TECHNICAL CHALLENGES AND OPPORTUNITIES IN COGASIFICATION OF COAL AND BIOMASS

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INTRODUCTION

Biomass gasification manufacturers are beginning to market 5 to 100 kW capacity gasifiers (e.g., Community Power Corporation (CPC), Littleton, CO and gasifier experimenters kit (GEK), AllPower Labs, Berkeley, CA) for producing electricity and synthetic gas (syngas). These gasifiers operate at 900 to 1000 °C, consuming 1.3 kg of biomass per hour for every kW power output. This corresponds to approximately 3 dry metric tons of biomass per day for a 100 kW gasifier. These types of small gasifiers have shown promise for rural economic development. While these systems run on biomass, inclusion of as much as 30 percent coal will bring down the biomass requirement significantly and increase the total fuel available, allowing for greater application of these systems. However, incorporating coal into these types of small scale biomass gasifiers presents an unknown that will need to be addressed and tested before it can be accepted. This paper presents technical and nontechnical challenges associated with cogasification of coal and biomass mixtures.

GASIFICATION SYSTEM

Gasification is a promising technology for producing syngas from coal and biomass, creating a clean energy fuel and electricity. However, the gasification process is only one of the unit operations in a typical gasification system (Fig. 1). After the feed material (biomass or coal) has been gathered, it goes through preprocessing operations including drying and size reduction. Some other options including torrefying biomass and demineralizing and desulfuring coal may also be considered to reduce downstream cleaning of the product synthesis gas.

In the gasification process, complex hydrocarbons from the feedstock (biomass or coal) decompose in the presence of a gasifying agent (air, steam, or oxygen) to produce smaller molecules like carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and other lower hydrocarbons (Kumar et al. 2009). Different types of gasifiers (fixed bed and moving bed) are used due to variations in feedstock

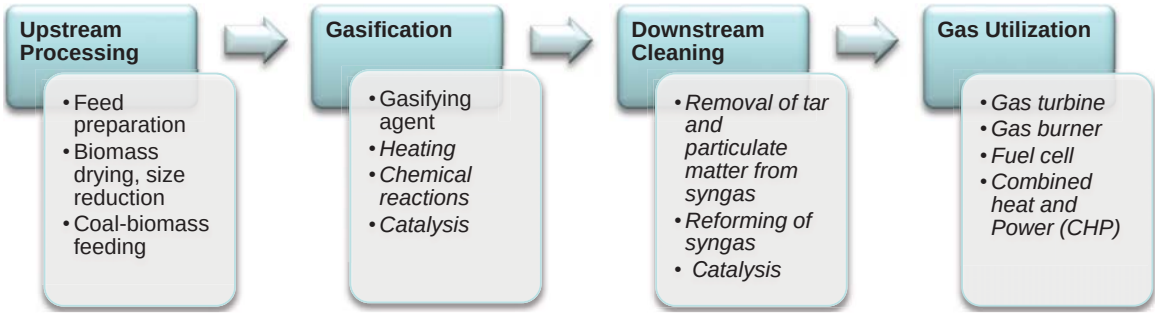

Figure 1.—Process flow diagram showing unit operations involved in a typical gasification system.

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properties and application-specific requirements for the quality of the resulting syngas, such as electricity generation, Fisher-Tropsch liquid (FTL) synthesis, or Dimethyl ether synthesis. Fixed bed gasifiers are divided into three types, (up-draft, down-draft, and cross-draft), depending on the direction of air/gasifying agent flow. In up-draft gasifiers, the gasifying agent is supplied from the bottom to the top of the reactor. In down-draft gasifiers, the gasifying agent is fed from top to bottom. In cross-draft gasifiers, the agent is fed from the left to the right of the reactor. In all three situations, feedstock is fed from the top; however, gas quality and impurities like sulfur, nitrogen, and tar compound vary significantly (McKendry 2002).

