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Exergoeconomic analysis of a biomass post-firing combined-cycle power plant

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ABSTRACT

Biomass can be converted thermo- and bio-chemically to solid, liquid and gaseous biofuels. In this paper, energy, exergy and exergoeconomic analyses are applied to a biomass integrated post-firing combined-cycle power plant. The energy and exergy efficiencies of the cycle are found to be maximized at specific compressor pressure ratio values, and that higher pressure ratios reduce the total unit product cost. Increasing the gas turbine inlet temperature and decreasing the compressor pressure ratio decreases the CO_2 mole fraction exiting the power plant. The exergoeconomic factor for the biomass integrated post-firing combined-cycle power plant at the optimum energy/exergy efficiency is 0.39. This implies that the major cost rate of this power plant configuration is attributable to the exergy destruction cost rate. Increasing the compressor pressure ratio decreases the mass of air per mass of steam in the power plant, implying a reduction in the gas turbine plant size. Increasing both the compressor pressure ratio and the heat recovery steam generator inlet gas temperature increases the capital investment cost compared with the exergy destruction cost. However, increasing the gas turbine inlet temperature decreases this ratio.

1. Introduction

Enhancing the utilization of renewable energy sources is an aim of many current energy policies, to help mitigate environmental issues and to improve national energy security [1]. The latter point is particularly important to countries that depend on imported fossil fuels [2]. Renewable energy sources are relatively clean and freely available in nature. However, their efficient utilization remains a concern by many in the scientific and business communities [3]. Much current research is focused on new concepts in biomass gasification technologies to improve the economic viability and sustainability of the utilization of biomass via gasification [4,5]. Globally, numerous studies and activities have been undertaken on the disadvantages and benefits of biomass technologies, with biomass integrated gasification combined cycle technology being identified as an efficient, safe, clean and cost-effective method for power generation [6].

Despite the benefits of biomass energy, the overall efficiencies of biomass fired power plants are relatively low. One approach that appears potentially beneficial is to use biomass as a fuel for a combined-cycle power plant [7]. For example, an externally fired combined-cycle power plant has been presented as a possible configuration for improved energy conversion [8].

Exergy analysis can be applied advantageously to biomass-related energy systems. The large number of variables in biomass systems often render their assessment challenging. Energy- and exergy-based sensitivity analyses can help identify a limited number of important variables for consideration in optimization, making the process more tractable.

Since a primary aim of research on biomass energy power plants is to improve economics, research based on exergoeconomics [9,10] can be beneficial and such studies have been reported recently [11]. For instance, Marbe et al. [12] have evaluated co-firing using a gasified CO_2-neutral biofuel in a retrofitted NGCC (natural gas combined cycle) for heat and power production. They considered the economics and environmental performance of the CHP (combined heat and power) plant. Additionally, a thermoeconomic analysis of a small-scale externally fired CHP plant has been carried out by Pantaleo et al. [13], highlighting the dual-fuel gas nature of the turbine cycle.

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Biomass and natural gas can be used simultaneously, i.e. co-fired, in a combined-cycle power plant for electricity generation [14]. These cycles have advantages such as relative high thermodynamic efficiencies (energetic and exergetic) as well as fuel flexibility. The authors recently reported an exergoeconomic analysis of an externally-fired combined-cycle power plant [15]. Advantages of such cycles include the facts that they use only biomass as a fuel and do not requiring filters [16]. However, the externally-fired combined-cycle has a low efficiency because of the low value of LHV (lower heating value) of biomass. In the latter study, the application of the biomass gasification for electricity production was investigated using the energy, exergy, and exergoeconomic analyses for two configurations: an externally fired biomass combined cycle and a combined-cycle with co-firing of biomass and natural gas [17].

The BIPFCC (biomass integrated post-firing combined-cycle power plant) has also been studied. For instance, Franco and Giannini [18] proposed a combined-cycle power plant with the potential of using biomass and natural gas. The BIPFCC is reported to be efficient, since energy from biomass is used at a low thermal level.

In the present paper, the BIPFCC concept is combined with a gasifier so that the co-fired cycle can use both natural gas and gasified biomass simultaneously. The objectives are to investigate and improve understanding of the performance and cost formation of the post-firing combined-cycle power plant. Various fractions of natural gas and fuel gas (derived from biomass gasification) are considered, and parametric studies are employed to assess the effects of significant design parameters on the thermodynamic and the exergoeconomic behaviors of this cycle. The obtained results are expected to benefit engineers and designers of biomass-related energy systems.

