NTRD Program Disclaimers

1. Disclaimer of Endorsement:

The posting herein of progress reports and final reports provided to TCEQ by its NTRD Grant Agreement recipients does not necessarily constitute or imply an endorsement, recommendation, or favoring by TCEQ or the State of Texas. The views and opinions expressed in said reports do not necessarily state or reflect those of TCEQ or the State of Texas, and shall not be used for advertising or product endorsement purposes.

2. Disclaimer of Liability:

The posting herein of progress reports and final reports provided to TCEQ by its NTRD Grant Agreement recipients does not constitute by TCEQ or the State of Texas the making of any warranty, express or implied, including the warranties of merchantability and fitness for a particular purpose, and such entities do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information,apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights.

Pyrolysis, Ignition, and Fuel Characteristics of Coal, Feedlot Biomass and Coal: Feedlot Biomass Blends

Task 1: Fuel Properties

Kalyan Annamalai
Brandon Martin
Mechanical Engineering, Texas Engineering Experiment Station
Texas A&M University
College station, TX 77843
And
John M. Sweeten
Kevin Heflin
Texas Agricultural Experiment Station
Texas A&M University Agricultural Research and Extension Center
Amarillo, Texas 70106

The preparation of this report is based on work funded in part by the State of Texas Through a Grant from the Texas Commission on Environmental Quality.

Submitted to
Texas Commission on Environmental Quality
Austin, Texas 78711
March 31, 2006

Abstract

About 110 million tons of dry animal manure is produced annually in the United States, which presents a difficult disposal problem in many watersheds and air shed. A possible solution is to develop an animal waste utilization technology through co-firing, use as a reburn fuel, and gasification. In order to efficiently utilize these potential fuels, they must be analyzed to determine their fundamental combustion properties such as chemical composition, heating value, activation energy, and ignition temperature. This report focuses on the properties of four types of animal waste, henceforth called feedlot biomass or FB to emphasize its potential fuel use. FB fuels will not likely be used as primary fuels but as supplementary mixed fuels for emission control; therefore, mixtures of feedlot biomass with coal were also tested. Pure coal was also tested for comparison. Experiments were performed using a thermogravimetric analyzer to generate a mass vs. temperature trace in both an inert environment as well as an oxidizing environment. The results from this testing were then evaluated to determine the activation energies and ignition temperatures for the biomass samples as well as coal and FB: coal blends.

1. Introduction

As of a 2002 census by the US Department of Agriculture, there are 33.4 million head of beef cattle in the US, all of which are eventually sent to a feedlot. In the Texas Panhandle region, which covers portions of New Mexico and Oklahoma, there are approximately 7.5 million head of cattle sent through feeding operations annually [5]; a $2 billion annual industry in Hereford, TX. These animals spend 90 to 180 days in the feedlots before being transported to house. On average each feedlot steer or heifer produces 2000 lb of as collected manure (30-50 % moisture) over a five month period [6], which means that it will produce 1200 lb of dry manure while in a feedlot. Currently, depending on locations, the feedlots pay $0.50 per ton to operators or farmers to haul away the waste and spread over lands as fertilizer. Typically for northern states, this application of manure is seasonal and cannot be done during the winter when the soil is frozen or during the summer when no crops are planted. The cost burden of disposal of this waste, which must be done during the short, early spring and fall seasons, have spurred research into environmentally friendly and economically viable means of disposal. One such disposal method is the use of manure as a fuel, henceforth referred to as Feedlot Biomass (FB). Panda Energy, a Dallas company, plans to produce ethanol from grain with heat energy generated from combustion of FB (100 million gallons per year) [7]. The plant will also produce a protein rich residue called distillers grain for feed as ration to animals.

This report focuses on the fuel properties of FB as a stand alone fuel or as blended in various ratios with coal. This report is divided into two parts: Thermo-chemical properties and Thermo-decomposition characteristics. Thermo-chemical properties include fuel and mineral matter composition as well as heating values of four types of FB as well as two types of US domestic coal. Thermo-decomposition characteristics include pyrolysis and ignition characterization (i.e. calculation of activation energies and ignition temperatures of various types of FB and coal: FB blends.)