In fixed bed gasifiers, four zones (drying, pyrolysis, reduction, and combustion) are formed during the gasification process. In the drying zone, moisture present in the feedstock is removed. After drying, pyrolysis starts at temperatures around 200-400 ºC. In the pyrolysis zone, most of volatile matter is lost, and only fixed carbon is left behind. In the combustion zone, fixed carbon reacts with a sub-stoichiometric supply of oxygen whereupon carbon dioxide is produced. When the oxygen is completely reacted, the reduction of CO_2 takes place, and CO is produced. The water gas shift reaction, which takes place during steam cracking of pyrolysis vapors, is important for increased H_2 content in syngas. In this reaction, CO reacts with steam and produces CO_2 and H_2. This CO and H_2 mainly comprise syngas. Depending upon the supply of gasifying agent, the position of the combustion zone and reduction zone varies. In the down-draft gasifier, gasifying agent is provided from the top of the reactor, and the combustion zone occurs on top. However, in moving bed gasifiers (fluidized, circulating, or bubbling bed), no separate zones are formed. Air is provided above the minimum fluidization velocity of the feedstock, and it behaves like a liquid (McKendry 2002).

After the synthetic gas is produced, downstream cleaning of the gas depends on how the gas will be utilized and includes the following: particulate matter removal, alkali removal, and tar removal. In addition, syngas produced from coal involves sulfur and mercury removal. Syngas produced from coal-biomass mixtures would need downstream cleaning processes applicable to both coal and biomass.

BENEFITS OF COGASFICATION

There has been significant research interest in cogasification due to environmental and technical benefits of various biomass and coal mixtures such as Japanese cedar (*Cryptomeria japonica*) wood and coal (Kumabe et al. 2007), coal and saw dust (Vélez et al. 2009), coal and pine chips (Pan et al. 2000), coal and silver birch (*Betula pendula*) wood (Collot et al. 1999), and coal and birch (*Betula* spp.) wood (Brage et al. 2000). Cogasification of forest residue with coal has rarely been explored (Pan et al. 1999, Ruoppolo et al. 2010).

Environmental Benefits

Coal contains high carbon (60 to 85 percent) depending upon the type of coal (Prins et al. 2006). Gasification of coal produces a gas with a high carbon footprint. Moreover, sulfur present in coal can produce sulfur-oxides (pollutant causing acid rain) during gasification. On the other hand, biomass consists of 15-20 percent fixed carbon, 70-80 percent of volatile matter, moisture, and ash (Kumabe et al. 2007). The greenhouse gas emission index (GHGI) is a unit for measuring and quantifying greenhouse gas emissions. It is defined as the lifecycle greenhouse gas emission associated with the energy products divided by the lifecycle greenhouse gas emissions associated with the fossil-fuel-

derived products displaced (Liu et al. 2011). Liu and his colleagues calculated a GHGI of 1.71 for the gasification of coal and 0.96 for the gasification of 60 percent coal and 40 percent biomass. The GHGI decreased in cogasification of coal and biomass as compared to that for coal alone. Also, in gasification of low-grade coal, the addition of biomass is helpful because the low ash content of biomass counterbalances the effect of high ash in coal (Prins et al. 2006). Along with benefits of cogasification of coal and biomass, there are some challenges as well.

Technical Benefits

The use of coal and biomass as a feedstock in gasification provides many technical benefits. Ruoppollo et al. (2010) found an increase from 4.0 MJ/Nm^3 to 4.52 MJ/Nm^3 in heating value of syngas when 30 percent of coal was mixed with biomass for gasification in a fluidized bed gasifier with quartzite bed material as compared to biomass alone. Cogasification of coal and biomass also helped to increase H_2 concentration in syngas. Syngas with a higher H_2 concentration is recommended for conversion into diesel-range hydrocarbons by the Fisher-Tropsch process (Kumar et al. 2009).

Use of biomass with coal in cogasification also helps to reduce smoke caused by sulfur. Blesa et al. (2003) found that saw dust and olive stones (used as biomass) have hydrogen donor capabilities which helped in desulfurization of Maria coal. Moreover, biomass char has high surface area and high reactivity and can be used as a cheap catalyst for the coprocessing of coal and biomass (Zhua et al. 2008).

