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Detailed exergetic evaluation of heavy-duty gas turbine systems running on natural gas and syngas

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ABSTRACT

Gas turbine systems are widely used for the production of electricity in a simple or combined-cycle mode today. Based on their ability to allow a fast load change, gas turbine systems will become even more important in the future since the volatile production of renewable energies will increase. In this study, a state-of-the-art gas turbine running on natural gas, having an overall net efficiency of approximately 40%, is modeled using Aspen Plus® and characteristic parameters are identified. Based on these parameters, a gas turbine running on syngas was simulated. The emphasis here is on a very detailed evaluation of the inefficiencies. The models consider cooling and sealing flows. The syngas considered in this study is typically used in IGCC processes with carbon capture resulting in a high concentration of hydrogen.

For both systems, twelve types of inefficiencies were identified and rated. A comparison of the inefficiencies within each system and between both systems represented by their exergy destruction ratios is presented.

In case of the gas turbine running on natural gas, the most important results show that the stoichiometric combustion, followed by the addition of excess air represent the largest inefficiencies. When just applying an isentropic efficiency, the exergy destructions associated with expansion and mixing at different temperatures and pressures of a gas turbine stage cannot be further sub-divided. Hence, this grouping of inefficiencies results to the third position. The effect of mixing at different compositions and the compression follows.

In the second case considered here (use of syngas instead of natural gas), the effects of mixing and adding excess air become more significant due to a higher specific heat capacity of the combustion gas. In both cases, the exergy destruction associated with mixing at different compositions can be neglected except the one at the inlet of the pre-mixed combustor, which strongly depends on the particular conditions of the fuel gas. Inefficiencies such as convective cooling of the vanes and blades, heat loss, losses associated with the shaft and generator were found to represent a very small part of the overall exergy destruction. The resulting exergy destructions and losses are shown in an exergy flow diagram.

1. Introduction

Based on the scenario of global electricity production published by the International Energy Agency (IEA), the relative consumption of natural gas will increase only slightly by about 0.4% points from the year 2011 to the year 2030. However, the relative consumption of coal will decrease by 6.7% points. Based on the growth of the Non-OECD nations, the demand for electricity will increase significantly by 54%, leading to an increase of the absolute coal consumption by 29.7% [1]. Since both types of fuel will play an important role in the future, a deep understanding of the energy conversion systems is highly interesting. Usually gas turbines are used in a simple or a combined-cycle mode when producing electricity. In the combined-cycle mode, the overall net electrical efficiency reaches approximately 60% at its maximum [2], which is the highest value among all used fossil energy conversion systems. Another advantage is the ability of fast load changes, which will become even more important in the future because the volatile production of renewable energies will increase. When using hard coal, a syngas has to be produced from it, to run a gas turbine system. One of the most efficient technologies available is an IGCC (Integrated Gasification Combined-Cycle) plant. In large scale operations the syngas is produced by an entrained-flow gasifier followed by a CO shift reaction. Before the syngas enters the gas turbine system,

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Nomenclature

Abbreviations
AC air compressor
CC combustion chamber
CFD computational fluid dynamics
COT combustion outlet temperature
GT gas turbine
IGCC integrated gasification combined-cycle
LHV lower heating value
NGGT case gas turbine system running on natural gas
SGT case gas turbine system running on syngas
TIT turbine inlet temperature

Variables
$\bar{e}$ mole specific exergy
$\dot{E}$ exergy rate
$\bar{h}$ mole specific enthalpy
$\dot{n}$ mole flow
Δp pressure loss
$\overline{R}$ universal gas constant
$\bar{s}$ mole specific entropy
T temperature
x mole fraction
y dimensionless exergy destruction

Subscripts and superscripts
ar As-received
CC combustion chamber
CH chemical
D destruction
F fuel
i index of components
j index of streams
P product
PH physical
0 associated with the environment

CO_2 can be captured by physical absorption resulting in a very high amount of hydrogen [3]. This study focusses on the understanding of the inefficiencies within both gas turbine systems.

In several studies it has been reported about an exergy analysis of a simple gas turbine model according to ISO 2314 to account for the thermodynamic inefficiencies within the compressor, combustion chamber and turbine [4–10]. Among others the authors of this study [11] presented a conventional exergy analysis of several IGCC concepts, using an enhanced gas turbine model that considers air flows from the compressor to the turbine. El-Masri [12] presented the results of a conventional exergy analysis based on a simplified three-stage gas turbine model focusing on the inefficiencies associated with the cooling system. It was found that the overall efficiency is influenced by the tradeoff between decreased combustion losses and increased turbine cooling losses. Khodak and Romakhova [13] also performed a conventional exergy analysis of an air-cooled gas turbine system. The applied approach separates the system into a topping cycle producing electricity and a bottoming cycle representing the process management of the cooling flows. The inefficiencies within the cooling system were found to be caused by heat transfer between the main gas and coolant, the bottoming cycle and mixing at different compositions. Staudacher and Zeller [14] performed a grouping of the inefficiencies of an aircraft turbine, evaluating different setups of the secondary air system. Based on data supported by Rolls-Royce, the inefficiencies were rated using an exergy analysis focusing on the secondary air system. The authors of this study published the results obtained from an advanced exergy analysis of a gas turbine system running on natural gas considering cooling flows [15]. By splitting the exergy destruction into its avoidable and unavoidable parts, the potential of improvement for each component is determined. It was found that a large amount of the exergy destruction associated with combustion, addition of excess air, and mixing is unavoidable. In comparison, this study focuses on the sources of inefficiencies based on an enhanced gas turbine system model presenting the results in more detail.

This paper focuses on the detailed modeling and evaluation of a gas turbine system running on natural gas. To improve the understanding of inefficiencies, the model is designed to calculate the distribution of inefficiencies among all components divided by its sources. Furthermore, the bleed air of the compressor provided to the gas turbine is further split into cooling and sealing parts. Based on the developed model, any syngas can be used for combustion, provided that the heating value is sufficient to reach the assumed firing temperature. In this study, the syngas is obtained through gasification of bituminous coal and is conditioned using also CO_2 capture.

2. Modeling

The gas turbine is a highly complex system. Even at steady-state conditions, CFD (Computational Fluid Dynamics) simulations solving differential equations, and other detailed simulations are necessary to approximate the real performance. In this study, the complex system is approximated using global balances. The process simulations were undertaken using Aspen Plus® Version 27 [16]. In this software, the gas path was modeled using the RKS-BM (Redlich–Kwong–Soave with Boston Matthias Alpha function) [17] property method. To manage all parameters, 19 calculators und six design specifications were used together with the Aspen software.

2.1. Determination of the inefficiencies

In general, exergy destruction is caused by friction, mixing, heat transfer and chemical reactions. In this paper, twelve processes are considered that are associated with characteristic inefficiencies in a gas turbine system.

- Compression.
- Stoichiometric combustion.
- Addition of excess air.
- Convective cooling in vanes/blades.
- Pressure drop (caused by the transport of working fluids).
- Expansion.
- Mixing at different pressures.
- Mixing at different temperatures.
- Mixing at different compositions.
- Heat loss.
- Transport of shaft work.
- Conversion of mechanical energy to electrical energy.

This approach is used to provide a comprehensible overview among the gas turbine system components based on an exergy analysis. Especially the mixing processes are subdivided into three

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