Energy xxx (2014) 1–10

Contents lists available at ScienceDirect

Energy

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

Using compressor discharge air bypass to enhance power generation of a steam-injected gas turbine for combined heat and power[☆]

Do Won Kang [a], Hyuck Jun Jang [a], Tong Seop Kim [b,*]

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

ARTICLE INFO

Article history:
Received 14 February 2014
Received in revised form
5 August 2014
Accepted 8 August 2014
Available online xxx

Keywords:
Gas turbine
Combined heat and power
Steam injection
Air bypass
Surge margin
Performance

ABSTRACT

In gas turbine combined heat and power systems, steam injection is a good way to cope with seasonal variations in electricity and heat demands. However, even though thermal energy demand decreases considerably in cooling seasons, the surplus exhaust heat cannot be fully utilized for steam injection in conventional operation because of a reduction in compressor surge margin. This study suggests a modified operation to increase power output without damaging the minimum allowable surge margin. This can be realized by extracting some of the compressor discharge air and supplying it to the turbine exhaust side. This paper shows that the modified operation allows for more steam to be injected in comparison to conventional steam-injected operation while maintaining the same compressor surge margin. The modified operation provides another merit of modulating the heat-to-power-generation ratio by controlling both the amount of air bypass and the steam injection rate. In particular, pure power generating operation, where generated steam is fully injected such that no heat output is available, is possible without decreasing the surge margin below a desired minimum value. The impact of the air bypass is demonstrated for a sample ambient temperature condition and the trend with ambient temperature variation is also illustrated.

1. Introduction

CHP (combined heat and power) systems are widely used because of their advantage of being able to respond to demand for electricity and heat at the same time. In general, the seasonal variation in the heat-to-power-demand ratio is usually large. In particular, the peak load in cooling seasons is quite high because of extensive use of electric air conditioners and refrigerators. However, the electricity generation capacity of conventional power generators usually decreases as the ambient temperature rises. This is especially true in gas turbines. In this regard, various efforts have been made to suppress or compensate for the power decrease of gas turbines. The most technically viable options are inlet air cooling, humidification and combinations of the two schemes.

In particular, the use of various kinds of humidification schemes is steadily increasing globally. The first group of humidification technology deals with the compressor side of the gas turbines. The net gas turbine power can be boosted by decreasing the compressor inlet air temperature or adding water vapor to the air flow. Both of these effects increase the air flow rate of the gas turbine, leading to a power boost. The main effect of compressor inlet fogging [1] and evaporative cooling using wet media [2] is to decrease the compressor inlet air temperature and thus increase the air flow rate. Wet compression (overspray) is a more intensive fogging in which water evaporates inside the compressor such that the power boost effect increases in comparison to the other two schemes [3]. The combination of inlet fogging and wet compression maximizes the power boost effect [4]. Some commercial aeroderivative gas turbine packages that use fogging and wet compression systems are available [5,6].

The major effect of the second group of humidification technology is an increase of the gas flow rate in the turbine by injecting steam or water in the combustor. This increases the turbine power and thus the net engine power output. An additional advantage of steam or water injection in the combustor is the high possibility of reducing NOx emission. Historically, steam injection has been widely studied and used commercially [7]. Studies on the performance variation according to the steam injection amount and pressure ratio [8] and on the enhancement of part load performance by steam injection [9] have been performed. Examining

☆ This paper was submitted to Energy after revisions to the paper presented in the ASME 2013 International Mechanical Engineering Congress & Exposition (IMECE2013-64371) with the permission of the ASME.

