Thermal characterization of various biomass materials for co-gasification with coal

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Abstract

The paper reports on an investigation into the thermal behavior of various biomass materials characterized for co-gasification of coal and biomass. Coal/biomass blends prepared at different ratios were also characterized using Thermogravimetric analysis. The devolatization behavior of different coal/biomass ratios under the same heating conditions (20°C/min and high N_2 flow rate), typical of pyrolysis were investigated for kinetic parameter determination. The initial results obtained established that the mixture of 50% coal and 50% eucalyptus wood could yield positive gasification results specifically using a downdraft biomass gasifier system. A number of mixing ratios for coal and biomass were investigated, however this paper reports on the recommended ratio and the results obtained with the various biomass materials.

1. Introduction

Gasification of biomass has attracted enormous interest among the thermochemical conversion technologies as it offers higher efficiency in relation to combustion and possesses great potential in utilization of biomass and waste for energy and material production (Kurkea *et al*. 2004, Maniatis 2001, 2004). In addition, fuels generated from biomass are considered to be a remedy to greenhouse gas emission. Biomass gasification is defined as the conversion of unprocessed raw biomass materials into gaseous energy carriers known as producer or synthetic gas (syngas). The producer gas is a mixture of various gases such as carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2) and steam (H_2O). The producer gas is used for heating, electricity generation and fine chemicals production. Biomass is a renewable energy source which is not only having a potential to meet the energy needs and demands of developed and developing countries throughout the world but also carbon dioxide (CO_2) reduction [European Commission, 1997]. Biomass fuel can be converted to energy through thermochemical processes (combustion, pyrolysis, gasification) and biological means (enzyme/fermentation)

Coal gasification technology turns coal and coke feedstocks into synthetic gas (syngas), a mixture of hydrogen and carbon monoxide that burns as cleanly as natural gas. Syngas can then be used to produce a wide range of high-value products such as electricity, fertilizers, transport fuels and chemicals. Compared to conventional coal-fired power plants, those producing electricity using coal gasification process emit less CO_2 and pollutants. Moreover, the CO_2 from gasification process can be more easily captured from smokestacks-potentially for storage underground (sequestration). Syngas is synthesized by mixing pulverized coal with oxygen and steam at higher temperature between 1400 – 1600 $^{\circ}$C. Compressed nitrogen is used to transport the dense stream of coal into the gasifier. This approach is more efficient than the slurry of coal and water used by other techniques. The process produce a number of by-products which is sold for use in other industries: fly ash is used in the cement industry; Sulphur is used to make fertilizer, explosives and for chemical applications; and slag is used in building materials and road fill [Parker, 2006].

Co-gasification of waste/biomass and coal technology offers several benefits such as combining the use of reliable coal supply with waste/biomass thus qualifying for renewable obligation and climate change benefits, this allows the economies of scale from larger plant than could be supplied just with waste biomass, capable of achieving high environmental standards on all fuel sources, flexible in choice of gas to electricity technology reciprocating engine, gas turbine, boiler and in future fuel cell, potential for petrochemical feedstock besides electricity, potential for sitting at collieries. Gas cleaning challenges are different for coal and biomass. Sulfur is a major concern for coal gasification but chlorine compounds and tar are more important for waste and biomass gasification [Livingston and Hall, 2002].

Co-gasification of coal and biomass can be considered as a potential for gasification and further syngas production and methanol synthesis with excess produced gas, an alternative liquid fuel which can be directly used for fuel cells. It allows economy of production, operational stability, optimal thermal efficiency and decreases impact on environment. Intergrated coal biomass co-gasification system combined with gas-steam cycle offers various advantages such as possible continuous operation of coal-gasification reactor at nominal rating, lowering the cost of electricity production, stabilizing of quality of the feedstock and gasifier operation and improvement of economic flexibility of the system (two final products) [Amigun *et al*, 2009].

Coal are classified as follows: anthracite (highest rank), bituminous, sub-bituminous and lignite (lowest rank). The chemical composition of coal has a strong influence on its combustibility. Lignite has been widely used as electricity generation and heat, besides producing various refined chemicals. Structural characterization of lignite coal presented major challenges because of extreme complexity and heterogeneity (different phases) of low rank coal. Morphological analysis of lignite is complicated. In coal gasification process for production of synthetic gas, coal is converted into gases that can be converted into quality gas having a higher heating value and with greatest efficiency.

