



Analysis of the influence of heat transfer on the stationary operation and performance of a solid oxide fuel cell/gas turbine hybrid power plant



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HIGHLIGHTS

- Heat losses from components are included to improve prediction of operating range.
- Adiabatic assumption underestimates high power operating range by 10%.
- Adiabatic assumption overestimates electrical efficiency by 4 percent points.
- Power output can be modulated to 30% by adjusting the SOFC operating temperature.
- Electrical efficiency (HHV) higher than 0.55 is maintained throughout the range.

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ABSTRACT

Hybrid power plants consisting of solid oxide fuel cells (SOFC) and a gas turbine (GT) can play an essential role in the future energy scenario due to the expected high electrical efficiency, fuel flexibility and good part-load performance. A demonstration SOFC/GT hybrid power plant is being setup in Stuttgart with state of the art, commercially available electrolyte supported cell (ESC) stacks and its operation is being simulated by means of a overall system model. However, the model used in this paper, in contrast to most models in literature, accounts for heat transfer based on actual geometries and materials. In the present study, the system model is integrated with a set of sub-models that predict the heat losses of the components of the hybrid power plant with a feasible computational speed. This allows for an improved prediction of the operating range as well as for the prevention of undesired operating conditions. The results of the simulations of the stationary operation of the hybrid power plant with varying heat losses are shown and discussed. Operating limitations are analyzed as well as system performance. It is shown that it is possible to operate the hybrid power plant from design power output to 30% of it. A system electrical efficiency higher than 0.55 considering the fuel's higher heating value is maintained throughout the entire range. Further design choices and developments could lead to an improvement of this condition. In addition, an adiabatic assumption can lead to about 4 percentage points overestimation of electrical efficiency and reduces the high power operating range by about 10%. This approach opens up a new perspective on the simulation of this type of power plant.

1. Introduction

According to the International Energy Agency (IEA), an increase in energy demand is to be expected in the next years, together with a further increase of renewable energy plants [1]. This is progressively leading to a change in the configuration of the global energy supply system, from a centralized to a distributed one. This requires low-size power generation plants with high flexibility instead of the traditional steady and centralized power plants. Typically, small decentralized

power plants suffer from reduced efficiencies due to operational constraints and system complexity. Furthermore, the growing penetration of the renewable energy systems has introduced the problem of fluctuating and discontinuous power supply, that is unable to properly follow the energy demand curve [2,3].

Hence, it is necessary to study new technical solutions that can be well integrated in the depicted scenario. A hybrid power plant composed of solid oxide fuel cells (SOFC) and gas turbine (GT) is a promising technology for providing electrical energy in stationary

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| Nomenclature | | Txy | Tube with address xy |
|---------------------|---|---------------------|---|
| <i>Acronyms</i> | | VES | Pressure Vessel |
| 0D | Zero-Dimensional | WCS | Worst Case Scenario |
| 1D | One-Dimensional | <i>Symbols</i> | |
| 2D | Two-Dimensional | A | area |
| ACP | Air Compressor | E | voltage |
| AMB | Ambient Atmosphere | FU | fuel utilization |
| AND | Anode | \dot{H} | enthalpy flow |
| ARI | Arithmetic Mean | HHV | Higher Heating Value |
| ASR | Area Specific Resistance | h | heat transfer coefficient |
| ASU | Air Supply | k | thermal conductivity |
| BCS | Best Case Scenario | L | length |
| BFS | Burner Fuel Supply | \dot{m} | mass flow |
| BUR | Burner | \dot{n} | molar flow |
| CAT | Cathode | OU | oxygen utilization |
| ctv | Combined Transfer Vector | P | power |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt/German Aerospace Center | \dot{Q} | heat flow |
| EGI | Electric Grid Input | R | resistance |
| EGO | Electric Grid Output | RR | anode recirculation ratio |
| ELO | Electric Load | r | radius |
| ESC | Electrolyte Supported Cell | T | temperature |
| EXH | Exhaust | t | thickness |
| FCP | Fuel Compressor | \dot{V} | volume flow |
| FST | Fuel Storage | ΔT | difference of temperature |
| GEN | Generator | η | electrical efficiency |
| GT | Gas Turbine | <i>Subscripts</i> | |
| HEX | Heat Exchanger | a | ambient conditions |
| IEA | International Energy Agency | aux | auxiliaries |
| LOG | Logarithmic Mean | cn | conductive |
| MFS | Main Fuel Supply | cnv | convective |
| MGT | Micro Gas Turbine | el | electrical |
| MIX | Mixer | me | mechanical |
| NFD | Neutral Face Discretization | i | insulation imperfections |
| REC | Recirculation | rad | radiative |
| REF | Reformer | S-A | SOFC-Anode Numbers refer to schematic in Fig. 2 |
| SEN | Sensor Compartment | <i>Superscripts</i> | |
| SEP | Separator | ' | sub-model input |
| SOFC | Solid Oxide Fuel Cell | " | sub-model output |
| SSM | SOFC Stack Module | | |
| TBI | Internal Tubes | | |
| TBO | External Tubes | | |
| TUR | Turbine | | |

applications. High electrical efficiency [4–7], fuel flexibility [8,9], operational stability [10,11], security in power supply [12], good part-load performance [13,14] and fast response to load changes [15–17] are the basic aspects that make the SOFC/GT hybrid power plant an encouraging field of research.

During the past years, many research groups worldwide, a few of which also test hardware, have been studying and improving the concept and the application of this technology [13,18–24]. Several system configurations for coupling SOFCs and GT are described by Buonomano et al. [25].

The German Aerospace Center is currently aiming at the realization of a SOFC/GT demonstration hybrid power plant with an electrical power output of around 30 kW [24,26–28]. The prototype power plant is currently under construction and the commissioning is expected to start in 2017.

System models are used to predict the operating characteristics of the system under different conditions and increase the knowledge concerning cycle layout, control strategies and part-load dynamics.

Nonetheless, previous models developed at DLR [24,26] do not consider a detailed implementation of energy losses of the system and system's components, as heat transfer is calculated only in the SOFC section.

Some research works investigate heat transfer effects in single SOFC systems. In [29] a detailed finite element thermal model of a planar SOFC stack is firstly built and then simplified to a reduced order 1D model to allow parametric analysis. The importance of thermal losses on efficiency is shown but no other components are included in the study.

In other cases, the thermal analysis is extended to additional SOFC plant components. In [30] finite element simulations are used to investigate thermal management strategies, while [31] shows that part-load efficiency of a SOFC plant is deeply affected by heat losses through the application of a basic thermal model that neglects interactions between components.

Braun and Kattke [32,33] account for heat transfer and thermal interactions at system level in a SOFC power system, comparing the

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