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Advanced exergy analysis applied to an externally-fired combined-cycle power plant integrated with a biomass gasification unit

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ABSTRACT

An advanced exergy analysis is reported for a recently developed configuration of an externally-fired combined-cycle power plant integrated with biomass gasification. The results identify the potential for improvement of the overall system considering interactions among the components. It is found that interactions between the components are not very strong, i.e. the endogenous exergy destruction within each component is higher than the exogenous ones. Also, the advantages are demonstrated of advanced exergy analysis over conventional exergy analysis; it is concluded that the focus for improving cycle performance should be on the heat exchanger and not the combustion chamber or gasifier, even though these have the highest exergy destructions among all the components. In addition, it is concluded that the unavoidable part of exergy destruction in almost all components is higher than the avoidable value. Therefore little can be done to reduce the irreversibilities for components of the externally-fired combined-cycle power plant.

1. Introduction

Many current energy policies promote research to enhance the utilization of renewable energy sources, in large part to help mitigate environmental problems and improve the national energy security of countries dependent on the use of imported fossil fuels [1]. Among renewable energy sources, biomass (e.g. paper, agriculture and forestry residues, straw, wood wastes, sawdust, paddy husk) is currently one of the most popular options. An important feature of biomass is its renewability and neutral CO_2 impact. When producing power from biomass, the initial conversion of biomass into a usable fuel involves several processes requiring additional plant components [2–4]. Despite the advantages of using biomass, the overall efficiencies of biomass fired power plants are relatively low, typically ranging from 15% to 30%. This drawback can often be resolved, however, by using biomass as a primary fuel in combined-cycle power plants [5–7].

Many configurations have been introduced for producing electricity from biomass [8–12]. One possible configuration has recently been developed and evaluated by authors [8].

The thermodynamic improvement or optimization of a complex energy conversion system such as an externally-fired combined-cycle power is difficult because of the large number of variables involved. In order to define a reasonable number of variables for consideration in optimization, energy- and exergy-based sensitivity analyses can be performed. Regardless of the advantages associated with exergy analysis, it cannot demonstrate the interactions among the components within an energy conversion system, i.e. the interactions among the irreversibilities within the components [13–15]. This type of interaction in energy conversion systems has recently received growing interest. In order to determine these interactions, the exergy destruction within each system component needs to be split into endogenous and exogenous parts. The analysis also differentiates between the avoidable and unavoidable parts of exergy destruction, thereby demonstrating the real potential for improving the components [16,17]. Splitting the exergy destruction into four parts (avoidable endogenous, unavoidable endogenous, avoidable exogenous and unavoidable exogenous) in advance exergy analysis can provide meaningful results not obtained through

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conventional exergy analysis [15,18,19]. Advanced exergy analysis has been successfully applied to such energy conversion processes as refrigeration [18–20], power generation [21–23] and others [24,25].

The present paper applies advanced exergy analysis to an EFCC (externally fired combined cycle). Particular attention is paid to the avoidable endogenous and avoidable exogenous parts of the exergy destructions for components; understanding these destructions arises important for improving system performance. The results are expected to help in exploiting biomass energy for electricity production more efficiently.

2. Process description

An externally fired biomass combined-cycle is shown in Fig. 1. The biomass, taken to be paper, is fed to the gasifier, as is the required air. The biofuel exiting the gasifier enters the combustion chamber of the gas turbine whose working fluid is air. The combustion products exiting the combustion chamber pass through a heat exchanger where they heat the pressurized air from the compressor. The combustion products leaving the heat exchanger enter the HRSG (heat recovery steam generator), where they heat water, which is the working fluid of the Rankine cycle. The exhaust gases exit to the atmosphere at a temperature above their dew points.