2. Objectives

The goal of this research is to evaluate how each type of biomass and biomass blend relates to coal because coal combustion mechanics have been extensively studied related to utility boilers. The fuels being considered are High Ash Raw Manure (HARM), Low Ash Raw Manure (LARM), High Ash Partially Composted Manure (HAPC), Low Ash Partially Composted Manure (LAPC), and Texas Lignite Coal (TXL). Low ash samples of each FB were gathered from fly ash surfaced, while high ash samples had a soil surface. The FB samples are representative of the types of fuels which may be used in utility boilers. Fundamental pyrolysis and ignition studies were performed on pure samples and blends of each biomass with coal. This was done to generate data on the kinetics of pyrolysis because the pyrolysis behavior is closely related to the reburn combustion mechanism in a utility boiler.

3. Fuel Collection & Preparation

About 28 tons of HARM was collected for composting by July 31, 2005. It was converted into HAPC. Abut 700 lbs of HARM was coarsely ground for greenhouse drying to reduce moisture < 10 % for further grinding. Similarly, about 40 tons of LARM was collected for composting. It was coarsely ground for greenhouse drying to reduce moisture < 10 % for further grinding. By July 24, 2005 it was converted into LAPC manure. Samples of each fuel were shipped to Hazen Research Inc. to be analyzed for ultimate and

proximate analyses. More details are given in section 6. Once dried, the remaining fuels were also ground and all fuels were shipped to Texas A&M Research Facility in College Station, TX.

4. Experiment Setup

All thermal decomposition tests were performed using a TA Instruments Q600 thermal analyzer. The analyzer is capable of Thermogravimetric Analysis (TGA), ± 1% accuracy, as well as Differential Scanning Calorimetry (DSC) measurements. The scope of this paper includes results obtained from TGA only.

Setup of the thermal analyzer is straightforward. A 120 V, 60 Hz power connection is required as well as an Ethernet connection to a computer. Other required connections are for carrier gas and purge gas. The carrier gases typically used are N2 for pure pyrolysis and air for oxidation and kinetics studies, regulated below 20 psi as required by TA instruments. The purge air line is also regulated to 20 psi, but can be as high as 90 psi. A schematic of the TGA is shown in Figure 4.1.

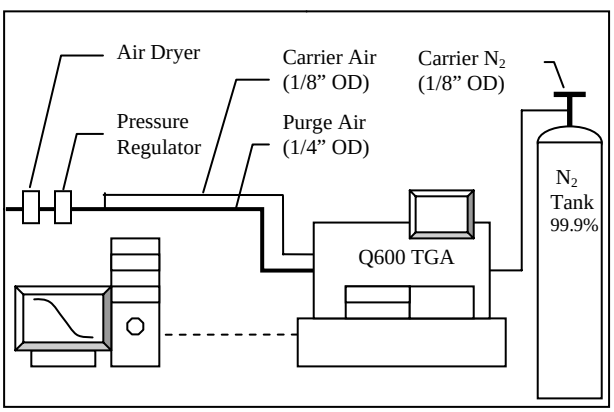

Figure 4.1: Schematic of TGA and connections.

Measurements were made using TA Instruments software and equipment calibration was performed by TA instruments personnel during the software installation prior to the beginning of testing. The Q600 has a wide range of test parameters that can be tuned for a particular test or adjusted as independent variables during testing. For the tests being conducted, temperature, time, particle size, and sample composition are considered independent variables, while weight and heat flow are dependent variables. Other possible variables include initial temperature, final temperature, heating rate, analysis gas flow rate, and sample size, which were held fixed during testing. The values for each of these parameters are given in Table 4.1. These parameters affect the shape of the temperature vs. time trace obtained from the TGA; they were chosen so that the curve fits used to analyze the data will give the best results. The details of how these values were obtained are in the procedure section of this paper.

Table 4.1: TGA Test Parameters

Test Parameters		
Initial Temp	~300 (K)	~75 (°F)
Final Temp	1373 (K)	2012 (°F)
Heating Rate	40 (K/min)	72 (°F/min)
Gas Flow Rate	50 (ml/min)	3.05 (in^3/min)
Sample Size	~10 (mg)	~3.5E-4 (oz)

5. Experiments

5.1 Sample Preparation

The four types of feedlot biomass being tested (LAPC, HAPC, LARM, HARM) were sieved to separate the sample into particle size groups. Three particle sizes were selected to show the effect particle size has on reaction kinetics, as received, 60 μm and 22.5 μm mean particle diameter. The surface mean diameters (SMD μm) of each fuel are as follows: HARM-37.48, LARM-57.54, HAPC-32.71, LAPC-56.28, and TXL-81.02 (1 mil = 25.4 μm). Once separated, each sample was mixed with Texas Lignite Coal of like particle size in the following concentrations: (TXL %: FB%) 90:10, 70:30, and 50:50. In addition, tests were conducted on pure biomass samples as well as the Texas Lignite Coal in

each size classification for a total of 51 samples.

