Co-firing Coal: Feedlot and Litter Biomass Fuels

Quarterly Progress Report # 9

Grant #: DE-FG26-00NT40810

Project Name: *Feedlot and Litter Biomass Co-firing in Pulverized Fuel and Fixed Bed
Burners*

Contractor name: Texas Engineering Experiment Station, Texas A&M University

Sponsor: US Dept of Energy, National Energy Technology Laboratory

Principal Investigator: Dr. Kalyan Annamalai, Mech. Eng., Texas A&M, College-
Station, TX 77843-3123
979-845-2562
Kannamalai@mengr.tamu.edu

Other Investigators: Dr. John Sweeten, Professor of Agricultural Eng. and
Resident Director of Agricultural Extension Service,
Dr. Saqib Mukhtar, Asst. Prof., Agricultural Engineering.

Graduate Students: Ben Thien (PhD)
Gengsheng Wei (PhD)
Soyuz Priyadarsan (MS)

Quarterly Report #: 9

Report Period: 6/15/02-9/14/2002

PROGRESS REPORT # 9

A. Proposed activities for quarter 9 (6/15/2001 – 9/14/2002)

Fuel Properties: (Task 1b)

1. Submit a full paper on fuel properties to the American Society of Agricultural Engineers.

Gasification: (Task 3)

2. Complete experiments with coal and chicken litter biomass blends.
3. Determine bed ash composition for different fuels.
4. Determine the gasification efficiency for different operating conditions.

Modeling and Simulation: (Task 4)

5. Complete the modeling task (which will lead to the defense of Mr. Wei's Ph.D. thesis)

B. Achieved during quarter 9 (3/15/2001 – 6/14/2002)

1. Submitted a full paper on litter biomass fuel quality and characteristics to the 2002 ASAE Annual International Meeting, held at Chicago, IL, July 28-July 31, 2002. (Task 1b)
2. Completed the experiments with coal and litter biomass blends. (Task 3, Appendix B)
3. Determined the ash composition and ash fusion temperatures for different fuels. (Task 3, Appendix B)
4. Determined the gasification efficiency for different operating conditions. (Task 3, Appendix B)
5. Completed the modeling of pf-fired burners using the PCGC3 code. (Task 4, Appendix C)
6. The modeling of fixed bed gasifier has not been done.; however elementary reburn modeling using simulated gas mixtures has been performed (Task 4)
7. Other activities; Full papers on 1) 'Co-Firing of Coal and Broiler Litter (BL) Fuels for Power Generation: BL Fuel Quality and Characteristics' (ASAE Paper Number: 024189; see Appendix A) , 2) "Combustion Characteristics of High and Low Phosphorus Partially Composted Cattle Manure Used in Co-Fire Combustion, (ASAE Number: 026087 ; not proposed under this project)" and 3) Cattle Feedlot Manure Quality for Combustion in Coal/Manure Blends, (ASAE Paper Number: 024092) have been presented at the 2002 ASAE Annual International Meeting / CIGR XVth World Congress, Chicago, IL, July 28-July 31, 2002

C. Proposed activities for quarter 10 (9/15/2001 – 12/14/2002)

If extension is granted, the following activities shall be done

Modeling and Simulation: (Task 4)

1. If approved for modification to the proposal, the fixed bed studies modeling shall be interchanged with detailed 1D reburn model

Milestone Log- **DE-FG26-00NT40810-Annamalai-Quarter # 9; Report Period:**
6/15/02-9/14/2002.

Appendix A: Broiler Litter Fuel Quality and Characteristics

A brief summary of the presented paper on 'Co-Firing of Coal and Broiler Litter (BL) Fuels for Power Generation: BL Fuel Quality and Characteristics' (ASAE Paper Number: 024189 is presented in the quarterly report.

1a. Materials and Methods

A large broiler integrator was contacted in the study area in east central Texas to gather information on broiler production systems and to procure broiler litter and wood shavings samples for physical and chemical analyses. The bedding material (litter) used in the broiler houses is wood shavings from pine trees. The study involved freshly excreted manure (EM) without bedding, bedding material (wood shavings), cake, and cleaned out litter (CL), cleaned out litter dried to around 10% moisture (DL), coal and a blend of 90% coal and 10 percent ground DL (C90:DL10) on a mass basis. Samples of all but cake and woodcarvings were analyzed to determine heating values, moisture, ash, and proximate and ultimate analyses for these materials. Both cake and wood shavings were analyzed for moisture content only. Huffman Labs Inc., Golden, Colorado, conducted the heating value, ash analysis, and ultimate and proximate analyses for all the fuels in accordance with the Standard American Society for Testing and Materials (ASTM) methods. All samples were air dried for 24-36 hours before delivery to the lab. The relevant standards are summarized in Table 1.1. Samples were ashed in air at 750°C and ash constituents, sulfur (S), and metals were analyzed and reported as oxides (Table 1.5). The higher or gross heating value (HHV) was determined with an adiabatic bomb calorimeter. Moisture content of wood shavings, cake, and clean out litter was measured by drying to 105°C, and then weighing using Standard Methods (APHA, 1995).

Drying	D3173
C and H	D5373
N	D5373
S	D4239
ASH	D3174
Volatile matter	D3175
HHV	D5865
Ash analysis	Measured with atomic emission spectroscopy

Table 1.1: ASTM coal and broiler litter analysis standards

1b. Fuel Properties

Moisture contents of wood shavings, cake and CL biomass are presented in Table 1.2. As indicated by range and standard deviations, all materials sampled had highly variable moisture contents

Material	Average Moisture Content*, wet basis (%)	Range (%) Min-max	Standard Deviation (%)
Pine Shavings	45.32	36.26-55.14	7.36

Cake	53.65	39.43-62.84	6.47
Clean out	26.42	22.89-32.25	3.74

* Average of 10 samples per material

Table 1.2: Moisture content for pine shavings, cake and clean out litter biomass.

1c. Ultimate and Proximate Analysis

Ultimate and proximate analyses were conducted on different fuels relating to broiler litter combustion to determine the most basic fuel properties. The fuels investigated were: EM, CL, DL, Coal, and the coal and DL blend (C90:DL10). A (C90:DL10) proportion by mass was chosen to minimize the change in fuel properties from the original fuel, thereby reducing the amount of modification that may have to be made before the blended fuel can be fired in existing boiler burners.

Parameter	EM	CL	Coal	DL	(C90:DL10)
	n=5	n=3	n=2	n=2	n=2
C, %	23.62	35.33	60.30	28.44	57.10
H, %	3.16	4.43	3.62	3.71	3.63
O, %	19.02	30.48	14.50	22.80	15.33
N, %	3.11	3.56	0.96	3.04	1.17
S, %	0.30	0.61	0.23	0.66	0.27
Dry loss, %	44.07	10.94	15.12	11.62	14.77
Fixed C, %	8.02	14.45	42.38	10.92	39.23
Volatile Matter, %	41.20	60.31	37.17	50.65	38.51
Ash, %	6.72	14.38	5.33	26.82	7.47
HHV (kJ/kg)	9545	14256.93	23709.80	12065.70	22545.39

Table 1.3: Ultimate and proximate analysis (as received)

The results of the ultimate and proximate analyses for the five fuels are shown in Table 1.3. The litter-based fuels have a higher ash, higher S, higher N, and a lower heating value than coal. Higher S and N can lead to significant pollutants such as oxides of sulfur (SO_x) and nitrogen (NO_x) causing acid rain and ozone depletion. Higher moisture and ash reduce the combustible portion of the fuel resulting in lower heating values and lower flame temperatures during combustion.

In order to compare the combustible portion of the fuels, the analysis was done on a dry ash free basis, and presented in table 1.4. The litter-based fuels are very similar in regards to the combustible portion of the fuel. As the fuel is processed, the increase in ash and the decrease in dry loss have a corresponding effect on the heating value. On the other the addition of the bedding materials to the excreted manure resulted in reduction of nitrogen as the clean out litter was formed. This is due to; lower nitrogen content of the bedding material as compared to the EM, and nitrogen is loss through volatilization form the EM. The higher VM in chicken litter results in faster pyrolysis and faster burning rates as compared to coal. The increase in volatile matter has the potential to enhance combustion when using the biomass fuels. Boiler burner testing is needed to fully determine the effect of increased volatile content.

