Performance Analysis of Evaporative Biomass Air Turbine Cycle With Gasification for Topping Combustion

J. Wolf
F. Barone
J. Yan

Department of Chemical Engineering and Technology/Energy Processes, Royal Institute of Technology, SE-100 44 Stockholm, Sweden

Abstract

This paper investigates the performance of a new power cycle, a so-called evaporative biomass air turbine (EvGT-BAT) cycle with gasification for topping combustion. The process integrates an externally fired gas turbine (EFGT), an evaporative gas turbine (EvGT), and biomass gasification. Through such integration, the system may provide the potential for adapting features from different advanced solid-fuel-based power generation technologies, e.g., externally fired gas turbine, integrated gasification combined cycle (IGCC), and fluidized bed combustion, thus improving the system performance and reducing the technical difficulties. In the paper, the features of the EvGT-BAT cycle have been addressed. The thermal efficiencies for different integrations of the gasification for topping combustion and the heat recovery have been analyzed. By drying the biomass feedstock, the thermal efficiency of the EvGT-BAT cycle can be increased by more than three percentage points. The impact of the outlet air temperature of the high-temperature heat exchanger has also been studied in the present system. Finally, the size of the gasifier for topping combustion has been compared with the one in IGCC, which illustrates that the gasifier of the studied system can be much smaller compared to IGCC. The results of the study will be useful for the future engineering development of advanced solid fuel power generation technologies. [DOI: 10.1115/1.1492834]

Introduction

Gas turbine systems that enable the use of solid fuels such as biomass and coal are of importance for future technologies for electricity production. The issues of the nuclear power phaseout in some European countries increase the interests for using other energy resources including biomass for electricity generation. For example, in Germany, 161 TWh/year of nuclear power will be replaced by other energy resources by 2021 according to a recent agreement between the German Government and the nuclear power industry (European Union [1] and IZE [2]). In Sweden, nuclear power today provides about 50% of the total electricity (Energikommissionen [3]) and the phaseout of nuclear power has already started. At the same time, the reduction of CO₂ emissions has recently been given great attention by the OECD countries due to their commitment to Kyoto agreement. Since biomass is a renewable energy resource and does not contribute to CO₂ emissions, using biomass in the place of fossil fuels for power generation has the potential for reducing CO₂ emissions. Therefore, developing an energy efficient, economically affordable, and technically reliable power generation system by using biomass becomes more important.

Sweden has large resources of biomass and the energy supply from biomass and peat reached 15% of the total energy supply in 1998 (Energimyndigheten [4]). However, the existing biomass power plants have low electrical efficiencies (Wahlund et al. [5]). Therefore, it is of importance to find a new approach for improving the biomass power generation systems.

The characteristics of fuels are of major importance when choosing an option in gas turbine systems. The use of solid fuels in gas turbines requires the resolution of technology issues which are of little, or no consequence for conventional natural gas and refined oil fuels. Some options for producing power and heat using solid fuels are under development. These are direct solid-fuel fired gas turbine, integrated gasification combined cycle (IGCC), pressurized fluidized-bed combustion (PFBC), and externally fired gas turbines (EFGT). Each of these advanced technologies is at a different stage of development, but all face some barriers, as for example, limited operating experience and unproven long-term reliability, an unwillingness by the risk-averse utilities to accept products with limited operating experiences, lack of ability to deal with fluctuating loads and alternative modes of operation, and high capital costs. Today, the market of cheap natural gas brings another challenge for using solid fuels such as coal and biomass for power generation. Therefore, the R&D strategy should focus on the integration of features of different technologies, e.g., PFBC, IGCC, and EFGT (Yan and Eidensten [6]).

In this paper, a new power cycle so called evaporative biomass air turbine (EvGT-BAT) cycle with gasification for topping combustion has been studied. The system integrates the externally fired gas turbine (EFGT), the evaporative gas turbine (EvGT) and biomass gasification to improve the performance and use existing technologies as much as possible.

