



The 8th International Conference on Applied Energy – ICAE2016

Control optimization of combined cooling and power system with prime mover of solid oxide fuel cell-gas turbine for building application

X.J. Luo^{a*}, K.F. Fong^b

^aDepartment of Architecture and Civil Engineering, College of Science and Engineering, City University of Hong Kong, Hong Kong, China

^bDivision of Building Science and Technology, College of Science and Engineering, City University of Hong Kong, Hong Kong, China

Abstract

This paper presents a control strategy for a combined cooling and power (CCP) system using a prime mover of solid oxide fuel cell (SOFC) with bottoming cycle of gas turbine (GT) for building application. Dynamic simulation model of the CCP system was developed in TRNSYS 17, and the control strategy was developed for year-round operation in response to the changing climatic and loading conditions. The capacity ratio of cells in operation; the ratio of exhaust heat delivered to GT; and the ratio of cooling load shared between absorption and compression chillers were chosen as the decision variables in the control strategy. In order to minimize the system energy consumption, particle swarm optimization (PSO) was constructed in MATLAB and coupled with TRNSYS 17 for control optimization. It was found that with the proposed control strategy, the yearly energy saving of the SOFC-GT CCP system would be 6.89% compared to the reference case.

© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: SOFC; Gas turbine; Combined cooling and power; Particle swarm optimization; Control optimization.

1. Introduction

Combined cooling and power (CCP) system has been proven to be an energy-efficient approach for providing cooling and electricity in building application [1-3]. Solid oxide fuel cell (SOFC) is a high-temperature prime mover with electrical efficiency above 40% and operating temperature around 1000 °C [4]. Bottoming cycle such as gas turbine (GT) can be energized by the high-grade waste heat from the exhaust flue gas of SOFC and used for additional electricity generation. After the bottoming cycle, the hot exhaust can still be used to drive absorption chiller for cooling generation. This would enhance both electrical and overall efficiencies of the CCP system. However, previous studies only focus on the system design and performance analysis, no control optimization was implemented for the year-round dynamic operation.

In the SOFC-GT CCP system investigated, SOFC and GT would share the electrical load, while two types of chillers, the absorption and compression chillers would share the cooling load. Since electrical efficiency of GT and coefficient of performance (COP) of both types of chillers decline in part load operation, it leads to a complex interaction among the prime mover, the bottoming cycle and the chillers in the changing building loads. Therefore, it is worth developing a control strategy to optimize the electricity and cooling load allocation, and ultimately minimize the energy consumption of the entire CCP system. As such, the objectives of this study are to develop an appropriate control strategy for operation optimization of the SOFC-GT CCP system, also to evaluate the effectiveness of the proposed system for building application from a year-round perspective.

2. Development of system model and control strategy

* Corresponding author. Tel.: +852-6584-9728; fax: +852-3442-0443.

E-mail address: xjluo3-c@my.cityu.edu.hk.

| Nomenclature | | | | | |
|--------------|-----------------------------|-----|--|----------|-------------------------|
| AbC | Absorption chiller | C | Capacity ($\text{kJ}\cdot\text{h}^{-1}$) | in | Inlet |
| CCP | Combined cooling and power | D | Demand ($\text{kJ}\cdot\text{h}^{-1}$) | is | Isentropic |
| CoC | Compression chiller | E | Energy (kJ) | N | Nominal |
| GT | Gas turbine | h | Enthalpy ($\text{kJ}\cdot\text{kg}^{-1}$) | out | Outlet |
| HX | Heat exchanger | m | Mass flow rate ($\text{kg}\cdot\text{h}^{-1}$) | | |
| PSO | Particle swarm optimization | P | Electrical power ($\text{kJ}\cdot\text{h}^{-1}$) | γ | Ratio of specific heats |
| SOFC | Solid oxide fuel cell | r | Expansion ratio | η | Electrical efficiency |
| | | T | Temperature ($^{\circ}\text{C}$) | | |
| | | x | Heat ratio | | |

The system model of SOFC-GT CCP was built on the component-based dynamic simulation platform TRNSYS 17 [5] and coupled with MATLAB [6], which contained the developed control strategy to minimize the yearly energy consumption of the CCP system.

