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Coal gasification integration with solid oxide fuel cell and chemical looping combustion for high-efficiency power generation with inherent CO_2 capture

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HIGHLIGHTS

- A novel power system integrating coal gasification with SOFC and chemical looping combustion.
- The plant net power efficiency reaches 49.8% with complete CO_2 separation.
- Energy and exergy analysis of the entire plant is conducted.
- Sensitivity analysis shows a nearly constant power output when SOFC temperature and pressure vary.
- NiO oxygen carrier shows higher plant efficiency than using Fe_2O_3 and CuO.

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ABSTRACT

Since solid oxide fuel cells (SOFC) produce electricity with high energy conversion efficiency, and chemical looping combustion (CLC) is a process for fuel conversion with inherent CO_2 separation, a novel combined cycle integrating coal gasification, solid oxide fuel cell, and chemical looping combustion was configured and analyzed. A thermodynamic analysis based on energy and exergy was performed to investigate the performance of the integrated system and its sensitivity to major operating parameters. The major findings include that (1) the plant net power efficiency reaches 49.8% with ~100% CO_2 capture for SOFC at 900 °C, 15 bar, fuel utilization factor = 0.85, fuel reactor temperature = 900 °C and air reactor temperature = 950 °C, using NiO as the oxygen carrier in the CLC unit. (2) In this parameter neighborhood the fuel utilization factor, the SOFC temperature and SOFC pressure have small effects on the plant net power efficiency because changes in pressure and temperature that increase the power generation by the SOFC tend to decrease the power generation by the gas turbine and steam cycle, and v.v.; an advantage of this system characteristic is that it maintains a nearly constant power output even when the temperature and pressure vary. (3) The largest exergy loss is in the gasification process, followed by those in the CO_2 compression and the SOFC. (4) Compared with the CLC Fe_2O_3 and CuO oxygen carriers, NiO results in higher plant net power efficiency. To the authors' knowledge, this is the first analysis synergistically combining in a hybrid system: (1) coal gasification, (2) SOFC, and (3) CLC, which results in a system of high energy efficiency with full CO_2 capture, and advances the progress towards the world's critically needed approach to "clean coal".

1. Introduction

Power plants based on coal feeding produce approximate 50% of the electricity in the United States, and much more, about 70%, in some other countries, such as China and India [1–5]. Among all fuels, coal produces the highest quantity of CO_2 per unit generated heat and electricity, so concerns about global warming have led to much work on effective CO_2 capture and storage (CCS) from power plants. While many methods were proposed for CO_2 capture in the power generation sector, they typically are energy intensive, thus resulting in significantly lowering the plant energy efficiency and in increasing the cost of electricity.

To take advantage of the high efficiency of combined cycles for power generation, which approaches 60%, but most conveniently

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Nomenclature

E_D	exergy destruction in the system (kW)
E_F	fuel input exergy into the system (kW)
E_{input}	component exergy input (kW)
E_{output}	component exergy output (kW)
E_P	exergy obtained in the system (kW)
$\dot{E}_s$	exergy of a stream (kW)
$\dot{E}_{s,d}$	exergy destruction rate (kW)
$\dot{E}_{s,i}$	inlet or input exergy (kW)
$\dot{E}_{s,o}$	outlet or product exergy (kW)
$\dot{e}_{ch}$	molar chemical exergy (kJ/mol)
$e_{ch,i}$	standard molar chemical exergy (kJ/mol)
$\dot{e}_{ph}$	molar physical exergy (kJ/mol)
e_{fuel}	fuel exergy (kJ/kg)
$\dot{e}_s$	exergy of a system (kJ/mol)
F	Faraday constant (96486 C/mol)
ΔH	enthalpy of reaction (kJ/mol)
h	enthalpy (kJ/mol)
h_0	enthalpy at the reference state (kJ/mol)
I	current (A)
LHV_{coal}	coal lower heating value (kJ/kg)
m_{coal}	coal input mass flow (kg/s)
$\dot{m}_{oc}$	actual oxygen carrier circulation rate (kg/s)
$\dot{m}_{oc,s}$	stoichiometric oxygen carrier circulation rate (kg/s)
NCV^0	solid fuels net calorific value (kJ/kg)
$\dot{n}_i$	component molar flow rate (mol/s)
P	pressure (Pa)
P_{ref}	reference pressure (101.325 kPa)
R	universal gas constant (8.31 J/mol K)
s	entropy (kJ/mol K)
s_0	entropy at the reference state (kJ/mol K)
T	temperature (K)
T_0	reference temperature (298 K)
Tol	default relative convergence tolerance
U_t	fuel utilization factor (–)
V_{ref}	reference cell voltage (0.7 V)
V_{SOFC}	SOFC voltage (V)
W_{ASU}	air separation unit power (kW)
W_{AUX}	auxiliary power consumption (kW)
$W_{COAL\cdot P}$	coal milling and handling power (kW)
$W_{CO_2\cdot COM}$	CO_2 compression power (kW)
$W_{CO_2\cdot EX}$	CO_2 expander power (kW)
W_{GT}	gas turbine power (kW)
$W_{SOFC\cdot AC}$	SOFC AC power output (kW)
$W_{SOFC\cdot DC}$	SOFC DC power output (kW)
W_{ST}	steam turbine power (kW)
w	moisture content of the solid fuel
X_i	calculated value in iteration
x_i	molar fraction (–)
η_e	plant net power efficiency (%)
$\eta_{ex,c}$	component exergy efficiency (%)
$\eta_{ex,system}$	system exergy efficiency (%)
$\eta_{inverter}$	DC–AC inverter efficiency (%)
η_{SOFC}	SOFC efficiency (%)
λ	oxygen carrier excess ratio (–)

