Applied Thermal Engineering 71 (2014) 301–309

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Performance of a triple power generation cycle combining gas/steam turbine combined cycle and solid oxide fuel cell and the influence of carbon capture

Ju Hwan Choi [a], Ji Ho Ahn [a], Tong Seop Kim [b,*]

[a] Graduate School, Inha University, Incheon 402-751, Republic of Korea
[b] Dept. of Mechanical Engineering, Inha University, Inha-ro 100, Nam-gu, Incheon 402-751, Republic of Korea

HIGHLIGHTS

- The triple combined cycle can achieve near 70% efficiency using state-of-the-art technology.
- The efficiency is a weak function of gas turbine technology.
- The power share of turbine sub-system increases with a higher gas turbine class.
- Turbine annulus area needs to be increased to operate the gas turbine close to designed conditions.

ARTICLE INFO

Article history:
Received 4 February 2014
Accepted 2 July 2014
Available online 9 July 2014

Keywords:
Gas turbine combined cycle
Triple combined cycle
Carbon capture
Efficiency
Power
Gas turbine class

ABSTRACT

This study simulated a triple combined cycle which combines a gas turbine combined cycle (GTCC) and a solid oxide fuel cell (SOFC) system, and the expected performance is presented. The impact of post-combustion carbon capture was also evaluated. Commercially available F-class and J-class gas turbines were considered, which represent the present technology standard and an emerging technology. A state-of-the-art post-combustion carbon capture technology was used. The analysis showed that the efficiency of the triple combined cycle is a weak function of the gas turbine class. The efficiency of the F-class-based system without carbon capture is slightly over 70%, and that of the J-class-based system is slightly lower. The efficiency penalty due to carbon capture is around 5 percentage points in the triple combined cycle. The power share of the gas and steam turbines increases with increasing turbine inlet temperature, reaching more than half in the J-class-based system. The degree of increase required for the turbine annulus area to operate the gas turbine safely without compressor surge problems was estimated. The relative efficiency reduction due to an increase in carbon capture rate is lower in the triple combined cycle compared to the GTCC.

1. Introduction

The steady increase in both the unit power output and thermal efficiency of gas turbines (GTs) in past decades has led to an increase in use in the power generation market. The very low amount of environmentally harmful gases emitted by the use of natural gas is another advantage of using gas turbines. The greatest reason for the rapid increase in the gas turbine's market share is that the gas turbine combined cycle (GTCC) has achieved thermal efficiency that is much higher than those provided by any other conventional power generation scheme. Recent technology evolution with leading gas turbine manufacturers has resulted in almost 60% combined cycle efficiency using the latest gas turbines (advanced F-class [1], H-class [2], and J-class [3]). The high efficiency is good for reducing the use of natural resources and for suppressing carbon dioxide emission into the atmosphere. The recent appearance of shale gas and the anticipation of its use in power generation is an important source of momentum for further increases in the gas turbine's market penetration [4].

Aside from conventional power generators, high-temperature fuel cells, especially solid oxide fuel cells (SOFCs), are promising future power sources for various applications, including small combined heat and power systems and large power stations [5,6]. Their major advantages are high efficiency and low emission of

* Corresponding author. Tel.: +82 32 860 7307; fax: +82 32 868 1716.
E-mail address: kts@inha.ac.kr (T.S. Kim).

http://dx.doi.org/10.1016/j.applthermaleng.2014.07.001
1359-4311/

Nomenclature

A_{AN}	annulus area (m^2)
CCS	carbon capture and storage
CR	CO_2 capture rate
CSU	CO_2 separation unit
F	Faraday constant (96,486 J/V mol)
GT	gas turbine
$\bar{h}$	molar specific enthalpy (kJ/kmol)
HP	high pressure
HRSG	heat recovery steam generator
IP	intermediate pressure
LHV	lower heating value (kJ/kg)
LP	low pressure
MEA	mono ethanol amine
$\dot{m}$	mass flow rate (kg/s)
$\dot{n}$	molar flow rate (kmol/s)
P	pressure (kPa)
R	gas constant (kJ/kg K)
$\bar{R}$	universal gas constant (kJ/kg K)
SOFC	solid oxide fuel cell
ST	steam turbine
U	fuel utilization
V	voltage (V)
$\dot{W}$	power (MW)
$\dot{Q}$	heat transfer rate (MW)