2. Methodology

Pure coal (100%) was analysed alone, and similar analysis were conducted on pure cow dung (100%), eucalyptus (100%), and pine wood (100%). Coal was blended with cow dung at various ratios i.e. Coal:Biomass (cow dung; eucalyptus and pine wood) (90:10; 80:20; 70:30; 60:40; 50:50; 40:60; 30:70; 20:80 and 10:90)

TGA was used to conduct thermal degradation analysis of the various biomass materials, coal as well as the various blends. TGA provides quantitative measurement of any weight changes (loss/gain) associated with thermally induced transition as a function of temperature or time. Volatile materials are removed (devolatization) during Thermogravimetric analysis. Thermogravimetric curves are characteristics of a given compound due to a unique sequence of physical transitions and chemical reaction that occurs over a definite temperature ranges. It allows thermal stability determination of various biomass and coal. Kinetics of thermal transformations is described by the following equation of a single step reaction [Vyazovkin, 2009].

$$\frac{d\alpha}{dt} = k(T) \ f(\alpha) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(1)$$
$$= k(T) \ x^n$$

with Arrhenius constant $= k = A \exp(-E_a/RT)$

And   the unreacted fraction $= \ x = 1- \alpha$

with $\alpha = (W_o - W) / W_o =$ Weight conversion $= \%$ mass loss

Where $W_o =$ sample weight at time $t = 0$

$W =$ Sample weight at time $t = t$

Where

$f(\alpha) =$ reaction model

α = The extent of reaction = % Weight

k (T) = Arrhenius rate constant described by Arrhenius equation

T = Temperature

t = time

For non-isothermal conditions and a constant heating rate B, equation (1) can be re-written as follows:

$$\frac{d\alpha}{dT} = (\frac{A}{B}) \exp(-\frac{E}{RT}) f(\alpha) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where

E = Activation Energy

R = Universal gas constant

From (1) , integration yields the following equation:

$$\ln \frac{d\alpha}{dt} = \ln(\beta \frac{d\alpha}{dT})$$

$$= \ln A + \ln[f(\alpha)] - \frac{E}{RT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3)$$

Equation (3) holds for any reaction order model $f(\alpha) = (1-\alpha)^n$

Where

E = E_a = Activation energy and can be obtained from the slope plot.

Plotting $\ln(\frac{d\alpha}{dt})$ vs $1/T_i$ yields a slope = E_a

For a given value of α, pre-exponential factor (A) can be determined from extrapolating of a plot of the intercept against α_i

2. Results and discussion

Figure 1 and 2 show the degradation curves and the reaction rates of coal and cow dung subjected to combustion in TGA at 20°C/min (maximum N_2 flow rate). The maximum temperature was 900°C. The rate of degradation of various carbonaceous materials subjected to TGA is an indication of the thermal behaviour of the particular material under gasification. Coal degrades much slower than cow dung as evident from figure 1due to its high fixed carbon content.
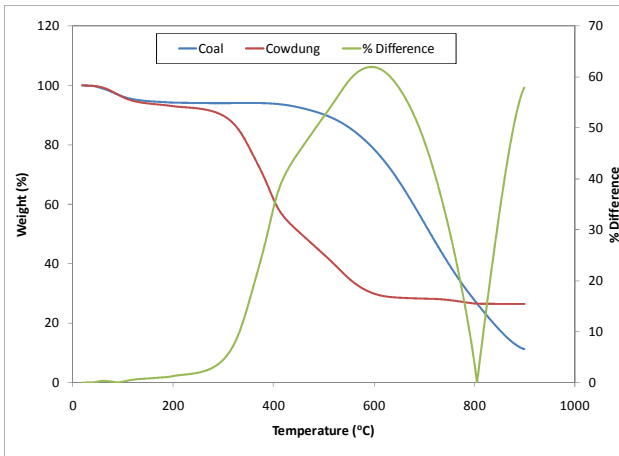

Figure 1: Coal and cow dung devolatization graphs
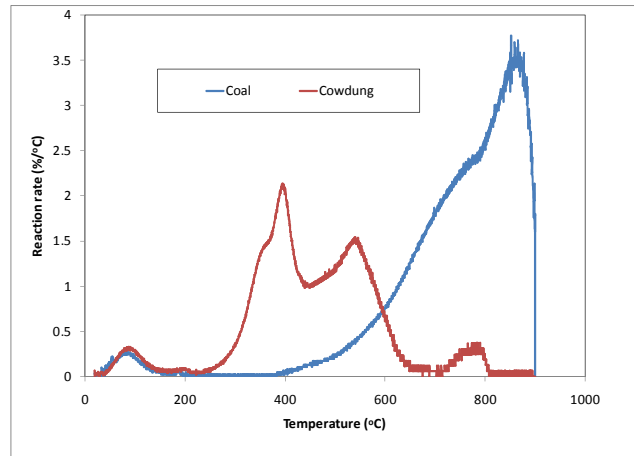
Figure 2: Coal and cow dung reaction rates