2.1 System configuration

Fig. 1 shows the schematic design of the SOFC-GT CCP system, which was used to serve a 30-storey reference office building in the subtropical Hong Kong. The CCP system was mainly composed of a cluster of SOFC, a GT, pre-heaters, an air compressor, a fuel compressor, a reformer, a heat exchanger (HX), a burner, an absorption chiller (AbC), a compression chiller (CoC), an auxiliary air heater and the associated parasitic equipment. The building zone was served by air handling unit containing supply air fan and coil.

In the SOFC-GT CCP system, fuel and air were compressed, pre-heated and pre-reformed in fuel compressor, air compressor, pre-heaters and reformer, respectively. After that, fuel reacted electrochemically with air in the SOFC to generate electricity to the building zone. The unreacted fuel was burnt in the burner and the hot exhaust flue gas was used to supply heat for reformer and pre-heaters before passing to the GT. The hot exhaust after the bottoming cycle would pass to HX in which hot water was delivered to energize the absorption chiller. The compression chiller was adopted to supplement the total cooling capacity. Auxiliary air heater was used to provide heat to the absorption chiller when the exhaust heat from bottoming cycle was not enough. Typical operating temperatures of the SOFC-GT CCP system are also presented in Fig. 1.

In order to demonstrate the effectiveness of the SOFC-GT CCP system, two reference systems were constructed: the SOFC CCP system and the sole SOFC system. The SOFC CCP system was similar to the SOFC-GT CCP system, the only difference was no bottoming cycle of GT and the exhaust flue gas after the pre-heaters would directly pass through the HX. Therefore, electricity load was solely provided by SOFC in the SOFC CCP system. Another reference system, the sole SOFC system, was similar to the SOFC CCP system, except that the air compressor, the fuel compressor, the HX, the absorption chiller and the associated parasitic equipment were not included. In other words, the sole SOFC system was simply used to generate electricity for the building, and the cooling load was fully provided by the compression chiller in a conventional way.

2.2 GT model

The isentropic efficiency of GT is a function of the mass flow rate and it decreases in part load operation. An empirical equation from [7] was used in this study, and the thermodynamic model of GT was built as follows:

$$\eta_{is,GT} = (h_{in,GT} - h_{out,GT}) / (h_{in,GT} - h_{out,s,GT}) \quad (1)$$

$$T_{out,s,GT} = T_{in,GT} (1/r)^{(\gamma-1)/\gamma} \quad (2)$$

$$P_{GT} = m_{GT} (h_{in,GT} - h_{out,GT}) \quad (3)$$

where $\eta_{is,GT}$ is the isentropic efficiency, $h_{in,GT}$ and $h_{out,GT}$ are the inlet and outlet turbine enthalpies ($\text{kJ}\cdot\text{kg}^{-1}$), respectively, $h_{out,s,GT}$ is the outlet enthalpy assuming isentropic expansion ($\text{kJ}\cdot\text{kg}^{-1}$). $T_{in,GT}$ is the inlet turbine temperature ($^{\circ}\text{C}$), $T_{out,s,GT}$ is the outlet temperature assuming isentropic expansion ($^{\circ}\text{C}$), r is the expansion ratio, and γ is ratio of specific heats of combustion gases. P_{GT} is the electrical power of GT ($\text{kJ}\cdot\text{h}^{-1}$), and m_{GT} is the mass flow rate of combustion gases in GT ($\text{kg}\cdot\text{h}^{-1}$).

Nominal input heat rate is defined as the input heat rate at full load, and input heat ratio x is defined as the operating

