experiments. The heating value of 15.93 MJ/kg is typical of most agricultural residues. Succeeding experiments were conducted using relatively dry manure of close to 10%. The proximate analysis showed volatile combustible matter of 59%, a rather high ash content of 29.8%, and fixed carbon was 11.15%. The ultimate analysis is shown in Table 2 and this was the basis for the establishment of the representative chemical formula for the dairy manure as shown in Equation 1.

Eq. 1

The above equation was used to estimate the stoichiometric air to fuel ratio shown in the table on a dry-ash free basis of 17.5. During gasification experiments, an air to fuel ratio of approximately 1.5 was used.

Table 1. Properties of the animal manure feedstock used in the experiment

BIOMASS	***Manure***
Moisture content, %	13.08 ± 0.54
Heating Value (dry basis), MJ/kg	15.93 ± 0.26
Proximate Analysis (dry basis), %	
Volatile Combustible Matter (VCM)	59.05 ± 0.39
Ash	29.80 ± 2.80
Fixed Carbon	11.15 ± 2.92
Ultimate Analysis (dry ash free basis), %	
C	43.5
H	6.19
N	2.19
O	47.63
S	0.49
Stoichiometric Air to Fuel Ratio (daf)	
mol/mol	17.5
kg/kg	5.00

Table 2. Ultimate analysis of dairy manure

Ultimate Analysis (%)	***Manure***
Drying Loss	13.26
Carbon	35.40
Hydrogen	5.04
Nitrogen	1.78
Oxygen	38.76
Sulfur	0.4
Ash	18.62

First Manure Gasification Experiment - Conducted on July 9, 2008

During this initial experiment, we analyzed the moisture content of the manure and found it to be around 50.5%. We set the gasification operating temperature at approximately 76°C (1400°F). We started feeding at approximately 540°C (1000°F), but encountered problems. We failed to increase the operating temperature with partial thermal conversion of the wet manure. This was primarily due to the very high moisture content of the manure (50.5%). We adjusted the feeding rate to maintain an average operating temperature of around 700°C (1300°F) as shown in Figure 3. We were not able to sustain the operating temperature at 1400°F without the use of the natural gas burner. We failed to measure appreciable amounts of combustible synthesis gas. Thus, in succeeding runs, we ensured that the moisture content of manure was set close to 10%.

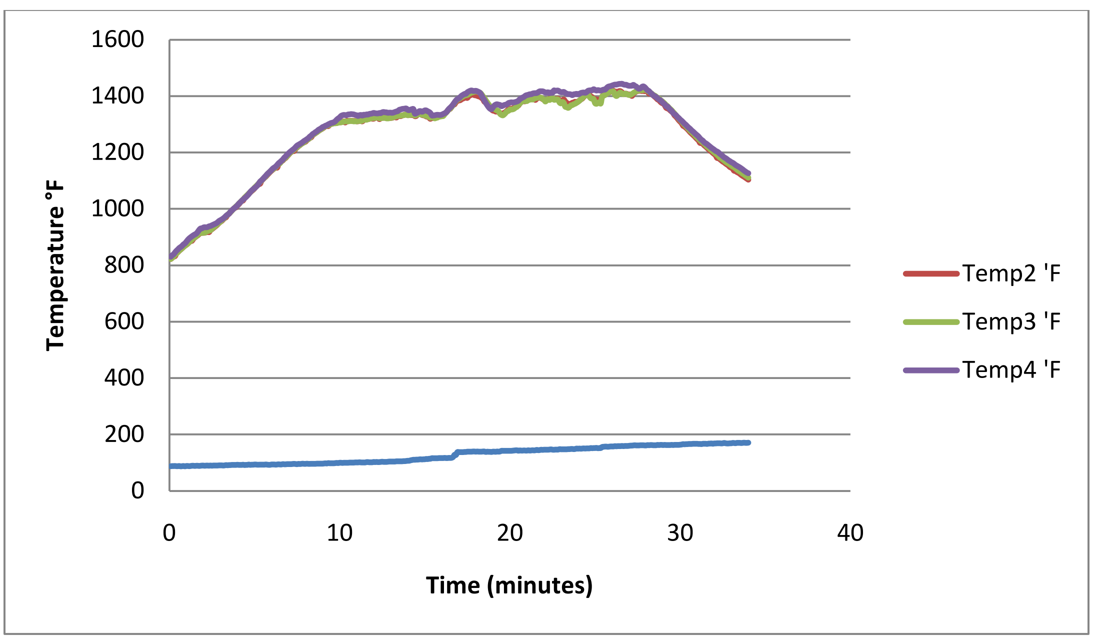

Figure 3. Temperature profile during the initial gasification of animal manure.

Manure Gasification Experiment Conducted on October 24, 2008

A gasification experiment was conducted on October 24, 2008 using multiple feed stocks. The parameters used during the operation of dairy manure are shown in Table 3. This experiment demonstrated the use of multiple feed stocks without shutting down the system. We started gasifying woodchips followed by switch grass and dairy manure. The temperature profile during the experiment is shown in Figure 4. The synthesis gas composition is shown in Table 4. Gas analysis was made using the old gas sampling system. Clogged pipes and leaks prevented proper gas sampling. Adjustments were made during future experiments to have a good estimate of the gas composition.

Table 3. Parameters used during gasification of animal manure at an average operating temperature of 1390°F.

