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Gas turbine steam injection and combined power cycles using fog inlet cooling and biomass fuel: A thermodynamic assessment

Hassan Athari [a], Saeed Soltani [b, *], Marc A. Rosen [c], Seyed Mohammad Seyed Mahmoudi [b], Tatiana Morosuk [d]

[a] *Department of Mechanical Engineering, University of Ataturk, 25240 Erzurum, Turkey*
[b] *Faculty of Mechanical Engineering, University of Tabriz, Iran*
[c] *Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada*
[d] *Institute for Energy Engineering, Technische Universität Berlin, Marchstr 18, 10587 Berlin, Germany*

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ABSTRACT

The results of energy and exergy analyses of two biomass integrated steam injection cycles and combined power cycles are reported. Fog cooling, steam injection and adding steam turbine cycles to gas turbine cycles can enhance the performance of power generation systems. Even with its lower heat value, biomass can be substituted for fossil fuels. The performances of the cycles are assessed under the same conditions. The assessments show that the combined cycle has a higher efficiency at lower values of compressor pressure ratio but the steam injection plant is advantageous at higher pressure ratio values. The steam injection plant has a higher net power under the same conditions, while the exergy loss rate is higher for the combined cycle at all pressure ratios. But the exergy destruction rate is higher for the steam injection cycle at lower compressor pressure ratios, and for the combined cycle at higher pressure ratios.

1. Introduction

An important clean, renewable and relatively abundant energy resource for electricity generation is biomass, which includes paper, agriculture and forestry residues, straw, wood wastes, sawdust and paddy husk. These biomass resources can be converted to more convenient fuels via various types of gasification, and the processes can be enhanced using optimization methods. Much research is presently ongoing into converting biomass to biofuels via thermo- and bio-chemical processes by developing and enhancing various energy systems. Also, advances are being reported annually regarding improving the economic viability and sustainability, and reducing the risks, associated with utilizing biomass and related technologies [1–3]. To investigate the potential of biomass gasification, which can be integrated with combined cycles for producing electricity and/or heat, methods have been developed that are efficient, cause relatively little environmental impact and are cost-effective [4,5]. For example Soltani et al. [6,7] have analyzed the thermal performance of gas-fired gas turbine cycles combined with biomass systems to enhance overall performance.

The humid and hot summer months when ambient temperatures and humidities are high, which are common in many countries, notably affects the output power and energy efficiency of power plants. Cooling the inlet air can be accomplished by spraying water droplets into the compressor inlet air, and is an effective strategy to mitigate the negative effects of such phenomenon. The cooling reduces the air temperature towards the corresponding wet-bulb temperature. The important factors in designing such fogging systems are typically optimized based on location in terms of amount water injected into the fogging cooling system. These are three main categories of systems: 1) fog intercooling, e.g., the system investigated by Bagnoli et al. [8], 2) high-pressure fogging, e.g., the system investigated by Bianchi et al. [9], and 3) overspray fogging (wet compression), e.g., the system analyzed by Bettocchi et al. [10].

A recent energy analysis of fogging inlet cooling with overspray showed that inlet air fogging increases the power input to the

* Corresponding author.
E-mail address: saeed929@tabrizu.ac.ir (S. Soltani).

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compressor, peaking when the inlet air is saturated [11]. Athari et al. [12] applied exergoeconomic analysis to biomass gasification in gas turbine power cycles, with and without fogging inlet cooling. They revealed that inlet cooling is effective for mitigating the decrease in gas turbine performance during hot and humid summer periods when electrical power demands peak, and steam injection, using steam raised from the turbine exhaust gases in a heat recovery steam generator, is an effective technique for utilizing the hot turbine exhaust gases. Their proposed cycle, which utilizes biofuel as an energy source, have a lower total unit product cost than a similar plant fired by natural gas.

An additional way to improve cycle performance involves injecting the superheated steam which exits the turbine stack can be into the combustion chamber via a method known as STIG (steam injection gas turbine cycle). This method improves gas turbine performance, and can be coupled with most existing methods to enhance energy efficiencies by avoiding the waste of energy.