Parameter	EM	CL	Coal	DL	(C90:DL10)
	n=5	n=3	n=2	n=2	n=2
C, %	48.00	47.30	75.80	46.20	73.43
H, %	6.42	5.93	4.55	6.03	4.67
O, %	38.65	40.81	18.23	37.03	19.71
N, %	6.32	4.77	1.21	4.93	1.50
S, %	0.61	0.82	0.29	1.07	0.35
FC, %	16.29	19.41	53.27	17.73	50.45
VM, %	83.72	80.76	46.73	82.27	49.52
HHV (kJ/kg)	19396	19090	29805	19598	28994

Table 1.4: Dry ash free ultimate and proximate analysis

If a lower heating value fuel with the same amount of nitrogen by mass is used to maintain the same throughput as the higher heating value fuel then, more fuel must be fired, resulting in a higher throughput of nitrogen. The results show that the amount of ash in the litter fuels is higher than the coal. Since, the EPA regulations stipulate that NO_x and SO_x emissions not exceed 260g per GJ (0.6 lb per million BTU), the contents of S and N are expressed in kg/GJ (Figures 1.1 and 1.2). Figure 1.1 shows that the amount of N on a heat basis for biomass fuels is higher than coal. The sulfur content on a heat basis as shown in Figure 1.2, shows that the sulfur released by the biomass fuels is very high as compared to coal.

Figure 1.1: Fuel nitrogen contents on a kg/GJ basis

Figure 1.2: Fuel sulfur content on a kg/MJ basis

High levels of ash in the fuel decrease the flame temperature, decrease the heating value, and increase fouling of the boiler tubes inside the furnace leading to boiler tube corrosion. The results of ash per heat value are given in Figure 1.3. The ash of analysis of the various fuels is shown in table 1.5. Coal ash consists mainly of Calcium and silicon, while the EM and CL consist mainly of calcium, phosphorus, and potassium. The ash appears as fly ash, partially fused ash that can stick to boiler tubes, and volatilized material that can condense later and form hard deposits. As shown in table 1.5, the total volatile oxides for EM and CL are nearly twice that of coal. This may result in increased boiler fouling and corrosion (the metal loss is typically measured as 200 nm to 1000nm per hour in coal fired plants). Corrosion can be caused by high amounts of Hydrogen Sulfide under reducing conditions (oxygen starved zones) and hydrochloric acid (HCl) near furnace tube walls. For example, up to 200 ppm of HCl can occur when chlorine is about 0.25 % in the fuel (Lawn, 1987), and ash deposits can accelerate the metal loss. Further testing in an operating boiler burner is necessary to fully assess the fouling performance of the fuels.

Figure 1.3: Fuel ash content on a kg/MJ basis

	EM	CL	Coal
Parameter	n=5	n=3	n=2
Aluminum, % as Al_2O_3	0.79	1.23	16.785
Calcium, % as CaO	15.084	21.50	23.08
Iron, % as Fe_2O_3	1.484	1.06	4.33
Magnesium, % as MgO	7.472	5.9	3.625
Manganese, % as MnO	0.626	0.22	0.055
Phosphorous, % P_2O_5	24.798	25.12	0.9
Potassium, % as K_2O	26.944	16.51	0.485
Silicone, % as SiO_2	3.686	6.34	33.275
Sodium, % as Na_2O	3.724	6.52	1.725
Sulfur, % SO_3	8.326	7.23	13.19
Titanium, % as TiO_2	0.122	0.10	1.305
Total Volatile Oxides (%) CaO+ MgO+ K_2O + Na_2O	53.22	50.40	28.90

Table 1.5: Ash analysis

Appendix B: Fixed Bed Studies on CFB and CLB Fuels (Task 3)

In portion of the report, the results of fixed bed gasification experiments with litter biomass (LB), and coal: chicken litter biomass blends (CLB) shall be discussed.

2. Fuel Properties

Parameter		Wyoming Coal	Chicken Litter	CLB
Proximate Analyses (as received)	Dry loss	21.23	7.48	14.35
	Volatile Matter	32.58	40.27	36.42
	Fixed Carbon	41.92	8.42	25.17
	Ash	4.28	43.85	24.06
Ultimate Analysis (DAF Basis)	Carbon	75.63	45.14	63.58
	Hydrogen	4.76	6.06	5.27
	Oxygen	18.10	42.02	27.55
	Nitrogen	1.14	5.41	2.83
	Sulfur	0.37	1.37	0.76
Empirical formula ⁽¹⁾		CH _{1.2452} O _{0.4306} N _{0.0129} S _{0.0018}	CH _{2.0437} O _{0.9249} N _{0.1023} S _{0.0113}	CH _{1.4692} O _{0.5693} N _{0.0380} S _{0.0045}
Empirical formula (DAF) ⁽¹⁾		CH _{0.7479} O _{0.1795} N _{0.0129} S _{0.0018}	CH _{1.5947} O _{0.6981} N _{0.1023} S _{0.0113}	CH _{0.9855} O _{0.3250} N _{0.0380} S _{0.0045}
Molecular Weight ⁽²⁾ (kg/kmole)		20.39	30.66	23.27
Molecular Weight (DAF) ⁽²⁾ (kg/kmole)		15.87	26.58	18.87
Heating Value (kJ/kg) (as received basis)		21809	9235	15522
A:F _{stiochiometric} ⁽²⁾ (as received)		7.39	4.74	6.41
A:F _{stiochiometric} (DAF) ⁽²⁾		9.51	5.48	7.92

⁽¹⁾ Determined from ultimate analysis

⁽²⁾ Calculated from empirical formula

Table 2.1: Fuel Properties

The proximate and ultimate analysis of the coal, LB, and CLB fuels is given in table 2.1. The ash content of the LB is almost 10 times as that in coal, and it can play a dominant role in temperature propagation in the bed. At the same time, the fixed carbon in LB is almost 20 5 of

that of coal, implying that for a given mass of coal and LB the LB shall burn out faster owing to its higher ash and volatile matter, and lower fixed carbon content.

2b. Temperature Profiles

A detailed study of the temperature profile dynamics of litter biomass shall be done. As in the case of coal, the study shall include the effect of air flow rate and the effect of particle size on the temperature profiles in the bed.

2b.1 Chicken Litter Biomass (LB)

For chicken litter biomass (LB) particle size range between 0.25" and 0.5", figure 2.1 shows the comparative temperature profiles in the bed under different air flow rates. As in the case of feedlot biomass, chicken litter biomass also displays a distinct peak in the bed, and the rate of peak shift is relatively high when compared to the feedlot biomass case. From the figure 2.1, it is evident that the ash seems to play the most determining factor in shaping the temperature profile in the bed.

Figure 2.1: Comparative temperature profiles for LB (0.25" – 0.5") at air flow rates of 45 and 60 SCFH

After 15 minutes into the run, it is observed that the peak for both the cases occurs relatively at same locations i.e. at 3.5" above the grate. The peak for the 60 SCFH case is about 100 K higher than the 45 SCFH case. This is because of the higher burning rate associated with higher flow rates, but similar initial location of the peaks show the ineffectiveness of the convective heat transfer rates in the bed, at least in the initial stages. Comparing the temperatures at 0.5" above the grate reveals, that the temperature at that location is similar for both the cases. However, the temperature for the 45 SCFH case is slightly higher by about 25 K than the 60 SCFH case. This proves that the reaction rates for the higher flow rates are higher, resulting in

faster ash accumulation in the lower portion of the bed. Beyond the 4.0" towards the top of the bed, the temperature profiles are similar for both the cases.