The reaction rate of coal is also slower at lower temperatures and it increases with an increase in temperature, this is evident in figure 2, which shows that the reaction rate started rising at 400°C whereas that of cow dung started rising at about 250°C. This implies that coal gasification takes place at much higher temperature than cow dung. Cow dung reaches maximum degradation/complete devolatization at about 650°C, thus implying that higher temperatures are not favorable for cow dung gasification and could lead to lower conversion efficiency, whereas higher conversion efficiencies could be achieved in coal gasification at higher temperatures. The percentage difference between the coal and cow dung degradation curves suggests a major difference around 600°C, which is where the cow dung shows complete devolatization. The complete devolatization of cow dung at that temperature range also implies the end of gas production during gasification. A mixture of coal and cow dung should be able to prolong gas production beyond the 600°C point.

Figure 3 and 4 shows the devolatization graphs and reaction rates for coal and pine wood respectively. The devolatization of pine wood follows a similar trend to that of cow dung, however the reaction rate differs significantly with the one for cow dung reaching a maximum of 1.5%/°C and it starts to pick at about 300°C. Like the one for cow dung it has its first pick at 100°C, which is when the moisture is being driven off, this is evident in both figure 3 and 4. High reaction rates for both cow dung and pine wood are observed at 400°C implying that most of the volatile matter content is released at temperature around 400°C. After the release of the major part of the volatile matter content follows the degradation of fixed carbon hence the reaction rate increases slowly at temperature between 400°C and 600°C due to the fact that more energy is required to break the fixed carbon.
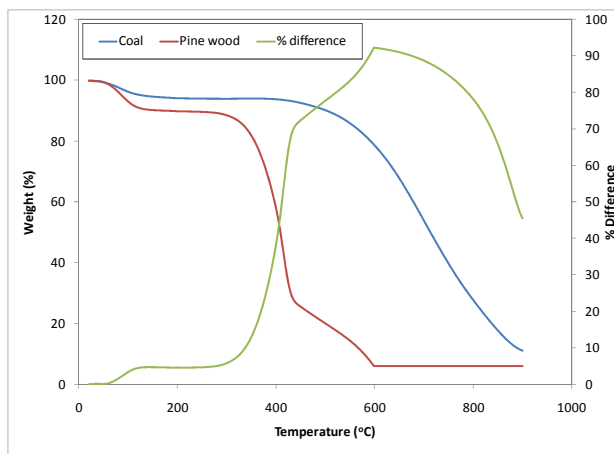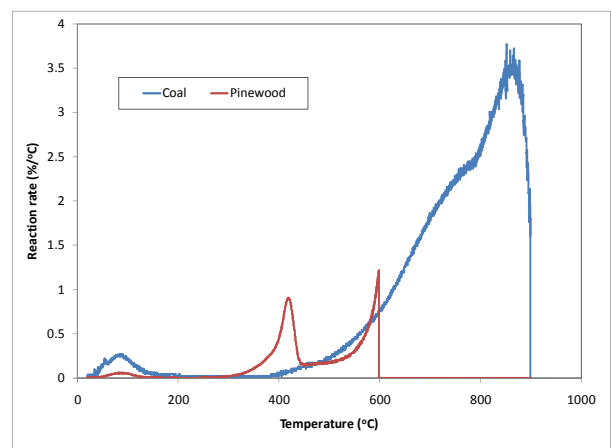