System Description

Previous work on biomass fired evaporative gas turbine can be found in Yan et al. [7–9]. The gasification process for topping combustion has been studied by Wolf and Yan [10]. This paper is a continued work of these previous studies with the focus on the integration of the various processes studied earlier. Figure 1 gives a flowsheet of an existing model presented in Yan et al. [8]. The model contains the gas turbine system, the solid fuel (biomass) combustion (SFC), and the heat recovery (HR) subsystem. The fuel for the topping combustor in the previous work was natural gas. For the present paper, natural gas has been replaced with syngas produced by a steam-based gasification process. Figure 2 shows the integrated system that has been studied in this paper.
the so-called EvGT-BAT. The furnace provides the main part of the thermal energy for producing electricity. The high-temperature heat exchanger (HTHx) heats the air to about 900°C. Before entering the turbine, the air temperature is further increased by mixing with the flue gas from the topping combustion to the required turbine inlet temperature of 1100°C. In order to further increase the thermal efficiency of the process, the technology of evaporative gas turbines (EvGT) is used. The thermal energy of the exhaust gas from the turbine and the furnace is used for preheating and humidifying the compressed air before it enters the HTHx. To produce the fuel gas, steam-based pyrolysis of biomass conducted in an entrained flow tubular reactor is used. This process is discussed by Wolf and Yan [10]. A screw feeder transports the feedstock to a carrier gas injector. The carrier gas is a high-temperature product gas, which is accelerated and slightly pressurized by a compressor. The carrier gas conveys the biomass very rapidly through an entrained flow tubular reactor. The mixture of product gas and biomass that enters the reactor is heated up to about 800°C in less than 1 sec. Under these conditions flash pyrolysis occurs. After pyrolysis, the gaseous products are separated from the pyrolysis char by a cyclone and the char is transported into the SFC. The stream of gaseous products is divided into a recycle stream, which flows back into the carrier gas injector, and the product gas stream. The product gas stream passes a gas cleaning system and if necessary, a water knock out unit. Since the gasifier suggested in this work operates close to atmospheric pressure, the product gas has to be compressed before it can be fed into the topping combustor. Syngas leaves the gasifier at about 800°C and is cooled down to 40°C and then compressed from 1 to 12 bar. After compression, the syngas of 12 bar and about 130°C is supplied to the topping combustor. Heat from the syngas cooler can be recovered in three ways, preheating the syngas stream after the compression, preheating the combustion air.
for the HITAF, or increasing the amount of water evaporated in the humidifier. In this paper three combinations of these options have been studied.

Features of the System

The studied system is an approach to use commercially available equipment as much as possible and new developing technologies only when necessary. For example, combustion occurs in a conventional atmospheric furnace. By using topping combustion to increase the turbine inlet temperature, the temperature of the high-temperature heat exchanger (HTHx) can be selected in a reasonable temperature range based on the development of the material and manufacturing technique. The gasification of biomass to produce the additional fuel for the topping combustion can be a simple pyrolysis process, which does not require a high conversion rate from biomass to gaseous fuel because the unconverted char can be further used in the SFC. The entrained flow tubular reactor, where the pyrolysis occurs, is housed in the SFC. In this way an extra building and combustor for the gasification is not necessary. Cooling down the syngas enables not only the use of a conventional cool gas cleaning, but also leading to a higher heating value of the fuel gas (Wolf and Yan [10]). Besides a high heating value, steam-based gasification supplies a syngas that contains a very low amount of nitrogen (about 1 Vol%).

Assumptions for the Process Model

The gasifier is modeled by a heat exchanger for heating the solid and moist biomass, a yield reactor for simulating the devolatilization reaction and a second heat exchanger for heating the syngas up to the final pyrolysis temperature of about 800°C. The gas composition listed in Table 1 is assumed to be achieved at a heating rate of about 1000°C/sec and an operating temperature of 800°C. The heating value of this gas has been calculated as 16 MJ/Nm³.

The heat requirement for the devolatilization reactions has been calculated by a heat balance based on the lower heating values of the biomass input and the output of syngas and char. Calculations showed that most of the energy needed for the pyrolysis is used to heat the biomass, the syngas, and the char to the required pyrolysis temperature. The required amount of energy for the devolatilization reactions is relatively small (Table 2). In this paper, the values from Table 2 are used in the model of the gasifier.

Further main assumptions used in the simulations are listed in Table 3. More detailed assumptions related to externally fired evaporative gas turbine can be found from the references (Yan et al. [9] Barone [11]). The pressure drop in the gasifier has not been considered in this study.

Table 1 Pyrolysis gas compositions for flash pyrolysis of woody biomass with a moisture content of about 14wt% (Wolf and Yan [10])

<table>
<thead>
<tr>
<th>Component</th>
<th>N₂</th>
<th>CO</th>
<th>H₂</th>
<th>CO₂</th>
<th>CH₄</th>
<th>C₂H₄</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol %</td>
<td>1</td>
<td>47</td>
<td>16</td>
<td>7</td>
<td>14</td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 2 Results of the heat balance for the devolatilization reactions (Yan et al. [7], Wolf [14], and Williams and Beslere [15])

<table>
<thead>
<tr>
<th>Stream</th>
<th>LHV (MJ/kg)</th>
<th>wt %</th>
<th>Total Energy (MJ/kg生物质)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>8.25</td>
<td>100</td>
<td>8.25</td>
</tr>
<tr>
<td>Syngas</td>
<td>7.9</td>
<td>93</td>
<td>9.59</td>
</tr>
<tr>
<td>Char</td>
<td>32</td>
<td>7</td>
<td>1.34</td>
</tr>
<tr>
<td>Required devolatilization energy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results and Discussion

The EvGT-BAT system with biomass gasification for fuel gas production for topping combustor has been compared with the EvGT-BAT system with natural gas as the additional fuel (reference system). The gasification is integrated into the whole power process. Thus, excess heat from the gasification process is recovered as much as possible to reduce any efficiency drops due to the introduction of gasification. The use of a dryer has been considered for both biomass streams, one entering the gasifier and one entering the SFC. The impact of the HTHx temperature on the systems performance is discussed, and finally the flow rate of biomass feedstock passing the gasifier is compared to the flow rate required in IGCC.