After 60 minutes into the run, it is observed that the peak temperature in the case of 60 SCFH has reached the top of the bed, where as for the 45 SCFH case it lies around 5.5" above the grate. Because of the higher burning rates, resulting in higher ash accumulation in the bed, and higher air flow rates, resulting in higher convective heat transfer rates in the bed, the temperature peak shift seems to be so fast for the 60 SCFH case. The rapid movement of the temperature peak signals a higher feed rate for the 60 SCFH case, and can be inferred from figure 2.3. The higher feed rate along with a higher air flow rate seems to some how make the air fuel ratios for both the case to be similar (refer figure 2.4). In the case of 60 SCFH, the conditions in the bed are more like combustion conditions rather than gasification. This is because the ash at the bottom of the bed could not be removed from the bed, resulting in an apparent decrease in the effective bed height available for gasification. One more reason for such rapid peak shifts in the bed a can be attributed to the properties of chicken litter biomass. It was observed that during gasification, the chicken-litter biomass particles tended to stick together, though not fuse due to ash melting. This caused them to burn as a single large porous particle rather than as separate particles. This shall be discussed in the last section of this chapter under ash fusion temperatures. The clumping tendency prevented the movement of burnt particles towards the bottom of the bed, thus resulting in the more rapid movement of the oxidation zone further into the bed. In other words, in this case the downward movement of the fuel is almost negligible, thus amplifying the peak shift for these fuels. Upon checking the temperatures at 0.5", and 2.0" above the grate, it can be seen that the temperatures at both the locations are almost similar at about 450 K. This is an indication that irrespective of the air flow rates, the fuel at the bottom of the bed has entirely burned out, resulting in ash accumulation in the bottom of the bed.

Figure 2.2: Comparative temperature profiles for LB (0.157'' – 0.25'') at air flow rates of 45 and 60 SCFH

For chicken litter biomass (LB) particle size range between 0.157'' and 0.25'', figure 2.2, shows the comparative temperature profiles under air flow rates of 45 and 60 SCFH. For smaller particles, the temperature dynamics in the bed seems to reflect the ones exhibited by the larger

particles. There is a distinct peak for both the cases, with the peak reaching the free board after 60 minutes into the run for the case of 60 SCFH. This behavior was also shown by the larger particles under air flow rates of 60 SCFH.

After 15 minutes into the run, the peaks for the 60 SCFH case is located much further into the bed as compared to the 45 SCFH case. The location of the peak suggests the affect of higher air flow rate on the burning rate of the particles. Thus, the higher burning rate as in the case of the 60 SCFH case results in a more rapid peak movement into the bed after 15 minutes into the run. The peak temperature in the case of 60 SCFH case is also higher as compared to the 45 SCFH case by about 100 K. The higher peak temperature is attributed to the higher air flow rate resulting in higher burn rates. The temperatures at 0.5", and 2.0" above the grate for the 60 SCFH case are higher than the 45 SCFH case by about 75 K. This suggests that, due to higher burning rates associated with higher flow rates, the ash content in this location is much higher as compared to the 45 SCFH case, resulting in lower combustible matter available for heat generation in this location. The higher temperatures recorded for the 60 SCFH case in the 4.0" to 6.75" region indicate a higher rate of drying and pyrolysis in the bed, ultimately leading to a higher fuel feed rate (refer figure 2.3) at least in the initial stages of gasification. In this case, the temperature peak shift is more affected by the ash content in the bed, rather than convective heat transfers associated with higher air flow rates.

After 60 minutes into the run, the temperature peak for the 60 SCFH case has moved to the top of the bed, whereas the peak for the 45 SCFH has moved to about 5.5" above the grate. As in the previous case discussed for larger sized chicken-litter biomass particles, the smaller sized particles also tend to clump and fuse, without slagging in the bed. This causes the fuel in the bed to fuse to form one large porous particle, and prevents the downward movement of the burnt fuel particles. The result, rapid movement of the temperature peak towards the free surface. The rate of movement is positively affected by the higher air flow rates, resulting in higher burn rates and higher peak temperatures. The fusion also makes the air flow through the large porous particle more tortuous thus reducing the spatial spread of the temperature profile. Nevertheless, the temperatures for both the cases, recorded at 0.5", and 2.0" above the grate are similar, showing same degree of reaction in the bed, irrespective of the air flow rates. The low temperatures reveal that the material in the base is almost ash. In the later stages of gasification, the rapid movement of the peak associated with fusion in the bed, tend to lower the fuel feed rate, and finally the overall feed rates for both the cases are relatively close (refer figure 2.4). A lower feed rate and higher air flow rate results in a higher air fuel ratio for the 60 SCFH case, and can be referred from figure 2.4. A continuous disposal of ash at the grate is required in order to achieve gasification conditions inside the gasifier.

Figure 2.3: Comparative average chicken litter biomass (LB) feed rates for different experiments

Figure 2.4: Comparative average A/F (DAF) and SR ratios for chicken litter biomass under different operating conditions (LB (1), 0.25” –0.5”, LB (2), 0.157” – 0.25”)

2b.2 Coal: Chicken litter biomass blend (CLB)

In the case of coal and feedlot biomass blends, the coal seemed to play an important role in determining the temperature characteristics in the bed. It not only reduced the rate of peak shift in the bed, but also inhibited the agglomeration in the bed. It shall be interesting to see, if it has such a beneficial effect on the temperature profiles for the coal and chicken litter biomass blends? The proximate and ultimate analysis of the coal and chicken litter biomass blend is given

in table 2.1. From the table it is obvious that the ash content of the blend is reduced to about 24 % as compared to nearly 44 % in the of chicken litter biomass. The reduced ash content will positively affect the temperature dynamics in the bed. Although, there is not much change in the volatile matter content of the blend, but the fixed carbon content of the blend increases by almost three folds as compared to the chicken litter biomass. At the same time, the heating value of the blend increases by almost 60 % as compared to that of chicken litter biomass.

Figure 2.5: Comparative temperature profiles for CLB (CLB (1), 0.25'' – 0.5'', CLB (2), 0.157'' – 0.25'') at air flow rates of 45 and 60 SCFH

For coal and chicken litter biomass blends (CLB) particle size range between 0.25'' and 0.5'', figure 2.5 shows the comparative temperature profiles under air flow rates of 45 and 60 SCFH. The presence of peak is evident for both the cases. The shape of the temperature profile is almost similar to that exhibited by the coal and feedlot biomass blends under similar operating conditions. Thus at first glimpse, coal seems to have a prominent effect on the temperature profile in the bed.

After 15 minutes into the run, the location of peak temperatures for both the case is at about 2.0'' above the grate. Initially the air flow rate does not seem to affect the location of the peak temperature. However, the peak temperature for the 45 SCFH is higher than the 60 SCFH case by about 100 K. This behavior is similar to that exhibited by large sized coal particles under similar operating conditions. In the case of coal particles, the peak temperature in the case of 45 SCFH was higher as compared to the 60 SCFH case. Thus, the peak temperature is affected by the presence of coal in the blend. The predominance of coal in dictating the peak temperature in the bed is due to the fact that the heating value of coal is about 2.5 times as that of chicken litter biomass. Thus for every kilogram of the blend burned, the contribution of coal towards the heating value is about 71 %, while the rest is contributed by chicken litter biomass. The lower peak temperature for a higher flow rate is due to two effects, one the faster burning rate of chicken litter biomass due higher air flow rates, and second due to the higher convective heat transfer rates in the bed associated with higher air flow rates. Comparing the temperatures in the bed at 0.5'' above the grate shows that the temperature in the 45 SCFH case is higher than the 60 SCFH case by about 160 K. This shows that the burnt fraction of the fuel at this location is higher in the 60 SCFH case. This results in higher ash concentration thus reducing the

temperature at this location. A lower temperature in the base, associated with a higher convective transfer rate in the bed results in lower peak temperatures in the bed. Another factor to be taken into consideration is that the as the sensible heat energy available at the base of the gasifier is lower, the heat energy available for the successive higher levels is also lower. This can be explained by referring figure 2.6.

Figure 2.6: Control volume for understanding the energy exchange in the bed

In figure 2.6, the energy balance for the control volume gives some interesting insights into the behavior of the bed. Consider, the bed to be divided in small control volumes, and the location of the control volume of interest is at the lower portion of the bed, i.e. around 0.5" above the grate. In the following discussion three consecutive control volumes $i-1$, i , and $i+1$ are taken into consideration, and the energy exchange across these control volumes shall be discussed. The assumptions in the following discussion are:

The gas phase average temperature and the solid phase average temperature are equal.

The specific heat of the solid phase is constant through out the bed.

The heat loss through the sidewalls is negligible.

The heat transfer due to conduction and radiation has been neglected.

