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Exergoeconomic study of gas turbine steam injection and combined power cycles using fog inlet cooling and biomass fuel

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ABSTRACT

Biomass energy has the potential to replace fossil fuels despite its lower heat value. Fog cooling and steam injection, as well as adding steam turbine cycles to gas turbine cycles, can enhance the performance of power generation systems. Here, the results are reported of energy, exergy and exergoeconomic analyses of two proposed biomass (wood) integrated steam injection cycles and combined power cycles. Their performances are assessed for similar sets of conditions. The thermodynamic analyses demonstrate that at lower values of compressor pressure ratio the combined cycle has a higher thermodynamic efficiency but at higher values of pressure ratio the steam injection plant is advantageous. For the same conditions, the steam injection plant exhibits a higher net power output. The exergoeconomic analyses show that electricity and component costs for the combined cycle are higher than for the steam injection plant. Also fog cooling is more influential on the thermodynamic performance of the BIFCC than the BIFSG plant and at compressor pressure ratios of 20 and 26 and higher, respectively, for the BIFCC and BIFSG plants, fog cooling is economic. The exergy loss rate and its cost are higher for the combined cycle at all pressure ratios.

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1. Introduction

Biomass (e.g., paper, agriculture and forestry residues, straw, wood wastes, sawdust, paddy husk) can be used as a clean, renewable and relatively abundant energy resource for electricity generation and other purposes. Biomass can be converted to more convenient fuels via many methods, including various types of gasification. Much research is presently aimed at developing and enhancing systems for converting biomass to biofuels via thermo- and bio-chemical processes, and to improve the economic viability, sustainability and risks associated with utilizing biomass and related technologies [1–5]. The potential has been examined of biomass gasification integrated with combined cycles, for producing electricity and/or heat, in ways that are efficient, incur relatively little environmental impact and are cost-effective [6,7]. Nevertheless, technological problems such as inadequate efficiencies exist for such technologies [8]. One recent approach to addressing these problems involves leveraging the thermal performance of gas-fired gas turbine cycles, by combining them with biomass systems to enhance overall performance [9–12].

Combined cycles can be integrated with various devices (e.g., biomass gasifier, fogging cooler) to enhance their energy efficiencies and exergoeconomic performances [13]. Ahmedi et al. [14] investigate combined cycle power plants using exergy, exergoeconomic and environmental analyses and multi-objective optimization with an evolutionary algorithm. Through energy and exergy analyses of an intercooled combustion-turbine in a combined cycle power plant, Sanjay et al. [15] show that the exergy destroyed in components of the inter-cooled cycle is lower for all components except the combustion chamber. Another method for improving power plant performance involves utilization of a fogging cooler on the compressor inlet air.

The output power and energy efficiency of power plants are notably reduced when ambient temperature is high, an occurrence

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particularly common in many locations during hot and humid summers. The conventional method for cooling inlet air involves spraying water droplets into the compressor inlet air, thereby reducing the air temperature towards the corresponding wet-bulb temperature. Depending on the injected water amount and location, fogging cooling systems typically fall into three categories: 1) high pressure fogging, e.g., the system investigated by Bianchi et al. [16]; 2) overspray fogging (wet compression), e.g., the system analyzed by Bettocchi et al. [17]; and 3) fog intercooling, e.g., the system investigated by Bagnoli et al. [18].

Factors affecting the selection of a system type include ambient air temperature and relative humidity, air flow rate to gas turbine, power output ratio and number of operating hours per day.

A recent energy analysis of fogging inlet cooling with overspray showed that inlet air fogging increases the power input to the compressor, peaking when the inlet air is saturated. This observation is attributable to the increase in density and mass flow rate of the inlet air caused by its decrease in temperature [19]. But the mass flow rate through the turbine significantly affects its power output. The power output declines on the hot days when the air is less dense, e.g., the power output is observed to decrease by approximately 1% per 1 °C increase in inlet air temperature, while the turbine heat rate rises correspondingly [20].

Also, the superheated steam which exits the turbine stack can be injected into the combustion chamber via a method known as STIG (steam injection gas turbine cycle). This method, which is useful for increasing gas turbine performance, can be coupled with most existing methods to enhance energy efficiencies by avoiding the waste of energy. Both techniques can be utilized through what is known as the gas-turbine cycle with steam injection and simultaneous cooling (FSG) method. However, this method has some disadvantages such as a reduction in the amount of water vapor produced in the boiler due to the drop in the turbine inlet temperature [21]. This cycle (FSG) is investigated with methane fuel [22]. The results show that utilization of a fogging cooler in a steam injection cycle increases the exergy destruction in the combustion chamber significantly.

