Energy Conversion and Management 117 (2016) 241–250

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermodynamic analysis of a solar-hybrid trigeneration system integrated with methane chemical-looping combustion

Jiangjiang Wang *, Chao Fu

School of Energy, Power and Mechanical Engineering, North China Electric Power University, Baoding, Hebei Province 071003, China

ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form 25 February 2016
Accepted 14 March 2016
Available online 22 March 2016

Keywords:
Trigeneration system
Chemical-looping combustion (CLC)
Solar energy
Thermodynamic analysis

ABSTRACT

Chemical-looping combustion (CLC) that occurs without reacting air and fuel is a promising technology for achieving CO_2 capture with a low energy penalty and without additional energy consumption. This paper proposed a solar-hybrid trigeneration system based on methane CLC to produce electricity, chilled water for cooling, and hot water. CaS and $CaSO_4$ are the cycle materials of the CLC, and the reduction reaction in the CLC is driven by solar thermal energy. The thermodynamic performances of the new CLC trigeneration system, including energy and exergy efficiencies, are analyzed and compared on the basis of design conditions and variable parameters, respectively. The results indicate that the optimal solar heat collection temperature is approximately 900 °C, the pressure ratio of the air compressor is 20, and the energy and exergy efficiencies reach 67% and 55%, respectively. The output ratios of the three products vary with the solar collection temperature and pressure ratio. Meanwhile, the net SCLC-to-exergy efficiency and the saving rate of the solar collection area are expected to be 24% and 63%, respectively.

1. Introduction

Carbon dioxide (CO_2) emissions that accompany fossil fuel consumption are the main contributor to global warming and climate change. One of the available alternatives to prevent these emissions is CO_2 capture and storage, which is a medium-term solution to stabilize atmospheric CO_2 concentrations [1]. However, conventional CO_2 capture technologies, such as oxy-fuel combustion, post-combustion separation and pre-combustion, have high energy consumptions and costs. In contrast, chemical-looping combustion (CLC) is an oxy-combustion technology that utilizes an oxygen carrier to transfer oxygen from air/oxidizing stream in an oxidation reactor to the fuel in a reduction reactor, which achieves the CO_2 capture without extra energy consumption [2].

In 1983, Richter and Knoche proposed the CLC concept, which aims to decrease the entropy change during fuel combustion in power plants and improve the energy utilization efficiency [3]. A CLC involves fuel conversion using of a solid oxygen carrier that transfers oxygen from the air to the fuel. Generally, a CLC system consists of two interconnected fluidized bed reactors, an air reactor and a fuel reactor, with the oxygen carrier material circulating between them. With the goal of mitigating climate change, various researchers have investigated CLC as a technology for CO_2 capture in the past two decades. The investigations are mainly classified into three categories: preparation and screening of oxygen carriers [4,5], analysis and simulation of reactor systems [6,7], integration with power cycles [1,8] and chemical-looping reforming [9,10]. Additionally, the solar thermal energy is usually utilized to drive the chemical reaction of CLC [11,12], which provides the necessary reaction heat.

Different CLC systems integrated with power cycles have been proposed to simultaneously separate CO_2 and improve the overall efficiency. The work of Ishida et al. [13] indicates that integrating a CLC with a gas turbine (GT) and solid oxide fuel cell (SOFC) can raise the overall efficiency to 50.2% and 55.1%, respectively. Jin and Ishida [14] proposed a type of coal gas fueled CLC coupled with a GT and determined that it may lead to a next-generation coal based power plant with both a higher thermal efficiency and more effective recovery of CO_2. Jin et al. [15] designed a new CLC integrated with a GT combine cycle; the performance analysis indicated that the new system achieves 60.6% thermal efficiency with 70% capture of the CO_2, which is at least approximately 10.7 percentage points higher than a chemically intercooled GT combined cycle. Petrakopoulou et al. [16] provided an exergy-based evaluation of CLC technology from an economic and environmental perspective by comparing it to a combined cycle power plant without CO_2 capture and reported that the integrated CLC system increased the efficiency and decreased the cost and environmental impact. These studies reported that cycles integrated with a CLC

* Corresponding author.
E-mail address: jiangjiang3330@sina.com (J. Wang).

http://dx.doi.org/10.1016/j.enconman.2016.03.039
0196-8904/

Nomenclature

AC	absorption chiller
CLC	chemical-looping combustion
CO_2	carbon dioxide
COP	coefficient of performance
GT	gas turbine
HT	high temperature
LHV	lower heating value
SASR	solar area saving rate

