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# Assessment of off-design performance of a small-scale combined cooling and power system using an alternative operating strategy for gas turbine

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## HIGHLIGHTS

- We develop an off-design model for a CCP system driven by gas turbine.
- An alternative operating strategy is proposed to improve the system performance.
- Off-design performance of the combined cooling and power system (CCP) is enhanced.
- Effects of both the different operating strategy are analyzed and compared.
- Performance enhancement mechanism of the proposed operating strategy is presented.

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## ABSTRACT

A small-scale combined cooling and power (CCP) system usually serves district air conditioning apart from power generation purposes. The typical system consists of a gas turbine and an exhaust gas-fired absorption refrigerator. The surplus heat of the gas turbine is recovered to generate cooling energy. In this way, the CCP system has a high overall efficiency at the design point. However, the CCP system usually runs under off-design conditions because the users' demand varies frequently. The operating strategy of the gas turbine will affect the thermodynamic performance of itself and the entire CCP system. The operating strategies for gas turbines include the reducing turbine inlet temperature (TIT) and the compressor inlet air throttling (IAT). A CCP system, consisting of an OPRA gas turbine and a double effects absorption refrigerator, is investigated to identify the effects of different operating strategies. The CCP system is simulated based on the partial-load model of gas turbine and absorption refrigerator. The off-design performance of the CCP system is compared under different operating strategies. The results show that the IAT strategy is the better one. At 50% rated power output of the gas turbine, the IAT operating strategy can increase overall system efficiency by 10% compared with the TIT strategy. In general, the IAT operating strategy is suited for other gas turbines. However, the benefits of IAT should be investigated in the future, when different gas turbine is adopted. This study may provide a new operating strategy of small scale gas turbine to improve the off-design performance of CCP system.


## 1. Introduction

Combined cooling heating and power (CCHP) system or combined heat and power (CHP) plants are broadly identified as a highly efficient way to use both fossil and renewable fuels and to make a significant contribution to the sustainable energy development [1–5]. When the CHP unit produces the amount of heat that is required to drive the thermal activated device in order to meet the cooling demand, the system is referred to as a combined cooling and power system (CCP). Because the energy demand usually varies from time to time, the part-load operation of CHP, CCP or CCHP plants account for long periods of the total plant operation time. The part-load operation of CHP decreases the thermal performance, and investigation of the off-design performance of CHP plants has become a hot topic.

The off-design performance of combined cooling, hating and power (CCHP) plants were investigated in previous studies. Mago et al. [6] presented the thermodynamic performance of CCHP and CHP plants under two operating strategies, including following the thermal and electric load. Wang et al. [7] compared the performance of a CCHP plant for a commercial building in Beijing

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**Nomenclature**

| | |
|---|---|
| *A* | heat exchanger area |
| *COP* | coefficient of performance |
| *CCP* | combine cooling and power system |
| CCHP | combine cooling, heating and power system |
| *F* | fuel energy consumption |
| GT | gas turbine |
| *h* | enthalpy |
| *HPG* | high-pressure generator |
| *HTX* | high-temperature heat exchanger |
| *IAT* | inlet air throttling |
| *k* | coefficient of heat transfer |
| *LHV* | lower heating value |
| *LPG* | low-pressure generator |
| *LTX* | low temperature heat exchanger |
| *m* | mass flow |
| *N* | spool speed |
| *P* | pressure |
| *Pe* | electric power of the gas turbine |
| *PGU* | power generation unit |
| *Q* | heating value |
| *SP* | separation production |
| *T* | temperature |
| *TIT* | turbine inlet temperature |
| *W* | work transfer |
| *X* | LiBr concentration |

*Subscripts*

| | |
|---|---|
| ab | absorption chiller |
| boiler | gas boiler |
| c | condenser |
| el | electric chiller |
| eva | evaporator |
| fuel | fuel burned in combustor |
| gen | high pressure generator |
| grid | national grid |
| in | inlet |
| out | outlet |
| ref | reference state |
| 01, 02, ... | state point in Fig. 1 |
| 0, 1, 2, ... | state point in Fig. 1 |

