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Thermodynamic analysis of alternative operating strategy for gas turbine waste heat recovery combined heating and power system

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ABSTRACT

This paper presented an off-design framework of gas turbine (GT) and its corresponding waste heat recovery system (WHRS) composed of a heat recovery steam generator (HRSG) and an organic Rankine cycle (ORC). Two different GT control strategies named turbine inlet temperature control (TITC) and inlet air throttling control (IATC) methods were chosen, as well as a novel combined IAT-TITC method was proposed. The CHP system was optimized based on the maximum thermal efficiency first at GT full-load conditions. Then, the off-design evaluation was conducted to predict the part-load conditions and system performance. Results showed that the novel proposed IAT-TITC method effectively increased the thermal efficiency during the entire part-load conditions, and could avoid the low temperature exhaust gas phenomenon. The maximum efficiency difference between traditional TITC and new IAT-TITC was about 13.78% at half-load conditions.

Keywords: CHP system; Off-design analysis; Gas turbine control strategy; Organic Rankine cycle.

NOMENCLATURE

Abbreviations	
GT	Gas turbine
FGRC	Flue gas reinjecting control
HRSG	Heat recovery steam generator
IATC	Inlet air throttling control
ORC	Organic Rankine cycle
PR	Pressure ratio
TITC	Turbine inlet temperature control
WHRS	Waste heat recovery system
Symbols	
m	Mass flow rate
N	Speed
P	Pressure
T	Temperature

1. INTRODUCTION

The major global issues such as energy crisis and environment pollution are the biggest challenges in the future [1]. Nowadays, distributed energy systems with great energy-saving potential and good economic feasibility have drawn lots of attentions to improve energy utilization efficiency and alleviate environmental problems. The CHP (combined heating and power), CCP (combined cooling and power) and CCHP (combined cooling heating and power) systems as typical structures are broadly identified as an effective approach to contribute significant efforts in sustainable development of energy field [2].

Recently, the research direction of distributed energy systems can be concluded as following aspects, for example system design optimization, customer side study and integrated conceptual design. Due to the load fluctuation on demand side, the energy system often runs at part-load (also called off-design) conditions. Thus, studies on the off-design performance is another hot research topic. As a critical power generation unit, the GT performance is crucial because it affects the off-design performance of the whole system. Thus, the control strategy of GT is also important. Several conventional control strategies have been analyzed by researchers including the traditional turbine inlet temperature control (TITC) [2], inlet air throttling control (IATC) [3], and adjusting the air inlet temperature control [4,5]. The characteristic of TITC method is reducing the fuel amount burned in the combustion chamber, while that of IATC method is constant value of turbine inlet temperature during the electric load variation process. With respect to adjusting air inlet temperature control,

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there are two types, i.e. inlet air cooling method [4] and inlet air heating method called flue gas reinjecting control (FGRC) [5]. Apart from above, Barelli et al. [6] proposed supercharged GT integrated with an additional compressor at air inlet. They declared the system would be more efficient than the traditional configuration with a lower achievable load condition. The wet operation strategy was also an alternative way to adjust the different loads for a micro GT [7], as well as the adjusting inlet guide vane position for heavy duty GT control [8].

Besides, WHRS design is also very important for distributed energy system due to its different forms of energy supply. Usually, the WHRS design depends on the conception of maximum energy utilization. For example, Han et al. [2] chose a double-effect absorption chiller to harness the waste heat from GT, and they studied the CCP system based on different GT control strategies. Results concluded that the IATC method could increase overall system efficiency by 10% compared with TITC method.

In this context, this work carried out an off-design framework for a CHP system considering different GT control strategies. The new proposed control method named IAT-TITC approach can effectively improve the thermal efficiency of GT-WHRS and avoid the acid corrosion phenomenon caused by low temperature exhaust flue gas.