Symbols

A	area (m^2)
ex	specific exergy (kJ/kmol)
Ex	exergy (kJ)
h	specific enthalpy (kJ/kmol)
LHV	lower heating value (MJ/Nm^3)
m	mass flow rate (kg/s)
P	pressure (Pa)
Q	heat (kJ)
R	universal gas constant (kJ/kmol)
s	specific entropy (kJ/(kmol K))
T	temperature (K)
W	work (kJ)
x	molar ratio
η	efficiency
ΔH	enthalpy difference

Superscripts

Q	heat
0	ambient

Subscripts

absorp	absorption
c	cooling
ch	chemical
cog	cogeneration
comp	compressor
des	destruction
f	fuel
gen	generation
GT	gas turbine
h	heat
in	inlet
net	net
out	outlet
opt	optical
ph	physical
r	region
ref	reference
sol	solar
sys	system

have lower energy losses and that CO_2 was captured at a higher rate. Sanjay et al. [17] evaluates competitiveness of CLC technology against pre-combustion and oxy-fuel combustion technology for IGCC plants with CO_2 capture, which indicated that IGCC-CLC achieved the highest net electrical efficiency of 39.74% and the CO_2 capture efficiency of 100%. Angel Jimenez Alvaro et al. [18] presents a set of simulations of an IGCC power plant with CLC including carbon capture. The conclusion showed that the thermal efficiency and CO_2 capture efficiency of new system achieved approximately 4 and 7 percentage points higher than those in conventional CLC system. Hamers et al. [19] applied a two stage CLC (TS-CLC) configuration to power plant based on coal gasification, which could achieve a net electric efficiency of 41.1%. Additionally, the exergy losses in the CLC power cycle were lower compared to conventional cycles.

Moreover, integration studies of a CLC with renewable energy have gradually become more common as concerns about environmental problems have increased in recent years. The integration of a CLC power cycle with solar thermal energy was first proposed by Hong and Jin in 2005 [20], and solar thermal energy was employed to drive the endothermic reaction of NiO and methane. Then, this power cycle was modified in 2006 to improve the thermal efficiency [21]. More recently, Hong et al. proposed an ethanol CLC coupled with a GT cycle that utilizes low-temperature solar thermal energy at 200 °C to reduce reactor and ethanol preheating. The exergy efficiency is expected to be 54.4% and the CO_2 emission is reduced by 14.9% compared to the conventional combined cycle [22]. Furthermore, the diurnal storage of solar thermal energy is an alternative to solving discontinuity and fluctuation. Jafarian et al. [23] proposed a novel hybrid solar CLC concept in which oxygen carrier particles are used as a storage medium of the concentrated solar thermal energy. This concept was extended and improved by Jafarian et al. [24] in 2014 to achieve a higher solar share in which two reservoirs are utilized to store the oxygen carrier particles with a cavity solar receiver for the fuel reaction. Then, a hybrid solar CLC system with solar energy storage was applied to a GT combined cycle by Jafarian et al. [25]; two configurations with and without an after-burner on the outlet from the air reactor were compared, and the results indicate a first law efficiency of 50.0% for the cycle employing an after-burner compared with 44.0% for that without an after-burner.

Additionally, studies on a multi-generation system based on a CLC were expanded to utilize waste heat to produce useful energy. Wolf and Jan [26] designed a novel configuration for heat, power and hydrogen production with an extended CLC; the parametric studies indicated that a 54% thermal efficiency for capturing 96% of CO_2 is theoretically achievable for a trigeneration system. Furthermore, Ozcan and Dincer [8] proposed a novel three-reactor chemical looping hydrogen generation unit in connection with a SOFC assisted GT for the trigeneration of power, hydrogen and heating. The energy and exergy analyses indicated that the overall system energy and exergy efficiencies are 56.9% and 45.05%, respectively. He et al. [27] designed a multi-generation system based on a dimethyl ether-fueled CLC driven by middle temperature solar thermal energy, which the fossil energy saving rate (FESR) could reach 29.3%. However, to date, multi-generation systems based on a methane-fueled CLC driven by solar thermal energy have not been evaluated for their thermodynamic performance.

The originality of this study is to propose a solar-hybrid trigeneration system based on a methane CLC that utilizes low grade heat to produce useful energy to decrease the waste energy content and increase the efficiency, and to perform the thermodynamic analysis to reveal the mechanism for improving efficiency. The thermodynamic performances of the new trigeneration system are presented and compared to a conventional trigeneration system. Exergy destruction throughout the system is analyzed to find the sources and locations of irreversibilities. Furthermore, the opti-