Subscripts

AC	alternating current
aux	auxiliary
C	compressor
cell	fuel cell stack
conv	conversion
DC	direct current
f	fuel
gen	generator
m	mechanical
in	inlet
P	pump
ref	reference
T	turbine

harmful exhaust gases. In addition to offering high efficiency as a stand-alone system, SOFCs provide extremely high efficiency when combined with conventional power generators. Their high operating temperature allows for a synergistic combination with various thermal power systems, especially with gas turbines [7]. The concept of hybrid systems which combine an SOFC and a gas turbine has been suggested, and developers have tried to prove relevant concepts via field tests [8–10]. Such SOFC-GT hybrid systems are appropriate in small-scale power systems using small gas turbines with capacity below several megawatts. For large power stations with capacity over several tens of megawatts, a more feasible system configuration seems to be a combination between an SOFC and a gas/steam turbine combined cycle.

The concept of the triple combined cycle aiming at a large plant capacity is relatively new compared with the hybrid system targeting at small sizes. Recently, a leading company that manufactures both large gas turbines for power generation and SOFCs announced the development of a triple combined cycle power plant to reach over 70% power generation efficiency [11]. The cycle is a combination of GTCC and SOFC, and the capacity is over 700 MW. Such a large system requires an SOFC with a capacity of hundreds of megawatts. The current size of commercially available SOFCs is less than 1 MW. However, intensive research and development efforts along with government support in leading countries may speed up the capacity enlargement. For example, the US Department of Energy (DOE) is aiming at 50 and 500-MW-class SOFC-based power generation systems as mid- and long-term targets [12]. Therefore, SOFC systems in the order of one hundred megawatts are a feasible goal in the future. A recent study [13] modeled the triple combined cycle proposed in Ref. [11] but it simply confirmed that the efficiency goal of the literature is feasible without suggesting any further useful technical results. A thermo-economic study on the triple combined cycle was published [14] but it was focused on plant capacities less than 10 MW, and the design parameters, especially those of the gas turbine, are quite different from those of commercially available large gas turbines. Aside from SOFCs, molten carbonate fuel cells (MCFCs) have also been considered as a component for the triple combined cycle. The predicted efficiency of a recent study is as high as 60% [15], but is lower than the expected efficiency of the SOFC based triple generation system of 70% [11].

In addition to extremely high efficiency, capturing carbon dioxide in power plants is currently another important issue. Careful integration between the power system and the capture process and optimization of the entire system layout are very important because carbon capture incurs a performance penalty. In general, proposed technologies are classified into three categories: post-, pre-, and oxy-combustion captures. The state-of-the art technologies and some basic studies including comparisons between several technologies can be found in recent studies [16]. The comparative performance and economic analysis of the influence of different capture options in GTCCs using natural gas as fuel have been carried out [17]. The post-combustion capture is relatively simple from the perspective of system layout, because a CO_2 capture process can be added to the exhaust gas line of a power plant. Therefore, the modification to existing power plants can be minimized. The most matured techniques are absorption-type capture methods such as the Selexol and MEA (Mono Ethanol Amine)-based processes, where CO_2 is selectively absorbed in recirculating solution and then stripped out [18].

Studies on the application of post-combustion capture to GTCCs have begun recently. System-level studies include configuring the capture unit and finding optimal integration between the capture unit and the power cycle Papers have been published on the topics of reduction of the efficiency penalty by modifying the carbon capture method [19,20], system optimization and economic evaluation [21,22] and improvement of carbon capture process focusing on regenerator and reboiler [23,24]. A good summary of recent works on the application of post-combustion capture to GTCCs and a comparison of predicted performance penalties reported in different studies can be found in a recent study [25]. The impact of carbon capture in high-temperature fuel cells and GT/fuel cell hybrid systems have also been examined [26–28]. In addition, studies on adopting carbon capture in integrated gasification plants based on SOFC have been published recently [29–31].

In this study, we aimed to predict the performance expectation of large GTCC–SOFC triple combined cycle plants depending on GTCC technologies at different levels, and also aimed to investigate the impact of post-combustion carbon capture. Firstly, Simulation models for the GTCC and SOFC were set up and validated. Then, the