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A conceptual design of catalytic gasification fuel cell hybrid power plant with oxygen transfer membrane

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HIGHLIGHTS

- A detailed modeling of catalytic gasification fuel cell system is performed.
- A strong-coupled catalytic gasifier with anode off-gas recycle is designed.
- System overall electricity efficiency reaches 60.7% (HHV) and can increase further.
- Membrane oxygen supply system facilitates CO_2 capture.

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ABSTRACT

A hybrid power generation system integrating catalytic gasification, solid oxide fuel cell (SOFC), oxygen transfer membrane (OTM) and gas turbine (GT) is established and system energy analysis is performed. In this work, the catalytic gasifier uses steam, recycled anode off-gas and pure oxygen from OTM system to gasify coal, and heated by hot cathode off-gas at the same time. A zero-dimension SOFC model is applied and verified by fitting experimental data. Thermodynamic analysis is performed to investigate the integrated system performance, and system sensitivities on anode off-gas back flow ratio, SOFC fuel utilization, temperature and pressure are discussed. Main conclusions are as follows: (1) System overall electricity efficiency reaches 60.7%(HHV) while the gasifier operates at 700 °C and SOFC at 850 °C with system pressure at 3.04 bar; (2) oxygen enriched combustion simplify the carbon-dioxide capture process, which derives CO_2 of 99.2% purity, but results in a penalty of 6.7% on system electricity efficiency; (3) with SOFC fuel utilization or temperature increasing, the power output of SOFC increases while GT power output decreases, and increasing system pressure can improve both the performance of SOFC and GT.

1. Introduction

Energy conservation and CO_2 reduction has been a significant strategy for many governments throughout the world. In China, one of the crucial strategies is to make clean and efficient use of coal. Integrated gasification combined cycle (IGCC) system is a typical and hopeful technology roadmap which mainly includes coal gasification, syngas cleaning, gas turbine(GT) and steam turbine(ST) combined cycle, and the overall energy efficiency is estimated to be 36–42% [1].

Solid oxide fuel cells (SOFCs) are devices via electrochemical process to generate power, and its electricity efficiency is not limited by Carnot cycle, which can easily reach 50% [2]. Unlike some other kinds of fuel cells, SOFCs are capable of using carbon-based fuel [2–4]. This prominent characteristic creates a possibility for the combination of coal gasification and solid oxide fuel cell. Meanwhile, SOFCs operate at high temperature (600–1000 °C [4]), in order to sufficiently utilize the high temperature off-gas, a combined cycle (CC) is normally adopted, and the overall efficiency of IGFC is able to increase further.

The fundamental designs of IGFC hybrid power generation system have been performed since early 1990s, and several critical technics in system have been discussed [5–10]. In gasification process, an oxygen blown, entrained flow fluidized-bed gasifier based on the prototype of Shell gasifier is normally used [8], [11],

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Nomenclature

A	pre-exponential factor of ASR ($\Omega\cdot cm^2$)
$ASR(T)$	area specific resistance of SOFC ($\Omega\cdot cm^2$)
B	index number of ASR (K)
D_{H_2}	diffusion coefficient of H_2 ($m^2\cdot s^{-1}$)
E_{rev}	reversible Nernst potential (V)
E_a	activation energy ($J\cdot mol^{-1}$)
HHV_i	high heat value of H_2, CO, etc. ($kJ\cdot mol^{-1}$)
j	current density ($A\cdot cm^{-2}$)
j_0	exchange current density ($A\cdot cm^{-2}$)
j_l	limited current density ($A\cdot cm^{-2}$)
k_a, k_c	pre-exponential factor of the anode/cathode exchange current density ($A\cdot cm^{-2}$)
k_d	coefficient of the limited current density ($A\cdot cm^{-2}$)
l_a	thickness of anode (m)
$\dot{n}_i$	mole flow rate of H_2, CO, etc. ($mol\cdot s^{-1}$)
U_f	fuel utilization
V_{cell}	practical voltage of cell (V)
W_i	power output of unit i (kW)
Z_{coal}	mole flowrate of coal ($kmol\cdot h^{-1}$)

Greek letters

α	carbon conversion ratio in gasifier
β	back flow ratio of anode off-gas
η_{act}, η_{ohm}, η_{con}	activation, ohmic and concentration polarization loss (V)
η_{inv}	efficiency of DC-AC inverter
η_{SOFC}, η_{GT}	electricity efficiency of solid oxide fuel cell/gas turbine
η_1, η_2	overall electricity efficiency with/without CO_2 capture
φ	ratio of porosity to tortuosity

[12]. A desulfurization process is necessary before the crude syngas entering SOFC stacks, and dry gas desulfurization (DGD) which can be operated at high temperature is preferred than wet gas desulfurization (WGD), because of less exergy loss during temperature change process [13–15]. Meanwhile, the combination modes between SOFC and GT have been analyzed as well [16–22]. S.K. Park and T.S. Kim [22] compared pressurized and ambient pressure design of SOFC-GT system, and concluded that the pressurized one performs a higher efficiency.