5.2 Software Preparation

The software package included with the thermal analyzer is a windows based program that allows for easy changes to the test procedure. A typical test procedure:

1. Select Gas (1 for N_2, 2 for Air)
2. Set Gas Flow Rate to 200 ml/min (12.2 in^3/min)
3. Heat at 40 K/min (72 °F/min) to 383 K (230 °F)
4. Hold at 383 K (230 °F) for 5 min
5. Set Gas Flow Rate to 50ml/min (3.05 in^3/min)
6. Heat at 40 K/min (72 °F/min) to 1373 K (2012 °F)

The initial gas flow rate was set to 200 ml/min (12.2 in^3/min) for 5 minutes to fully clear the furnace of gaseous impurities before testing; hence, the temperature is held at 383.15 K (230 °F). This also dries the sample, ensuring that any changes in the temperature/weight trend are due to volatile losses or ignition depending on the carrier gas. The heating rate is set to 40 K/min to maximize the slope of the temperature/weight trend for calculations without causing excess equipment wear, the higher this value, the greater the slope. The heating rate could be as high as 100 K/min (180 °F/min).

5.3 Procedure for Fuel Properties

Ultimate and proximate analyses were performed on each of the five test fuels. Several fuel properties were calculated based on the results including the volatile matter, higher heating value (HHV_{VM}), mass based stoichiometric air/fuel ratio (A:F ratio), and adiabatic flame temperature (AFT).

HHV_{VM} was calculated using equation 1,

$$HHV_{VM} \cong \frac{\left(HHV - FC\% \cdot HHV_{FC}\right)}{VM\%} \qquad (1)$$

where HHV is higher heating value of "as received" fuel, FC% is the amount of fixed carbon (FC) in the "as received" fuel, HHV_{FC} is the higher heating value of the FC (= -enthalpy of formation of CO_2 / molecular weight of carbon), and VM% is the amount of volatile matter in the "as received" fuel.

5.4 Procedure for Pyrolysis

The TGA is preheated by heating the furnace to 1273 K (1832 °F) and letting it cool without a sample in the sample cups. The sample cups are alumina and have a 90 μL capacity. To begin testing, the furnace is opened, and the sample cups are checked for any residual material and cleaned if necessary. The furnace is then closed to tare the balances. The Q600 is a dual beam balance capable of measuring up to 350 mg (0.012 oz) per balance. After tarring, the furnace is opened and the test cup is carefully removed with tweezers, noting the cup orientation before removal. The test cup is nearest the front of the machine; the other cup is a reference cup used for heat flow calculations (DSC), see Figure 5.3.

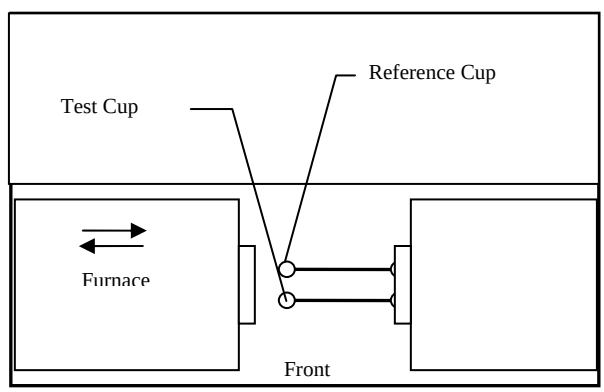

Figure 5.3: Balance Schematic

Once removed, 10 mg (3.5E-4 oz) of the sample are added to the cup. No excess material should be on the top or exterior of the sample cup as these can damage the platinum thermocouples embedded in the

balance beams. The sample cup is placed back on the beam in the same orientation. The furnace is closed and testing begins.

Using the previously described procedure, data is generated for sample mass vs. temperature or time using N_2 as the carrier gas; a sample trace is shown in figure 5.4. Region A-B represents the mass loss due to moisture evaporation, region B-C is the heating up to pyrolysis temperature, region C-D represents the primary volatile loss, and region D-E represents the remaining volatile loss. The results of the mass vs. temperature trace are then analyzed to determine the activation energy based on region C-D.