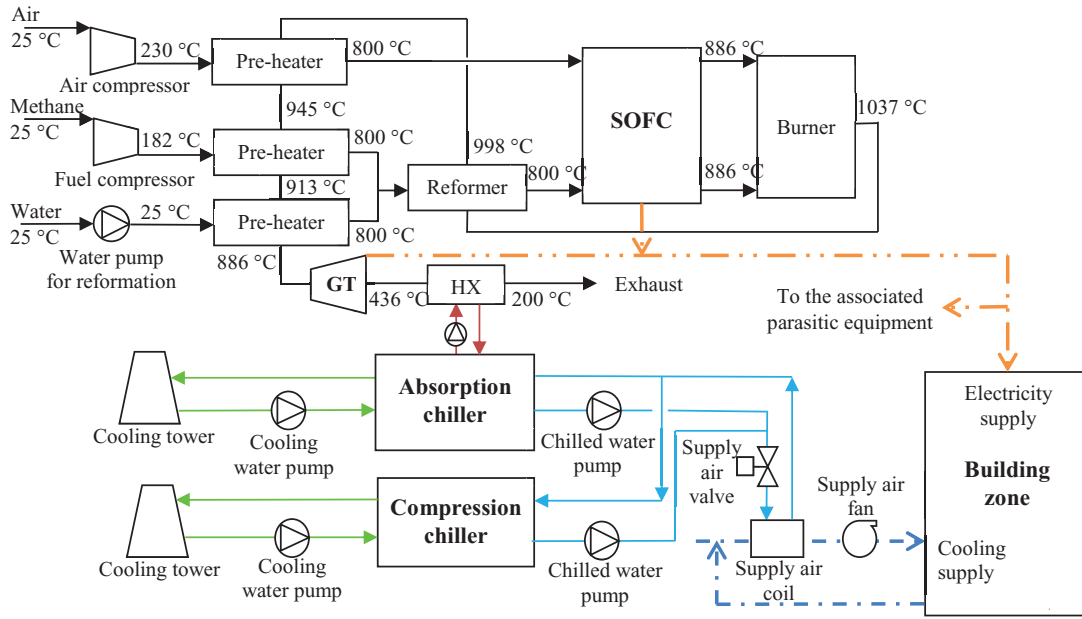


Fig. 1. Schematic design of the SOFC-GT CCP system.

input heat rate to the nominal input heat rate as:

$$x = Q_{m,GT}/Q_N \tag{4}$$

where $Q_{m,GT}$ and Q_N are the operating and nominal input heat rates of GT ($\text{kJ}\cdot\text{h}^{-1}$), respectively. With the thermodynamic model of GT, the correlation between x and P_{GT} can be calculated as:

$$P_{GT} = -0.0064x^4 + 0.014x^3 - 0.0071x^2 + 0.001x - 10^{-5} \tag{5}$$

2.3 Details of other component models

In this study, the SOFC model introduced in [8] was used, it was assumed that the SOFC worked at constant voltage and electrical efficiency. The manufacturing data of absorption chiller and compression chiller were based on [9]. Each chiller was equipped with the corresponding chilled water pump, cooling water pump and cooling tower. Methane was used as fuel for both the SOFC and the auxiliary air heater. It was also assumed that the air compressor, the fuel compressor, the pre-heaters, the reformer, the burner and HX operated at constant efficiencies. The reference office building had 30 stories with area of $200 \text{ m}^2/\text{floor}$. The building zone was developed according to the details covered in [9].

2.4 Formulation of control strategy

2.4.1 Objective function

Total energy consumption was chosen to develop the objective function. Since the fuel methane was only supplied to the SOFC and the auxiliary air heater, the total energy consumption E (kJ) can be calculated as:

$$E = (Q_{SOFC} + Q_{AH}) \Delta t \tag{6}$$

where Q_{SOFC} and Q_{AH} are energy consumption rates of SOFC and auxiliary air heater, respectively ($\text{kJ}\cdot\text{h}^{-1}$), Δt is the time step (h).

2.4.2 Decision variables

There were three decision variables (or optimization variables) in this optimization problem for the SOFC-GT CCP system, namely the capacity ratio of cells in operation a , the ratio of exhaust heat delivered to GT b , and the ratio of cooling load shared between absorption and compression chillers c . These decision variables are developed as follows:

$$a = C_{SOFC}/C_{SOFC,N} \quad (7)$$

$$Q_{in,GT} = b (Q_{SOFC} - C_{SOFC} - Q_{pre-heater} - Q_{reformer}) \quad (8)$$

where C_{SOFC} and $C_{SOFC,N}$ are the hourly operating and nominal capacities of SOFC ($\text{kJ}\cdot\text{h}^{-1}$), respectively. $Q_{pre-heater}$ is the total heat consumption of the three pre-heaters. $Q_{reformer}$ is the heat consumption of reformer.

$$C_{Abc} = (1 - c)D \quad (9)$$

$$C_{CoC} = cD \quad (10)$$

where D is the hourly cooling demand ($\text{kJ}\cdot\text{h}^{-1}$). C_{Abc} and C_{CoC} are operating hourly cooling capacity of absorption chiller and compression chiller, respectively ($\text{kJ}\cdot\text{h}^{-1}$).