Laminar Flow Element	1.088	inches of water
Average Air Flow Rate	**54.4**	**Cfm**
Mass per bucket	13.25	Lbs
Manure run time	34	Minutes
Estimated Mass flow rate	**2.34**	**lbs/min**
Estimated Mass flow rate	**63.7**	**kg/hr**

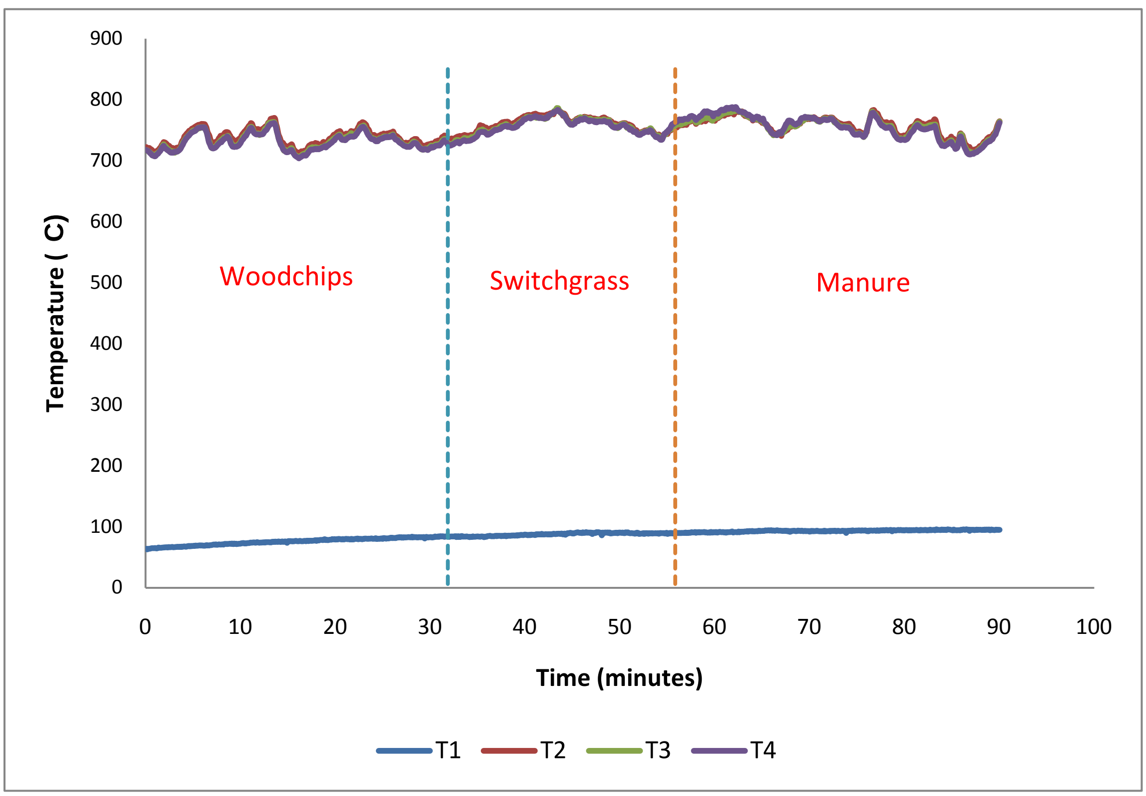

Figure 4. Gasification of various biomass feed stocks (woodchips, switchgrass, and dairy manure).

Table 4. Synthesis gas composition from gasification of animal manure.

Syngas Composition				
CO	CO2	THC	O2	H2
2.58	2.37	1.66	17.25	1.09
1.92	1.56	1.38	18.07	0.84
1.07	1.20	1.09	18.67	0.74

Manure Gasification Experiment Conducted on September 9, 2009

A gasification experiment was performed on September 9, 2009 to evaluate the new computer control system for the operation of dairy manure in the fluidized bed. The same experiment was used to generate char for eutectic point analysis. The Labview control panel display is shown in Figure 5. The temperature profile during the run is shown in Figure 6. Note that at the end of 10 minutes of heating to a temperature of 430°C (800°F), natural gas was turned off and biomass was fed into the reactor. The reactor temperature started to increase after 10 minutes of the run until the reactor temperature of 760°C (1400°F) was reached. This reactor temperature was maintained until the end of the experiment.

The bulk density of the material used was 265 kg/m3 (16.5 lb/ft3). The loading factor used in the screw conveyor was 0.49 corresponding to the actual feed rate used during the experiment.