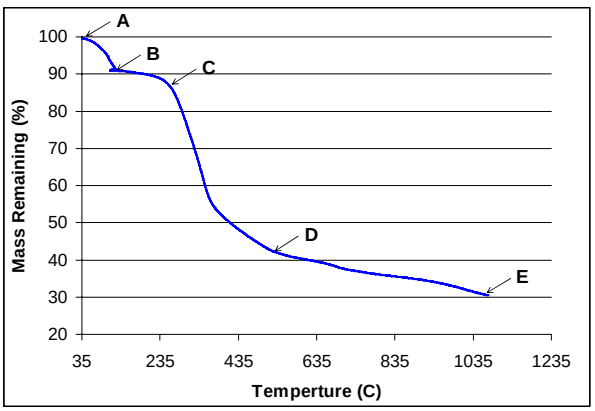

Figure 5.4: Mass vs. Temperature – LAPC (multiply °C by 9/5 and add 32 to obtain °F)

The volatile mass loss, region C-D, is modeled using a single reaction model.

$$-\frac{dm_v}{dt} = k(T) \cdot m_v \qquad (2)$$

where m_v is the mass of volatiles remaining in the sample and k (T) is given by the Arrhenius expression [1]:

$$k(T) = B \cdot \exp(-E/\overline{R}\,T) \qquad (3)$$

where, T is temperature, B is frequency factor, E is activation energy, and R is the gas constant. Activation energy and frequency factor were determined using equation 4:

$$-\ln\left(\frac{m_v}{m_{vo}}\right) = \left(\frac{B}{\beta}\right) \cdot \int_{T_o}^{T} \exp\left(\frac{E}{\overline{R} \cdot T}\right) dT \qquad (4)$$

where β is the rate of change for temperature with time (40 K/min or 72 °F/min). See Martin [3] for more details.

Method A: Approximate Method

Using an approximation for the right side of equation 4 the following equation is obtained

$$\ln\left[\ln\left(\frac{m_v}{m_{vo}}\right)\right] \cong \ln\left[-\left(\frac{B}{\beta}\right) \cdot \left(0.00482 \cdot \frac{E}{\overline{R}}\right)\right] - \left(1.052 \cdot \left(\frac{E}{\overline{R}}\right) \cdot \left(\frac{1}{T}\right)\right) \qquad (5)$$

The activation energy was found from the slope of $\ln(\ln(m_v/m_{vo}))$ vs. 1/T.

Method B: Rigorous Method

Due to the limited range of equation 5, a second solution method was used. Equation 3 can be directly integrated, and the solution is given in terms of an exponential integral [2]. See Martin [3] for more details.

Values for activation energy and frequency factor were found iteratively and used to obtain a calculated value of m_v/m_{vo} for a range of temperatures representing the primary volatile loss, see Figure 5.6

5.5 Procedure for Ignition

The procedure for the ignition temperature calculations are the same as for pyrolysis with one exception. Testing is performed using air as the carrier gas instead of nitrogen. The mass vs. temperature traces for the nitrogen tests and air tests are then compared to determine the ignition temperature.

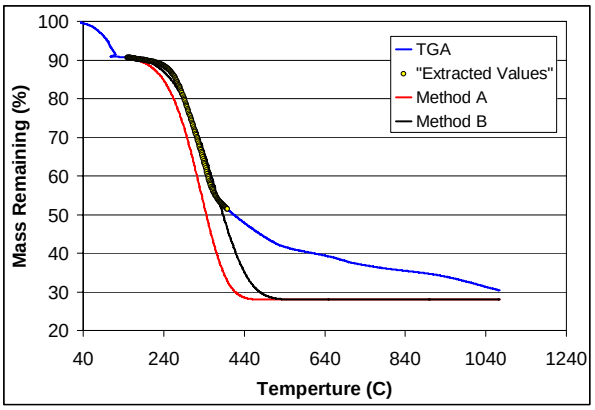

Figure 5.6: Mass Remaining vs. Temperature with Activation Energy Solution Methods: LAPC (multiply °C by 9/5 and add 32 to obtain °F)

The ignition temperature is the point at which the mass vs. temperature traces for N_2 and air deviate. For the mass loss traces obtained during testing, ignition is defined as the point at which the difference between the moisture normalized traces begin to deviate by more than 5% of the average value at that point and continue to deviate thereafter.

$$\frac{(m\%)_{N2} - (m\%)_{air}}{\left[\frac{(m\%)_{N2} + (m\%)_{air}}{2}\right]} > 5\% \qquad (6)$$

This is illustrated graphically as in Figure 5.7.