2. SYSTEM DESCRIPTION AND OFF-DESIGN MODELS

2.1 System descriptions

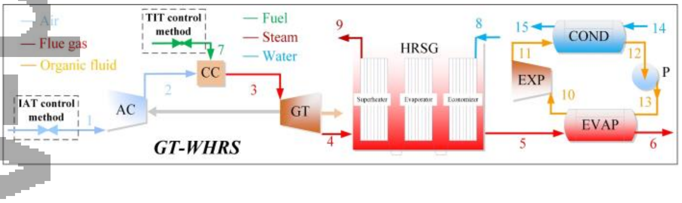


Fig 1 Schematic diagram of the GT-WHRS.

The detailed schematic diagram of GT-WHRS is shown in Fig. 1. Based on the concept of energy cascade utilization, the waste flue gas exhausted from GT is firstly absorbed by a single-pressure HRSG to generate superheat steam, and then drives a bottoming ORC to produce more power. Considering the environmental requirements (0 ODP and low GWP) and non-flammable characteristics, the fluid of R1336mzz(E) (with critical temperature of 444.45 K, critical pressure of 2.90 MPa, nearly zero ODP, and low GWP approximately 7) is selected as working fluid in ORC. The basic design parameters of the CHP system is shown in Table 1 according to the optimization results of maximum thermal efficiency.

Table 1 Design parameters of the GT-WHRS system at full-load conditions.

State	Fluid	*P* (MPa)	*T* (K)	*m* (kg/s)	*h* (kJ/kg)	*s* (kJ/(kg·K))
1	Air	0.10	298.15	14.70	326.95	6.91
2	Air	1.52	688.13	14.70	736.55	7.00
3	Flue gas	1.46	1472.30	15.04	1820.64	7.86
4	Flue gas	0.11	885.21	15.04	1084.93	7.97
5	Flue gas	0.10	423.15	15.04	563.21	7.17
6	Flue gas	0.10	393.28	15.04	531.24	7.10
7	Fuel	1.20	298.25	0.34	899.37	5.37
8	Water	3.50	298.15	2.24	108.06	0.37
9	Steam	3.50	845.21	2.24	3615.16	7.36
10	R1336mzz(E)	1.40	410.44	1.99	483.56	1.78
11	R1336mzz(E)	0.11	355.06	1.99	449.03	1.81
12	R1336mzz(E)	0.11	308.15	1.99	241.03	1.14
13	R1336mzz(E)	1.40	309.00	1.99	242.40	1.14
14	Water	0.10	298.15	15.65	104.92	0.37
15	Water	0.10	304.49	15.65	131.41	0.46

2.2 Off-design modeling

2.2.1 Gas turbine

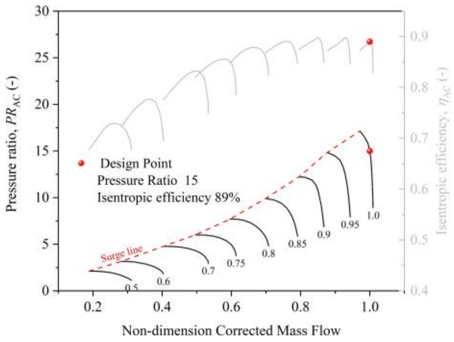


Fig 2 Compressor performance map.

The AC performance map includes characteristic curves relating pressure ratio and isentropic efficiency as a function of non-dimensional speed and corrected mass flow. The compressor map in this work is scaling from the reported data [2] to fit our work as shown in Fig. 2 based on the optimal working conditions from design results, where the corrected speed and corrected mass flow are represented as follows:

$$N_{\mathrm{correct}}=\frac{N_{\mathrm{d}}/\sqrt{T_{\mathrm{d}}}}{N_{\mathrm{od}}/\sqrt{T_{\mathrm{od}}}}=\frac{N_{\mathrm{d}}}{N_{\mathrm{od}}}\sqrt{\frac{T_{\mathrm{od}}}{T_{\mathrm{d}}}} \quad (1)$$

$$m_{\mathrm{correct}}=\frac{m_{\mathrm{od}}\sqrt{T_{\mathrm{od}}}}{P_{\mathrm{od}}}\Bigg/\frac{m_{\mathrm{d}}\sqrt{T_{\mathrm{d}}}}{P_{\mathrm{d}}}=\frac{m_{\mathrm{od}}}{m_{\mathrm{d}}}\frac{P_{\mathrm{d}}}{P_{\mathrm{od}}}\sqrt{\frac{T_{\mathrm{od}}}{T_{\mathrm{d}}}} \quad (2)$$