*Greek*

| | |
|---|---|
| $\eta$ | efficiency |
| $\Delta t_m$ | logarithmic mean temperature difference |

in different operation modes and found that the electrical demand management mode achieves more benefits in winter than in summer. In these investigations, the efficiency of a gas turbine is assumed to be constant independently of the electric demand, and the decrease of gas turbine efficiency in off-design conditions was not considered. The assumption of constant efficiencies was observed to lead to an overestimation of the optimal CHP results [8]. To ensure a more accurate performance evaluation, other researchers improved the constant efficiency model. Smith et al. [9] analyzed a CCP system driven by an internal combustion engine (IC). The IC engine models are based on linear fits between fuel input and power output variables. Fang et al. [10] and Mago et al. [11] used second-order polynomial curve fit equations to assess both electric and thermal performance of the power generation unit (PGU). Wang et al. [12] conducted a sensitivity analysis of the optimal model of the CCP system. The efficiency of the PGU was interpolated by a third-order polynomial curve fit equation. Bischi et al. [13] presented a detailed Mixed Integer Nonlinear Programming model (MILP) optimization model for the planning short-term operation of a CCHP system. To describe the off-design behavior of equipment, highly nonlinear performance curves were taken into account. Zhou et al. [14] developed new mathematical model for the optimal design of the CCHP system using off-design characteristics of all equipment, and then investigated the impacts of the off-design characteristics by comparing the optimal design results with that obtained with constant efficiency model.

The off-design performance of the gas turbine is affected by the part load control modes. Kim and Ro [15] investigated the effects of two gas turbine control modes including the constant and variable air flows, and found that the variable control of coolant fraction has a favorable effect on the overall fuel economy in the cogeneration system. Haglind [16] studied the effects of variable geometry gas turbines on the part-load efficiency for combined cycles used for ship propulsion and found that the use of variable area nozzle and variable guide vane can improve the part-load performance of the combined cycle. Variny and Mierka [17] found that the gas turbine inlet air preheating can improve the partial load efficiency of a combined cycle based on online monitoring data. Carcasci and Cormacchione [18] reviewed and examined the performance of the gas turbine CHP system for different operating conditions based on fuel usage and overall economy. Kim and Hwang [19] analyzed the performance characteristics of recuperated gas turbines in the part-load conditions. Various part-load operating strategies, including fuel-only control, variable speed, and variable inlet guide vane operations for the single-shaft configuration, as well as simple and variable area nozzle operations for the two-shaft configuration, were considered. Apart from the CHP system, the CCP systems are commonly used in commercial buildings worldwide.

As it is obvious, most of studies mentioned above investigated the off design performance of CCHP or CHP system with the constant gas turbine efficiency, and the off design gas turbine performance. Although the off-design characteristics have been used in the optimal system design, few investigations are focused on the off-design performance of the CCP system considering the effects of the off-design characteristics of components on the CCP system and the performance improvement of the CCP system under par load condition.

The objectives of this study are to investigate the off-design performance of a combined cooling and power system as well as to identify the effects of operating strategies for gas turbines on the off-design performance of the entire system.

## 2. CCP system description

Fig. 1 presents a schematic of a combined cooling and power (CCP) system. The CCP system incorporates a small-scale single shaft gas turbine integrated with a gas-fired double-effect absorption chiller. The gas turbine, which is driven by natural gas, is used to meet the electrical demand. The high-temperature exhaust gas of the gas turbine is utilized by the absorption chiller to help meet the cooling load. The double effect system is used in the CCP system due to the higher coefficient of performance (COP) compared to those of single effect absorption chiller.

### *2.1. Small-scale gas turbine*

Before the off-design performance of a CCP system is investigated, the off-design model of gas turbine has to be developed.