6. Results & Discussion

6.1 *Fuel Properties*

The FB and coal samples were analyzed for the following parameters: moisture, ash, volatile matter (VM), fixed carbon (FC) higher heating value (HHV), carbon, hydrogen, oxygen, nitrogen and sulfur. Table 6.1 presents the proximate and ultimate analyses of each of the five fuels on an as received basis. These analyses were performed by a commercial laboratory using FB fuels supplied by the Texas Agricultural Experiment Station (TAES) Research Cattle feedlots near Amarillo, TX. As seen in the table, the moisture content of the FB fuels is very similar (17 – 20%), while the ash content varies greatly between the low ash (11-16 %) and high ash (47-54%) samples. In order to determine whether the fuels are chemically similar, table 6.2 presents the proximate and ultimate analyses of each of the fuels on a dry ash free (DAF) basis.

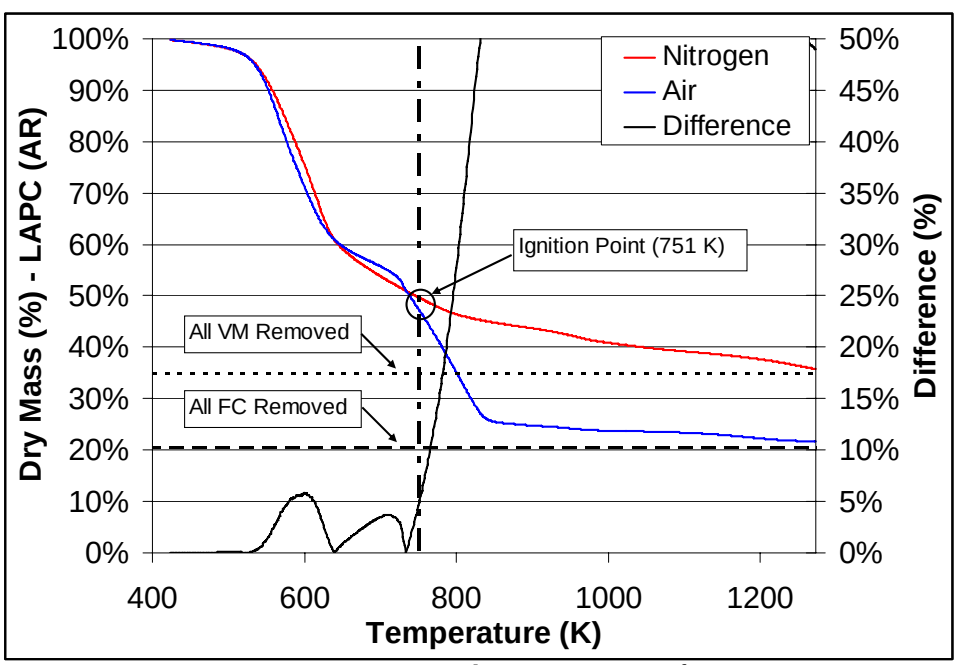

Figure 5.7: Dry Mass vs. Temperature with Ignition point Definition (Multiply K by 9/5 and subtract 460 to obtain °F)

The data in the table shows that the three of the FB fuel compositions are very similar on a DAF basis. Only HAPC differs from the other three. It has higher VM content (88.5 % vs. 81-82%) and lower FC content (12 % vs. 18-19%). The VM content of FB is about 60 % higher than that of coal.

Table 6.1: Ultimate & Proximate Analysis (As Received)

Ultimate and Proximate Analysis					
As Received (%)					
Fuel:	HAPC	LAPC	HARM	LARM	TXL
Proximate:					
Moisture	17.00	19.64	19.81	20.27	38.34
Ash	53.85	16.50	47.10	16.10	11.46
Volatile	25.79	52.33	27.08	51.47	24.79
Fixed Carbon	3.36	11.54	6.02	12.16	25.41
Ultimate:					
Moisture	17.00	19.64	19.81	20.27	38.34
Carbon	14.92	33.79	17.39	34.35	37.18
Hydrogen	1.39	3.65	2.10	4.17	2.12
Nitrogen	1.13	1.97	1.56	2.48	0.68
Sulfur	0.31	0.51	0.34	0.53	0.61
Oxygen	11.40	23.94	11.70	22.10	9.61
Ash	53.85	16.50	47.10	16.10	11.46

Table 6.2: Ultimate & Proximate Analysis (Dry Ash Free)