Assumptions used during the simulations follow:

- Air enters the compressor at atmospheric conditions, i.e. $p_1 = 101.325$ kPa, $T_1 = 298$ K.
- The composition of air (by vol.) is 79% nitrogen and 21% oxygen.
- The equivalence ratio (φ) at the gasifier is 2.426.
- The gasification process is adiabatic and chemical equilibrium is reached in the producer gas at the gasifier exit.
- The ultimate analysis of the dry biomass fuel (paper), on a mass basis, is C: 43.4%, H: 5.8% and O: 44.3%, N: 0.3%, while the higher calorific value of the biomass (on a dry basis) is 454,864 kJ/kmol [26].
- The biomass moisture content is 20% on a mass basis.
- The compressor isentropic efficiency is $\eta = 0.87$ [27].
- The gas turbine isentropic efficiency is $\eta = 0.89$ [27].
- The pressure drops for the cold and hot sides of the heat exchanger are 3.0% and 1.5% of inlet pressures, respectively [27,28].
- Complete combustion takes place in the combustion chamber under adiabatic conditions, with a pressure drop of 0.5% of the inlet pressure [27].
- The pinch point temperature difference in the HRSG is 10 K.
- The steam turbine inlet temperature and pressure are 773 K and 50 bar, respectively.
- The minimum acceptable steam quality at steam turbine exit (x_{out}) is 0.9.
- The condenser pressure is 0.08 bar.
- The steam turbine isentropic efficiency (η) is 0.9.
- The pump isentropic efficiency is 0.7.

3. Conventional analyses

3.1. Energy analysis

For the gasification process, a thermodynamic model is developed [29] assuming that the producer gas is in chemical equilibrium. The validation for this model is shown in Table 1, in which good agreement is observed between the obtained results and

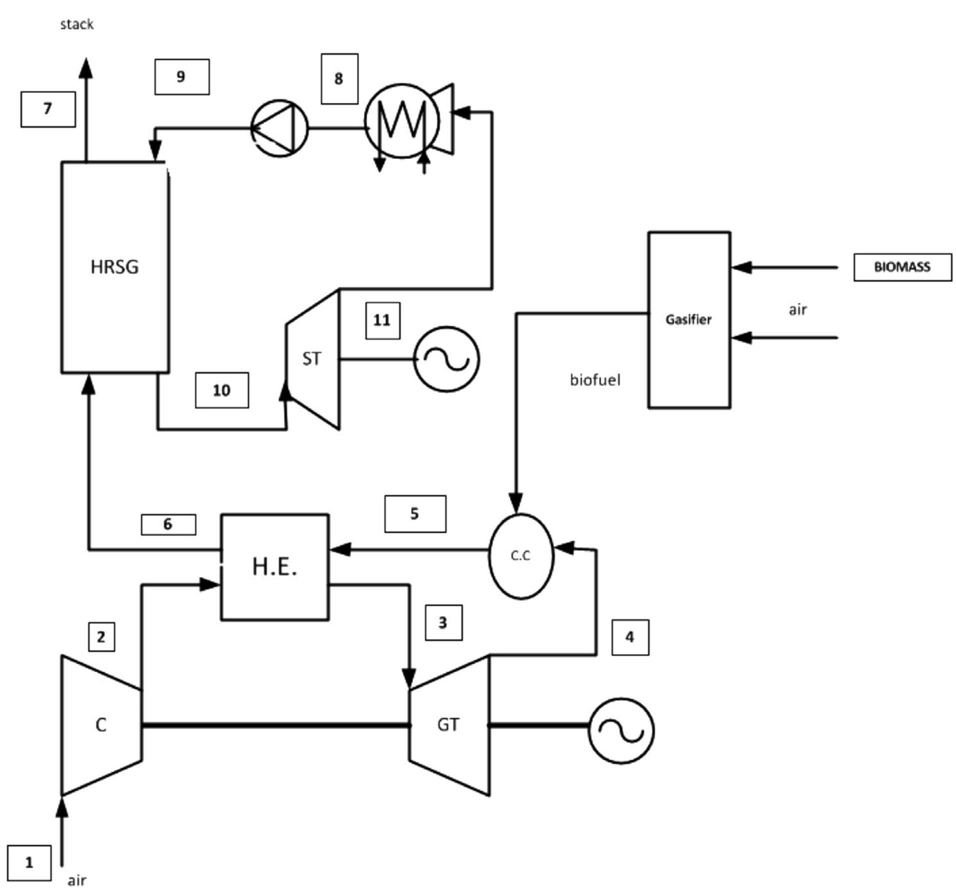

Fig. 1. Schematic of the EFCC plant.