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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

Acronyms

0D	Zero-Dimensional
1D	One-Dimensional
2D	Two-Dimensional
ACP	Air Compressor
AMB	Ambient Atmosphere
AND	Anode
ARI	Arithmetic Mean
ASR	Area Specific Resistance
ASU	Air Supply
BCS	Best Case Scenario
BFS	Burner Fuel Supply
BUR	Burner
CAT	Cathode
ctv	Combined Transfer Vector
DLR	Deutsches Zentrum für Luft- und Raumfahrt/German Aerospace Center
EGI	Electric Grid Input
EGO	Electric Grid Output
ELO	Electric Load
ESC	Electrolyte Supported Cell
EXH	Exhaust
FCP	Fuel Compressor
FST	Fuel Storage
GEN	Generator
GT	Gas Turbine
HEX	Heat Exchanger
IEA	International Energy Agency
LOG	Logarithmic Mean
MFS	Main Fuel Supply
MGT	Micro Gas Turbine
MIX	Mixer
NFD	Neutral Face Discretization
REC	Recirculation
REF	Reformer
SEN	Sensor Compartment
SEP	Separator
SOFC	Solid Oxide Fuel Cell
SSM	SOFC Stack Module
TBI	Internal Tubes
TBO	External Tubes
TUR	Turbine
Txy	Tube with address xy
VES	Pressure Vessel
WCS	Worst Case Scenario

Symbols

A	area
E	voltage
FU	fuel utilization
$\dot{H}$	enthalpy flow
HHV	Higher Heating Value
h	heat transfer coefficient
k	thermal conductivity
L	length
$\dot{m}$	mass flow
$\dot{n}$	molar flow
OU	oxygen utilization
P	power
$\dot{Q}$	heat flow
R	resistance
RR	anode recirculation ratio
r	radius
T	temperature
t	thickness
$\dot{V}$	volume flow
ΔT	difference of temperature
η	electrical efficiency

Subscripts

a	ambient conditions
aux	auxiliaries
cnd	conductive
cnv	convective
el	electrical
me	mechanical
i	insulation imperfections
rad	radiative
S-A	SOFC-Anode Numbers refer to schematic in Fig. 2

Superscripts

′	sub-model input
″	sub-model output

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