Ultimate and Proximate Analysis					
DAF (%)					
Fuel:	HAPC	LAPC	HARM	LARM	TXL
Proximate:					
Moisture	0.00	0.00	0.00	0.00	0.00
Ash	0.00	0.00	0.00	0.00	0.00
Volatile	88.47	81.94	81.82	80.89	49.38
Fixed Carbon	11.53	18.06	18.18	19.11	50.62
Ultimate:					
Moisture	0.00	0.00	0.00	0.00	0.00
Carbon	51.19	52.91	52.56	53.99	74.06
Hydrogen	4.77	5.72	6.36	6.55	4.22
Nitrogen	3.87	3.08	4.70	3.90	1.35
Sulfur	1.08	0.79	1.03	0.84	1.22
Oxygen	39.10	37.49	35.35	34.73	19.14
Ash	0.00	0.00	0.00	0.00	0.00

Mineral Matter

The mineral matter (mm) analyses are extremely important for high ash FB since the mm affects the deposition rate, corrosion rate, and erosion rate of heat transfer tubes. The HAFB contains almost 54% ash while lignite coal contains only 11% ash. Thus a 90:10 blend will essentially double the ash output compared to coal. Alkaline matter such as Na, K, etc. are believed to vaporize, react with SO2, and form Na2SO4, K2SO4, etc, which become sticky around 750 K (890 F). Higher alkaline oxide content results in a higher probability of fouling. Once ash is stuck to a metal surface, the oxide layers grow and are accompanied by an increase in surface temperature (as much as 1000 K or 1800 °F), which will accelerate the deposition process. The mineral analysis of ash for the fuels tested is presented in table 6.3.

Ash fusion temperatures depend upon the percent of ash acid (SiO2, Al2O3, TiO2 etc.) vs. the percent basic (Fe2O3, CaO, MgO, Na2O, and K2O etc.) [5], the higher the basic percentage, the lower the fusion temperature, which is typically lower than the adiabatic flame temperature. Alkaline oxides ranged from around 1.4 – 20 % for FB with dominant components being CaO and K2O, while for coal it is about 0.6 – 12% with the dominate compound being CaO. The highest elemental compound of manure ash is SiO2 especially for HAFB samples.

Table 6.4 gives some additional calculated fuel properties of each of the five fuels used in testing. Among these are the higher heating values for as-received and dry ash free fuels as well as the heating value of the volatile matter contained within each fuel sample. PC manure is preferable compared to FB-raw because the heating value of the fuel is stabilized. See section 5.4 for details on these fuel properties calculations.

It should be noted, that on a dry ash free (DAF) basis the higher or gross heating values (HHV) for three of the four biomass fuels are very similar (19,000-21000 kJ/kg or 8190 – 9060 BTU/lb) which agree with earlier findings [Sweeten et al, 2003]; however HAPC-FB seems to be an exception. This is due to the high ash content and differences in volatile matter and fixed carbon content of

HAPC-FB noted previously in table 6.1 and 6.2.

Table 6.3: Elemental Ash Analysis (Dry)

Elemental Ash Analysis					
Dry (%)					
Fuel:	HAPC	LAPC	HARM	LARM	TXL
SiO_2	65.55	20.78	64.68	25.55	48.72
Al_2O_3	11.20	4.94	7.72	1.94	16.04
TiO_2	0.52	0.22	0.44	0.27	0.85
Fe_2O_3	2.99	1.71	2.90	1.37	7.44
CaO	7.47	21.00	7.09	20.20	11.70
MgO	2.29	7.54	2.34	7.17	1.93
Na_2O	1.38	5.26	1.38	4.94	0.29
K_2O	4.66	14.60	4.50	12.70	0.61
P_2O_5	2.43	13.77	2.81	11.11	0.10
SO_3	1.30	4.47	1.06	4.46	10.80
Cl	0.41	5.07	0.68	5.02	<0.01
CO_2	0.51	0.59	1.35	1.71	0.08
Hg (mg/kg)	0.03	0.04	<0.01	<0.01	0.01

Table 6.4: Combustion Properties of selected fuels: AR-as received, DAF-dry ash free, VM-volatile matter

Combustion Properties						
Fuel:		HAPC	LAPC	HARM	LARM	TXL
HHV - AR	kJ/kg	5208	13268	6305	13409	14290
	BTU/lb	2239	5704	2711	5765	6144
HHV - DAF	kJ/kg	17867	20775	19052	21074	28467
	BTU/lb	7682	8932	8191	9060	12239
HHV - VM	kJ/kg	15948	18168	16041	18351	24229
	BTU/lb	6856	7811	6897	7890	10417
A:F Ratio	kg/kg	5.84	6.42	6.70	6.95	9.14
	lb/lb	5.84	6.42	6.70	6.95	9.14
Adiabatic	K	1680	2110	1652	2010	2075
Flame Temp	°F	2564	3338	2514	3158	3275

The slight differences between HAPC-FB and the other three FB fuels are also apparent in the stoichiometric A: F (air/fuel) ratio. The A: F ratio is lower for HAPC-FB than the other three fuels.