CHALLENGES

Technical Challenges

Feeding Coal and Biomass to the Gasifier

Feeding coal and biomass to the gasifier is a technical challenge due to the differences in specific gravity of the particles (approximately 1.47 for woody biomass and 1.52 for coal) and the material handling properties of coal and biomass. The differences in density, shape, and size of the coal and biomass particles cause segregation during transport of the mixture and as it is processed inside the gasifier. Cogasification requires preconditioned, uniform mixtures of coal and biomass feedstock (Kumabe et al. 2007, Pan et al. 2000). A durable feedstock material that will not segregate during handling and feeding into a gasification system is essential for producing a homogeneous feedstock. Several options for feeding biomass and coal into the gasification system are shown in Figure 2.

While biomass and coal can be separately fed into a gasifier, doing so complicates plant operation. If coal and biomass are simply blended together and fed into a gasifier, they tend to segregate during

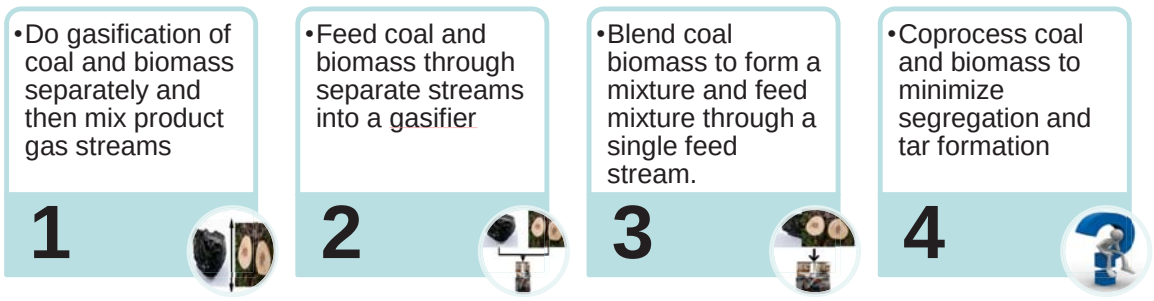

Figure 2.—Options for feeding coal and biomass into the gasification systems.

storage (i.e., piling) and transportation to the gasifier. Inside the gasifier, segregation of coal and biomass particles may also take place due to differences in aerodynamic properties which will limit the benefit of biomass ash catalysis to the gasification of coal. Through pelletizing and briquetting biomass/coal mixtures, the segregation during storage and transportation can be eliminated.

Difference in Gasification Behavior

Gasification is a three-stage process of pyrolysis (devolatilization), gasification (reduction), and combustion. The stages are dependent upon the fixed carbon and volatile matter content of the coal and biomass. Coal mainly consists of 60-70 percent of fixed carbon and 15-20 percent of volatile matter. On the other hand, biomass has 70-80 percent volatile matter and 15-20 percent fixed carbon. Moreover, the devolatilization temperatures of coal and biomass are different. Biomass starts to volatilize at low temperature (200-430 ºC) as compared to coal (400-600 ºC) (Fig. 3). Different devolatilizing temperatures coupled with segregation of coal and biomass can significantly reduce the volatilization of coal because volatiles formed due to pyrolysis of biomass will not get sufficient time to react with the coal structure.

Additionally, coal and biomass exhibit different combustion characteristics (Fig. 4). While biomass completely burns between 230 to 430 °C, coal combustion begins after 530 °C and is complete at 600 °C. In between the devolatilization and combustion stages, reduction of char formed during pyrolysis takes place.

