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Conceptual design of light integrated gasification fuel cell based on thermodynamic process simulation

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HIGHLIGHTS

- Light integrated gasification fuel cell (L-IGFC) power plant is proposed.
- Dry gas desulfurization (DGD) is a key to increase the efficiency of the L-IGFC.
- Atmospheric L-IGFC gives electrical efficiency over 46%LHV.
- Pressurized operation of solid oxide fuel cell offers electrical efficiency of L-IGFC over 50%LHV.

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ABSTRACT

Integration of solid oxide fuel cell (SOFC) in coal gasification power plant technology would be one of the most promising technology in the coal utilization for power generation. The clean syngas from gas cleanup unit serves as fuel for SOFC in integrated gasification fuel cell power plant. The heat generated by SOFC can be utilized by heat recovery steam generator to drive steam turbine for electricity production. In this study, proposed plants consisting of coal gasifier and SOFC on the top of a steam turbine (ST), called light integrated gasification fuel cell (L-IGFC), are investigated thermodynamically by using Aspen Plus software to evaluate their performance. The analyses are based on the SOFC module considering ohmic, activation and concentration losses at a certain current density of the cell operating at the intermediate temperature. The influences of gas cleanup unit models were also investigated. The results indicated that the proposed atmospheric L-IGFC plant could achieve electrical efficiency in the range of 39–46.35% in lower heating value.

1. Introduction

Solid oxide fuel cells (SOFCs) have grown in recognition as a viable high temperature fuel cell technology. One of the main advantages of SOFC over other fuel cells is its ability to use a wide range of hydrocarbon-based fuels [1,2].

Due to high operation temperature of the SOFC module, systems integrating SOFC and gas turbine (GT) have been studied extensively for power plants applications using natural gas as fuels [3–14], meanwhile limited investigations have been done on integrated SOFC with steam turbine (ST) [15,16].

As hydrogen can be produced by a pyrolysis and a gasification process, several systems integrating biomass pyrolysis or gasification with SOFC have also been analyzed [17–22]. Colantoni et al. [23] proposed the basic plant electric power as integrated pyrolysis fuel cell plant (IPFCP). The system is based on the integration of a high temperature fuel cell with a biomass pyrolysis reactor for combined heat and power (CHP) application. They also expanded the IPFCP to combine with GT (IPFCP-GTP) for power generation.

Coal is one of the most abundant fossil resources in the world. Most coal is burned directly to produce electricity at the low efficiency of 30% - 40% with a large release of pollutants [24]. In recent years, integrated SOFC with a coal gasification plant have become very popular as an alternative for high efficiency power plant with low CO_2 emissions compared to the traditional coal combustion

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Nomenclature

D	diffusion coefficient ($cm^2\ s^{-1}$)
E^0	fuel cell voltage under standard conditions (V)
E_{act}	activation energy ($kJ\ mol^{-1}$)
F	Faraday's constant (96,485 $C\ mol^{-1}$)
ΔG	Gibbs free energy change ($J\ mol^{-1}$)
ΔH	enthalpy change ($J\ mol^{-1}$)
I_{tot}	total current (A)
i	current density ($A\ cm^{-2}$)
i_0	exchange current density ($A\ cm^{-2}$)
i_l	limiting current density ($A\ cm^{-2}$)
j	molar flow rate ($kmol\ h^{-1}$)
M	molecular weight ($kg\ kmol^{-1}$)
n_e	number of electrons participating in the electrochemical reaction (–)
p	partial pressure (bar)
P_{ref}	reference pressure (bar)
P_{fresh}	fresh clean syngas pressure (bar)
P_{SOFC}	SOFC working pressure (bar)
Q	heat (J)
R	universal gas constant (8.314 $J\ mol^{-1}\ K^{-1}$)
r_{pore}	electrode pore radius (μm)
$r_{cat,inner}$	inner radius of the cathode tube (cm)
$r_{cat,outer}$	outer radius of the cathode tube (cm)
ΔS	entropy change ($J\ K^{-1}\ mol^{-1}$)
T	temperature (°C)
U_a	air utilization factor (%)
U_f	fuel utilization factor (%)
V	reversible open circuit voltage (V)
V_{cell}	cell voltage (V)
V_{Nernst}	Nernst potential (V)
V_{act}	activation polarization (V)
V_{conc}	concentration polarization (V)
V_{ohm}	ohmic polarization (V)
v	specific Fuller diffusion volume (–)
W_{SOFC}	work produced by SOFC (J)
$W_{expander}$	work produced by syngas expander (J)
$W_{turbines}$	work produced by steam turbine (J)
x_{O_2}	molar fraction of oxygen in air (–)
y_a^0	molar fraction of gaseous component a in bulk flow (–)
Z	mass flow rate ($kg\ h^{-1}$)

