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Performance evaluation of a direct-biogas solid oxide fuel cell-micro gas turbine (SOFC-MGT) hybrid combined heat and power (CHP) system

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HIGHLIGHTS

► We evaluate a combination of direct-biogas SOFC with MGT CHP system.
► We examine effects of reforming agent, U_f, TIT, compression ratio on system performance.
► The results show the optimal operating parameters on SOFC and system performance.

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ABSTRACT

The combination of a direct-biogas solid oxide fuel cell (SOFC) with a micro gas turbine (MGT) system offers great potential as a green decentralized combined heat and power (CHP) system. To evaluate the potential use of biogas as the main source of energy for a direct-biogas SOFC-MGT hybrid CHP system, a sensitivity analysis was conducted under diverse operating conditions to investigate the influence of key operating parameters of the hybrid CHP system with the consideration of operational constraints. The key parameters in this study were SOFC reforming agent, SOFC fuel utilization factor (U_f), turbine inlet temperature (TIT), and compression ratio. The influence of variation in operating parameters on plant performance was evaluated for the overall system and SOFC efficiencies as well as the heat-to-power ratio (TER), the power ratio of MGT to SOFC (P_{MGT}/P_{SOFC}), and the size of the SOFC stack. As a reforming agent for direct-biogas SOFC, steam is more preferable than a traditional air–steam mixture in terms of material limitations and SOFC efficiencies; however, an air–steam mixture with a small amount of air boosts the useful heat output and electricity generated by an MGT without significantly affecting overall system efficiency. The increase in U_f improves the electrical power output produced by the SOFC stack, but also requires more fuel to be fed to the burner, resulting in an increase in useful heat energy. Increasing the compression ratio improves the system electrical efficiency but lowers useful heat generation; nevertheless, increasing TIT decreases the system electrical efficiency but improves the efficiency of the CHP system. To achieve the optimum operating conditions of the hybrid CHP system, the operating parameters should be determined based on the desired energy outcomes.

1. Introduction

Biogas typically refers to a gas produced by the biological breakdown of organic matter in the absence of oxygen. Organic waste such as sludge from municipal wastewater treatment plants, kitchen refuse from households and restaurants, and organic waste from the food-processing industry can be converted into a gaseous fuel called biogas (a mixture of methane, carbon dioxide, and other minor gases). Biogas is a readily available but underexploited energy source, because its high levels of carbon dioxide hinder its use in conventional power-generation systems, resulting in relatively low electrical conversion efficiency. Solid oxide fuel cells (SOFCs) are a promising solution to this problem, owing to their tolerance of fuel contaminants and flexibility of operation even with diluted fuel mixtures.

Direct feeding of biogas to SOFCs has been proven to be feasible for different SOFC configurations and materials by several experimental studies [1–6]. However, during the operation of a direct-biogas SOFC, carbon tends to form, which gradually deactivates the anode catalysts of the system. Shiratori et al. [6] performed an experimental study of anode-supported button-cell SOFCs fuelled by biogas with an internal reforming mode of 800 °C. That study

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Nomenclature

E_{CH4}	activation energy of the methane reforming reaction
ex	specific exergy flow, kJ kg^{-1}
Ex	exergy flow rate, kW
F	faraday constant, 96,487 C mol^{-1}
HRSG	heat recovery steam generator
HX	heat exchanger
K	equilibrium constants
LHV	lower heating value, kJ kmol^{-1}
M_i	molecular weight of species i, kg mol^{-1}
m	mass flow rate, kg s^{-1}
n_e	number of electrons participating in the electrochemical reaction
n_i	mole flow rate of species i, kmol s^{-1}
P	electrical power, kW
P	total pressure, kPa
p_i	partial pressure of species i, kPa
Q	heat transfer rate, kW
R	universal gas constant, 8.31434 J mol^{-1} K^{-1}
r	reaction rate, kmol s^{-1}
T	temperature, K
TER	heat-to-power ratio
TIT	turbine inlet temperature, K
U_f	fuel utilization factor
V	voltage, V
x_i	mole fraction of species i