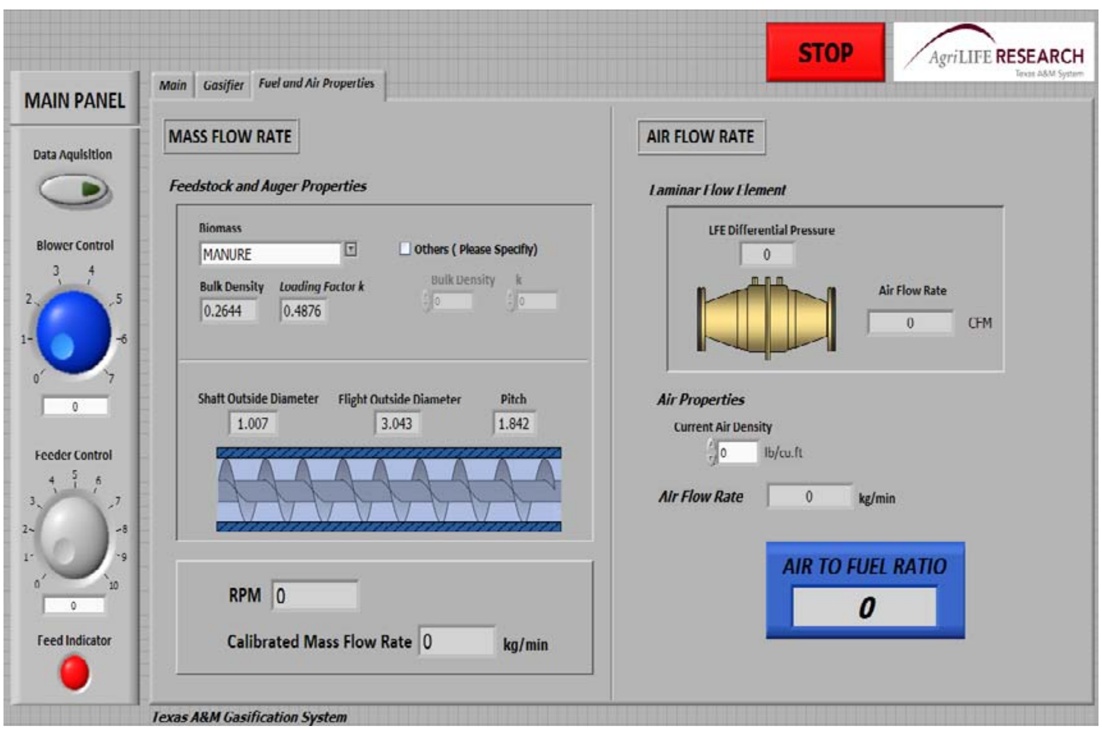

Figure 5. Labview control panel display used during testing of animal manure.

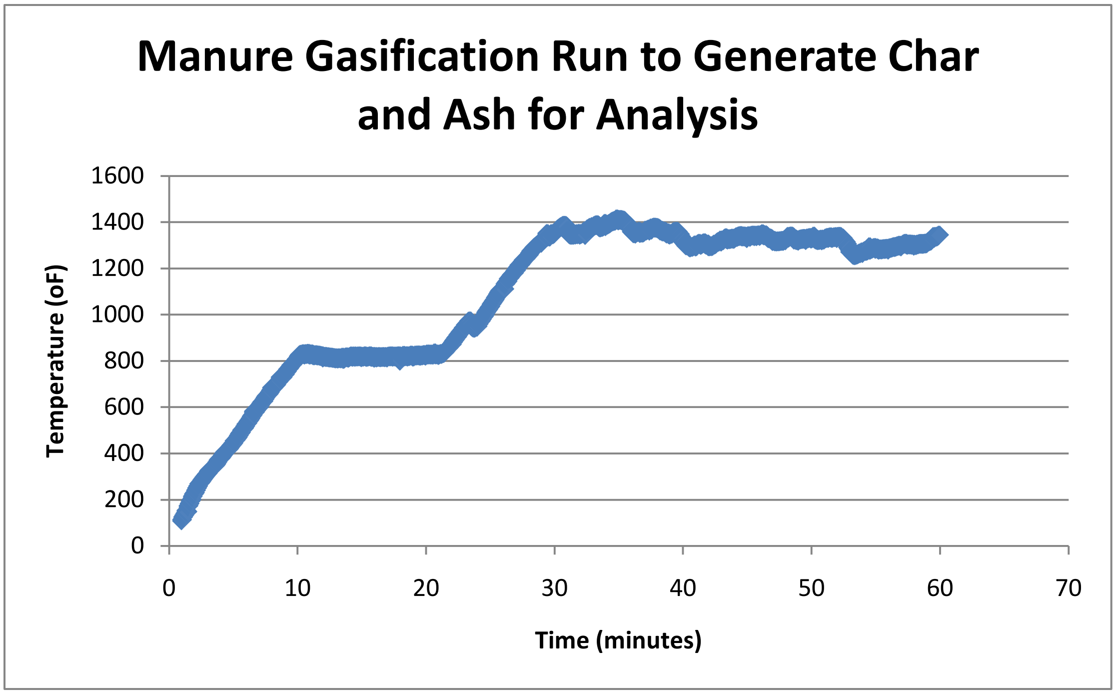

Figure 6. Temperature profile for manure gasification to generate char and ash for analysis.

Experiments Using a Higher Gasification Temperature

We attempted to perform an experiment to test the performance of dairy manure at a higher gasification temperature of approximately 815°C (1500°F). The reactor was heated to approximately 450°C and animal manure was fed until the reaction temperature was 815°C. This was maintained for several hours and the reactor was shut down, cooled, and the bed material was inspected after the run. The photo of the reactor bed in Figure 7a shows sag formation in the reactor. When the bed material was cleaned, we collected a bag of different-sized agglomeration of the ash.

a. Slag formation in reactor **b. collected slag after a day of experiment**

Figure 7. Photo showing slag formation during gasification at very high reaction temperature.