Greek letters

α	apparent charge transfer-coefficient (–)
ρ	material resistivity (Ω cm)
δ	thickness (cm)
γ	exchange current density constant ($A\ cm^{-2}$)
ε	electrode porosity (%)
τ	electrode tortuosity (–)

Subscripts

an	anode
cat	cathode
elyt	electrolyte
int	interconnection

Superscripts

ex	exit
in	inlet

power generation systems [14,25–37]. Kivisaari et al. [29] studied the integration of an oxygen-blown entrained-flow gasifier with either molten carbonate or solid oxide fuel cell technology for CHP application. Kuchonthara et al. [30] proposed an integrated gasification fuel cell (IGFC) system called thermochemical recuperative coal gasification cycle. The basic idea was to use the thermal energy in the gas turbine exhaust for the endothermic methane reforming reaction so that the thermal energy can be considered both thermally and chemically. Ghosh and De [32] evaluated a 20 MWe system based on a slurry feed, oxygen-blown entrained-flow GE (Texaco) gasifier. After cooling and heat recovery, a dry gas cleanup system operating at 400 °C is used, purifying syngas from particulate and sulfur compounds before utilization in the fuel cell. In a follow-up work Ghost and De [33] also conducted exergy analysis of the proposed system and concluded that major part of total exergy loss occurs in the gasifier and the SOFC owing to combustion and electrochemical reactions; in addition, sensitivity analysis showed that increasing the operation pressure of the SOFC would decrease exergy losses in most of the equipment thus yielding better cogeneration performance.

Recently most application of IGFCs for power plants designs have been focusing on gas turbine to be integrated with SOFC as a topping cycle. For such system, high temperature SOFCs operate in the temperature region of 850–1000 °C can provide high system electrical efficiencies from integration with gas turbines for large-scale centralized power generation. However, recent progress in lowering operating temperature and improvements in power density have made SOFCs offer high potential for power generation in not only centralized, but also decentralized applications. Lowering operating temperatures contributes to the longer durability, the use of wider range of materials allowing cheaper fabrication, particularly in relation to interconnects and balance of plant (BOP) components, as well as the advantage of vastly simplifies the integration of BOP components [38,39]. By lowering the temperature of SOFC into so-called intermediate temperature SOFC (650–800 °C), the integration with gas turbine, which requires higher inlet temperature for higher efficiency, might become less advantageous. Thus the use of a bottoming steam cycle in the integrated SOFC plant may become more suitable.

In this study, we propose a system integrating the gasifier, intermediate temperature SOFC and steam turbine (ST) and thermodynamically analyze the performance of the proposed system. To avoid the confusion with existing general IGFC plant, the term of light integrated gasification fuel cell (L-IGFC) will be used to refer to the proposed plant in this study. In the following sections, the L-IGFC plant layout with different desulfurization processes will be considered for the analyses by using the Aspen Plus.

2. System description

2.1. Integrated energy system adopting conventional wet gas desulfurization

The layout of the L-IGFC power plant system is schematized in Fig. 1. The system is based on the coal gasifier, the SOFC and the bottoming steam cycle. An entrained-flow, oxygen-blown, and dry feed gasifier that operates at 40 bar and 1500 °C is adopted in this study. A 99% purity oxygen flow is produced in standalone air separation unit (ASU) and compressed to the gasifier working