Both techniques can be utilized via 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 which results in a drop in turbine inlet temperature [13]. The FSG method can alter cycle performance by coupling renewable and environmental friendly energy sources such as biomass, which is clean and widely available in the nature [14], via the biomass integrated fogging steam injected gas turbine (BIFSG).

The high temperature gases exiting the turbine stack can be utilized in two types of systems: steam injection gas turbines and combined cycles. The use of fogging along with steam injection in a gas turbine has been analyzed by Kim et al. [13]. Also the combined cycle with fog cooling has been assessed by authors [15,16]. But it is often not clear which is more advantageous in a particular situation and with biomass fuel.

The objective of this article is to address this problem by determining which method provides better performance for various conditions. Hence, 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 assessed and compared with the biomass integrated fogging combined cycle (BIFCC), using energy and exergy analyses. The thermodynamic effects of selected design parameters on cycle performance are examined parametrically. The two cycles are compared with the corresponding cycles in which no fog cooler systems are present, to provide better understanding of the benefits of the fog cooler in these plants, especially from energy and exergy points of view. The results are expected to provide reliable knowledge, and to be of significant benefit to researchers and engineers.

2. Descriptions of proposed cycles and assumptions

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

- The fogging steam injection and biomass cycle shown as a BIFSG in Fig. 1 is considered in this study. In this cycle, the saturated fog cooling causes the air dry bulb temperature to approach the wet bulb temperature adiabatically. Correspondingly, the relative humidity exiting the fog cooler approaches 100% as water is evaporated into the air flow. If the overspray (by about 2%) is used, the exit relative humidity can rise further by this process. However it is not desired to have the remaining water particles enter the compressor from the fog cooler exit. The gasifier produces a biofuel from wood and the biofuel 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. An additional cycle is also investigated here to examine the effect of the fog cooler on the combined cycle. In this cycle air enters the compressor at ambient conditions without the fogging process, in a process called the biomass integrated steam injection gas turbine cycle without fog cooling (BISG).

The assumptions used for simplifying the analyses of the BIFCC, BIFSG, BICC, and BISG cycles, as well as input parameter values, are listed in Table 1.

3. Analysis

3.1. Energy

Energy analyses are described of the main components of the cycles. For the downdraft gasifier used here, thermodynamic equilibrium models and gasifier reactions and equilibrium information are taken from a recent analysis by the authors [18]. Assuming the gasifier is adiabatic, the chemical reaction in the gasification process and an energy balance for the reactions occurring within it can be expressed respectively as in the following two equations:

$$CH_aO_bN_c + n_{H2O}H_2O + n_{air}(O_2 + 3.76N_2) \rightarrow n_aH_2 + n_bCO + n_cCO_2 + n_dH_2O + n_eCH_4 + n_fN_2 \tag{1a}$$

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

where n_{H2O} is the kmoles of water per kmole of biomass and n_{air} is the kmoles of oxygen per kmole of biomass in the gasification process; and n_a, n_b, n_c, n_d, n_e and n_f are the kmole numbers of the constituents of products.

The enthalpy of formation of biomass is determined from its heating value [21]. As terms on the right side of Eq. (1b) are evaluated at the gasification temperature, $\Delta\bar{h}$ represents the specific enthalpy difference at the gasification and reference temperatures.

The cooler outlet temperature and water flow rate are determined with a conventional energy balance:

$$ha_3 + W_3\,hv_3 + OS \times h_{f3} = ha_1 + W_1\,hv_1 + (W_3 - W_1 + OS)h_{f2} \tag{2}$$

where h_v and h_f respectively denote the specific enthalpies of vapor and water injected into the air. Also, ha_3 denotes the specific enthalpy of dry air in the cooler output and W the specific humidity.

Biogas and compressor outlet air are input to the combustion chamber. Complete combustion is assumed, in accordance with the