The GT efficiency under off-design conditions is related with the design parameters at GT inlet, and it can be described as follow:

$$\bar{\eta}_{\mathrm{t}}=[1-\mathrm{t}\left(1-N_{\mathrm{t,correct}}\right)^{2}](N_{\mathrm{t,correct}}/m_{\mathrm{t,correct}})\left(2-N_{\mathrm{t,correct}}/m_{\mathrm{t,correct}}\right) \quad (3)$$

where *t* is a constant value, which is taken as 0.3; $N_{\mathrm{t,correct}}$ and $m_{\mathrm{t,correct}}$ are the corrected speed and corrected mass flow rate of GT, respectively, which can be calculated by Eqs. 1 and 2.

The turbine isentropic efficiency at off-design conditions is determined as:

$$\eta_{\mathrm{t}} = \bar{\eta}_{\mathrm{t}} \eta_{\mathrm{t,d}} \tag{4}$$

Besides, the turbine off-design performance should also be satisfied the Flügel formula, which can be expressed as follows:

$$m_{\mathrm{fg,od}} / m_{\mathrm{fg,d}} = \alpha \sqrt{T_{3,\mathrm{od}} / T_{3,\mathrm{d}}} \sqrt{\left(PR_{\mathrm{t,od}}^2 - 1\right) / \left(PR_{\mathrm{t,d}}^2 - 1\right)} \tag{5}$$

$$\alpha = \sqrt{1.4 - 0.4 N_{\mathrm{t,od}} / N_{\mathrm{t,d}}} \tag{6}$$

where PR_{t} is the pressure ratio of turbine.

2.2.2 Heat recovery steam generator

The single-pressure HRSG is modeled as the cascade form of three heat exchangers. The logarithmic mean temperature difference (LMTD) method is adopted to predict its off-design performance through the overall heat-transfer coefficient at off-design conditions. Since the overall heat-transfer coefficient is mainly affected by the mass flow rate of waste flue gas at off-design conditions [9], the simplified equation can be expressed as follow:

$$(UA)_{\mathrm{od}} = (UA)_{\mathrm{d}} \left(\frac{m_{\mathrm{fg,od}}}{m_{\mathrm{fg,d}}} \right)^{0.} \tag{7}$$

Besides, since the heat exchanger area of HRSG is determined during the design stage, when predicting the off-design performance, the area should be the cycle criterion as a constant value during the off-design calculation procedure.

2.2.3 Organic Rankine cycle

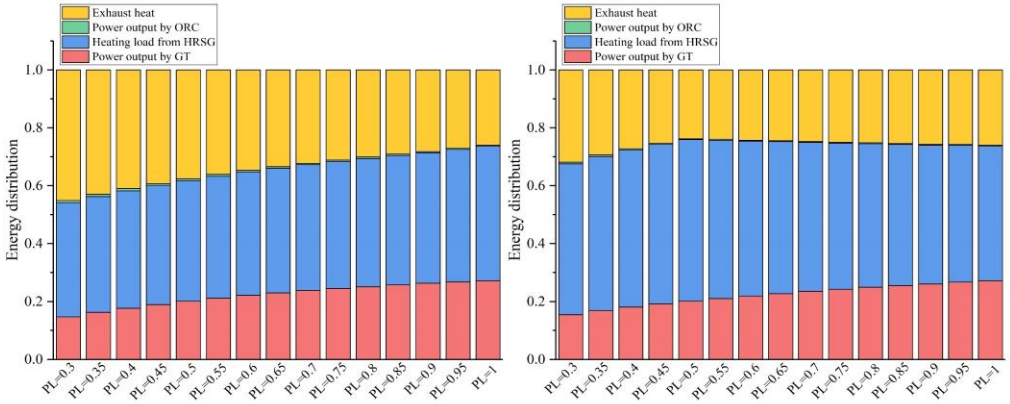
The main focuses are on the investigation of the evaporator and expander performance since it is a reasonable assumption to fix the pressure level at the condenser which being equal to the design conditions. Besides, the modified sliding pressure operation method is conducted to search the optimal evaporating pressure. The relative heat exchanger, expander and pump models can be found in the references [10,11].