Efficiency of EvGT-BAT Systems When Introducing Biomass Gasification. The reference system for the present study is the EvGT-BAT system with natural gas as the additional fuel. Under the assumptions listed in Table 3, the thermal efficiency of this process is 42%. When gasification is used, due to the extra energy demand and the losses during the syngas cooling before the compression, the total thermal efficiency decreases by almost four percentage points if heat from the gasification is not recovered. The main loss appears in the product gas cooler. In this paper three options have been studied to increase the thermal efficiency:

• using the excess heat for raising the water-to-air ratio of the compressed air (HR 1),
• preheating the combustion air entering the HITAF and the syngas before entering the topping combustor (HR 2), and
• increasing the water-to-air ratio and preheating the combustion air (HR 3).

The possible increase in efficiency if the three modified heat recovery systems (HR 1–HR 3) are used is shown in Fig. 3. The first modification of the heat recovery system (HR 1) achieves an
efficiency increase of 1.5 percentage points compared to the syngas case, where heat from the gasifier is not recovered. The water-to-air ratio increases to 23.6%, thus the larger mass flow through the turbine results in a higher work output from the turbine. The second modification (HR 2) achieves an efficiency increase of 2.3 percentage points without changing the water-to-air ratio. This case leads to a decrease in the fuel consumption of the furnace (7.9% less biomass) and in the gasification process (1.5% less biomass). However, the low temperature heat (<130°C) cannot be used because after compression, the syngas has a temperature of about 120°C. A combination of both modifications, preheating the combustion air, and raising the water-to-air ratio from 19.5 to 21% (HR 3) leads to an overall thermal efficiency of 41.13%. This efficiency is less than one percentage point lower than the reference system with natural gas. This shows the gasification process, if well integrated into the whole process, does not inevitably cause a large drop in efficiency.

**Increase of Efficiency When a Drier is Used.** A further increase in the thermal efficiency can be achieved by drying the biomass feedstock. It has been assumed that the biomass leaves the drier at a temperature of 70°C. Figure 4 shows that drying only the biomass that enters the gasification does not lead to a significant increase in efficiency. This is because the flow rate of biomass feedstock to the gasifier is smaller. A different result is achieved by drying both biomass streams entering the gasifier and the furnace. This leads to a significant increase in the overall efficiency. It is also important to consider that the lower amount of flue gas from the furnace means less energy is available for the HR. Thus, the water-to-air ratio and the net power decrease.

Regardless of whether natural gas or syngas is used for the topping combustion, the thermal efficiency increases with 8% if the biomass is dried from 50% to 10% moisture content.

**Impacts of the HTHx Operation Temperature.** The development of HTHx is of importance for externally fired gas turbine systems. Thus, the impact of the HTHx temperature on system performance has been studied. The temperature of HTHx will affect the feedstock flow rate (biomass) into the topping combustion via the gasifier and into the solid fuel furnace. Figure 5 shows the flow rate of the feedstock and the efficiency versus the HTHx temperature. The simulations show that at higher temperatures, the major part of biomass feedstock is consumed in the solid fuel combustion. The higher the HTHx operation temperature is, the less fuel gas is required to increase the temperature to the TIT. Thus the gasifier can be designed smaller. On the other hand, the less fuel gas that enters the topping combustor, the less its exhaust mass flow, thus the air stream has to be increased in order to produce the same amount of power in the turbine. Therewith, in the case of a higher HTHx temperature, the heat requirement for the SFC increases because the temperature that must be reached is higher while at the same time the mass flow rate of the compressed air is larger. The efficiency of the process confirms that for the above-mentioned reason, very high HTHx temperatures are not meaningful in the EvGT-BAT system. This effect is a special feature of the present system in which the gasifier is housed in the solid fuel combustion chamber like a heat exchanger. An increased syngas production leads simultaneously to an increased amount of char, which is used as additional fuel in the solid fuel combustion. However, it is not possible to decrease the input in the furnace by much, because the increasing biomass stream passing the gasifier has to be heated and gasified. It will increasingly become complicated to design the solid fuel furnace if the size of the entrained flow tubular gasifier increases and at the same time the feedstock for the furnace and its dimension decreases. Furthermore, the investment cost for the gasifier, the gas compressor, the gas cooler, and the syngas cleaning system will rise. However, by further analyzing the EvGT-BAT system, an optimum HTHx temperature considering the overall efficiency and the investment cost might be found.