It is seen that the heating values of volatiles ranged from 16000-18000 kJ/kg (6880-7740 BTU/lb), while the HHV of DAF coal is about 30000 kJ/kg (12900 BTU/lb). The volatiles are released more rapidly in FB at lower temperatures compared to coal; consequently, the flame is expected to be more stable when firing a coal: FB blend.

The adiabatic flame temperatures of the "as received" fuels were also calculated. It has been reported that the DAF higher heating value per unit of stoichiometric air is roughly constant for most biomass fuels, 3800 kJ/kg (1634 BTU/lb) [4]. Thus, if DAF biomass fuels are fired into a boiler, they will all have similar adiabatic flame temperatures under identical air: fuel ratio conditions. Hence, variations in flame temperatures for biomass fuels are essentially due to variation in the ash and moisture contents of the biomass fuels. High ash fuels yield lower temperatures.

6.2 *Activation Energy*

Tests were performed to see the variation of activation energy with changes in volatile matter (VM) of fuel and mean particle diameter. The activation energy of each sample was then calculated two different ways in the manner described in section 4.4.

6.2.1 *Effect of VM*

Figure 6.1 shows the activation energies for "as received "pure samples of all four FB fuels as well as TXL coal using both calculation methods. The higher volatile matter fuels have higher activation energy for both solution methods.

Comparisons were made to results from a paper by Anthony & Howard [2] in which Montana lignite (MTL) and Pittsburgh seam bituminous (PSB) coals were compared using the single reaction model to validate the effect of VM on activation energy. The volatile matter percentage for each of these coals was 37.4 % (MTL) and 39.81 % (PSB) on an as received basis, with corresponding activation energies of 37.7 MJ/kmol (35.7 BTU/mol) (MTL) and 55.7 MJ/kmol (52.8 BTU/mol) (PSB). These results support the findings that higher VM fuels have higher activation energy. Direct comparison of activation energies is not warranted since different heating rates were used (650 K/min vs. 40 K/min or 710 °F/min vs. 72 °F/min), [2].

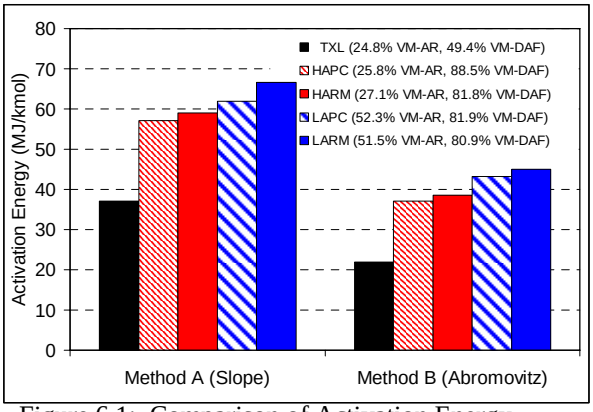

Figure 6.1: Comparison of Activation Energy Calculation Methods (multiply MJ/kmol by 0.947 to obtain BTU/mol)

6.2.2 *Effect of Particle Size*

Fuel particle size was also tested to determine its affect on the activation energy. The results for activation energy are shown in Figures 6.2. The activation energies for the particle group and the 60 µm particle group differ slightly with no apparent correlation. However, the activation energies of the 22.5 µm particle group are consistently lower than the other two groups for all the FB samples tested.

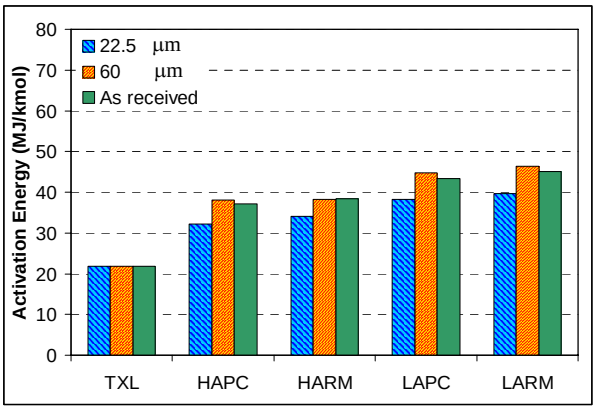

Figure 6.2: Activation energy comparison based on particle size using Method B (multiply MJ/kmol by 0.9478171 to obtain BTU/mol)

6.2.3 *Effect of Blend*

Since FB fuels will likely be blended with coal in utility applications due to the high ash content of FB fuels, various coal: FB blends were tested to determine variation of activation energy with blend composition. Figure 6.3 shows the variation of activation energy with increasing amount of FB in the blend for the as received particle size using method B for the calculations. The curvature of the plots also suggests that the activation energy of a blend is not directly dependent on the masses of fuels in the blend. A straight line would indicate a close correlation to mass.

