EFFECT OF FUEL MOISTURE CONTENT ON BIOMASS-IGCC PERFORMANCE

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ABSTRACT

The moisture level in biomass fuels potentially impacts efficiency in conversion to power. This paper examines the efficiency and net power output of a circulating fluidized bed gasifier-combined cycle with flue gas drying for a range of as-received raw biomass moisture contents and levels of pre-gasification drying. Due to the lack of empirical data available, a modeling approach is used to simulate the effects of varying moisture content in the gasifier feed biomass. Below 30%, the raw-biomass moisture content has a negligible effect on the cycle efficiency and net power output. Higher moisture contents significantly reduce cycle efficiency. For a specified as-received biomass moisture content, drying prior to gasification increases overall efficiency, but the gains in efficiency decrease with increasing levels of drying.

INTRODUCTION

Typical moisture contents of freshly cut woody biomass are in the range of 30 to 60%. Many annual biomass crops, e.g. wheat straw, have a moisture content of 8 to 20% when harvested [Hall et al., 1993]. In an integrated gasification combined cycle (IGCC), efficiency penalties and some operational challenges may arise when using wetter compared to drier fuels. During gasification, high moisture contents lead to lower raw product gas heating values, in part through the dilution of the product gas with additional water vapor. Directly-heated (partial oxidation) gasifiers require a greater degree of combustion to provide heat for additional drying, increasing carbon dioxide levels. In air-blown gasifiers the higher air requirement leads to increased dilution of the product gas with nitrogen. While tests by gas turbine manufacturers indicate that, with small modifications, some gas turbine combustors can be operated effectively on low heating value fuels (see below), low product gas heating values do pose technical challenges and potentially increased equipment costs.

The objective of the work presented here is to examine for a biomass pressurized fluidized bed gasifier combined cycle the effect on cycle efficiency and power output of (a) fuel moisture content at the plant gate, and (b) level of drying prior to gasification. In this paper, “raw biomass” refers to the biomass at the plant gate; “feed biomass” refers to the biomass entering the gasifier after drying.

Due to the lack of empirical data, a modeling approach is necessary. The software used here for cycle modeling is able to accurately predict full-load design-point power and efficiency for cycles incorporating commercially-available gas turbines. Details of the software are described elsewhere [Consonni et al. 1991; Consonni and Larson, 1996]. Simulations were run for raw-biomass moisture contents of 50%, 40%, 30% and 20%. For each raw biomass moisture level, several feed-biomass moisture contents were considered ranging no drying to complete drying. This paper focuses exclusively on the overall thermodynamic impacts of biomass moisture. Operational and cost challenges associated with drying and using wet feedstocks are not trivial, but are not addressed in this paper.

SYSTEM DESIGN AND TECHNOLOGICAL CONSIDERATIONS

Cycle selection

The system modeled here is a combined cycle with a pressurized
Figure 1: Cycle Layout

circulating fluidized bed gasifier, hot product gas cleaning and flue gas drying (Fig. 1). Chipped raw biomass is dried, pressurized with nitrogen in a lock-hopper, and fed to the gasifier operating at 24 bar. Characteristics assumed for the bone dry woody biomass are shown in Table I. Gasification air is bled from the gas turbine compressor, cooled and boosted to the required pressure. Product gas from the gasifier is cooled to 400°C before the filter. Heat from cooling the syngas is recovered as additional steam for the bottoming cycle. Ash is removed primarily at a downstream filter. The clean product gas is burned in the gas turbine combustor. Heat from the gas turbine exhaust is recovered in the heat recovery steam generator (HRSG) which feeds the steam turbine bottoming cycle. The exhaust gas from the HRSG is then used to directly dry the raw biomass before being vented at the stack.

Gasifier options

The gas turbine in this analysis is modeled on the GE LM2500 aeroderivative gas turbine with a slightly increased pressure ratio (20.2 instead of 18.8) that results from higher flow volumes typical of lower energy-content fuels. Closing the compressor inlet guide vanes was simulated in order to limit the pressure ratio to this value.

For large power plants, the lower pressure ratios and higher gas turbine outlet temperatures characteristic of heavy-duty industrial gas turbines (rather than aeroderivatives) are closer to the optimum parameters for maximum efficiency of natural gas-fired combined cycles [Macchi et al., 1995; Hotlock, 1995, Corman 1995]. However, below 50 MW (a likely scale for many biomass applications), aero-engine-based combined cycles show higher efficiencies than industrial-based systems due to high topping cycle efficiencies even at relatively small scales [Macchi et al., 1995]. The LM2500 is especially appropriate for the scale considered here since the pressure ratio is toward the low end for large modern aeroderivative turbines while efficiency is still high.