* 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.energy.2014.08.043
0360-5442/

Nomenclature

A	area
C_p	constant pressure specific heat (kJ/kgK)
CHP	combined heat and power
COMB	combustor
ECON	economizer
EVAP	evaporator
GT	gas turbine
h	specific enthalpy (kJ/kg)
HRSG	heat recovery steam generator
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
N	shaft speed(rpm)
P	pressure
PR	pressure ratio
R	gas constant(kJ/kgK)
SM	compressor surge margin (%)
SPHT	superheater
T	temperature (°C)
$\dot{W}$	power (kW)
γ	specific heat ratio
η	efficiency
κ	parameter in turbine characteristic equation ($(\text{kJ/kgK})^{-0.5}$)

Subscripts

amb	ambient
c	coolant
C	compressor
d	design point
EOS	equation of state
g	gas
gear	gear box
gen	generator
in	inlet
mech	mechanical
N	normal operation without steam injection
NG	natural gas
out	outlet
s	steam (or water)
SI	steam injection
T	turbine

changes in performance and component characteristics by injecting steam into an existing gas turbine [10] has been an important research topic. Relatively complex system configurations with compressor intercooling by water injection [11] and additional components [12] have also been studied. Injection of steam in micro gas turbines were studied both theoretically [13] and experimentally [14]. Injection of water in micro gas turbines was also examined [15] and its effect was compared with that of steam injection [13]. Steam injection combined with hot gas bypass in a small recuperated cycle gas turbine was investigated as well [16]. Recently, the feasibility of integrating a steam-injected gas turbine and thermal desalination system was investigated [17]. Steam injection combined with innovative cycle configurations, such as a system with an air bottoming cycle [18] and a solid oxide fuel cell/gas turbine hybrid system [19], have also been suggested. Many of these studies can be classified into two categories. The first are design studies where optimal design specifications and performance are determined for the newly designed systems adopting steam/water injection and other additional components. The others are studies which dealt with injecting steam/water in an existing engine. Performance enhancement by steam/water injection has usually been studied within the limits of engine operability.

In this study, we aimed to investigate the possibility of maximizing the steam injection effect (i.e. power augmentation) in small CHP systems in cooling seasons. In small-scale gas turbine CHP systems, it is not very economical to design a new steam-injected gas turbine, because this would require the full revision of many components. Therefore, the injection of steam into an existing engine with minimal hardware modifications is more practical. In usual CHP systems, thermal energy demand sharply decreases as ambient temperature rises such that the gas turbine exhaust heat is not fully recovered, or the generated thermal energy in the form of steam is wasted. The main idea of this study is to inject as much steam as possible using the surplus thermal energy in cooling seasons.

In established gas turbines, the amount of steam injection is limited by operating restrictions. Steam injection increases the turbine flow rate. According to operating characteristic of turbines (the detailed equation will be shown in Eq. (3) in section 2.2), the increased turbine mass flow causes the turbine inlet pressure to rise if the turbine inlet temperature is to be maintained at the original value. This in turn causes the compressor discharge pressure to rise according to thermodynamic matching between the compressor and the turbine. As a result, the compressor pressure ratio increases, and thus, the surge margin of the compressor decreases. This phenomenon was observed in previous studies such as in a steam injected simple cycle gas turbine [10] and recuperated cycle gas turbines [13,16]. A reduction in surge margin affects the operation of the gas turbine negatively. In general, it is difficult to inject all of the generated steam by recovering the full turbine exhaust heat. Therefore, even though the thermal energy demand becomes very small, making the majority of exhaust heat available for generating steam for injection, the surplus heat could not be fully utilized for steam injection.

This study proposes a new method to take full advantage of the surplus heat and to maximize the power boost effect by steam injection in existing gas turbines governed by surge margin limitations. The main idea is to bleed some portion of the compressor discharge air and supply it to the turbine exit side by adding an air bypass route. This concept is introduced to maintain the compressor discharge pressure (i.e. the compressor surge margin), while injecting as much steam as possible using the surplus heat of the exhaust gas. Simple extraction of compressor air and bleeding it to the ambient has been generally adopted to prevent compressor surge during start-up. However, the use of air bypass to the heat recovery steam generator in the steam injected operation is proposed in our study for the first time. We adopted a 5 MW-class gas turbine and simulated the steam-injected operation considering the compressor surge margin limitation in representative hot ambient conditions.

2. System layout and analysis

2.1. System layout

Fig. 1 shows the layout of the gas turbine CHP system. The system consists of a 5 MW-class gas turbine and a heat recovery device. The latter is composed of two parts. The purpose of the