Expressing the energy exchange in the control volume (i) in mathematical form gives the following results:

Energy of the gas and solid phase entering the control volume (i) is:

$$\dot{m}_{fuel,in,i+1} c_{p,fuel} T_{gas,out,i} + \dot{m}_{gas,in,i-1} c_{p,gas} T_{g,i-1} T_{gas,in,i-1} \quad (2.1)$$

Energy of the gas and solid phase exiting the control volume (i) is:

$$\dot{m}_{fuel,out,i} c_{p,fuel} T_{gas,in,i-1} + \dot{m}_{gas,out,i} c_{p,gas} T_{g,i} T_{gas,out,i} \quad (2.2)$$

Energy generation in the control volume (i) is:

$$\dot{m}_{chem,hetro,i} h_c - \dot{m}_{pyro} h_{pyro} - \dot{m}_{evap} h_{fg} \quad (2.3)$$

Simplification of the above terms gives:

$$\dot{m}_{gas,out,i} = \dot{m}_{gas,in,i-1} + \dot{m}_{chem,hetro,i} \quad (2.4)$$

$$\dot{m}_{fuel,out,i} = \dot{m}_{gas,in,i-1} - \dot{m}_{chem,hetro,i} \quad (2.5)$$

Energy balance for the control volume (i) gives:

$$E_{in} + E_{gen} = E_{out} + E_{stored} \quad (2.6)$$

$$\begin{aligned} \dot{m}_{gas,in,i-1} \left(c_{p,gas,T_{g,i}} T_{gas,out,i} - c_{p,gas,T_{g,i-1}} T_{gas,in,i-1} \right) = \\ \dot{m}_{fuel,in,i+1} c_{p,fuel} \left(T_{gas,out,i} - T_{gas,in,i-1} \right) + \\ \dot{m}_{chem,hetro} \left(h_c + c_{p,fuel} T_{gas,in,i-1} - c_{p,gas,T_{g,i}} T_{gas,out,i} \right) - \\ \dot{m}_{pyro} h_{pyro} - \dot{m}_{evap} h_{fg} + E_{stored} \end{aligned} \quad (2.7)$$

When the burnt fraction in the bed is high (i.e. in the lower portion of the bed), then:

$$\dot{m}_{chem,hetro} \approx 0 \quad (2.8)$$

Since the gas is not stored in the control volume, and the specific heat capacity of the ash is very small as compared to the fixed carbon, then:

$$E_{stored} \approx 0 \quad (2.9)$$

In addition, due to high burnt fraction, the mass loss due to evaporation and pyrolysis is almost negligible.

Under these conditions the above equation reduces to:

$$\begin{aligned} \dot{m}_{gas,in,i-1} \left(c_{p,gas,T_{g,i}} T_{gas,out,i} - c_{p,gas,T_{g,i-1}} T_{gas,in,i-1} \right) = \\ \dot{m}_{fuel,in,i+1} c_{p,fuel} \left(T_{gas,out,i} - T_{gas,in,i-1} \right) \end{aligned} \quad (2.10)$$

Since the high ash content in the bed makes the flow rate of fuel almost negligible, the above equation reduces to (this is only applicable in the lower portion of the bed):

$$T_{gas,out,i} \approx T_{gas,in,i-1} \quad (2.11)$$

The above result shows that in the lower portion of the bed when the ash content is high, resulting in low heterogeneous reactions, then the temperature rise between two successive control volumes is small. In the 60 SCFH case for the large sized coal and chicken litter biomass blends, the temperature at 0.5" above the grate is low owing to the higher ash content in the bed, so as the incoming gas comes into the gasifier through the grate, the sensible heat addition to it is low due to the low heat capacity of the ash in the bed. When the sensible heat gained by the gas phase is low then at each successive control volumes the lower temperature of the incoming gas results in lower reaction rates in the bed, thus resulting in lower peak temperatures. The lower gas phase temperatures results in lower burning rates, hence lower peak temperatures.

The temperatures in the 3.0" to 6.75" region is almost similar for both the cases, hinting at a similar air flow rate. This also proves that initially the higher air flow rate has not affected the initial drying and devolatilization rates in the bed.

After 60 minutes into the run, the peak shift for the 60 SCFH case is about 0.5" greater than that of the 45 SCFH case. It is interesting to note that in the case of 45 SCFH, there is less spatial spread of the temperature curve, where as for the 60 SCFH there is a higher spread. This spread causes the temperatures in the 4.0" to 6.75" region to be higher, hence resulting in a drying and devolatilization rate. This causes an increase in the fuel feed rate. For the 60 SCFH case, the

temperature spread causes more portion of the bed to be at temperatures higher than the pyrolysis temperatures of both coal and chicken litter biomass. This further enhances the drying and devolatilization rate in the bed, and further boosts the fuel feed rate. The fuel feed rates can be observed in figure 2.8 and the air fuel ratios can be observed in figure 2.9.

In spite of the higher peak achieved in the case of coal and chicken litter blends, there was no appreciable agglomeration in the bed. This may be due to the lower ash content of the blend, and the lower inter particle contact between the chicken-litter biomass particles. This proves that the agglomeration in case of the chicken litter biomass is more influenced by the inter particle contact between particles, rather than by the temperature in the bed. At this point it should be mentioned, that there was small clinker formation in the bed (though on a very small scale), which was caused due to contact between chicken-litter biomass particles at elevated temperatures. Nevertheless, the clinker formation also proves that at high temperatures in the bed of about 1500 K the ash melting takes place, resulting in the formation of clinkers.

For coal and chicken litter biomass blends (CLB) particle size range between 0.157" and 0.25", figure 2.7 shows the comparative temperature profiles for the different air flow rates. As expected, both the cases exhibit a distinct peak in the bed.

After 15 minutes into the run, the temperature peak for the 45 SCFH case is located at 1.5" above the grate, while it is located at about 2.0" above the grate for the 60 SCFH case. Surprisingly the peak temperature for both the cases are almost equal to about 1475 K. The temperature at 0.5" above the grate for the 45 SCFH case is higher than the 60 SCFH case by about almost 300 K. Such a huge difference can only be explained due to the higher burning rate associated with the higher flow rate. The vast temperature difference shows a huge disparity in the burning rates for both the cases. As discussed in the earlier case for larger particles, a lower temperature at the bottom translates into a lower peak temperature. However, in this case this is not the reason for such a peak, the higher convective transfer rates in the bed are a more likely cause. This can be ascertained by checking the spatial temperature distribution in the bed. In the case of 60 SCFH, it is clearly seen that the temperatures at 3.0" and 4.0" above the grate are way higher than those for the 45 SCFH case. This proves that the higher convective rates in the bed cause the lower of peak due to higher rates of heat loss in the bed. The higher convective transfer rates cause unequal burning of the blends. The chicken-litter biomass in the blend burns at a lower temperature due to its lower ignition temperature. This increases the void fraction in the bed, and further boosts the convective heat transfer rates, and causes more spatial distribution of the temperature in the bed. The higher temperatures in the 3.0" to the 6.75" region of the bed in case of the 60 SCFH result in higher drying and devolatilization rates, ultimately translating into a higher feed rate for the 60 SCFH case.

After 60 minutes into the run, it can be seen that the peak temperature for the 45 SCFH case lies at about 2.5" above the grate, whereas for the 60 SCFH case it lies at about 3.75" above the grate. The rate of peak shift is higher for the 60 SCFH case due to higher convective heat transfer rates resulting in faster burning in the bed. The temperature at the 4.0" to 6.75" is consistently higher for the 60 SCFH case. This proves that the higher air flow rate influences the temperature profile in the bed for smaller sized particles.

In the 60 SCFH air flow rate case there was ash fusion in the bed. Although not as severe as observed in the chicken litter biomass case, but it was more pronounced than that observed for the larger blend particles under an air flow rate 60 SCFH. This again goes on to prove that the particle size does play an important role in the ash fusion in the bed. In this case, the clinkers formed were larger in dimension, but not large enough to affect the temperature distribution in the bed. The ash fusion was localized and mostly present at about 4.0" above the grate. Since in the initial stages of the experiment, tar condensation was invariably observed at about this location, this gives a hint that the condensed tar coupled with the clumping tendency of chicken litter biomass is the starting point of the agglomeration. In the case of blends, due to higher temperatures, the ash fusion takes place resulting in clinker formation.