Combustion of low heating value fuel

A concern with using low-heating value fuels is ensuring stable, complete combustion while achieving the desired temperature. In these simulations, the turbine inlet temperature was set at 1232°C. The oxygen concentration in the combustor outlet stream was used as an indicator of potential combustion stability problems [Larson and Hughes, 1996]. If the heating value of the product gas resulted in an oxygen mole fraction of less than 5%, the turbine inlet temperature was reduced until 5% was achieved. This criterion ensures that a minimum requirement is met, i.e., that the specified flame temperature can theoretically be reached with the given fuel.

Ultimately, combustion stability and efficiency must be addressed empirically. Test results show that operation of gas turbine combustors on many low-heating value fuels is feasible. A GE LM2500 combustor has been tested under conditions simulating rated power operation, with fuels containing 5.6 to 8.4 MJ/m³ (150 to 225 Btu/scf) [Sbla and Kutzko, 1985]. Only two modifications were made: the fuel nozzle was enlarged, and in one set of tests the swirl cup venturis were removed. Despite some adverse effect on the combustor exit temperature distribution, the researchers concluded that "operation of the engine at maximum power output with the current combustion system with appropriately sized gas nozzles appears completely viable." Flammability results showed that combustion could be maintained with fuel lower heating values (LHV) as low as 3.72 MJ/m³ (100 Btu/scf) at a H₂:CO ratio of about 0.7 and as low as 2.88 MJ/m³ (50 Btu/scf) as the ratio approaches 1. Tests with a GE LM500 combustor showed stable combustion and acceptable combustion efficiency and exit temperature.
distribution with fuel heating values as low as 3.72 MJ/m³ (100 Btu/scf) [Rahn et al. 1985]. Fuels with heating values as low as 3.0 MJ/m³ were successfully combusted in a one-fifth-scale model combustor of the ABB gas turbine type 11N2-LBtu [Liu and Schmidt, 1996].

In this analysis, feed biomass with 30% moisture yields a product gas LHV of 3.72 MJ/Nm³, which is within the range of some of the tests noted above. A feed moisture content of 50% gives a LHV of 1.97 MJ/Nm³, requiring gas turbine inlet temperature denting by almost 200°C (to 1037°C). Combustion of such a fuel might require significant combustor modification and/or blending with a higher heat content fuel.

**GASIFICATION MODELING**

**Approach**

Fluidized bed biomass gasifiers operate in a temperature range between 850°C and 1000°C [Consonni and Larson, 1996]. Since at these temperatures (and for characteristic residence times) the product gas composition is far from equilibrium, the gasification modeling reported here relies on empirical data from gasifier developers. Currently, a consistent set of empirical data showing the effect of feed biomass moisture content on gasifier performance is not available from gasifier developers. This section describes the approach used in this analysis to estimate the performance of a gasifier for different feed biomass moisture levels.

The approach can be summarized in three steps: (i) a "base" cycle was designed using available empirical data for 15% moisture content feed biomass [Larson and Hughes, 1996]; (ii) all inputs to the gasifier were fixed at the base-case values, except for the feed moisture and the air/dry-biomass ratio (A/B); (iii) the product gas composition was calculated so as to close the heat and mass balance for each set of feed moisture and A/B values.

Adjustments to the available empirical A/B (for 15% feed moisture content) were calculated based on the assumption that additional moisture to the gasifier requires additional combustion for a fixed gasifier temperature. Figure 2 shows the variation of the calculated A/B with feed moisture content and the resulting heating value of the product gas.

**Justification for the approach**

Since the objective of this work is to estimate the effect of biomass moisture content on overall cycle efficiency and power output, the gasifier modeling focuses on the aspects most relevant to cycle efficiency and power output. For a fixed set of gasifier inputs and gasifier temperature there is an important split between "sensible" and "chemical" energy production. The chemical energy leaving the gasifier is passed to the more efficient topping cycle (gas turbine). Most of the sensible heat in the product gas is recovered in the syngas cooler and passed to the less efficient steam cycle. The modeling approach taken here is focussed on accurately accounting for the relative quantities of sensible and chemical energy leaving the gasifier.

