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Thermodynamic analysis of an integrated solid oxide fuel cell, Organic Rankine Cycle and absorption chiller trigeneration system with CO_2 capture

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ABSTRACT

A novel trigeneration system which integrates a SOFC system, an Organic Rankine Cycle (ORC), and an ammonia water absorption chiller with a CO_2 capture system is proposed and investigated. The exhaust gas from SOFC anode combusts with pure O_2 instead of air and thus the combustion products mainly consist of CO_2 and H_2O, which the CO_2 can be captured easily by the condensation method; in SOFC cathode side, a series-connected ORC and ammonia water absorption chiller heat recovery system which can produce power, heat and cooling is employed to recover the waste heat of SOFC cathode exhaust gas. A mathematical model is developed to study the system performance under steady-state conditions. The calculated results show that the net electrical efficiency and the exergy efficiency of the integrated system can reach 52.83% and 59.96%, respectively. The trigeneration efficiencies of the combined system without and with CO_2 capture are 74.28% and 72.23%, respectively. The effects of the SOFC inlet temperature, the current density, the steam-to-carbon ratio, the pinch point temperature difference and the turbine II inlet pressure on the trigeneration system performances are investigated in detail. The research achievement in this paper can provide the useful reference for SOFC based trigeneration system with low energy consumption for CO_2 capture.

1. Introduction

In recent years, the over exploitation of fossil fuels has caused a series of ecological problems, and more attention has been paid to the global warming and air pollution. Therefore, the approaches and technologies are being developed to improve energy conversion efficiency and reduce greenhouse gas emissions. Fuel Cells attracts more and more attention due to their high efficiency, modularity, simple structure, environmentally friendly and potential of cogeneration features [1–3]. Compared with other types of fuel cells, Solid Oxide Fuel Cell (SOFC) has the advantages of fuel flexibility, low emissions, long-term stability and high efficiency and thus SOFC has been paid more attentions by governments, developers and researchers [4,5].

Generally, SOFC operates at a high temperature around 600 °C to 1000 °C [6,7] and generates high grade waste heat. It is commonly coupled with a gas turbine (GT) to form a SOFC-GT hybrid system, which can improve the overall efficiency [8–10]. However, the flue gas temperature from the SOFC-GT system is still high, so it can further improve the system efficiency by recovering SOFC-GT waste heat [11–13]. From the earlier researches, it showed a better performance to recover the waste heat of SOFC-GT hybrid system employing the Organic Rankine Cycle (ORC) and Kalina Cycle (KC) as the bottom cycle [14,15]. Zhang et al [1] established an integrated SOFC-GT-ORC power system, and an electrical efficiency of 66.27% was achieved. Ebrahimi et al. [16] proposed a SOFC-GT-ORC power system and the results showed that the fuel saving of about 45% was achievable and the overall electrical efficiency could reach more than 65%. Wang et al. [17] integrated the SOFC-GT with a KC, and the overall electrical efficiency and exergy efficiency of the system could reach about 70% and 67%, respectively. Fahad A et al. [18,19] investigated a trigeneration plant including a SOFC, an ORC, and a heat exchanger for the heating process and a single-effect absorption chiller for cooling, and the results obtained from this study showed that there was 3%-25% gain in efficiency compared with power cycle (SOFC-GT-ORC), and the maximum efficiency of the trigeneration could reach about 76%. Furthermore, some researches referring to comparisons between the SOFC-GT-ORC and the SOFC-GT-KC system were made by Gholamian et al. [20] and Yan et al. [21], and the results showed that the exergy efficiency of the combined SOFC-GT-ORC system was higher than the combined SOFC-GT-KC system, and the power output of ORC was more than that of the KC.

Unlike the conventional power generation system, SOFC-GT system has high generation efficiency even though CO_2 capture system is employed [6]. Dijkstra et al. [22] summarized three different methods of

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Nomenclature

Ex	exergy (kW)
h	specific enthalpy (kJ/kg)
I	exergy destruction (kW)
j	current density (A/cm^2)
j_0	exchange current (A/cm^2)
LHV	lower heating value of the fuel (kJ/kg)
M	molecular mass (kg/kmol)
m	mass flow rate (kg/s)
n	molar flow rate (mol/s)
n_e	number of electrons participating in the electrochemical reaction
P	pressure (kPa)
P_{high}	cycle high pressure of absorption chiller (kPa)
P_{low}	cycle low pressure of absorption chiller (kPa)
Q	heat rate (kW) or quality (–)
R	universal gas constant (J/(mol·K)) or resistivity (Ω)
s	specific entropy (kJ/(kg·K))
T	temperature (K or °C)
V	cell voltage (V)
V_{loss}	voltage loss (V)
W	power (kW)
x	ammonia mass concentration
$\triangle G^0$	Gibbs free energy at standard pressure and temperature (J/mol)
α	charge transfer coefficient
η	efficiency