Figure 2.7: Comparative Temperature profiles for CLB (0.157'' – 0.25'') under air flow rates of 45 and 60 SCFH

Figure 2.8: Comparative average coal and chicken litter biomass blend (CLB) feed rates for different experiments

In conclusion, it is seen that the peak temperature in the case of coal and chicken litter biomass blends is more affected by the coal in the blend, due to the higher heating value of coal. The reduction in the overall ash content of the blend reduces the agglomeration in the bed. However, it is observed that smaller sized particle show a higher tendency to agglomerate. Nevertheless, in the case of only chicken litter biomass, the particle size had no effect on the ash fusion in the bed. Thus, from the above discussion it can be concluded that if the ash content is high, then particle size does not affect the agglomeration in the bed, whereas in case of lower ash

content, the smaller particles tend to exhibit higher tendencies for agglomeration. The higher temperature in the bed caused ash fusion at some locations resulting in clinker formation in the bed. The rate of peak transfer in the bed is reduced due to the lower ash content in the blend. The slower rate of peak transfer shall enable a lower frequency of ash disposal at the grate in order to maintain proper gasification conditions in the bed. In case of larger particles, the air flow rate does not affect the peak transfer rate, but a higher air flow rate results in lower peak temperatures in the bed. For smaller particles, the air flow rate shows no effect on the peak temperature in the bed, but increases the rate of peak shift in the bed in case of higher air flow rates.

Figure 2.9: Comparative average A/F (DAF) and SR ratios for coal and chicken litter biomass blends under different operating conditions

2c Gas Species Profiles

2c.1 Chicken litter biomass (LB)

For chicken litter biomass the pyrolysis data is not openly available. So, the important gas species released during the pyrolysis process cannot be anticipated for this fuel. However, since the chicken litter biomass is expected to behave more like feedlot biomass, it would be safe to conclude that the main gas released during LB pyrolysis is CO_2 . This conclusion can only be validated after studying the gas profiles for LB. Figures 2.10, and 2.11 show the gas species profiles for large sized LB particles under air flow rates of 45 and 60 SCFH.

Figure 2.10: Gas species profiles for LB (0.25'' – 0.5'') under an air flow rate of 45 SCFH

In figure 2.10, it is observed that the concentration of CO increase until 4.0'' above the grate. At the same time, the concentration of CO₂ decreases until 4.0'' above the grate. Looking at the temperature in the bed until this location, suggests that the burn fraction is slowly decreasing along the bed. Due to higher burn fraction at the base the production of CO and CO₂ is low, as smaller amount of fuel surface area is available for reaction. However, moving from 0.5'' towards the 4.0'' mark, the decrease in burn fraction enable more surface area available for reactions, thus increasing the concentration of CO. The presence of H₂ at the lower portion of the bed, also indicates that devolatilization is not yet complete in the bed. Owing to the low temperature in the bed, CH₄ production is totally inhibited in the bed. Beyond the 4.0'' mark, the temperature in the bed drops, indicating the dominance of drying and devolatilization in this region. The concentrations of H₂, CO₂, and CH₄ increase rapidly in this region, which is mainly due to accelerated pyrolysis taking place because of the higher temperature in this region.

Figure 2.11: Gas species profiles for LB₁ under an air flow rate of 60 SCFH

Form figure 2.11, which shows that the CO concentration in the bed increases and the CO₂ concentration decreases until 4.0" above the grate. This is due to the similar reasons as discussed for the 45 SCFH case. Looking at the temperature profile in the until 4.0" shows that the low concentration of CO is due to high burn fraction of the fuel in this region. Beyond 4.0", the concentrations of H₂, CO₂, and CH₄ increase rapidly, indicating the drying and devolatilization in the bed. The air flow rate does not seem to have that significant an effect on the calorific value of the gas leaving the gasifier and can be easily inferred from figure 2.18. The small difference is because of the temperature in the drying and devolatilization region. The higher temperature in the 45 SCFH case, results in higher devolatilization rate, thus resulting in increased gas yield from the fuel.

Figure 2.12, shows the gas species profiles for the smaller sized LB particles under an air flow rate of 45 SCFH. The trend in the profiles is same as that shown by the larger LB particles under similar operating conditions. The CO, and H₂ concentrations increase almost monotonically in the bed. The temperature profile provides the reason for such a behavior. The decrease in burn fraction of the fuel along the bed, results in such a behavior. Until 4.0" into the bed, both oxidation and gasification dominant, but the presence of H₂ in the lower portion of the bed shows that the devolatilization process is not yet complete for the fuels even at 0.5" above the grate. Beyond the 4.0" mark, the temperature drops significantly, making the drying and devolatilization the main processes in this region.

Figure 2.12: Gas species profiles for LB (0.157'' – 0.25'') under an air flow rate of 45 SCFH

Figure 2.13: Gas species profiles for LB (0.157'' – 0.25'') under an air flow rate of 60 SCFH

Figure 2.13 shows the gas species profiles for the smaller sized LB particles under an air flow rate of 60 SCFH. The striking feature of this profile is the presence of O₂ at 0.5'' above the bed. This indicates that the air fuel ratio is very high locally at the bottom of the bed and is caused due to the very burn fraction at the location. The higher burn fraction is due to higher burning rates associated with higher air flow rates. This decreases the concentration of CO, and

H₂, and increases the concentration of CO₂ at this location. Moving further into the bed the concentration of O₂ goes to zero, resulting in an increase in the concentrations of CO, and H₂. Until 4.0" above the grate, the concentration of CO increases, showing the dominance of reactions I ($C + \frac{1}{2} O_2 \rightarrow CO$), and III ($C + CO_2 \rightarrow 2CO$) in the bed. However, beyond 4.0" above the grate, the temperature drop is significant, and once again, the pyrolysis process become dominant in this region and causes the rapid release of CH₄, H₂, and CO₂.

An interesting observation is that the CO₂ release in the pyrolysis region is high for all the cases of LB. This result is similar to that observed for feedlot biomass, and it can be concluded that the main gas of pyrolysis for chicken litter biomass is CO₂. Thus, the pyrolysis products for both the feedlot biomass and chicken litter biomass seem to be similar.

2c.2 Coal and chicken litter biomass blend (CLB)

As in the case for CFB fuels, it shall be interesting to observe whether the coal and chicken litter biomass exhibit any favorable synergistic behavior. The figures 2.14, and 2.15 show the gas species profiles for the large sized CLB particles under air flow rates of 45 and 60 SCFH respectively.

Figure 2.14: Gas species profiles for CLB (0.25'' – 0.5'') under an air flow rate of 45 SCFH

In figure 2.14, it can be observed that the temperature in the bed increases until 2.25" above the grate. Initially the lower temperature at the base of the bed is low indicating a high ash fraction in the bed, and a higher local air fuel ratio in this region causes the gas phase oxidation of CO to CO₂. This causes the CO concentration in the 0.5" location of the bed to be lower. Further into the bed the ash fraction in the bed decreases, increasing the surface area available for heterogeneous reactions, and hence causing higher temperatures in the bed. The outcome of this is the dominance of reaction III ($C + CO_2 \rightarrow 2CO$) that causes the reduction of CO₂ back to CO thereby increasing its concentration in this region. The H₂ and the CH₄ concentrations also show an impressive rise at the 2.25" location, indicating that the devolatilization of the CLB fuels is not complete at this location. Moreover, the high temperature at this location enhances the formation of hydrocarbons, which is CH₄ in this case. Beyond 2.25" into the bed, the temperature decreases, signaling the end of the gasification reactions, and the dominance of the drying and

devolatilization processes in the upper region of the bed. Thus, there is not much variation in the gas profiles in between 2.25" and 6.75" of the bed.

