Energy Conversion and Management 116 (2016) 32–41

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Optimum design and thermodynamic analysis of a gas turbine and ORC combined cycle with recuperators

Yue Cao, Yike Gao, Ya Zheng, Yiping Dai *

Institute of Turbomachinery, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 15 December 2015
Accepted 25 February 2016
Available online 9 March 2016

Keywords:
Gas turbine
Organic Rankine cycle
Recuperator
Optimum design
Thermodynamic analysis

ABSTRACT

Gas turbines are widely used in distributed power generation because of their high efficiency, low pollution and low operational cost. To further utilize the waste heat from gas turbines, an organic Rankine cycle (ORC) was proposed as the bottoming cycle for gas turbines in this paper. Two recuperators were coupled with the combined cycle to increase the thermal efficiency, and aromatics were chosen as the working fluid for the bottoming cycle. This paper focused on the optimum design and thermodynamic analysis of the gas turbine and ORC (GT-ORC) combined cycle. Results showed that the net power and thermal efficiency of the ORC increased with the ORC turbine inlet pressure and achieved optimum values at a specific pressure based on the optimum criteria. Furthermore, compared with the GT-Rankine combined cycle, the GT-ORC combined cycle had better thermodynamic performance. Toluene was a more suitable working fluid for the GT-ORC combined cycle. Moreover, ambient temperature sensitivity simulations concluded that the GT-ORC combined cycle had a maximum thermal efficiency and the combined cycle net power was mainly determined by the topping gas turbine cycle.

1. Introduction

As a consequence of high energy costs, the utilization of waste heat sources has been receiving more and more attention. Waste heat sources can be categorized into exhaust gases from turbines and engines and waste heat from industrial plants [1]. Exhaust gas from gas turbines is always used by conventional steam power cycles in distributed energy systems to meet the demand of power, heating or cooling [2]. Since conventional steam power cycles cannot achieve better performance from recovering the waste heat sources [1], there is a growing interest in designing more efficient gas turbine combined cycles.

The organic Rankine cycle (ORC) has been suggested as the bottoming cycle to utilize the waste heat of gas turbines [1,3–9]. Meanwhile, other researchers also used the ORC bottoming cycle to recover waste heat from externally fired gas turbines [10,11] and internal combustion engines [12–14]. The ORC has a simpler construction and a higher thermal efficiency than conventional steam power cycles [15]. Such technique has already been applied into commercial operations [16]. Typical applications for ORC are low grade heat (<350 °C) [7] which is lower than the exhaust temperatures of gas turbines (>450 °C) [17]. Therefore, it is important to find a proper way to match ORC with gas turbines.

Several researchers have considered lowering exhaust temperature of gas turbines by recuperators [18,19]. They pointed out that the recuperators preheated the air exiting from the compressor and as a consequence decreased the exhaust gas temperature. A diathermic oil circuit was introduced to transfer heat between the gas turbine and ORC for matching ORC with gas turbines [3,5]. Lecompte et al. reviewed ORC with different configurations, showing some of them were suitable for recovering high temperature waste heat, including ORC with a recuperator, transcritical ORC and ORC with multiple evaporation pressures [7]. ORC with a recuperator was also investigated by Feng et al. [20] and Meinel et al. [21]. Wu et al. found that the transcritical ORC had a better performance than the subcritical ORC for recovering high temperature waste heat [22]. Further study was conducted by Meinel et al. on ORC with multiple evaporation pressures [23]. In addition, a suitable working fluid should be selected for recovering a given waste heat [1]. Since refrigerants and hydrocarbons have lower critical temperatures [24], they are not applicable in this circumstance. Lai et al. had investigated the working fluids characteristics for the high-temperature ORC, and suggested alkanes, aromatics and linear siloxanes could be used to recover the waste heat from gas turbines [25]. Other articles further corroborated this idea [17,26,27]. Feng et al. reported that a mixture of working fluids

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* Corresponding author at: Institute of Turbomachinery, Xi'an Jiaotong University, No. 28 Xianning West Road, Xi'an 710049, PR China. Tel./fax: +86 029 82668704.