Greek letters

ΔG^0	change of standard Gibbs free energy, kJ mol^{-1}
ΔH	enthalpy change, kJ mol^{-1}
η	efficiency
ψ	rational efficiency

Subscripts

0	properties of the environment
act	activation
air	air, air channel
ch	chemical
CHP	combined heat and power overall system
conc	concentration
ele	electrical
FOX	methane full oxidation
fuel	gas mixture at the fuel channel, fuel channel
in	inlet value
inv	inverter
MGT	micro gas turbine
OC	open-circuit
ohm	ohmic
out	outlet value
PEN	positive-electrolyte-negative structure
ph	physical
shift	shift reaction
react	anode reaction
SOFC	solid oxide fuel cell stack
SR	steam reforming
sys	overall system

revealed that the use of air in addition to actual biogas reduces the risk of carbon formation and leads to more stable operation without deteriorating cell voltage due to the lowering of anodic overvoltage.

In parallel with experimental studies, system models have attracted tremendous interest in the past decade as tools for providing theoretical guidance for SOFC-based systems. Yi et al. [7] evaluated integrated SOFC reformer systems and found that system efficiency drops insignificantly by around 1.1% when biogas is used instead of natural gas. Piroonlerkgul et al. [8] investigated the performance of biogas-fed SOFC systems utilizing different reforming agents (steam, air, and combined air/steam) through thermodynamic analysis to determine the most suitable fuel processor. Steam is considered the most suitable reforming agent, as steam-fed SOFCs provide a much higher power density than air-fed ones, although their electrical efficiencies are slightly lower. While adding steam to an air-fed SOFC in the case of a co-fed SOFC can improve power density, it may lower electrical efficiency compared to an air-fed SOFC. Farhad et al. [9,10] performed a sensitivity analysis of three different biogas-reforming processors in SOFC micro-combined heat and power (CHP) systems using a computer model. They considered anode exit gas recirculation, steam reforming, and partial oxidation. In three-dimensional computational fluid dynamics (CFD) simulations preformed by Vakouftsi et al. [11], mass, heat, and momentum transfer equations were combined with chemical and electrochemical phenomena within the inlet region of a planar SOFC unit-cell configuration directly fed with biogas/steam mixtures. When steam was added to biogas, carbon deposition was prevented but the electrical efficiency of the system decreased owing to an increase in voltage losses.

Along with the development of SOFC technology, efforts have been made in the past decade to integrate gas turbines (GTs) with SOFCs to keep pace with rising demand for highly efficient energy production while also minimizing environmental impact. SOFC-GT plants with outputs of tens to hundreds of electrical kilowatts (kW_e) have been demonstrated experimentally [12–17], making conceptual SOFC-GT hybrid systems feasible. Because biogas is increasingly being regarded as a potential renewable energy source for distributed power generation, biogas-fed SOFC-GT systems appear to be one of the most promising alternatives for distributed power generation. Moreover, extending this hybrid system to CHP generation provides heat recovery from exhaust, resulting in high overall efficiency.

In this study, a sensitivity analysis was performed to evaluate the influence of the key operating parameters of a direct-biogas SOFC-micro gas turbine (MGT) hybrid CHP system with an electrical power output of 200 kW_e. Energy and exergy analyses were used to determine the causes of exergy losses and identify areas in need of improvement while adhering to material thermal constraints. Attention was paid to the influence of air–steam mixtures as reforming agents on the direct internally reformed SOFC stack as well as on the SOFC-MGT hybrid CHP plant. The other key operating parameters considered in this study were fuel utilization factor (U_f), turbine inlet temperature (TIT), and compression ratio. The influence of variation in operating parameters on plant performance was evaluated for the overall system and SOFC efficiencies as well as the heat-to-power ratio (TER) and the power ratio of MGT to SOFC (P_{MGT}/P_{SOFC}). Because of the fact that the SOFC stack is the most expensive part in the initial investment cost, the number of cells required in the SOFC stack was also taken into consideration.

2. System configuration and description

A schematic of the direct-biogas SOFC-MGT hybrid CHP system used in this study is shown in Fig. 1. The direct internal-reforming