Figure 2.15: Gas species profiles for CLB (0.25'' – 0.5'') under an air flow rate of 60 SCFH

In case of higher air flow rate of 60 SCFH for the larger CLB particles, the gas species profiles are similar to the 45 SCFH case of the same fuel. The CO concentration increases from the bottom of the bed towards the 2.25" mark. This is due to the same reasons as discussed in the previous case of air flow rate of 45 SCFH. In addition, the increased air flow rate has not only increased the burn rate at the bottom of the bed, but also increased the dilution of the product gas due to higher N₂ flow rate through the bed. Moving further into the bed, the concentrations of H₂ and CH₄ monotonically increase, this is also due to the same reason as discussed in the 45 SCFH case for the same fuel. The region beyond the 2.25" location is the drying and devolatilization zone in the bed. Thus, it can be concluded that the higher air flow rate for the CLB fuel does not affect the gas species profiles in the bed to a great extent. Although the higher generation of CO, due to increased reactions I ($C + \frac{1}{2} O_2 \rightarrow CO$), and III ($C + CO_2 \rightarrow 2CO$), slightly increase the heating value of the gas leaving the gasifier, the dilution due to high N₂ flow rate tend to slightly decrease the calorific value of the gas leaving the gasifier. This result can be inferred from figure 2.18, which shows that the heating value of the gas for the 60 SCFH case is slightly lower when compared to the 45 SCFH case of the same fuel.

Figures 2.16, and 2.17 show the gas profiles for the small sized CLB particles under air flow rates of 45 and 60 SCFH respectively. For both the air flow rates the gas profiles are not only similar, but also similar to the large particle sized CLB fuel case. This shows that neither the air flow rate nor the particle size seem to affect the gasification characteristics for the CLB fuel to such an extent.

In figure 2.16, it can be observed that the CO concentration increase as the distance above the grate increases, and tends to stabilize at about 2.25" above the bed. Beyond this point the temperature in the bed decreases, and is too low to support gasification reactions. Therefore, the formation of CO is almost negligible beyond the 2.25" mark. Though the high temperature at the 0.5" location in the bed is high, the concentration of CO is low because of the gas phase oxidation of the CO to CO₂. For H₂ and CH₄ there is also an increased concentration at 2.25"

above the grate, this signals that the fuel at this location is actively undergoing pyrolysis. Thus, the region beyond the 2.25" mark in the bed is mostly drying and pyrolysis region.

Figure 2.16: Gas species profiles for CLB (0.157'' – 0.25'') under an air flow rate of 45 SCFH

Figure 2.17: Gas species profiles for CLB (0.157'' – 0.25'') under an air flow rate of 60 SCFH

From figure 2.17, it can be observed that the gas species profiles are very similar to the lower air flow rate case of the same fuel. As in the previous case, in this case also the CO concentration in the bed increases as the distance above the grate increases. The higher burn fraction of the fuel at the 0.5" location, along with a high air flow rate causes a decrease in the

concentrations of all the gases, excepting N_2 . The CH_4 and H_2 release rate seems to increase beyond the 2.25" mark, indicating the dominance of the pyrolysis region beyond this location in the bed. Thus beyond the 2.25" mark, the gas species concentration profile are relatively variance free.

It is interesting to observe that in all the cases of CLB fuel, there was no marked increase in the CO_2 concentration towards the top of the bed. However, in the case of LB fuel, there was always an increase in the CO_2 concentration towards the top of the bed. Therefore, the presence of coal seems to decrease the CO_2 release and slightly increase the CH_4 release at the top of the bed. In some cases, like the 45 SCFH case for both the small and large sized particles, it boosts the calorific value of the fuel. The results can be observed in figure 2.18. However, for all the other cases, the heating value of the product gas produced by the CLB fuels seems to be in between the heating values of the product gas produced by the coal and litter biomass fuels.

Figure 2.18: Comparative Higher Heating Values of the product gas leaving the gasifier, for coal, LB, and CLB gasification under different operating conditions

VI.6 Ash fusion temperature study

As reported in the earlier section there was agglomeration and even clinker formation in the fuel bed for some fuels. For coal, there was no agglomeration or ash fusion in the bed, while for the feedlot biomass there was agglomeration in the bed to a certain extent (for the smaller particles at an air flow rate of 60 SCFH). However, litter biomass showed the most severe form of agglomeration in the bed. Moving on to gasification of coal blends, the peak temperature for the blends was higher as compared to the biomass fuels, which resulted in ash fusion (clinker formation) in the bed. Before moving further, it would be of interest to learn the difference between ash fusion and agglomeration in the bed.

Bed agglomeration is when relatively small particles stick together forming larger masses of material. Bed agglomeration causes problems like local hot spots in the bed, and poor flow distribution in the bed. Agglomeration is due to the melting of mineral matter in the ash that causes the particles to stick to each other. On the contrary, the ash fusion in the bed is also due to melting of ash, but in this case, the high temperature causes the ash to slag and upon cooling, the

slag solidifies and forms clinkers in the bed. It is worthwhile to note that the clinker formation is also an agglomeration process.

The fuel samples were sent to the Huffman laboratories, CO. for determination of ash fusion temperatures for all the fuels. The ash fusion temperatures were determined by the procedure outlined in the ASTM D-1857 standard (1992). Table 2.2 shows the ash fusion temperature for all the fuels under reducing as well as oxidizing conditions.

Ash fusion Temperature (K)	Coal		FB		LB		SFB	
	Red*	Oxi**	Red*	Oxi**	Red*	Oxi**	Red*	Oxi**
Initial Deformation Temperature	1419	1459	1456	1484	1419	1413	1457	1483
Softening Temperature	1422	1461	1475	1508	1475	1449	1520	1524
Hemispherical Temperature	1428	1462	1499	1528	1505	1502	1558	1575
Fluid Temperature	1435	1463	1580	1587	1579	1561	1622	1636

* Reducing conditions

** Oxidizing conditions

Table 2.2: Comparative ash fusion temperatures for all the fuels

Table 2.2 shows that the IDT for coal and LB under reducing conditions are similar, and in fact, it is less than those of FB, and SFB. Interestingly during the gasification experiments, coal did not exhibit any tendency to fuse, but the other biomass fuels did exhibit such tendencies. This means, that under actual gasification conditions, the biomass fuel has a lower IDT as compared to coal. This observation is not consistent with the AFT results obtained in the laboratory conditions.

Wall *et al.* (1999) have reported that the ash fusion tests are highly inaccurate, as it is subjective, and empirical test, which is made on observation instead of actual measurements. Due to these reasons, the ash fusion tests give no direct indication of the propensity of the heated ash to become sticky and cause agglomeration.

Wall *et al.* (1998) have attributed the difference between ash fusion temperatures for laboratory and combustion ash to the loss of potassium and reactions between the mineral residues at the higher temperatures experienced during actual combustion conditions. Kyi *et al.* (1999) have reported that during combustion the sodium in Loy-Yang coals was released primarily in the form of NaCl, which caused severe slagging. They concluded that the Na in coals was present in a form readily released into the gas phase during combustion, and the presence of alkali metals seems to affect the actual ash fusion temperatures of the ash. Table 2.3 shows the ash composition of the various fuels.

Compound	Coal	FB	LB	SFB
Aluminum, % as Al_2O_3	15.66	9.12	5.26	9.98
Calcium, % as CaO	21.7	9.5	11.85	8.1
Iron, % as Fe_2O_3	4.68	2.91	3.06	3.06
Magnesium, % as MgO	5.35	2.88	3.86	2.4
Manganese, % as MnO	0.01	0.06	0.12	0.06
Phosphorous, % P_2O_5	2.11	3.1	13.93	2.18
Potassium, % as K_2O	0.1	5.05	11.56	4.37
Silicone, % as SiO_2	29.86	60.22	33.02	57.9
Sodium, % as Na_2O	1.53	1.63	5.08	1.4
Sulfur, % SO_3	10.34	1.86	4.03	1.33
Titanium, % as TiO_2	1.23	0.62	0.52	0.62

Table 2.3: Ash analysis of various coal and biomass fuels

Parameter	Coal	FB	LB	SFB
Basic Oxides (%)	40.57	23.12	40.17	21.48
B/A ratio	0.71	0.31	0.91	0.28
$Na_2O + K_2O$ (%)	1.98	7.03	18.88	6.41
Rs	0.25	0.23	0.66	0.12

Table 2.4: Ash slagging propensity indicator for various fuels.