Figure 3: Coal and pine wood devolatization graphs

Figure 4: Coal and pine wood reaction rates

Figure 5 and 6 present the degradation graphs for coal and eucalyptus hard wood. The degradation of eucalyptus is also not much different from that of the latter two biomass materials (cow dung and pine wood) as evident from the two figures, however the coal/eucalyptus blend of 50/50 was observed to yield positive results in terms of devolatization rate and maximum temperature at which complete devolatization takes place.
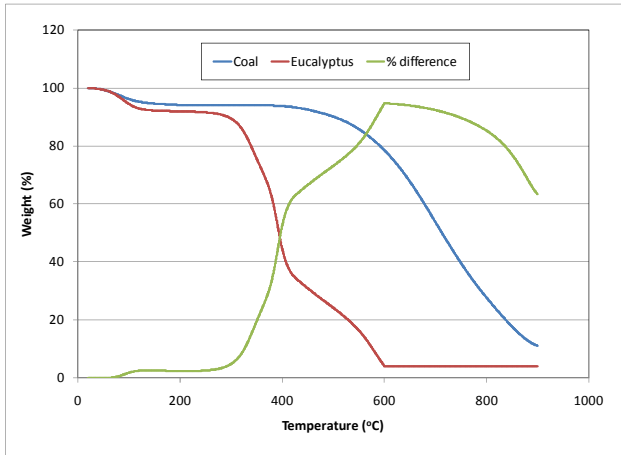
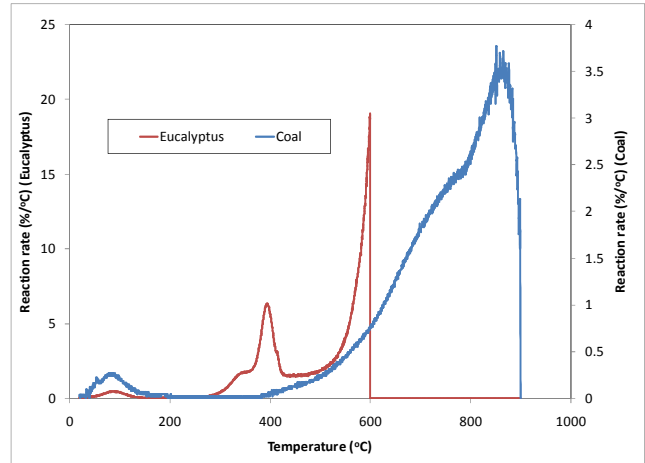Figure 5: Coal and eucalyptus devolatization.

Figure 6: Coal and eucalyptus reaction rates.

Figure 7 presents the reaction rates for a blend of 50% eucalyptus and 50% coal, coal as well as reaction rate for eucalyptus hard wood. It is evident from the figure that the reaction rate of the blend picks at temperature around 400°C because of the presents of eucalyptus wood whereas the one for coal is starting to pick at that temperature range.
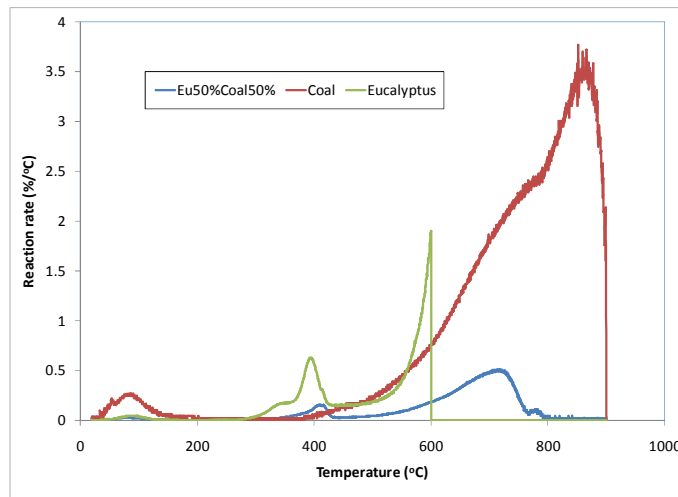

Figure 7: Reaction rate of the Coal/eucalyptus wood blend (50/50), coal as well as eucalyptus wood.

The reaction rate for the blend picks slowly again at temperature above 500°C owing this to the degradation of fixed carbon, which requires more energy that volatile matter content. Interesting to note is the fact that the reaction rate for the blend reaches its maximum at temperature around 700°C,

above the 600°C where complete degradation of the eucalyptus took place, which implies that the mixture of coal and eucalyptus wood would prolong gas production during gasification. Complete degradation of the coal will take place at temperatures around 900°C after which the gas formed would undergo tar cracking at temperatures above 900°C.

4. Conclusion

There are a number of challenges facing gasification of coal alone for electricity generation. Biomass gasification for heat and power generation is a well established area. The challenges experienced during coal gasification includes but are not limited to high reaction temperature of coal, which most gasifiers cannot achieve, and if achieved in most cases combustion of the resultant syngas usually occur leading to low conversion efficiency and the risk of reaching extremely high temperatures that may result in pressure build up and explosion. This paper investigated ways in which the co-gasification of coal and biomass can be undertaken at reasonable temperatures. The 50/50 coal to biomass (eucalyptus wood) mixing ration was observed to yield the best results by lowering the reaction rate at an intermediate temperature at which the gasification of both coal and biomass would yield positive results. This paper presented the initial results obtained using TGA analysis; it did not present the gasification results as well as the calorific values of the various materials used and their proximate as well as ultimate analysis.

5. References

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