2. Theory and analysis

2.1. Description of cycle

The biomass integrated post-firing combined-cycle power plant (BIPFCC) is illustrated in Fig. 1. It can be beneficial to use fossil fuel and biomass together because biomass and biomass-derived fuels have limits regarding the system reliability and fuel flexibility/availability, and biomass-fired gas turbines usually cannot attain an adequately high TIT (turbine inlet temperature). For the cycle evaluated here, the fuel is a combination of biomass (wood) and natural gas. In the combined-cycle power plant, compressed air from the compressor is input to the combustion chamber along with natural gas fuel. The producer gas exiting the downdraft gasifier is input to the post-combustion unit, where it is combusted with the exhausted gases after the turbine. Exhaust gases from the post-combustion unit pass through the HRSG (heat recovery steam generator).

The following has been assumed for the simulation and evaluation of the BIPFCC power plant.

Regarding the fuel and air, the following assumptions have been used:

- Heating value (dry basis) of biomass is 449,568 kJ/kmol [19].
- Ultimate analysis of dry wood (biomass fuel) yields the following gravimetric composition: 50% C, 6% H, 44% O.
- Moisture content of biomass, on a mass basis, is 20%.
- Air (with a volumetric composition 21% oxygen, 79% nitrogen) is input to the compressor at $T_1 = 298$ K and $P_1 = 101.325$ kPa (i.e., atmospheric conditions).
- Natural gas cost is 9.03 $/GJ [20].
- Biomass cost is 2 $/GJ [21].

Regarding the equipment and operating conditions:

- Compressor isentropic efficiency ($\eta_{is,C}$) is 0.87 [16].
- Gas turbine isentropic efficiency ($\eta_{is,GT}$) is 0.89 [16].
- Steam turbine isentropic efficiency ($\eta_{is,ST}$) is 0.9 [14].
- Pump isentropic efficiency ($\eta_{is,pump}$) is 0.8.
- Equivalence ratio for gasification is 0.4188.
- Combustion chamber is adiabatic.
- Combustion chamber pressure drop is 1%.
- Pinch point temperature difference in HRSG is 10 K.
- Maximum steam temperature ($T_{MAX,ST}$) for BIPFCC is 850 K [18].
- Maximum pressure in steam cycle (P_{MAX}) is 8000 kPa [14].
- Minimum steam quality (x_{out}) is 0.9.
- Condenser pressure is 8 kPa.

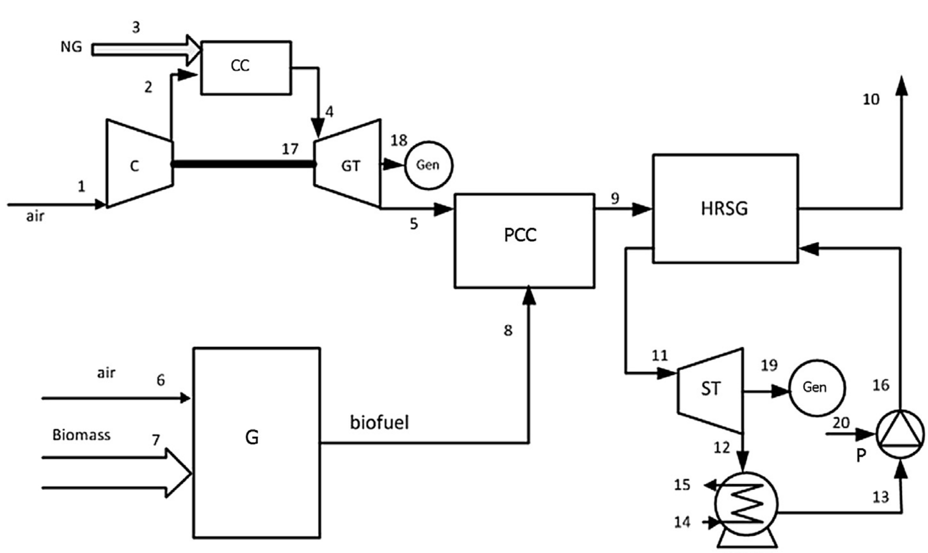

Fig. 1. BIPFCC plant.