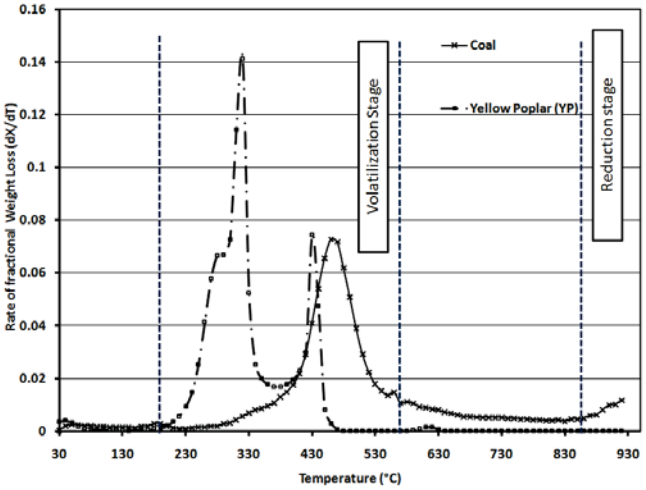

Figure 3.—Rate of fractional weight loss as a function of temperature of West Virginia bituminous coal and yellow-poplar (*Liriodendron tulipifera* L.) obtained from thermo-gravimetric analysis. The samples were heated from 30 to 950 °C under the gasifying agent CO_2 at a flow rate of 50 cm^3/min.

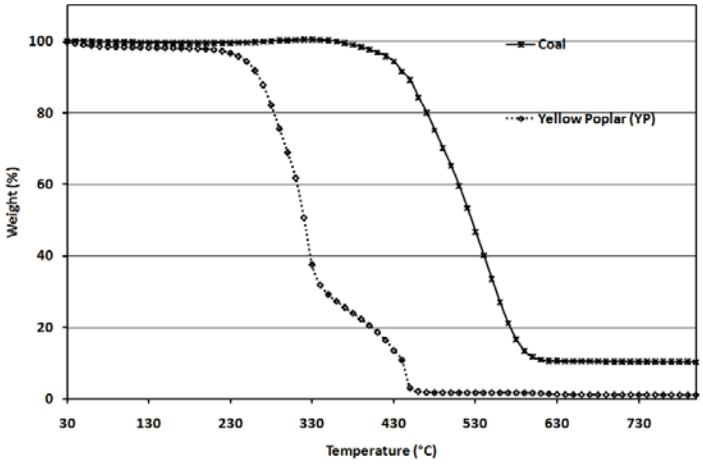

Figure 4.—Weight loss as a function of temperature during combustion of West Virginia bituminous coal and yellow-poplar obtained from thermo-gravimetric analysis. The samples were heated from 30 to 950 °C under air at a flow rate of 50 cm^3/min.

In laboratory experiments, the gasification rates for coal have been shown to be close to 45 times slower than biomass at the same temperature. This can cause buildup of coal in the gasifier and eventual stoppage. Furthermore, biomass has a tendency to form tars during pyrolysis at lower temperatures. One way to address these issues is gasification via a down-draft style gasifier where there is a strong temperature gradient between the oxidative and reducing environments. This kind of design could allow biomass to pyrolyze in the upper, lower temperature section of the gasifier. The syngas/tar mixture is then forced through the hot coal bed where tar cracking can occur. In addition, the coal will likely remain in the ash bed until it enters the high temperature oxidation zone and can supply the fuel for gasifying the biomass. The conditions needed to produce this kind of gasification behavior will have to be identified and may require modification of existing equipment and/or its operation.

OPPORTUINTIES

Technical Opportunities

Coprocessed Coal-Biomass Hybrid Fuel

One option to remove differences in the gasification behavior and decrease the segregation problems is to coprocess coal and biomass to produce a hybrid fuel. Our preliminary lab data showed that a coal and yellow-poplar (*Liriodendron tulipifera* L.) mixture exhibited the individual combustion signatures of coal and yellow-poplar with combustion temperatures from 230 to 630 °C; however, coprocessed samples decomposed in a relatively small temperature range (330 to 600 °C). Similarly, the gasification temperature for the coal and yellow-poplar mixture ranged from 230 to 930 °C with three reaction zones (major reaction zone from 230 to 400 °C and two minor reaction zones from 400 to 530 °C and 830 to 900 °C). Coal gasification had two reaction zones (a major reaction zone at 300 to 530 °C and a minor reaction zone at >830 °C). However, coprocessed samples had just two major reaction zones (330 to 730 °C and >800 °C). Moreover, coprocessed biomass had gasification rates almost four times higher than that of coal alone in the temperature range of 830 to 930 °C.