Acronym

AC	alternate current
ASU	air separation unit
CCS	carbon capture and storage
CLC	chemical looping combustion
CLHG	chemical looping hydrogen generation
DC	direct current
HHV	higher heating value
HRSG	heat recovery steam generator
IGCC	integrated gasification combined cycle
LHV	lower heating value
MEA	monoethanolamine
SOFC	solid oxide fuel cell

need gaseous fuel, integrated gasification combined cycles (IGCC) can be used [6], where the coal is first converted into syngas in a gasifier, which is then used to fuel the gas turbine in the combined cycle. The processes in an IGCC are based on energy cascade utilization to maximize the energy and exergy efficiencies. The overall IGCC efficiency without carbon capture is estimated to be 36–42% [7]. If CO_2 capture is added, an energy penalty around 6–7% points will be imposed for conventional IGCC [7].

Solid oxide fuel cells (SOFC) are electrochemical direct energy conversion devices with high efficiency, and need high temperatures (600–1000 °C) for their operation because their electrolyte is inadequately conductive at lower temperatures. A SOFC produces electricity directly from fuel gases through electrochemical oxidation reactions rather than combustion [8]. Their operation at high temperatures and pressures provides an opportunity for using their exhaust gases for preheating the input fuel and air and to provide the heat source for gas and/or steam turbines to generate more power. Many studies have been made about the integration of SOFC with steam and combined cycles (e.g., [9–15]). In such systems the high temperatures allow the internal reforming of light hydrocarbon fuels, such as methane, propane and butane, within the anode, or external reforming upstream of the anode can be employed to use heavier hydrocarbons, such as gasoline, diesel, jet fuel (JP-8) or biofuels [16]. The reformates are generically syngas, mixtures of hydrogen, carbon monoxide, carbon dioxide, steam and methane. The syngas then reacts in the fuel cells to produce electricity [17].

Since coal is a very abundant fossil fuel, especially in high-energy consuming countries like China and India, and SOFC has potential to attain efficiencies of around 60%, significant attention was given to use SOFC for replacing or augmenting the gas turbine power output in IGCC plants to attain higher overall efficiency of coal power plants [18,19]. The system of combining SOFC and IGCC is usually as follows: coal is gasified to syngas in a gasifier and cleaned, fed to the SOFC that produces power, the SOFC exhaust gases are mixed and burned in a combustor, and then fed to a gas turbine, producing additional power, the gas turbine exhaust flows into a heat recovery steam generator (HRSG). The steam is fed to the steam turbine for additional power generation. Romano et al. [20,21] performed a thermodynamic analysis of integrated gasification fuel cell plants. A simple cycle gas turbine works in a hybrid cycle with a pressurized intermediate temperature SOFC, integrated with coal gasification with a syngas cleanup island and a bottoming steam cycle, but without CO_2 capture. A net electric efficiency of 52–54% was predicted. El-Emam et al. [22] examined an integrated gasification and SOFC system with a combined cycle. The energy efficiency of the overall system was predicted to reach 38.1% without carbon capture. The influences of pressure ratio on the component performance were also presented in their study. Adams et al. [23] proposed an integrated gasification-SOFC power plant, with separated anode and cathode streams. Air is used as oxygen source without diluting the fuel exhaust, enabling CO_2 recovery from the exhaust with a very small energy penalty. The optimization process predicted that 46% power