Determination of Slagging and Fouling Indices for Dairy Manure Ash

Formation of ash deposits in reactors similar to the fluidized bed as shown earlier referred to as slagging and fouling, is one of the biggest problems for thermal conversion of high-ash biomass such as animal manure. The only way to avoid slag formation is to identify the melting point temperature (or the eutectic point) of the ash present in the biomass and thermally convert the material below this temperature. The complete inorganic ash analysis for the dairy manure ash is shown in Table 5. The different slagging and fouling indices evaluated were shown in Table 6. The alkali index (AI) showed that slagging and fouling potential is certain to occur during combustion. The base -to-acid ratio (Rb/a) was more than unity and indicated an increase in fouling tendency, while the bed agglomeration index (BAI) showed that bed agglomeration will occur during combustion. These calculations validated the physical formation of slag from experiments conducted at very high reactor temperature. Note that the slagging and fouling indices used for coal (Rf and Rs) showed that this material has very low slagging and fouling potential, which is contrary to physical evidence shown and the indices described earlier. The R_s and R_f factors are normally not recommended for lignites, with which most agricultural biomass have similar characteristics.

The determination of the actual melting point of ash in the dairy manure may be measured using the results of the compressive strengths of the ash pellets exposed at various combustion temperatures. The results are shown in Figure 8 and indicate that the ash in this manure sample will melt around 600°C (1112°F). This temperature was lower than the gasification temperature used and thus, slagging formation is expected to occur even during gasification experiments.

Scanning electron microscopy photos of manure ash exposed at various combustion temperatures is shown in Figure 9. The electron microscopy images indicate the bonding behavior and granular structure of the ash samples at various furnace exposure temperatures. As shown in the figure, the dairy manure ash already showed bonding or fused state even at a lower exposure temperature of 550^oC. As the exposure temperature increased, even more agglomeration of the particles was seen.

Table 5. Complete Inorganic Analysis of Dairy Manure Ash

Ash Analysis (%)	*Dairy Manure Ash*
Al_2O_3	3.12
CaO	27.41
Fe_2O_3	1.84
MgO	10.90
MnO	0.14
P_2O_5	4.98
K_2O	5.28
SiO_2	32.46
Na_2O	1.82
SO_3	6.12
TiO_2	0.22
Total	94.29

Table 6. Calculated slagging and fouling indices of the ash from manure and cotton gin trash

Slagging and Fouling Index	*Manure Ash*	*Slagging and Fouling Potential/Degree*
Alkali Index	0.95	*> 0.34 certain to occur*
Base to Acid Ratio	1.32	> unity – the fouling tendency increases
Rf (Fouling Factor)	0.02	*< 0.2 Low*
Rs (SlaggingFactor)	0.08	*< 0.6 Low*
Bed Agglomeration Index	0.26	*Bed agglomeration occurs when index < 0.15*

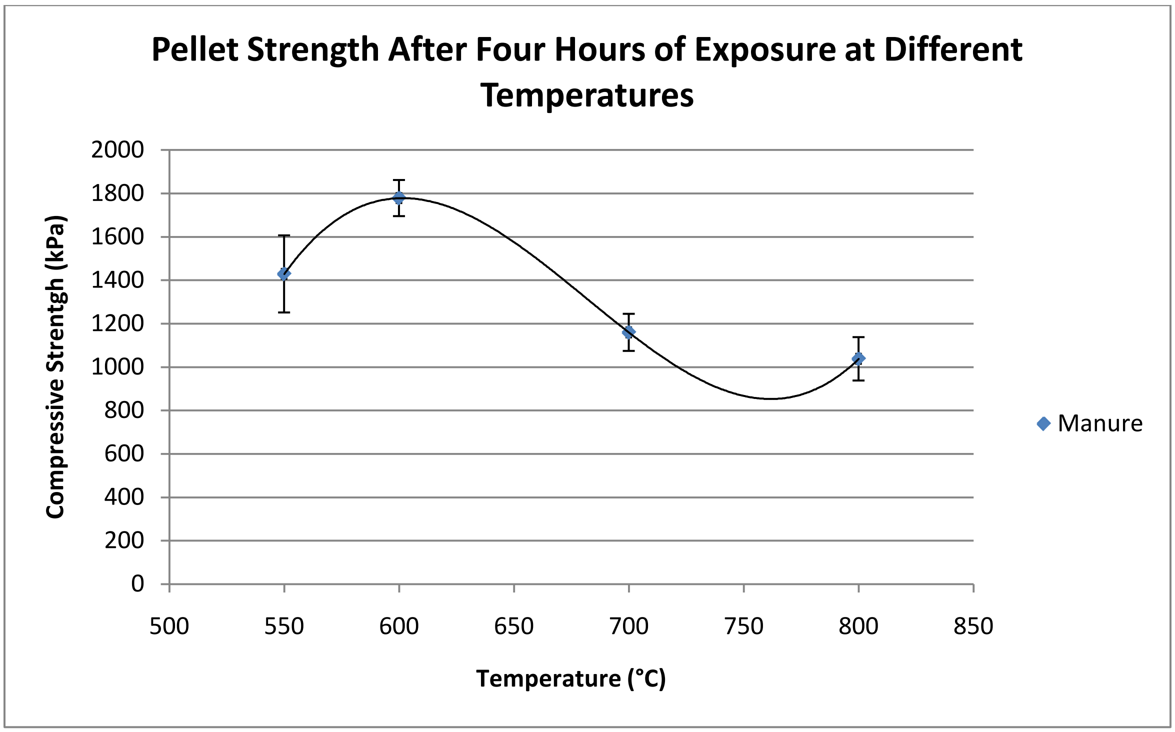

Figure 8. Eutectic point analysis for animal manure ash showing melting point of ash at 600°C.