Preprocessing of Biomass

One feasible option for improving the gasification properties of biomass is through torrefaction. Once torrefied, biomass is more easily reduced in size because it has lost some fibrous nature and tenacity (Bergman et al. 2005). Additionally, the resulting torrefied woody biomass is mainly comprised of cellulose and lignin. By using torrefied biomass with increased lignin content, it should be possible to improve pellet durability when coal is added. Bergman (2005) reported that torrefied pellets possessed an energy density of 14 to 18.5 GJ/m^3, which is comparable to the energy density of bituminous coal (16-17 GJ/m^3).

The fixed carbon content in bituminous coal (50.58 percent) was significantly higher than red maple (*Acer rubrum* L.)(14.71 percent) and yellow-poplar (15.85 percent). Torrefaction increased fixed carbon content of both biomass samples by more than threefold; however, the volatile matter content reduced to half. Similar findings were reported by Phanphanich and Mani (2011) for forest logging residue chips where fixed carbon content increased from 16.07 to 44.76 percent, but hydrogen content decreased. Decreased hydrogen content due to torrefaction reduced the H/C ratio from 0.13 to 0.04 for red maple and from 0.13 to 0.07 for yellow-poplar which was similar to the 0.07 for coal. Using coal alone as a feedstock for gasification produces gas with higher energy content as compared to biomass alone (Liu et al. 2011).

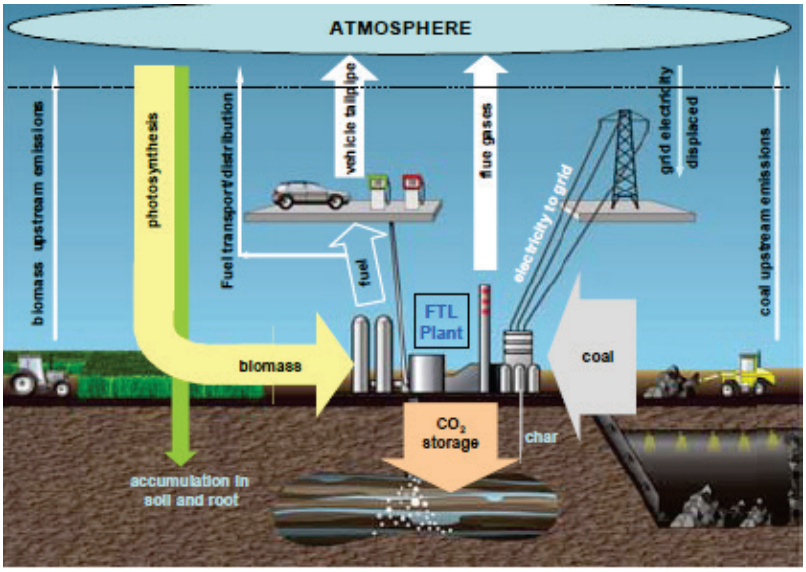

Figure 5.—Schematic of all flows considered in estimating net fuel cycle greenhouse gas emissions. (Source: Larson et al. 2009).

Nontechnical Opportunities

In the Clean Energy and Security Act (July 14, 2009), developing carbon capture and sequestration technologies were emphasized. The Clean Energy Act encouraged production of electricity and transportation fuel with low carbon emissions. According to this act, emission allowance rebates and other incentives would be provided for reducing greenhouse gasses. The concept of selling carbon credits (amount of carbon sequestered) was promoted in this act. Cogasification of coal and biomass produces less greenhouse gas (GHG) emissions than coal gasification alone and helps in reducing carbon footprints. There is an opportunity for seeking carbon credit benefits by producing energy via the cogasification of coal and biomass. Larson et al. (2009) demonstrated reductions in carbon footprint and greenhouse gas emissions from a coal biomass to liquid fuel (CBTL) system utilizing coal and biomass (Fig. 5) for producing Fischer-Tropsch liquids and electricity compared to another coal-based integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS) (90% of CO_2 captured).