The choice of a fixed gasification temperature ensures that variations in cycle performance are due to changes in biomass moisture content rather than simply from a shift in the proportion of product gas energy from chemical to sensible heat. The selected temperature (953°C) is within the range specified by gasifier developers based on consideration of kinetic rates and avoiding ash agglomeration.

In an actual gasifier, for a fixed set of inputs and gasifier exit temperature, a unique gas composition is produced. Since no data are available for how the product gas composition actually varies with feed moisture content, the specific gas composition cannot be predicted by the modeling here. Instead, for fixed inputs and gasifier temperature, alternative gas compositions that close the gasifier mass and energy balance can be calculated. One of these alternative compositions may be close to what would be achieved in an actual gasifier, but the precise composition used in the model calculations turns out to have an essentially negligible impact on the overall cycle results, which can be explained as follows.

By fixing the inputs, the mass and energy entering the gasifier are determined. Fixing the gas outlet temperature determines the fraction of incoming energy that leaves the gasifier as "sensible" energy. The remaining fraction of the input energy is expressed as the enthalpy of formation of the product gas at the output temperature. Because the input and sensible energy terms are constant, the enthalpy of formation is uniquely determined and thus is also independent of the gas composition. Calculations using the empirical gasifier A/B ratio with 15% feed moisture show that over a range of product gas compositions, overall cycle efficiency changes very little compared to the calculation based on the original empirical gas composition (Table 2).

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6 Sensible energy is defined here as

\[ \sum m c_p dT \]

where the summation is over all input streams, \( m \) is mass, \( c_p \) is specific heat capacity, and \( T \) is temperature. The mass of each atomic species is conserved from inlet to outlet of the gasifier. For fixed input and output temperatures, the overall temperature rise is constant. For a fixed set of atoms and a given pressure, the specific heat capacity (a thermodynamic variable) is a constant at each incremental temperature and is independent of the particular molecular arrangement of the atoms. Thus, the summation term as a whole has a constant value for fixed input and fixed output temperature.

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5 The fixed inputs are biomass elemental composition and heating value, air temperature, gasifier heat loss, carbon conversion, and gasifier exit temperature.
Table 2: Impact of Gas Composition on Overall Cycle Efficiency

<table>
<thead>
<tr>
<th>Composition</th>
<th>Empirical</th>
<th>Alternative Calculated Compositions</th>
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<tbody>
<tr>
<td>Ar</td>
<td>0.481</td>
<td>0.471</td>
</tr>
<tr>
<td>CH₄</td>
<td>5.410</td>
<td>4.224</td>
</tr>
<tr>
<td>CO</td>
<td>16.237</td>
<td>9.465</td>
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<tr>
<td>CO₂</td>
<td>11.852</td>
<td>19.14</td>
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<tr>
<td>C₂H₄</td>
<td>0.121</td>
<td>0.094</td>
</tr>
<tr>
<td>H₂</td>
<td>10.167</td>
<td>20.70</td>
</tr>
<tr>
<td>H₂O</td>
<td>12.103</td>
<td>3.185</td>
</tr>
<tr>
<td>H₂S</td>
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<td>0.015</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.059</td>
<td>0.119</td>
</tr>
<tr>
<td>N₂</td>
<td>43.477</td>
<td>42.51</td>
</tr>
<tr>
<td>temp. (°C)</td>
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<td>953.1</td>
</tr>
<tr>
<td>enthalpy (kJ/kg)</td>
<td>-2541</td>
<td>-2541</td>
</tr>
<tr>
<td>HHV (MJ/kg)</td>
<td>5.130</td>
<td>5.095</td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td>4.553</td>
<td>4.518</td>
</tr>
<tr>
<td>sp. heat cap. (kJ/kg °C)</td>
<td>1.3483</td>
<td>1.348</td>
</tr>
<tr>
<td>relative HHV CC efficiency</td>
<td>1.001</td>
<td>1.001</td>
</tr>
</tbody>
</table>

 RESULTS AND DISCUSSION

Table 3 lists the cycle characteristics that were fixed for all simulations. Figures 3 and 4 show the variation of cycle efficiency and net power output with varying feed-moisture content. Curves are shown for raw-biomass moisture contents from 50% to 0%.