The ash analysis can be used to predict the slagging and fusing propensities of the fuels. Table 2.4 lists a few indicators of slagging tendency in the bed. The base to acid (B/A) ratio is another way of calculating the basic oxides percentage. A higher base acid ratio favors evaporation of mineral species enriching the ash vapor with vaporized alkalis, increasing the ash-fusing propensity. Table 2.4, shows the similarity of the base acid ratios for coal and LB, proving that in this case, the basic oxides percentage, or the base acid ratio clearly have no effect on the actual ash fusion temperatures observed during gasification experiments. Since Na, and K seems to play important roles in ash fusion temperature, comparing the values of these alkalis for the various fuels, tends to reveal the actual cause of agglomeration in the bed. From table 2.4 it can be observed that the alkaline oxides in the form of Na, and K are very high for LB (18.88 %), and FB (7.03 %) as compared to the other fuels. In fact, the alkaline oxides percentage for LB is almost ten times as that of coal and about three times as that of FB, and SFB. This indicates that Na, and K oxides tend to decrease the actual AFT for the fuels. The slagging index (Rs) for LB is about 2.5 times as that for coal, and FB, indicating that the sulfur in the fuel also plays an important role in agglomeration in the bed.

2d Gasification efficiency

An important factor determining the actual technical operation, as well as the economic feasibility of using a gasifier system, is the gasification efficiency. Updraft gasifiers are generally used to produce gas used in direct burning. The product gas from the gasifier is directly burned generating heat. The equation used for determining the gasification (thermal) efficiency is as follows:

$$\eta_{th} = \frac{\left(\dot{m}_{gas} \times HV_{gas} \right) + \left(\dot{m}_{gas} c_{p, gas} \left(T_{gas, exit} - T_{(fuel + air), inlet} \right) \right)}{\left(\dot{m}_{fuel} \times HV_{fuel} \right)} \times 100 \quad (G.1)$$

There are a few assumptions that have been assumed for this case, they are:

- There is no combustible fuel accumulation in the bed.
- The N_2 in the air is inert.
- Moisture in the incoming primary air is negligible.
- The temperatures of the incoming fuel and incoming air are equal to 300 K.
- The product gas composition determined at the top of the bed is assumed to represent the average composition of the product gas leaving the gasifier.

During the current study, the mass flow rate of the product could not be measured due to high tar content in the product gas leaving the gasifier. In addition, there was no ash disposal at the grate, and the system was not under a steady state operation. The product gas composition at the top of the bed was measured midway into the run. It was assumed that the gas sample represented the average product gas composition for the entire experiment. Keeping these factors in mind the theoretical thermal efficiency of the gasifier was determined.

Figure 2.19, shows the comparative (theoretical) thermal gasification efficiencies for different under different operating conditions.

Figure 2.19: Comparative thermal gasification efficiencies and corresponding stoichiometric ratios, for coal, LB, and CLB fuels under different operating conditions

From figure 2.19, it can be observed that the gasification efficiency is the lowest for coal (for an air flow rate of 45 SCFH), as compared to LB, and CLB fuels. However, as the air flow rate increase to 60 SCFH, the efficiency increases by about 68 %. This is because an increase in the air flow rate increases the stoichiometric ratio, thereby higher burning rates and higher temperatures in the bed, which lead to higher pyrolysis of the fuel in the devolatilization region. The higher pyrolysis gas yield increases the calorific value of the product gas, and thus the thermal efficiency. This is also observed for LB, and CLB fuels, implying that an increased air fuel ratio increases the thermal efficiency of the gasifier. This is because of the assumptions made while calculating the thermal efficiency. Under steady state operations, there shall be ash discharge taking place from the grate at a higher interval, resulting in higher heat loss from the system, and increasing the fuel feed rate into the gasifier. Both these processes shall decrease the thermal efficiency of the gasifier when operating at a very high stoichiometric ratio. Therefore, based on the current assumptions, an increase in the stoichiometric ratio increases the thermal efficiency, but this might not hold good under actual steady state operations, due to the reasons cited above.

Appendix C: NUMERICAL STUDY OF MOISTURE EFFECTS IN PULVERIZED CLB COMBUSTION

Assuming coal and LB have the same moisture level, numerical study of moisture effects on combustion behavior and pollutant emissions were conducted with different moisture levels in CLB blend. Computations were also performed with dry coal and wet LB to study effects of biomass moisture only.

3a. Effects of moisture of CLB blend

Moisture in fuel is regarded as liquid water, and its latent heat is significant (2,443.8 kJ/kg). Under combustion condition, since more heat is taken from fuel particles with higher moisture content during vaporization, increasing moisture level could decrease particle temperature thus delay occurrences of pyrolysis and char burning causing increase of flame standoff distance, lower burnout, and variation of pollutant emissions. Combustion behavior could also be affected by moisture content due to the reaction

especially in the near burner region where H_2O level is high.

Assuming coal and LB have the same moisture percentage, numerical predictions for coal-LB blend combustion are conducted for 10%, 20%, and 30% moisture contents in fuel blend. Figure 3.1 show the cross-sectional averaged burnout versus axial distance. It is obvious that burnout decreases with increasing moisture content. At the end of furnace, burnout is 0.909, 0.892, and 0.874 for 10%, 20%, and 30% moisture respectively. It is also found that, different from excess air and swirl number, which mainly influence burnout during char burning stage, moisture affects burnout obviously in both pyrolysis and char burning stages. Figure 3.2 shows the cross-sectional averaged percentage of moisture release versus axial distance. It is found vaporization is faster for lower moisture content based on what percentage of moisture is released from fuel. For 10%, 20% and 30% moisture levels, 95%, 86% and 48% of total moisture are released from fuel within the quarl ($x < 0.08$ m) respectively, and 98%, 96%, and 94% of the total moisture are released in $x < 0.16$ m (twice of the quarl length) respectively.

Figure 3.1: Burnout versus axial distance for coal-LB blend combustion at different blend moisture levels.

Figure 3.2. Cross-sectional averaged moisture loss from coal-LB blend versus axial distance for different blend moisture levels.

Figure 3.3 presents distributions of mixture fraction 3 (denoted as η_3) in the center plane. Figure 3.4 gives η_3 profiles along the furnace axis η_3 physically represents mass fraction of vaporized moisture in gas phase. The high η_3 region represents high vaporization zone. It is seen that the vaporization zone has a larger area for higher moisture level than lower moisture level. For the 10% moisture level, vaporization occurs mainly in the quarl; while for 30% moisture about half of the vaporization occurs outside the quarl. In the downstream region of furnace, η_3 distributions are nearly uniform indicating that vaporized moisture mixes well with other gases. As expected, the η_3 increases with increasing moisture content.

Figure 3.3. Distributions of η_3 in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.4. Profiles of η_3 along centerline for coal-LB blend combustion at different blend moisture levels.

Figure 3.5 shows distributions of mixture fraction 2 (denoted as η_2) in the center plane of furnace. η_2 represents mass fraction of fuel offgas in its mixture with air. The high η_2 region near burner represents strong pyrolysis zone. It is found that as moisture level in fuel increases, the pyrolysis zone moves farther away from burner, implying higher moisture content delays occurrence of pyrolysis. Figure 3.6 shows the η_2 profiles along furnace axis. The η_2 peak drops as the moisture content increases because higher moisture causes lower particle temperature resulting in lower pyrolysis rate. After the peak, η_2 on the axis increases with increasing the moisture content due to delay of pyrolysis and char burning.

Figure 3.5. Distributions of η_2 in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.6. Profiles of η_2 along centerline for coal-LB blend combustion at different blend moisture levels.

Figure 3.7 shows temperature distributions in the furnace center plane. In the flame core, temperature decreases as moisture level increases because more heat is removed from gas phase during vaporization for higher moisture level. Figure 3.8 presents temperature profiles on the furnace axis. The sharp peak near burner corresponds to the small high temperature area very close to the primary inlet. The low peak next to it corresponds to the flame core. The second high peak corresponds to the flame location. It is found in the post flame region, temperature around the centerline is slightly higher for higher moisture since fuel is lean in gas phase, and more fuel offgas exists around the axis as moisture content increases, as observed from η_2 profiles in Figure 3.6.

Figure 3.7. Temperature distributions in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.8. Profiles of centerline temperature for coal-LB blend combustion at different blend moisture levels.

Figure 3.9 shows H_2O distributions in the center plane. Figure 3.10 presents H_2O profiles along the furnace axis. As described previously, the high H_2O region in quarl is due to strong vaporization. Following that there exist a comparatively low H_2O region due to reaction (R-1). In the post-flame region, H_2O is reproduced due to oxidation of the combustible gases by the secondary air. It is seen that H_2O increases significantly almost everywhere in furnace as moisture content increases from 10% to 30%.