In the studied system, the first approach in Figure 2 was adopted to avoid technical complications involved in cogasification. The study considered separate gasification of coal and biomass and then mixed resulting synthetic gases. The mixture of gases was then passed through the Fischer-Tropsch process to convert some gases into liquid fuels. Remaining gases were burnt to produce electricity. During the three processes of gasification, FTL, and electricity generation, the byproducts of carbon emissions were captured and stored using carbon capture and storage technology.

The CBTL system was studied for two types of biomass, namely, corn stover and mixed prairie grasses (MPGs) with flow rates of 3,044 dry tons/day. Coal input rate was set such that FTL liquid could be produced with zero net lifecycle GHG emissions. Some results of the lifecycle analysis are presented in Table 1. In the table, the proportion of biomass in the CBTL system was defined as the percent of the total energy supplied by biomass. The results showed that both coal-based and CBTL systems had 46.7 percent total energy conversion. After performing the carbon balance and converting vented

Table 1.—Electricity conversions and net greenhouse gas (GHG) emissions by coal-based integrated gasification combined cycle (IGCC) system equipped with carbon capture and storage and coal biomass to liquid fuel (CBTL) systems equipped with carbon capture and storage (CCS) and using corn stover and mixed prairie grasses (MPG) (Source: Larson et al. 2009).

	Coal Only	Coal + Stover	Coal + MPG
Percent energy contribution from biomass in the CBTL system (% higher heating value [HHV])	0	37.4%	23.9%
Equivalent energy produced Fisher-Tropsch liquid (FTL) fuel, MW HHV	2,483	521	883
Net electricity to Grid, MW	1,075	246	406
Energy conversion ([energy from FTL+ electricity]/total energy input), %	46.7%	46.7%	46.7%
Carbon (C) input as feedstock, kgC/s	179	39	66
C stored as CO_2	51.1%	51.7%	50.9%
C in char (unburned)	5%	6.9%	6.2%
C vented to atmosphere	18.6%	17.5%	18.4%
C in FTL	24.7%	23.3%	23.9%
C stored, 10^6 tCO_2/yr (90% cap factor)	9.52	2.14	3.49
Net GHG emission ($kgCO_2$/GJFTL HHV)	118	1	-9

carbon into equivalents of GHG emissions, Larson et al. (2009) concluded that the coal-based IGCC systems will have net GHG emissions of 118 $kgCO_2$/GJFTL higher heating value (HHV). In contrast, CBTL plants had either zero or negative GHG emissions.

In the Clean Energy and Security Act 2009, the possibilities of a GHG tax and carbon credit were discussed which may significantly change the economics of the traditional and renewable energy sources. Larson et al. (2009) mentioned that raising GHG emissions price from \$20/tCO_{2equiv} to \$37/tCO_{2equiv} is sufficient to make the CBTL option competitive against coal-based IGCC plant with a corresponding breakeven oil price of about \$56/bbl.

SUMMARY

Cogasification of coal and biomass helps in reducing the carbon footprint and greenhouse gas emissions for energy production from coal. It allows for the opportunity of selling carbon credits. It has other benefits like increased H_2 content in syngas and the reduction of sulfur and mercury pollutants. It also helps in increasing the energy content of syngas. As there are many benefits of cogasification, there are some technical challenges also for using both coal and biomass together in a reactor. Coal and biomass have different density and material handling properties which cause segregation inside the gasifier. Moreover, the different gasification rates of coal and biomass also create problems with unburnt carbons. These challenges can be overcome by coprocessing coal and biomass before feeding them into the gasifier. Coprocessed hybrid fuel showed uniform properties, but reductions in segregation can be expected during gasification. Overall, it can be concluded that cogasification of coal and biomass has advantages and it can create ample opportunities in the energy sector in near future.

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