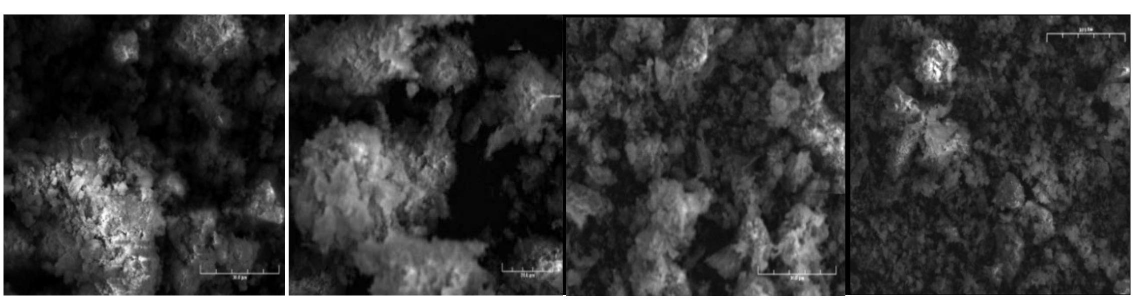

Figure 9. SEM pictures of manure ash at 1200x

Final Gasification Experiments

New dairy manure samples were acquired from the cooperating dairy located near Comanche, Texas. The manure was carefully selected to limit the ash content. The samples were carefully taken from the solids separator system with compost as bedding. The final ultimate analysis is shown in Table 7. The ash content was quite low at 7.73%.

Final gasification experiments were made to establish the operational parameters as well as average composition of synthesis gases. A newly redesigned fluidized bed gasifier was used (Figure 10). The synthesis gas was simply flared after the measurement of gas composition. Figure 11 shows the temperature profile during experiments to establish the range of gasification temperature that may be used for dairy manure. We observed that we can continuously operate the gasifier between 700-800°C (1300-1470°F). Figure 12 shows the pressure profile.

Table 7. New ultimate analysis of dairy manure samples used during final gasification experiments.

Dairy Manure Ultimate Analysis	Composition (%)
Carbon (C)	47.79 + 0.43
Hydrogen (H)	5.54 + 0.14
Oxygen (O)	36.87 + 1.38
Nitrogen (N)	1.71 + 0.30
Sulfur (S)	0.36 + 0.03
Ash	7.73 + 1.05

Figure 10. The photo of the TAMU fluidized bed gasifier used in the experiments and mounted on 2.44 m x 6.1 m skid (8 ft x 20 ft).

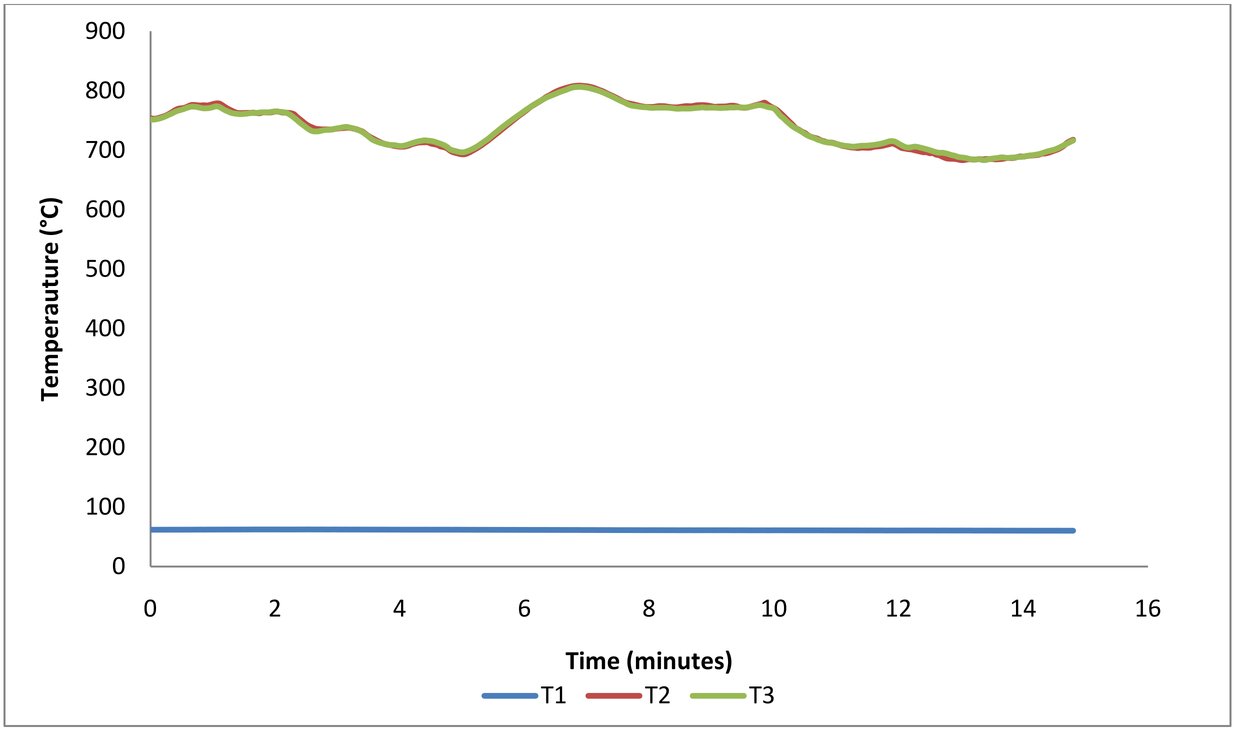

Figure 11. Typical temperature profile during gasification of dairy manure.