**Comparison of the Size of the Gasifier in EvGT-BAT and IGCC.** The high investment cost for gasification in IGCC is one of the obstacles for adopting this technology in commercial applications. An advantage of the EvGT-BAT system in comparison to IGCC is the lower flow rate of fuel gas that is needed to heat the compressed air to the turbine inlet temperature. This will greatly reduce the size of gasifiers in EvGT-BAT compared to the IGCC by reaching about the same thermal efficiency between 41–46% (Foster-Pegg [12]). In IGCC, the compressed air has a temperature of about 190°C when it leaves the compressor and enters the turbine combustor. This temperature is much lower than the one of the compressed air that enters the topping combustor in the present system. As the gasifier is housed in the solid fuel combustion, the present system gives a further advantageous feature. All required energy for heating the biomass feedstock and sustaining the devolatilization during the gasification comes from the solid fuel furnace. In an IGCC, this energy must also be produced in the gasifier by either burning syngas or using partial oxidation, which increases the biomass throughput in the gasifier. In the EvGT-BAT system, a steam-based gasification is suggested. Steam-based gasification supplies a fuel gas with a heating value up to 16 MJ/Nm³ when the water vapor concentration of the product gas is about 7 Vol% (Wolf and Yan [10]). If steam-based gasification is used in both technologies and for the EvGT-BAT system a HTHx temperature of 750°C is assumed, the biomass stream passing the gasifier in EvGT-BAT is one-sixth the one in IGCC. This means the reactor volume of the gasifier in IGCC will be six times the one in EvGT-BAT. When increasing the HTHx temperature to 900°C, the biomass flow rate in IGCC will be about 12 times the one in the EvGT-BAT system (Fig. 6).
The advantages of a smaller size and no requirement for high gasification conversion for the gasification in EvGT-BAT (because the unconverted char can be further used in the furnace) give a great potential to reduce the investment cost.

Discussion on Technical Issues. Since the main objective of this paper is to investigate the performance of the system, some of the technical issues have not been studied. For example biomass fuels contain a significant amount of fuel-bound nitrogen, which may convert into NOx in the combustion process. Topping combustion is still a relatively new and novel concept and needs further development. Some work regarding topping combustion in PFBC applications has been carried out by Domeracki et al. [13]. Combustion of humid air with lower or medium-heating-value fuels is an interesting area for further investigation.

Conclusions

A new process, called EvGT-BAT, which integrates the features of IGCC, EFGT, and EvGT is introduced. The efficiency and main flow rates have been studied while changing the moisture content of the biomass feedstock and the temperature of the high-temperature heat exchanger. The results of the study are:

- the process converts solid fuel as biomass into electrical power with a thermal efficiency of more than 41% if the raw biomass has a moisture content of 50% and the temperature in the high-temperature heat exchanger is 900°C. If a drier is used this efficiency can be increased to about 44.5%.
- it is possible to integrate the gasification process into the whole cycle so that the efficiency drop is just 1% in comparison to a system with natural gas as the additional gaseous fuel for topping combustion.
- a comparison between the required fuel gas generation for IGCC and the presented EvGT-BAT system shows that the EvGT-BAT system has a great potential to reduce investment costs for the gasification section of the cycle.
- contrary to EFGT, the optimum temperature of the high-temperature heat exchanger is not as high as the turbine inlet temperature. A lower temperature results in higher requirements for the gasification process, but also a higher efficiency, while a higher temperature leads to a smaller gasifier, but efficiency decreases.

Acknowledgments

Financial supports from the Swedish National Energy Administration (Energimyndigheten) and Ångpanneför-enigen’s Foundation for Research and Development (Ångpanneföreningens Forskningsstiftelse) are gratefully acknowledged.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFGT</td>
<td>externally fired gas turbine</td>
</tr>
<tr>
<td>EvGT</td>
<td>evaporative gas turbine</td>
</tr>
<tr>
<td>EvGT-BAT</td>
<td>evaporative biomass air turbine</td>
</tr>
<tr>
<td>HTAF</td>
<td>high-temperature air heater furnace</td>
</tr>
<tr>
<td>HR</td>
<td>heat recovery</td>
</tr>
<tr>
<td>HTHx</td>
<td>high-temperature heat exchanger</td>
</tr>
<tr>
<td>IGCC</td>
<td>integrated gasification combined cycles</td>
</tr>
<tr>
<td>PFBC</td>
<td>pressurized fluidized bed combustion</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>research and development</td>
</tr>
<tr>
<td>SFC</td>
<td>solid fuel combustion</td>
</tr>
<tr>
<td>TIT</td>
<td>turbine inlet temperature</td>
</tr>
</tbody>
</table>

References