3. NEW PROPOSED GT CONTROL METHOD

During the off-design analyses, we find out that the final exhaust temperature of flue gas under TITC method increases while that under IATC method decreases quickly. These temperature decreasing variations are harmful for the bottoming ORC system, which may cause the acid corrosion phenomenon at evaporator outlet operating at low temperatures for a long time. Herein, a new control strategy composed of TITC and IATC methods is proposed in this work to avoid this phenomenon. The GT works with IATC method at high-level part-load conditions (from full-load to half-load), and the exhaust temperature decreases along with the load reducing. When the exhaust temperature decreases to nearly 100 ºC, the GT changes to the TITC method (from half-load to 30% load) which could avoid further temperature decreasing phenomenon, although the TITC approach brings lower thermal efficiency.

4. RESULTS AND DISCUSSIONS

The energy distribution of the proposed GT-WHRS under part-load conditions for traditional TITC method and novel IAT-TITC method is shown in Fig. 3, including four different parts of the energy and they are net power output produced by GT, heating capacity generated by HRSG, net power output produced by ORC, and the waste heat dissipated to the environment, respectively. When the proposed system operates under the full-load conditions, about 27.23% of the fuel energy is harnessed



(a) Part-load (PL) conditions of GTC under TITC method

(b) Part-load (PL) conditions of GTC under IAT-TITC method

Fig 3 Variations of energy distribution under part-load conditions for (a) TITC strategy and (b) IAT-TITC method.

by GT to generate power; 46.46% of the fuel energy is recovered by HRSG to produce steam, and only 0.35% of the fuel energy is utilized by the bottoming ORC system. Besides, almost 25.96% of the fuel energy dissipates into the environment as the form of waste flue gas. For the traditional TITC method, the amount of exhaust heat to the environment of the GT-WHRS increases with the part-load decreasing. After reducing the half-rated power, less fuel energy only about 41.65% is recovered by the HRSG, but more fuel energy is utilized by the bottoming ORC (about 0.66%). This signifies more fuel energy around 37.57% is dissipated into the environment directly. As the GT power output drops to 1380kW, approximately 45.07% of the fuel energy is dissipated into the environment. This means that the total thermal efficiency of the GT-WHRS reduces quickly under part-load conditions as shown in Fig. 3a. Analogously, the energy distribution under part-load conditions adopting the new proposed IAT-TITC strategy is exhibited in Fig. 3b. Unlike the variation trend under TITC method, the waste heat directly dissipated into environment decreases with the GT load reducing from full-load to half-load conditions. After that, the amount of exhaust heat increases under the load range of 30% – 50%. When the GT-WHRS operates at half-load conditions, approximately 31.84% of the fuel energy dissipates into the environment. At the same time, the heat utilized by the HRSG reaches the highest value about 55.82%. There also exhibits the maximum thermal efficiency difference between traditional TITC and new IAT-TITC approach about 13.78% at half-load conditions. In summary, the IAT-TITC strategy has higher thermal efficiency than the TITC method for the entire load range under off-design conditions, although their GT efficiencies are very close.

5. CONCLUSIONS

In this study, an off-design model and evaluation are carried out to study a CHP system named GT-WHRS composed of a GTC, a HRSG and an ORC. The influences of employing different GT control strategies, including the traditional TITC method and the new IAT-TITC method, on the whole system performance are investigated. The main conclusions of this work can be summarized as follows:

A new proposed IAT-TITC approach can effectively avoid the phenomenon of the low temperature exhaust gas. Under the part-load conditions, the GT-WHRS with two different control methods appears almost the same GT electric efficiency. However, the HRSG produces larger heating loads with the IAT-TITC method than that with TITC method. Thus, the IAT-TITC method results in higher thermal efficiency for entire the load range.

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