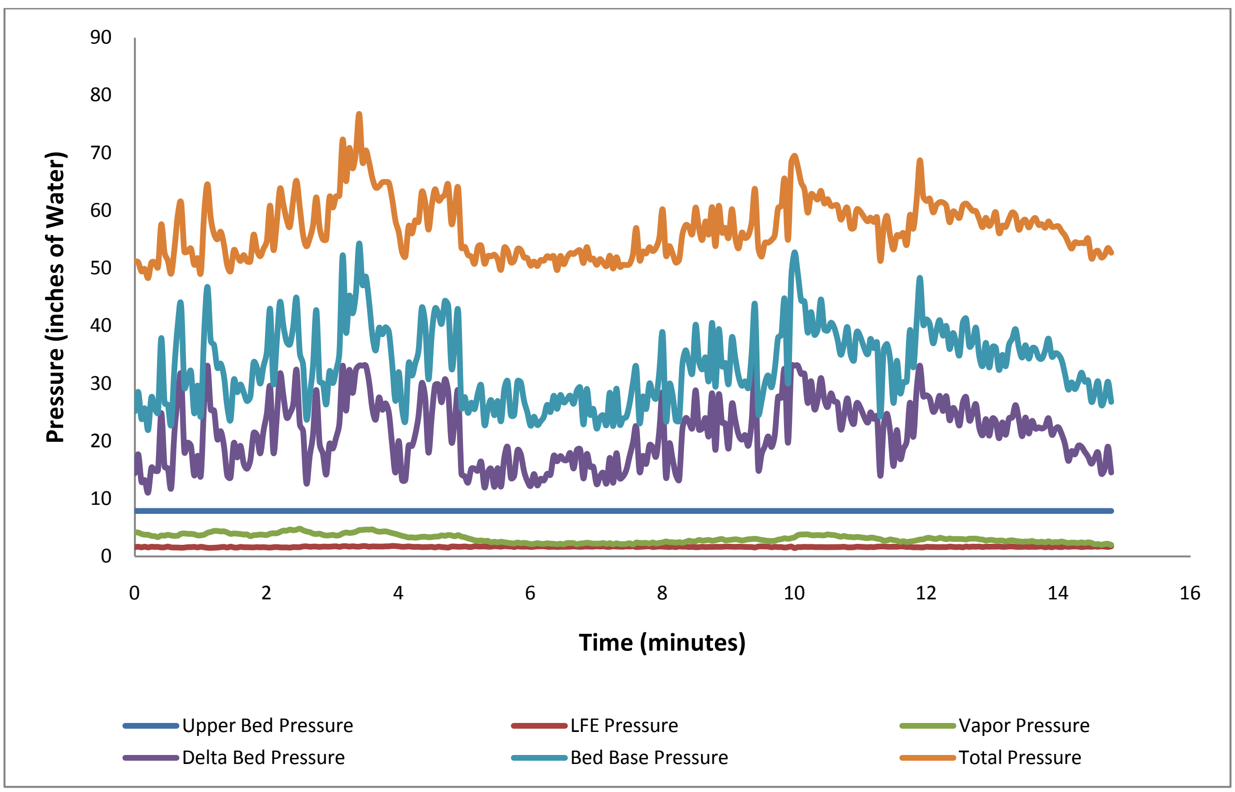

Figure 12. Pressure profile during gasification of dairy manure.

Synthesis Gas Production from Dairy Manure

Table 8 shows the typical synthesis gas composition during the final gasification experiments. We did not report the data for a much higher temperature range of 800°C (1472°F) due to difficulty in maintaining both the temperature and uniform pressure through the reactor bed. The heating value of synthesis gas was 4.2 MJ/m^3 at an operating temperature of 730°C. The gas yield at this temperature was 2.11 m^3/kg. Around 56% of the energy was contained in the synthesis gas and 24% was contained in the char. The energy used to sustain gasification was around 20% and considered heat losses. This energy may also be used for drying purposes. Char yield was approximately 20% with an energy content of around 19 MJ/kg.

The TAMU 30 cm pilot fluidized bed gasifier has a throughput of 1.6 tonnes/day. At the above rates of synthesis gas production and at a conversion efficiency of a mere 15% in gas engines, we expect to generate at least 25 kW of electrical power output.

A newly fabricated fluidized bed gasifier is shown in Figure 12, which is being prepared for demonstration and commercialization purposes. Complete technical drawings have been made (Figure 13) and a provisional patent has been filed.

Table 8. Synthesis gas production using animal manure (dairy)

Synthesis Gas Production	***Manure Gasification at***	
	730°C	***750°C***
Hydrogen	7.72	8.23
Methane	4.38	4.13
Carbon Monoxide	10.92	10.45
Ethane	0.43	0.40
Nitrogen	56.67	57.32
Oxygen	3.40	3.15
Carbon Dioxide	14.18	14.11
Heating Value, MJ/m^3	4.19	4.08
Gas Yield, m^3/kg biomass	2.11	2.17
Gas Production, kg/min	5.35	5.41
Carbon Conversion Efficiency (STP),%	82.29	
Cold Gasification Efficiency (STP), %	51.05	
Char Proximate Analysis		
VCM	81.18	
ASH	16.20	
FC	2.62	
Char Yield (%)	20	
Heating Value (MJ/kg)	19	

Figure 13. The newly fabricated TAMU fluidized bed gasifier mounted on a trailer.