E-mail address: ypdai@mail.xjtu.edu.cn (Y. Dai).

http://dx.doi.org/10.1016/j.enconman.2016.02.073
0196-8904/

Nomenclature

g	mass flow rate (kg s^{-1})
h	enthalpy (kJ kg^{-1})
P	net power (kW)
p	pressure (kPa)
Q	absorption of heat (kJ)
T	temperature (K)

Greek letters

ε	efficiency of heat exchange (%)
η	efficiency (%)

Subscripts

AI	auto-ignition
b	burner
C	critical
c	compressor
cc	combined cycle
con	condenser
e	electric
eva	evaporator
exh	exhaust gas
f	friction
fluid	organic working fluid
fuel	fuel gas
gt	gas turbine
orc	organic Rankine cycle
p	pump
pinch	pinch point
re	recuperator
s	isentropy
t	turbine
1–15	state point

could have better thermodynamic performance than pure working fluids for the purpose of recovering waste heat with the correct mass fraction of mixtures [28]. However, the safety and leakage issues should also be taken into consideration when organic fluids were selected [13,29]. Luo et al. investigated organic fluids with EHS (environment, health and safety) criteria [30]. And Sarkar and Bhattacharyya considered the suitable working fluids selection for ORC should base on operational, environmental and safety criteria [31].

Some researchers have focused on thermodynamic analysis and economic analysis for GT-ORC combined cycles. Chacartegui et al. conducted a thermodynamic analysis on the GT-ORC combined cycle [17]. They considered that the GT-ORC combined cycle had better performance than the GT-Rankine combined cycle when the topping cycle was gas turbines with recuperators or high pressure ratios. However, they did not interpret whether their comparisons were under optimum conditions. Also their selected organic working fluids were not suitable for the waste heat recovery of gas turbines. Carcasci et al. focused on the thermodynamic analysis of an organic Rankine cycle for waste heat recovery from gas turbines [3]. They used a diathermic oil circuit to match the working temperature between gas turbines and ORC. Though it was a good solution and the combined cycle had satisfactory performance, the high equipment cost would hinder the application of their design on distributed energy systems. Zare and Mahmoudi had a thermodynamic comparison between ORC and Kalina cycles for waste heat recovery from the gas turbine-modular Helium reactor (GT-MHR) [9]. They considered that the ORC was more appropriate than the Kalina cycle for GT-MHR waste heat recovery. Furthermore, Khaljani et al. tried to utilize the waste heat from the GT-Rankine combined cycle [6,32]. Although their research had a comprehensive thermo-economic investigation on the combined cycle, they made the combined cycle more complex which might lower the benefits. Mohammadkhani et al. assessed a GT-MHR combined with two organic Rankine cycles by exergoeconomic analysis [33]. They reported that the values of optimal decision variables from the viewpoints of thermodynamics and exergoeconomics are different. Shokati et al. investigated the exergoeconomic analysis of waste heat recovery from a GT-MHR via ORC with various configurations [8]. They found that the regenerative ORC bottoming cycle had the lowest unit cost of electricity generated by the ORC turbine. In addition, part-load performances of GT-ORC combined cycles were analyzed by Escalona et al. [34]. Their work confirmed the benefit of merging gas turbines and ORC units for efficient power generation under variable operating conditions.

A review of the literature shows that many researchers focused on utilizing ORC as the bottoming cycle for recovering waste heat from gas turbines. It suggested that ORC could be coupled with gas turbines by both raising the ORC working temperature and decreasing the exhaust temperature of gas turbines. Some of the researchers have already done the thermodynamic and exergoeconomic analysis on GT-ORC combined cycles. However, very few studies have been done on the system optimization of the GT-ORC combined cycle. Moreover, little attention has been paid to the specific organic working fluid selection of the GT-ORC combined cycle. Therefore, a study of optimum design and thermodynamic analysis was conducted on the GT-ORC combined cycle with recuperators. Firstly, thermodynamic models are established to examine the performance of the GT-ORC combined cycle under different ORC turbine inlet pressures. Based on the simulation results, the optimal thermodynamic conditions of the GT-ORC combined cycle are obtained. Next, the combined cycle with different organic working fluids and commercial gas turbines are compared in simulation. In order to verify the advantages of the GT-ORC combined cycle, each of the optimized GT-ORC combined cycle is compared with a GT-Rankine combined cycle as a reference. Finally, a sensitivity analysis of cycle performance to the ambient temperature is done to show the variation of the GT-ORC combined cycle performance.

2. System configuration and modeling

2.1. System configuration

The GT-ORC combined cycle is made up of two parts- the gas turbine and the ORC. The gas turbine system consists of five components: a compressor, a combustion chamber, a turbine, a recuperator and a generator. For the ORC there are six components: an evaporator, an ORC turbine, a recuperator, a condenser, a working fluid pump and a generator. Fig. 1 illustrates the schematic diagram of the GT-ORC combined cycle whose principle of operation can be decomposed into the following processes:

1–2: The compressor pressurizes the air from atmospheric pressure to the specific value by required pressure ratio.
2–3 (5–6): The compressed air is preheated by the waste heat of the turbine exhaust gas before combustion.