Applied Energy 212 (2018) 465–477

Contents lists available at ScienceDirect

Applied Energy

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

Study on the configuration of bottom cycle in natural gas combined cycle power plants integrated with oxy-fuel combustion

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HIGHLIGHTS

- An integrated oxy-fuel combustion NGCC power plant with carbon capture is proposed.
- The oxy-fuel combustion systems with CO_2 or H_2O as dilute gas are compared.
- The performances of five different kinds of bottom cycle are investigated.
- H_2O is not suitable to be employed as dilute gas in oxy-fuel combustion NGCC system.

ARTICLE INFO

Keywords:
NGCC
Oxy-fuel combustion
Carbon capture
LNG
Bottom cycle
Efficiency

ABSTRACT

With the increasing demand of energy and urgent need of CO_2 emissions reduction, seeking for an approach to achieve carbon capture in a power generation system with high efficiency is a great challenge. Natural gas combined cycle (NGCC) power plants with high power generation efficiency have attracted more and more attention. Oxy-fuel combustion is considered one of the most potential methods for carbon capture in power plants. An integrated system of NGCC and oxy-fuel combustion is proposed to realize the carbon capture in the work. The cold energy of liquefied natural gas (LNG) is utilized to condense CO_2 with high efficiency. The simulation of the system is conducted using Aspen Plus. Five kinds of bottom cycle: single pressure (SP) cycle, dual pressure non-reheat (DPN) cycle, dual pressure reheat (DP) cycle, triple pressure non-reheat (TPN) cycle and triple pressure reheat (TP) cycle are established. The oxy-fuel combustion systems considering CO_2 and H_2O as dilute gas are investigated. The result shows that H_2O is not suitable to moderate the combustion temperature in the study case because the latent heat of the flue gas is difficult to release. The efficiency of TP steam cycle is the highest among five kinds of bottom cycle. Taking the power consumption of carbon capture and O_2 production into account, the energy and exergy efficiency of the system with the TP steam cycle is 55.3% and 52.9% respectively. The sensitivity analysis is carried out to study the effects of the flow rate of recycled CO_2 and carbon capture pressure on system performance. The results show that with the increase of the amount of recycled CO_2, the system power generation decreases. As the CO_2 capture pressure increases, the carbon capture rate is elevated, while the CO_2 purity drops.

1. Introduction

With the rapid economic development, the demand of electricity, the most direct and convenient form of energy, is steadily increasing. Coal is widely used in power generation systems especially in developing countries for its availability, energy density and relatively low costs [1]. However, combustion of coal causes serious environmental problems. According to the published statistics by the International Energy Agency (IEA), the amount of global CO_2 emissions is 31.6 billion tons in 2011 and over 40% of the total is attributed to the coal combustion [2]. The Intergovernmental Panel on Climate Change (IPCC) noted that CO_2 has the greatest impact on climate change in all greenhouse gases (GHGs), and it accounts for 63% of the total warming effects of all GHGs [3]. Nevertheless, with the increasing energy consumption requirements, fossil energy is projected to remain a major source of energy in the near future [4]. Natural gas (NG) with the lowest carbon emission coefficient and a relatively low carbon-to-hydrogen ratio, has become one of the most potential energy sources. Currently, in natural gas power plant, natural gas combined cycle (NGCC) is most widely used for its mature technologies and high efficiency. The world's electricity demand will rise continually up to 34,290 TW h in 2030 and 20% of the total electricity will be generated

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https://doi.org/10.1016/j.apenergy.2017.12.049
Received 26 September 2017; Received in revised form 6 December 2017; Accepted 8 December 2017
0306-2619/

Nomenclature

Q	heat rate (MW)
W	electrical power (MW)
m	mass flow rate (kg/s)
h	specific enthalpy (MJ/kg)
s	specific entropy (MJ/(kg K))
e	specific exergy (MJ/kg)
η	efficiency
T	temperature (°C)
$W_{turbine}$	power generation of turbines (MW)
W_{pump}	power generation of pumps (MW)
W_{net}	net power generation (MW)
P	pressure (MPa)

Subscripts

0	reference state
f	fuel gas
p	product
ex	exergy
out	outlet
in	inlet

Abbreviations

LNG	liquefied natural gas
ASU	air separation unit
LHV	low heat value
NGCC	natural gas combined cycle
SP	single pressure bottom cycle
DPN	dual pressure non-reheat cycle
DP	dual pressure reheat cycle
TPN	triple pressure non-reheat cycle
TP	triple pressure reheat cycle
NG	natural gas

from NGCC power plants [5].