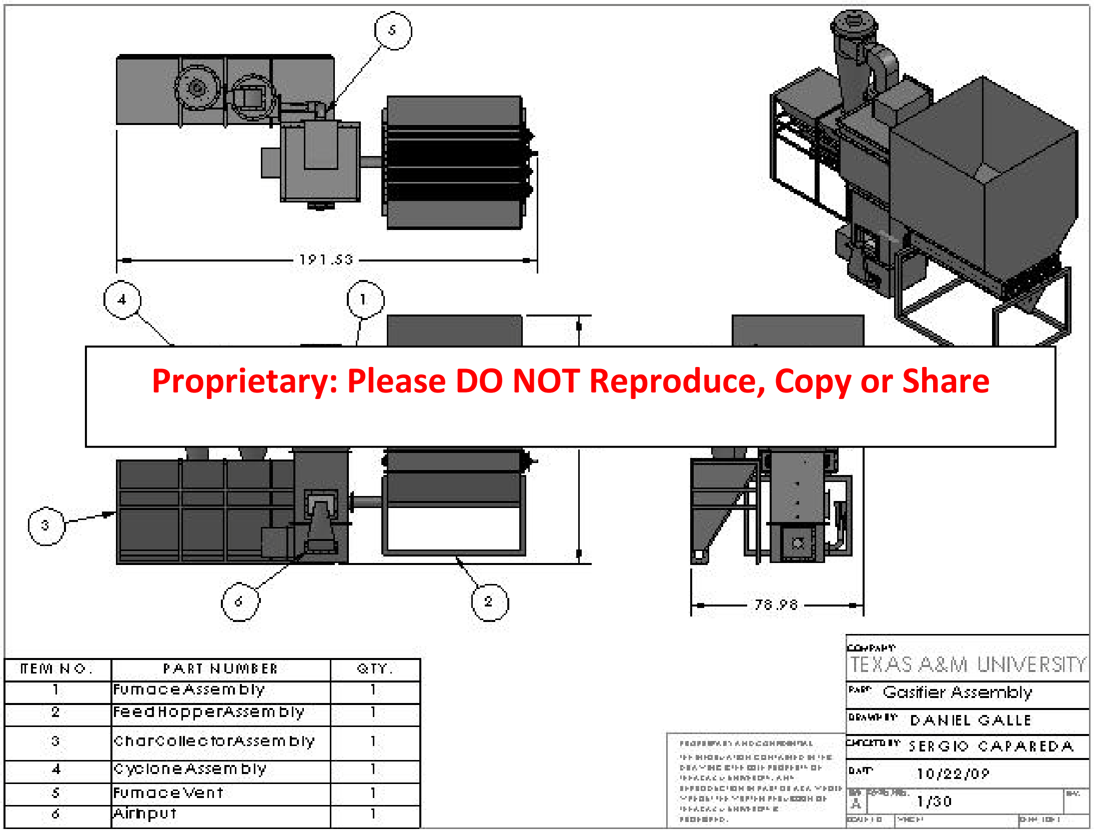

Figure 14. The completed technical drawings for the new TAMU fluidized bed gasifier.

Assembly of Skid-Mounted Pilot-Scale Anaerobic Digester

The pilot-scale anaerobic digester was designed for a feedstock consisting of the liquid portion of flushed dairy manure from which solids have been separated by screening or settling. This type of feed will generally have a solids concentration of less than 4% for which a stirred tank design is preferred. Such a design was selected for the pilot-scale digester with mixing provided by circulating the tank contents using a pump.

The digester system is shown in Figure 15. A 470 gal high density polyethylene (HDPE) tank (4 ft ID x 5 ft high) was available to use for construction of the digester. A cover was constructed from 0.5-in thick HDPE sheet, and the tank and cover were insulated with 2 in of urethane foam. The volume of biogas produced in the process is measured by water displacement using a 120 gal HDPE tank inverted in a 170 gal tank filled with water. Biogas produced in the digester flows through a pipe that discharges inside the inverted tank causing it to rise in the water. The volume of biogas collected above the water level is measured along with the temperature and pressure of the biogas to allow correction of the measured volume to standard conditions. As the biogas is discharged from the tank, its composition is measured using a non-dispersive infrared gas analyzer.

A heat exchanger coil constructed from 0.5-in pipe was fabricated and placed inside the digester tank. Hot water heated by a small water heater is circulated through the coil to maintain the digester temperature. Operation of the system was partially automated using a data logger/controller. The entire system is mounted on a 5 ft x 8 ft skid to allow transportation to demonstration sites. Initial testing of the system is currently underway using flush water from a local commercial dairy.