Based on the IGFC-GT system, if considering CO_2 capture, different strategies have been designed by researchers [23–26]. Siefert N S et al. [24] made an exergy and economic analysis of a CaO-looping gasifier for an IGFC-CCS system, and results showed that the calculated exergetic efficiency was 60% at the parameters values that maximized the internal rate of return (IRR). Methanation process before the syngas entering SOFC also has advantages in system optimization, for it can not only increase the fuel temperature, but also remove CO_2 if coupled with CaO-looping system [10], [27]. Moreover, Chen S et al. [25] put forward a novel combined cycle integrating coal gasification, solid oxide fuel cell, and chemical looping combustion (CLC), one of whose major findings was that the plant net power efficiency reached 49.8% with ~100% CO_2 capture.

However, traditional methods of CO_2 capture at the bottom of system need to separate the CO_2 from N_2, and this process consumes lots of energy. Though the CaO-looping or CLC technology seems to be promising, they undoubtedly will increase system complexity and electricity consuming because of the transportation of solid material.

In this work, we bring in oxygen transfer membrane (OTM) for oxygen supplication, which is simple-structured and energy saving but rarely used in IGFC system [23–25]. The compressed air will be firstly blown into SOFC cathode and then blown into OTM to provide pure oxygen for combustion and gasification. After oxygen enriched combustion, the flue gas with high concentration of CO_2 (>99%) will be captured without purification process.

Meanwhile, the gasifier is designed to be tightly coupled with SOFC stack, and catalytic gasification [9], [28–30] is adopted. It is proved in literature that a gasifier with an external heater will significantly increase the CO and H_2 concentration, and increase overall efficiency in the end [23]. Thus we adopt catalytic gasification whose operating temperature can be lower than SOFC stack, in order to absorb the high quality heat from the irreversible energy loss of SOFC.

2. System description

Based on the project “Development of power generation technics and devices on carbon-based fuel cell” (MD2014-08) conducted by Shanxi province, a 150 kW IGFC-GT system is designed and the schematic flowsheet is shown in Fig. 1. The basic IGFC-GT system in this work includes a catalytic gasifier, a DGD unit, a SOFC unit, an OTM oxygen supplication system, a gas turbine and a CO_2 capture unit.

2.1. Catalytic gasifier

The catalytic gasifier here is based on the Exxon's concept, a fluidized bed gasifier which operates at 700 °C and 35 bar, using K_2CO_3 as catalyst to produce methane-rich syngas [31]. Equilibrium calculation shows that this gasifier produces more CO and H_2 in a lower pressure, which is also confirmed by N.C.Nahas [31]. In this work, the gasification temperature is also controlled at 700 °C, but considering the operation pressure of SOFC, the gasification pressure is set between 3.04 bar and 5.07 bar. A 10 wt% of coal of catalyst K_2CO_3 is used, and this amount of catalyst is proved to have a good catalytic ability by Yeboah Y D et al. [32]. Meanwhile, we recycle the off-gas from SOFC anode, which mainly contains CO, H_2, CO_2, H_2O. This process can not only raise the CO and H_2 flow rate in syngas, but also recover the high quality energy of anode off-gas. Due to the limitation of equilibrium between CO and CO_2, the carbon in coal can not be thoroughly converted, so we supplement steam from a steam generator in cooler and pure oxygen from OTM system. Further, we use a heat exchanger designed inside the gasifier in order to absorb heat from cathode off-gas. In addition, syngas from catalytic gasifier is cooled to 460 °C by compressed air in a heat exchanger (HX2), and then the sulfur is removed through DGD process [33].

2.2. SOFC unit

As an electrochemical device with high electricity efficiency, SOFC generates most of the electricity power in IGFC-GT system. The syngas from catalytic gasifier is mainly composed of CO, H_2, CO_2, H_2O and little CH_4, and it is assumed that only H_2 to take part in the electrochemical reaction on anode surface. Because with the existence of H_2O, CH_4 will be reformed into CO and H_2O, and CO will further be converted into H_2 through water gas shift (WGS) reaction due to the fact that the reforming and shift reactions are more