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Optimization of a novel cogeneration system including a gas turbine, a supercritical CO_2 recompression cycle, a steam power cycle and an organic Rankine cycle

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ABSTRACT

According to the principles of energy grade recovery and cascade utilization, a novel cogeneration system including a gas turbine, a supercritical CO_2 (S-CO_2) recompression cycle, a steam power cycle and an organic Rankine cycle (ORC) is proposed. In particular, a part of waste heat from the supercritical CO_2 recompression cycle is used to preheat the steam power cycle, and ORC uses the zeotropic mixture as working fluid. Comprehensive thermodynamic and exergoeconomic analyses are presented for the proposed cogeneration system. Parametric studies are conducted to study the effects of key system design parameters as pressure ratio of gas turbine, pressure ratio of the S-CO_2 cycle, split ratio of the S-CO_2 cycle, evaporation temperature of the steam power cycle, mass fraction of isopentane in the zeotropic mixture, evaporation temperature of ORC and pinch point temperature difference in the ORC evaporator on the exergy efficiency and total product unit cost. The optimum system parameters are obtained through the multi-objective optimization method based on GA (genetic algorithm) and TOPSIS (Technique for Order Preference by Similarity to Ideal Situation) decision making. The optimization results indicate that the optimum values of exergy efficiency and total product unit cost are 69.33% and 10.77$/GJ, respectively. Furthermore, the superiority of the proposed cogeneration system is verified by comparison with other seven forms of power generation systems.

1. Introduction

Due to the increase in fuel price and the reduction of fossil fuel resources, the optimal operation and management of energy system are crucial. Gas turbine power generation has a series of advantages such as high efficiency, small footprint, short construction period, low water consumption, quick startup, and flexible operation. Therefore, it has received increasing attention from many countries [1]. However, a stand-alone gas turbine emits high-grade heat into the atmosphere, resulting in low thermal efficiency. It is an effective way to improve the efficiency of gas turbines by constructing combined cycle to recover the waste heat [2]. At present, the conventional gas turbine waste heat recovery way is to design a gas-steam combined power generation system. Sahu [3] carried out the comparisons between the stand-alone gas turbine and the gas-steam combined cycle and found that the combined cycle has 21.16% higher exergy efficiency while the cost of electricity is only 13.3% higher. However, as the exhaust temperature range of gas turbine is large, gas-steam combined cycle may not be the best way to recover the waste heat of gas turbine [4]. According to the principles of energy grade recovery and cascade utilization, the temperature of gas turbine exhaust can be divided into three grades: high, medium, and low. Each level of waste heat can be recovered through its corresponding most suitable power cycle to achieve higher efficiency.

The supercritical carbon dioxide (S-CO_2) cycle is used to recover high-grade waste heat, which is very attractive as a replacement of the steam power cycle when the heat source temperature is higher than 500 °C [5]. The S-CO_2 cycle has the advantages of high efficiency, compactness, simplicity, better economy and safety priority [6]. Kouta et al. [7] conducted the performance and cost analyses of the solar power tower integrated with S-CO_2 cycle. They found that the S-CO_2 recompression cogeneration cycle has a lower levelized cost of energy than the S-CO_2 regeneration cogeneration cycle. Cao et al. [8] proposed a novel combined gas turbine and CO_2 cycle and showed that it has better thermodynamic performance than the gas-steam combined cycle. Nami et al. [9] proposed and optimized a combined cycle including a gas turbine, a supercritical CO_2 recompression cycle, an organic

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Nomenclature

Glossary

A	heat transfer area, m^2
CRF	capital recovery factor
$c_{p,tot}$	total product unit cost, \$/GJ
e	specific exergy, kJ/kg
$\dot{E}$	exergy rate, kW
f	exergoeconomic factor
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
ORC	organic Rankine cycle
P	pressure, bar
PRc	compressor pressure ratio
Q	heat capacity, kW
r_p	pressure ratio of compressor1
S-CO_2	supercritical carbon dioxide
s	specific entropy, kJ/kg·K
T	temperature, °C
W	output power, kW
x	split ratio
Z	capital cost, \$
$\dot{Z}$	capital cost rate, \$/s

Subscripts

0	ambient (temperature)
1, 2···	state points
cr	critical
D	destruction
o	outlet
F	fuel
H	heat exchanger
i	inlet
in	input
k	k-th component
net	net power
P	product
ph	physical exergy
q	heat
W	power

Greek symbols

η	exergy efficiency
η_i	isentropic efficiency
ΔT	pinch point temperature difference
φ	correction factor

Rankine cycle (ORC) and a heat recovery steam generator. The result showed that the average product unit cost of the optimized condition is lower by 0.56 \$/GJ than that of the basic condition.