Subscripts

Abs	absorber
act	activation
as	anodic current
C	cooling
ch	chemical
comp	compressor
cont	concentration
cs	cathodic current
exg	exergy efficiency
h	heat
in	input
net	net work
ohm	Ohmic
out	output
ph	physical
re	reversible
s	isentropic progress
tur	turbine

CO_2 capture based on the SOFC system (pre-fuel cell CO_2 capture, post-fuel cell CO_2 capture, post-fuel cell oxidation). Duan et al. [23] made a comparison study on three different SOFC hybrid systems with zero-CO_2 emission, and their efficiencies were more than 62%, which only decreased 3–4% compared with that of the basic SOFC hybrid system without CO_2 capture. In SOFC, because the anode gas is separated from the cathode air by the solid electrolyte, and the CO_2 concentration in anode products keeps high, which makes it possible to use less energy consumption for CO_2 capture. This interesting feature may help SOFC to compete with traditional power station system in which CO_2 is diluted by N_2 in combustion products leading to CO_2 capture consuming more energy [23–26].

In this paper, a novel integrated trigeneration system which integrates a SOFC system, an ORC and an ammonia-water Absorption chiller (AC) with CO_2 capture is proposed and investigated. A mathematical model is developed to simulate the novel integrated

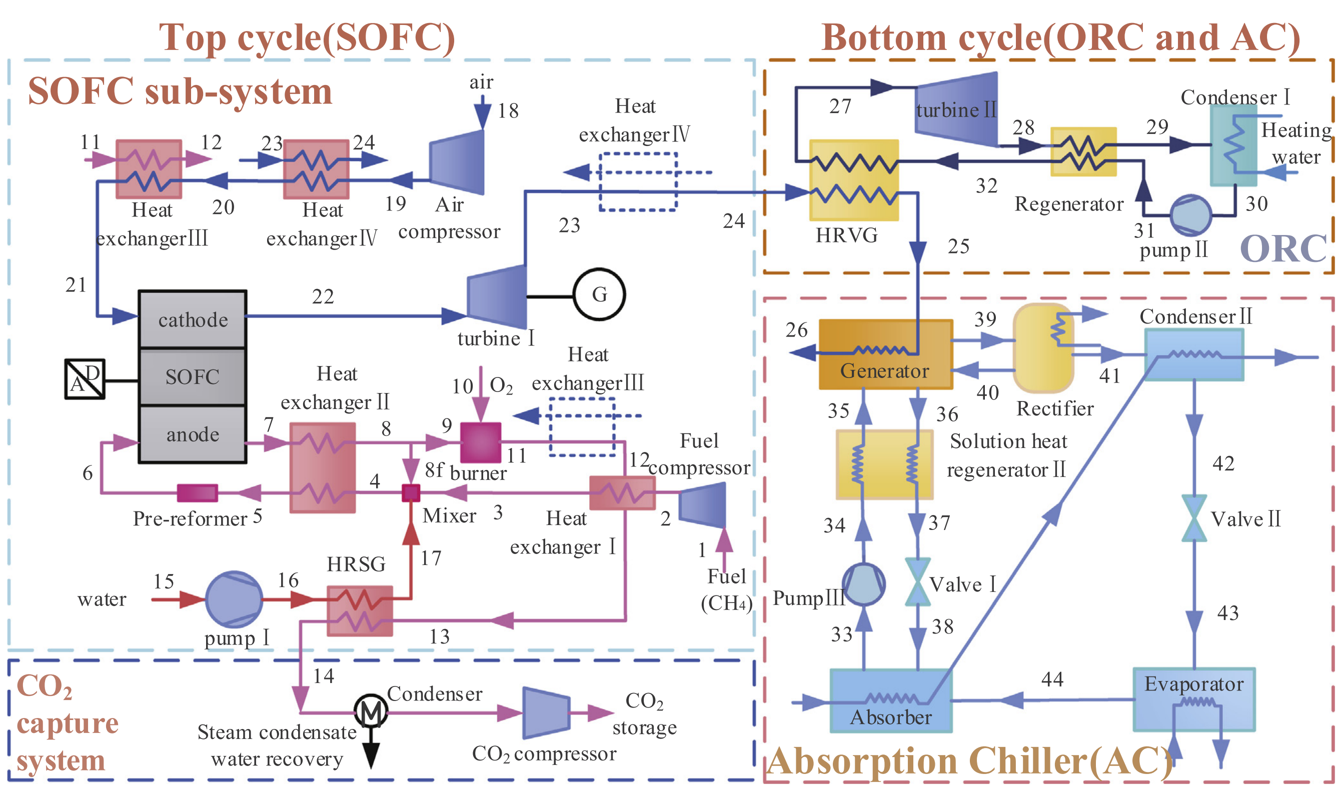

Fig. 1. Schematic of the trigeneration system based on the SOFC-ORC-AC system.