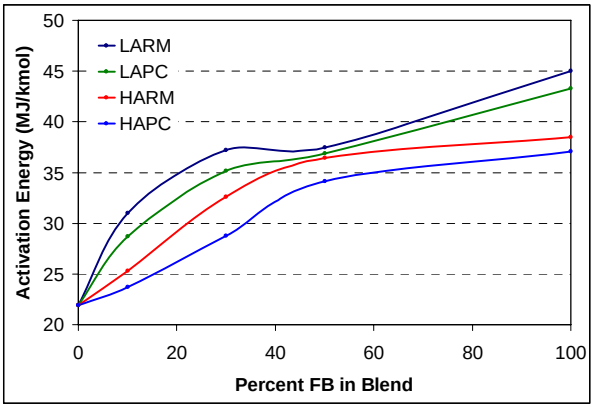

Figure 6.3: Comparison of activation energy based on coal: FB blend ratio for Method B, As Received particle size. (Multiply MJ/kmol by 0.9478171 to obtain BTU/mol)

6.3 *Ignition Temperature*

The ignition behavior of the biomass fuels was analyzed with similar independent variables as those used to analyze the activation energy behavior. The average ignition temperature for fuels with coal was 566 K (559 °F) with a standard deviation of only 2. 9 %. The only appreciable difference in ignition temperature is for biomass fuels. No matter the particle size, the average ignition temperature was 747 K (885 °F) with a standard deviation of 2.7 % for pure FB fuels. Ignition temperatures of the fuel samples for all three particle sizes are given in table 6.5.

Table 6.5: Ignition temperature of pure fuel samples (Multiply K by 9/5 and subtract 460 to obtain °F)

Particle Size:	AR	75	45
Fuel	Temperatures (K)		
LAPC	751	752	742
HAPC	733	774	787
LARM	755	728	746
HARM	715	757	726
TXL Coal	574	543	566

7. Summary

1. The DAF-HHV was almost constant, 20000 kJ/kg (8600 BTU/lb) for FB.
2. On the basis of heating value and alkaline oxide, the PC is better fuel compared to raw-FB.
3. The LA-FB (whether as RM or PC) has a much higher heating value rather than HA-FB fuels
4. The properties of ground FB are very consistent when analyzed on a dry ash free basis for HARM, LARM, and LAPC feedlot biomass with only slight differences for HAPC feedlot biomass.
5. Activation energy was seen to increase with higher volatile matter fuels.
6. Ignition temperature of blended fuels was shown to only be dependent on the presence of coal in the sample.
7. There was no appreciable difference in ignition temperature for the pure FB samples with changes in volatile matter content, fixed carbon content, or particle size.

References

[1] Annamalai K, Puri I. Advanced thermodynamics engineering. Boca Raton, FL: CRC Press; 2001. Software at www.CRCpress.com/Electronic download/Advanced Thermodynamics Engineering.

[2] Anthony DB, Howard HC, Hottel HC, Meissner HP, 1974, "Rapid Devolitization of Pulverized Coal", Fifteenth Symposium (International) on Combustion, pp. 1303-1317.

[3] Martin BR, "Pyrolysis and Ignition Behavior of Coal, Cattle Biomass, and Coal: Cattle Biomass Blends", Master's Thesis, August 2006.

[4] Sami, M., Annamalai, K., and Wooldridge, M., (2001) "Co-Firing of Coal and Biomass Fuel Blends," Progress in Energy and Combustion Science, Vol. 27, pp. 171-214.

[5] Sweeten JM, Annamalai K, Thien B, and McDonald LA. Co-firing of coal and cattle feedlot biomass (FB) fuels. Part I. Feedlot biomass (cattle manure) fuel quality and characteristics. Fuel, Volume 82, Issue 10, July 2003; Pages 1167-1182.

[6] Sweeten, JM. "Manure Management for Cattle Feedlots". Texas Agricultural Extension Service Publication L-1094, 1979.

[7] Wall Street Journal, "They Produce a Cheap fuel," Jan 24, 2006, page A1