The FSG method can alter cycle performance by coupling renewable and environmental friendly energy sources such as biomass, which is clean and freely available in the nature [23], via the biomass integrated fogging steam injected gas turbine (BIFSG). Also this type of cycle has been investigated by Athari et al. (2015) [22], in the form of comparative exergoeconomic analyses of the integration of biomass gasification and a gas turbine power plant with and without fogging inlet cooling. They show that biomass gasification can be integrated with a gas turbine cycle to provide efficient, clean power generation and also that a gas turbine cycle with fog cooling and steam injection can be a good alternative within the scope of energy, exergy and exergoeconomic analyses [24]. The question of whether or not this cycle can be replaced by a combined cycle is the focus of another work by these authors, executed from a thermodynamic perspective [25].

The high temperature gases exiting the turbine stack can be utilized in two types of systems: steam injection gas turbines and combined cycles. But it is often not clear which is advantageous in a particular situation. The objective of this article is to address this problem by determining which method provides better performance for various conditions. To this end, the biomass integrated fog cooling steam injection gas turbine cycle (BIFSG) cycle, which can play a role in supplying energy for villages and small towns in tropical regions, is proposed and assessed, and then compared with the proposed biomass integrated fogging combined cycle (BIFCC), using energy, exergy and exergoeconomic analyses. The thermodynamic and exergoeconomic effects of selected design parameters on cycle performance are examined parametrically.

2. System descriptions and assumptions

2.1. Descriptions of investigated systems

Descriptions of the biomass-fogging steam injection and biomass-fogging combined cycles examined here and their operations follow:

- The BIFSG cycle (Fig. 1) uses biomass (wood) and fogging steam injection. Adiabatically saturated fog cooling causes the air dry bulb temperature to approach the wet bulb temperature. Water is evaporated in the air flow and the relative humidity exiting the fog cooler approaches 100%. Overspray by up to 2% can raise the exit relative humidity, but leaves water particles in the fog cooler exit that enter the compressor. Wood fuel is input to the gasifier, from which producer gas exits and is compressed before entering the combustion chamber. Hot combustion gases are input to the gas turbine to produce mechanical power, and then the gases pass to the heat recovery steam generator (HRSG), where superheated vapor is produced for injection to the combustion chamber. To investigate better the effect of the fog cooler on the steam injection cycle, an additional cycle is examined here, the biomass integrated steam injection gas turbine cycle without fog cooling (BISG) system. In that cycle, air at ambient conditions enters the compressor without fogging.
- The BIFCC cycle (Fig. 2) utilizes biomass and includes a fogging combined cycle. All BIFCC and BIFSG processes are similar, except that the hot gases exiting the turbine of the BIFCC pass through a HRSG, in which steam for the steam cycle is produced. To investigate better the effect of the fog cooler on the combined cycle, as with the previous cycle, an additional cycle is been examined here, the biomass integrated combined cycle without fog cooling (BICC) system.

2.2. Assumptions and input data

Assumptions used to simplify the analyses of the BIFSG, BIFCC, BISG, and BICC cycles are listed in Table 1, along with values for input parameters.

3. Analyses

3.1. Energy analyses for primary components of cycles

Descriptions are provided here for the energy analyses of the primary components of the cycles. Descriptions for other components are available elsewhere [27,30].

3.1.1. Gasifier

The downdraft type gasifier used in present work has been analyzed by the authors recently [27]. Therefore, thermodynamic equilibrium models and gasifier reactions and equilibriums are obtained from that study. Assuming an adiabatic gasifier, an energy balance for the reaction equations can be written as:

$$\begin{aligned}\overline{h}^{o}_{f_{\text{biomass}}} + n_{H_2O} \times \overline{h}^{o}_{f_{H_2O}} + n_{air}\overline{h}_{air} = {} & n_a\left(\overline{h}^{o}_{f_{H_2}} + \Delta\overline{h}_{H_2}\right) \\ & + n_b\left(\overline{h}^{o}_{f_{CO}} + \Delta\overline{h}_{CO}\right) + n_c\left(\overline{h}^{o}_{f_{CO_2}} + \Delta\overline{h}_{CO_2}\right) + n_d\left(\overline{h}^{o}_{f_{H_2O}} + \Delta\overline{h}_{H_2O}\right) \\ & + n_e\left(\overline{h}^{o}_{f_{CH_4}} + \Delta\overline{h}_{CH_4}\right) + n_f\left(\overline{h}^{o}_{f_{N_2}} + \Delta\overline{h}_{N_2}\right)\end{aligned} \tag{1}$$

The right-hand side of Eq. (1) is for the gasification temperature,

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