ORC can be used to recover low-grade waste heat, which is more suitable for heat source below 200 °C than steam power cycle [10–12]. The thermodynamic and the economic optimization of ORC is performed by Quoilin et al. [13]. Result indicated that the optimal economics profitability and thermodynamic efficiency are obtained at different fluids and evaporation temperatures. Khaljani et al. [14] proposed a new cogeneration cycle which combines a gas turbine and an ORC through an HRSG (heat recovery steam generator) and assessed thermodynamic, exergo-economic and environmental impacts. They found that the most exergy destruction occurred in the combustion chamber. Pan et al. [15] introduced an ORC and Kalina cycle combined power generation system using the exhaust gas from solid oxide fuel cell and gas turbine as the heat source. Result indicated that the thermal efficiency and the annual power generation of the system are 53% and 1.964 MkW·h/a. Kosmadakis et al. [16] compared 33 organic working fluids and concluded that R245fa is the most appropriate fluid. The comparisons between the pure and zeotropic mixture fluids of ORC was investigated by Heberle et al. [17]. Result showed that the use of mixtures leads to higher efficiency than pure fluids.

At present, in order to meet the practical application environment, researchers began to optimize the system using multi-objective optimization method and obtained good results. Multi-objective optimization considering exergy efficiency and total cost rate of gas turbine is conducted by Ahmadi et al. [18] who reported 4% increase in exergy efficiency and 5% reduction in environmental impacts by optimization. Ganjehkaviri et al. [19] performed multi-objective optimization for gas-steam combined cycle and found that the optimal quality of the vapor at steam turbine outlet is 88%. Hou et al. [20] reported multi-objective optimization for a cogeneration system including a gas turbine, a supercritical CO_2 regenerative cycle and an ORC. Result showed that the optimal values of the system parameters could be obtained by the multi-objective optimization method based on genetic algorithm. Garg et al. [21] investigated mixture R245fa/Isopentane as ORC working fluids and reported that the ORC could achieve cycle efficiency of 10–13% at an optimum expansion ratio of 7–10.

Therefore, the S-CO_2 recompression cycle, the steam power cycle and the ORC are suitable for recovering high-temperature, medium-temperature and low-temperature waste heat, respectively. For gas turbine waste heat recovery, it would be possible to achieve good results if the three power cycles could be combined according to this characteristic. However, the studies on recovering waste heat from gas turbine through the combination of the S-CO_2 recompression cycle, steam power cycle and ORC have not been reported yet.

Thus, in this paper, according to the principles of grade recovery and cascade utilization, a novel cogeneration system including a gas turbine, a supercritical CO_2 recompression cycle, a steam power cycle and an ORC is proposed. The supercritical CO_2 recompression cycle, steam power cycle and ORC are used to recover high, medium, and low grades waste heat from the gas turbine, respectively. Detailed thermodynamic analysis and exergoeconomic analysis are performed. The multi-objective optimization method is selected to obtain the optimum system parameters.

2. Cycle description and assumptions

Fig. 1 shows the schematic diagram of the novel cogeneration system which includes a gas turbine, a supercritical CO_2 recompression cycle, a steam power cycle and an ORC. Supercritical CO_2 recompression cycle, steam power cycle and ORC recover high, medium, and low grades gas turbine waste heat in turn. In addition, a part of the waste heat of the supercritical CO_2 recompression cycle is used to preheat the steam power cycle.

As shown in Fig. 1, air at ambient conditions is compressed in the compressor (C1). The compressed air and fuel are mixed and combusted in the combustion chamber (CC). The high-temperature gas exiting combustion chamber enters the gas turbine (GT) to drive C1 and generator. Gas turbine exhaust is the hot source of supercritical CO_2 recompression cycle, steam power cycle and ORC.

The high-temperature exhaust discharged from gas turbine first enters heat exchanger (H1) to heat CO_2. The heated CO_2 expands in the S-CO_2 turbine (T1) to generate power and then flows into the high temperature recuperator (HTR) and low temperature recuperator (LTR) to sequentially heat the stream 12 and the stream 10. Stream 17 exiting LTR is split into two streams: stream 18 and stream 20. Stream 20 enters the evaporator to preheat the water of steam power cycle and