One important result shown in figure 3 is the effect of the raw-biomass moisture content on efficiency, i.e., the vertical spacing of the curves. The "*" symbol on the vertical axis shows the efficiency that would be achieved if the raw biomass were bone-dry, so that no heat from the cycle is used for drying. Below 30%, the raw biomass moisture content has very little effect on overall efficiency: the curves for 0, 20, and 30% lie on top of each other. This occurs because excess low grade heat exists which can not be used anywhere in the cycle other than in drying and thus its use for drying imposes no efficiency penalty. Above 30% moisture content, the heat required for biomass drying exceeds the amount of available excess heat. In this case, drying reduces the heat that would be used in other parts of the system (such as in boiler water pre-heating) thereby imposing an efficiency penalty relative to a drier fuel. This result suggests significant increases in efficiency are possible if green biomass (50% moisture) can be air-dried to 30% moisture content before being used at a power plant. Results from a study conducted in Brazil indicate that 30% is a realistic target under appropriate climatic conditions (Gomes et al., 1996).

A second important result shown in Fig. 3 is that for a given raw biomass moisture content, reducing the feed-biomass moisture increases efficiency but at a decreasing rate. For example, reducing feed moisture content from 50% to 35% increases the efficiency by 2.5 percentage points, reducing from 15% to 0% changes the efficiency by less than 1%. This suggests a trade-off between efficiency and additional dryer capacity/cost. If air-drying to 30% raw moisture content were achieved outside the cycle, without any further drying the efficiency would be comparable to the baseline efficiency (drying from 50% to 15% moisture content). In this situation, it might be more cost effective to eliminate the dryer entirely.

Figure 4 shows the effect of moisture content and drying on the net power generated. The general trend is that for a given raw-biomass moisture content, increasing the feed-biomass moisture increases efficiency but at a decreasing rate. As the heating value of the product gas falls with higher feed moisture content, the combustion occurring in the gas turbine moves from a very lean overall mixture toward stoichiometric combustion in order to reach the required turbine inlet temperature. This is achieved by increasing the fuel-air ratio in the gas turbine combustor. In the system...
Figure 3: Cycle HHV Efficiency vs Feed Moisture Content. The bars around the 50% raw-biomass line show the efficiencies calculated using A/B ratios of ± 10% of the values shown in Fig. 2. The conclusions are not qualitatively different within this range of A/B ratio values. Note that for 15% feed-biomass moisture, the results are calculated directly from empirical data, and can be considered precise.

Figure 4: Net Cycle Output vs Feed Moisture Content

At high feed-biomass moisture (above about 35%) the rated turbine efficiency can no longer be reached with the low heating value fuels. Turbine inlet temperature must be reduced. Gross gas turbine power output falls sharply (Fig. 5) and net power output levels off (Fig. 4).

SUGGESTIONS FOR FUTURE WORK

For the biomass-IGCC system modeled here, efficiency and power output are unaffected by the moisture content of the raw biomass feedstock for moisture levels of 30% or less. Higher moisture contents significantly reduce cycle efficiency. For a specified raw biomass moisture content, drying prior to gasification increases overall efficiency, but the gains in efficiency decrease with increasing levels of drying. These results were developed for a cycle configuration that includes a pressurized circulating fluid-bed gasifier, hot gas cleanup, and a gas turbine with the characteristics of the LM2500. A number of alternative gasifier and gas cleanup technologies have been proposed for biomass-IGCC applications. The conclusions reached here may not hold for cycle configurations using other gasifier, gas cleanup, and/or gas turbine designs. Similar analyses for other cycle configurations, for example using atmospheric, directly or indirectly heated gasification, would be of interest.

Flue gas drying has been assumed in the results reported here. It may be worthwhile to carry out similar analyses for other drying technologies that have been proposed. One technology that may be especially interesting is the IVOSDIC dryer under development by Imatra Voima Oy (IVO), a Finnish electric utility. In the IVOSDIC process, biomass is dried under pressure using steam, and the resulting steam evolved from water in the biomass is recovered and used downstream in the cycle. This process—direct pressurized drying with super-heated steam—is reported to greatly reduce the efficiency penalty of drying compared to a flue gas drying system when starting with very high moisture content (> 60%) fuels (Hulkkonen et al., 1991, 1993). (A trade-off may be greater capital cost and operational complexity for the IVOSDIC system.) In a comparison of drying-system options with fuel dried from 62% to 15% moisture content, an increase in combined cycle efficiency...
higher-heating value efficiency of up to 3 percentage points compared with flue gas drying is reported by Hulkkonen, et al. [1993]. The possibility that the IVOSDIC process might reduce the drying penalty associated with flue gas drying under a range of raw and feed biomass conditions deserves consideration.

REFERENCES