Figure 3.9. H_2O distributions in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.10. Profiles of centerline H_2O for coal-LB blend combustion at different blend moisture levels.

The CO mole fractions distributions are presented in Figure 3.11. Due to the delay effect of moisture vaporization to combustion, the high CO region near burner becomes larger and moves farther away from burner as the moisture content increases. It is also seen that the peak value of CO level decreases with increasing the moisture content. This is because more water vapor is released near burner as moisture content increases, causing higher transformation of CO into CO_2 through reaction (R-1). Figure 3.12 shows CO profiles along the furnace axis. It is found that in the post flame region (i.e. after the second peak), CO increases with increasing moisture content. This is possibly due to the delay effect of vaporization to combustion.

Figure 3.11. CO distributions in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.12. Profiles of centerline CO for coal-LB blend combustion at different blend moisture levels.

Figure 3.13 shows the CO_2 mole fractions distributions. Figure 14 shows CO_2 profiles along the furnace axis. It is observed that near burner CO_2 level increases with increasing the moisture content. This is because more water vapor is released near burner for higher moisture content, causing higher transformation of CO into CO_2 through reaction (R-1). It is also observed that with increasing the moisture content, the high CO_2 region moves significantly farther away from burner, and in the post-flame region CO_2 level decreases with increasing moisture content. This is possibly due to the delay effect of moisture vaporization to combustion.

Figure 3.13. CO₂ distributions in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.14. Profiles of centerline CO₂ for coal-LB blend combustion at different blend moisture levels.

Figure 3.15 shows NO distributions in the center plane. Figure 16 gives cross-sectional average NO mole fraction versus axis distance. With increasing the moisture level, the high NO region around the quarl moves away from burner due to the delay effects of vaporization to combustion. In the downstream region, NO level decreases as the moisture content increases. This is because higher moisture causes lower burnout, or less nitrogen release. Since the gas phase is fuel lean, less nitrogen release causes less NO production. Figure 3.17 shows NO emission at furnace exit for different moisture levels. For moisture content 10%, 20% and 30%, NO emission at furnace exit is below the 0.26 kg/GJ, which is the national standard for NO emission for boiler furnace.

Figure 3.15. NO distributions in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.16. Cross-sectional averaged NO versus axial distance for coal-LB blend combustion at different blend moisture levels.

Figure 3.17. NO emissions at furnace exit for coal-LB blend combustion at different blend moisture levels.

Figure 3.18 shows the P_4O_{10} concentration distributions on the center plane. Figure 3.19 shows the P_4O_{10} profiles along the furnace axis. The high P_4O_{10} region inside flame core shifts away from burner as moisture increases due to the delay effect of vaporization to pyrolysis. It is also found the peak value of P_4O_{10} concentration decreases as increasing moisture due to the decrease of O_2 concentration as shown in Figure 3.20. As mentioned previously, less O_2 causes less P_4O_{10} but more PO_2 due to reaction

At furnace exit, the cross-sectional averaged P_4O_{10} level increases slightly.

Figure 3.18. P_4O_{10} distributions in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.19. Profiles of centerline P_4O_{10} for coal-LB blend combustion at different blend moisture levels.

Figure 3.20. Profiles of centerline O_2 for coal-LB blend combustion at different blend moisture levels.

Figure 3.21 shows the PO_2 distributions in the center plane. Figure 3.22 shows the PO_2 profiles along the furnace axis. As moisture increases, the post-flame high PO_2 region outside the quarl shifts away from burner due to the increasing flame length, and its peak value decreases because more oxygen is available to oxidize PO_2 into P_4O_{10} . At furnace exit, the cross-sectional averaged PO_2 level decreases from 274 to 244 ppm as moisture content in fuel mixture increases from 10% to 30%.

Figure 3.21. PO₂ distributions in center plane for coal-LB blend combustion at different blend moisture levels.

Figure 3.22. Profiles of centerline PO₂ for coal-LB blend combustion at different blend moisture levels.

In summary, increasing moisture content in fuel blend delays pyrolysis and char combustion causing longer flame length, lower-temperature flame core, and lower burnout. Higher moisture content causes higher H₂O level in the whole furnace. In the near burner region, as moisture increases, 1) CO level decreases while CO₂ and H₂ levels increases due to the reaction (2.8), 2) the high PO₂ level inside flame core and the high P₄O₁₀ level downstream of flame decrease, and 3) the high CO, CO₂, H₂, NO, PO₂, and P₄O₁₀ regions shift away from burner due to the delay effect of vaporization to combustion. In the downstream region, with increasing moisture content, 1) CO and H₂ increases, 2) NO and CO₂ decreases, and 3) PO₂ and P₄O₁₀ have no obvious change.

3b. Effects of biomass moisture only

Assuming coal is dry while LB has respectively 10%, 20%, and 30% moisture content, numerical computations are carried out for combustion of coal-LB blend to investigate the effects of biomass moisture only. Mass ratio of coal to LB (dry part) is 9:1 in fuel blend. Other parameters are the same as in section 1. Figure 3.23 shows variation of the cross-sectional averaged burnout with axial locations. Burnout distributions are found similar for different biomass moisture contents. This is because the fuel blend contains 10% biomass only. Increasing biomass moisture from 10% to 30% means moisture content in fuel blend increases from 1% to 3% only. Such a small moisture increase could not result in obvious influence to combustion. Figure 3.24 shows temperature profiles along the furnace centerline. Temperature distribution does not change obviously with moisture, and no obvious increase of flame length is found, which indicate biomass moisture does not affect flame structure when fuel blend contains small fraction of biomass.

Figure 3.23. Burnout versus axial distance for coal-LB blend combustion at different biomass moisture levels.

Figure 3.24. Profiles of centerline temperature for coal-LB blend combustion at different biomass moisture levels.

Figures 3.25 and 3.26 show distributions of CO and CO₂ mole fractions along the furnace centerline respectively. Slight increases of CO and slight decrease of CO₂ are found in a few small regions near burner due to reaction (R-1). In most region of the furnace, both CO and CO₂ levels are similar for different levels of biomass moisture. Figure 3.27 shows NO profiles along the furnace centerline. Different biomass moisture levels give similar NO distributions. In the post-flame region, NO increases very slightly with increasing the moisture content in biomass. Figures 3.28 and 3.29 present P₄O₁₀ and PO₂ distributions along the furnace centerline respectively. Again, influences of biomass moisture to both P₄O₁₀ and PO₂ are very small. In the post-flame region, the curves for different moisture levels collapse. Near burner, the high peak of P₄O₁₀ increases slightly while the low peak of PO₂ decreases a little as biomass moisture increases.

Figure 3.25: Profiles of centerline CO for coal-LB blend combustion at different biomass moisture levels.

Figure 3.26: Profiles of centerline CO₂ for coal-LB blend combustion at different biomass moisture levels.

Figure 3.27: Profiles of centerline NO for coal-LB blend combustion at different biomass moisture levels.

Figure 3.28: Profiles of centerline P_4O_{10} for coal-LB blend combustion at different biomass moisture levels.

Figure 3.29: Profiles of centerline PO₂ for coal-LB blend combustion at different biomass moisture levels.

From above computational results, it is seen that when biomass fraction in fuel blend is low (10%), increasing moisture content in biomass does not cause obvious changes in flame length, flame structure, temperature distribution, and species distributions.

References

Wall, T. F., Creelman, R. A., Gupta, R. P., Gupta, S. K., Coin, C., and Lowe, A. (1998) Coal Ash Fusion Temperatures – New Characterization Techniques, and Implications for Slagging and Fouling. *Prog. Energy Combust. Sci.*, **24**, 345-353.

Wall, T. F., Gupta, S. K., Gupta, R. P., Sanders, R. H., Creelman, R. A., and Bryant, G., W. (1999) False Deformation Temperatures for Ash Fusibility Associated with the conditions for Ash Preparation. *Fuel*, **78 (9)**, 1057-1063.

Kyi, S., and Chadwick, W. L. (1999) Screening of Potential Mineral Additives for use as Fouling Preventives in Victorian Brown Coal Combustion. *Fuel*, **78 (7)**, 845-855.