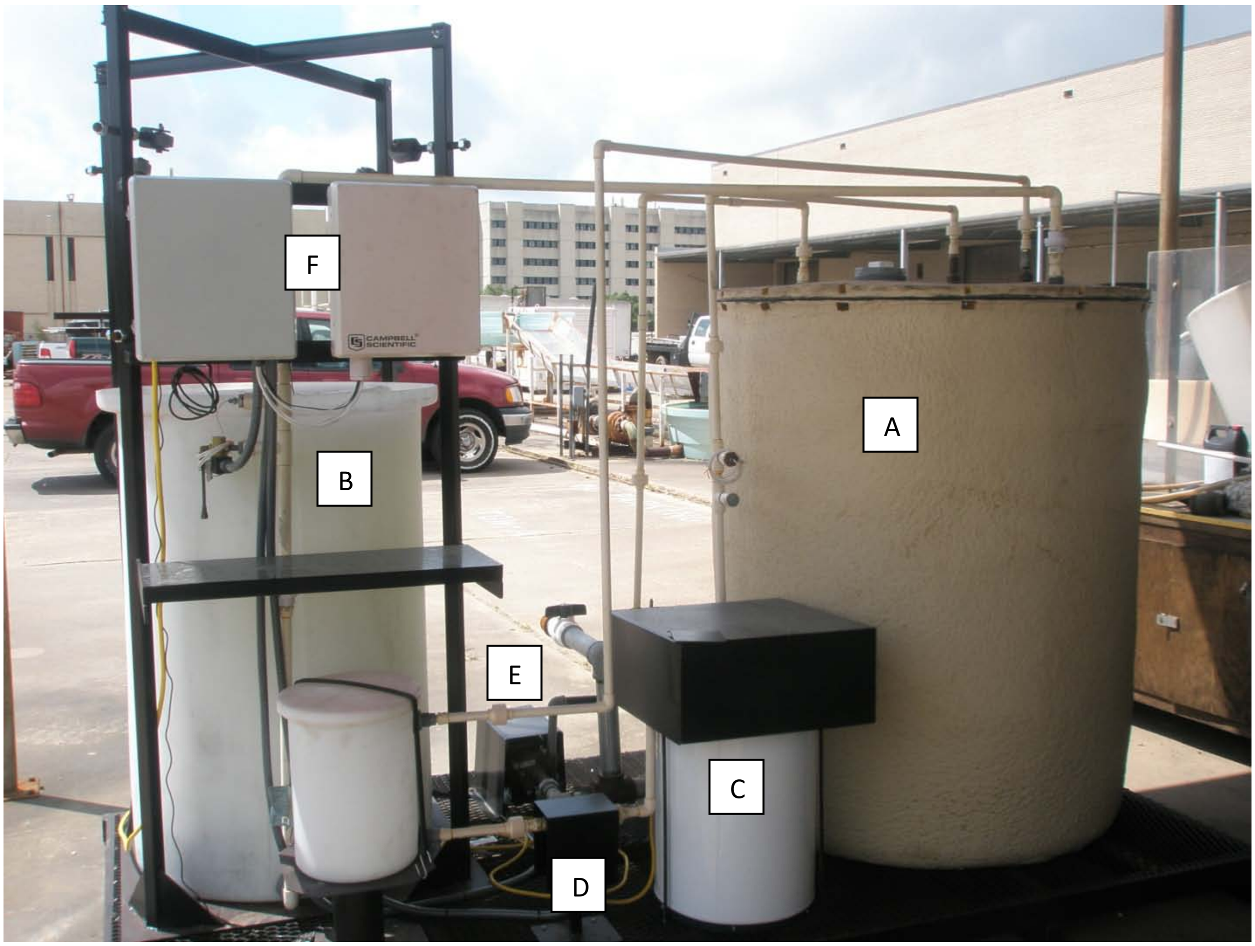

Figure 15. Skid-mounted pilot-scale anaerobic digester and gas collector system including the digester (A), gas collector (B), water heater (C), hot water circulating pump (D), digester circulating pump (E), and data logging and controls (F).

CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated the feasible conversion of animal manure in a fluidized bed gasifier. A low calorific value synthesis gas can be continuously produced with a heating value of around 4.2 MJ/m^3 (113 Btu/ft^3) or about one tenth the quality of natural gas. The gas was combustible and may be used to generate heat and power. About 20% of the feed input was converted into char with an average heating value of 19 MJ/kg (8186 Btu/lb). Around 55.6% of the energy from the manure was converted into combustible gas and 24% of the energy remained in the char. The char may be recycled back into agricultural soil or used as material for making activated carbon adsorbent.

We determined the eutectic point temperature of the manure ash. We found this to be around 600°C (1112°F). This indicates that at the gasification temperature of 760°C (1400°F) some ash materials contained in the biomass would have melted in the reactor bed and may either be retained in the reactor or removed through the series cyclones. Thus, care should be observed even with the low gasification temperatures using during gasification experiments. It will be difficult for this manure to be thermally converted using the high temperatures of combustion processes. The normal combustion temperatures run from 1000-1500°C (1800-2700°F). At these temperatures, the ash constituents in the manure will start to melt, potentially causing problems in the reactor. (See previous photos of manure slag in this report.)

The low calorific value gas may be used as fuel for power generation. Perhaps the most cost-effective option is to clean, cool, and upgrade the heating value of the synthesis gas. This high energy synthesis gas may be used as fuel for natural gas-type engine-generator. For a 30 cm fluidized bed gasifier with a throughput of 1.6 tons/day, an estimated 25 kW of electrical power may be produced using a conversion efficiency of only 15%.

A patent application was filed for the new TAMU fluidized bed gasifier. A new mobile unit was fabricated and installed on a trailer and is ready for demonstration and commercialization.