The layout of NGCC power plants is various, among which the extensively used technology is the waste heat boiler combined cycle. The system integrates a Brayton cycle and a Rankin cycle to economically and effectively satisfy the energy demand. The heat recovery steam generator (HRSG) is the main focus point of combined cycles. In the case of certain gas turbine (GT) exhaust fuel gas, the design of HRSG directly affects the performance of the whole system [6]. At present, there are five kinds of HRSG: single pressure (SP), dual pressure non-reheat (DPN), dual pressure reheat (DP), triple pressure non-reheat (TPN) and triple pressure reheat (TP). To provide better heat recovery in the HRSG, multi-pressure levels and the reheat of steam are employed.

In recent years, many investigations on NGCC power plants have been carried out. Bassily [7] applied gas reheat with recuperation to a regular TP combined cycle to reduce the irreversibility of the HRSG, and the results indicated that the novel cycle was 1.9–2.15% higher in efficiency and 3.5% higher in the total specific work than the regular gas reheat cycle. Feng et al. [8] discussed the dual pressure HRSG under three different layouts. The results showed that the optimization of heat exchangers layout of HRSGs had a great significance for waste heat recovery and energy conversion. Manassaldi et al. [9] addressed the optimal arrangement and design of a DP steam generator coupled to two steam turbines, and the optimal number of heat exchangers and pumps and the coupling of them were discussed. Mansouri et al. [10] found out that an increase in the number of pressure levels reduced the exergy losses in HRSG. Sanjay [11] investigated the impacts of HRSG configuration on exergy destruction of bottom cycle and claimed that the distribution of exergy destruction was sensitive to the layout of bottom cycle. Woudstra et al. [12] conducted the thermodynamic evaluation for different bottom cycles in NGCC power plants, and the exergy losses of the three-pressure bottom cycle was significantly reduced compared to the SP bottom cycle. Rahim [13] performed a sensitivity analysis for single, double and three pressure HRSG in a NGCC, and the influence of working parameters on the thermodynamic efficiency was analyzed. As described above, the configurations of bottom cycle play important roles in the thermodynamic performance in NGCC power plants.

The CO_2 emissions of NG power plants are just half of that in the state-of-the-art coal-fired power plants. However, the reductions are not enough to meet the global emission reduction targets proposed by the IPCC [14,15]. Therefore, it is necessary to seek suitable approaches to reduce the CO_2 emissions in NG power plants. Currently, three basic approaches are employed to capture CO_2 from energy systems: pre-combustion, oxy-fuel combustion and post-combustion technology [16–21]. At present, air combustion is generally applied to NGCC power plants, and the post-combustion technology is employed to realize carbon capture [22–24]. Van Der Spek et al. [25] studied a NGCC with exhaust gas recycle (EGR) and optimized electric swing adsorption (ESA) and a NGCC with EGR and standard monoethanolamine (MEA). However, the efficiency penalty due to the carbon capture was relatively high, which ranges between 10% and 28% for NG fueled plants [26]. Oxy-fuel combustion is considered one of the most potential approaches to capture CO_2 in power plants due to the low risk inherent during the implementation of new technologies [27,28]. Fuel is burned in a nitrogen-lean environment in oxy-fuel combustion, achieved by feeding the combustor with an O_2-rich stream and the recycled medium, which commonly is CO_2 or H_2O [29]. The primary combustion products are simply CO_2 and H_2O. Thus, the merely cooling of the flue gas is able to condense water and produce high purity CO_2, ready for sequestration [30]. When oxy-fuel combustion is introduced in NGCC power plants, the reduction of CO_2 with a relatively high efficiency can be achieved. The typical oxy-fuel combustion system is O_2/CO_2 combustion, and CO_2 is dilute gas H_2O is a potential dilute gas as well, termed as O_2/H_2O combustion [31,32]. Different dilute gases result in different compositions of flue gas and different outlet temperatures of GT, which directly affect the heat transfer in the HRSG, and further have an important impact on the efficiency of bottom cycle. Few studies have explored the integrated system of oxy-fuel combustion NGCC power plants, and the influence of different dilute gases on the entire NGCC power systems has not been reported. Further efforts to uncover oxy-fuel combustion NGCC power plants are urgently needed to promote carbon capture in natural gas power plants.

Searching for a carbon capture process with low energy consumption is a challenge for the practical operation of an oxy-fuel combustion NGCC power plant. The employment of LNG cold energy in carbon capture process is a beneficial attempt to neutralize the penalty in power generation [33]. The temperature of LNG is −162 °C, much lower than that of the ambient air and water. A large amount of coldness exergy of LNG is wasted in practice due to the direct heat exchange with air or sea water [34,35]. To withdraw the cryogenic energy from LNG evaporation process, many researchers dedicated to the utilization of the coldness exergy of LNG. LNG could be utilized as a heat sink in power generation cycles [36–38]. Additionally, the LNG coldness was employed into GT inlet air cooling and intercooling processes to improve the system performance [34,39]. However, the maximum heat transfer temperature difference between the heat and cold source reaches 188 °C [40], which results in great exergy loss in the heat exchanger [41]. CO_2 condensation requires a temperature of approximately −50 °C, making it sensible to utilize the cryogenic exergy of