2.4.3 Constraints

The constraints consisted of the indoor condition, the bounds of decision variables and the energy balance relationships. The indoor condition is to maintain the dry-bulb air temperature not higher than $26\text{ }^{\circ}\text{C}$. For the decision variables a , b and c , their bounds $\in [0,1]$. The energy balance relationships cover the balance between the electricity supply of SOFC-GT and the building electricity demand as reflected in Eq. (11); while the balance between the heat consumption of absorption chiller and the heat supplies from the exhaust flue gas and the auxiliary air heater as indicated in Eq. (12):

$$C_{SOFC} + C_{GT} = P_{light} + P_{lift} + P_{off-equip} + P_{CoC} + P_{air-comp} + P_{fuel-comp} + P_{para-equip} \quad (11)$$

where P_{light} , P_{lift} , $P_{off-equip}$, P_{CoC} , $P_{air-comp}$, $P_{fuel-comp}$ and $P_{para-equip}$ are hourly electricity consumption of lighting, lift, office equipment, compression chiller, air compressor, fuel compressor, and parasitic equipment (like pumps, fan, cooling tower, etc.) respectively ($\text{kJ}\cdot\text{h}^{-1}$). C_{GT} is the hourly operating capacity of GT ($\text{kJ}\cdot\text{h}^{-1}$).

$$Q_{Abc} = \eta_{HX} (Q_{SOFC} - C_{SOFC} - C_{gt}) + \eta_{AH} Q_{AH} \quad (12)$$

where η_{HX} and η_{AH} are efficiencies of the HX and the auxiliary air heater, respectively. Q_{Abc} is the heat consumption of absorption chiller ($\text{kJ}\cdot\text{h}^{-1}$).

2.5 System parameters

The major parameters used for the CCP system design and PSO are given in Table 1. The other parameters were set according to [9].

Table 1. System design and PSO parameters.

| Parameter of CCP system | Value | Parameter of PSO | Value |
|--|-------|------------------------------|-------|
| Electrical efficiency of SOFC (%) | 44 | Population size | 100 |
| SOFC voltage (V) | 0.73 | Maximum number of iterations | 100 |
| Expansion ratio of GT | 7 | Cognitive parameter | 1 |
| Efficiency of pre-heater (%) | 98 | Social parameter | 3 |
| Efficiency of reformer (%) | 90 | Constriction factor | 1 |
| Efficiency of air/fuel compressor (%) | 93 | | |
| Efficiency of auxiliary air heater (%) | 98 | | |
| Efficiency of HX (%) | 98 | | |

2.6 Solution method

Dynamic system simulation was conducted in a simulation time step of 1 h for one year (i.e. 8760 hours) by using TRNSYS 17 and its component library TESS. In each time step, the three decision variables were optimized in order to obtain the minimum energy consumption of the SOFC-GT CCP system and the reference SOFC CCP system. The

weather data of typical meteorological year of Hong Kong was used. Particle swarm optimization (PSO) was adopted since PSO is a robust algorithm in handling engineering problems [10]. PSO was constructed in MATLAB and coupled with TRNSYS 17 for this control optimization.

3. Results and discussion

3.1 Determination of capacities of SOFC, GT and chillers

The design capacity of SOFC was determined in a way that it was enough to satisfy the peak electricity and cooling demands of the office building. Fig. 2 depicts the load profiles of design day, with the peak cooling load of 8.7×10^6 kJ·h⁻¹ and the simultaneous electricity demand of 4.6×10^6 kJ·h⁻¹. If the cooling demand was satisfied by either absorption or compression chiller, and the electricity demand was fully provided by SOFC, then the nominal capacities of SOFC, absorption/compression chiller were determined to be 6.3×10^6 kJ·h⁻¹ and 8.7×10^6 kJ·h⁻¹, respectively. Meanwhile, the capacity of GT was 1.5×10^6 kJ·h⁻¹, which was determined by the condition of exhaust heat for full capacity operation of SOFC.

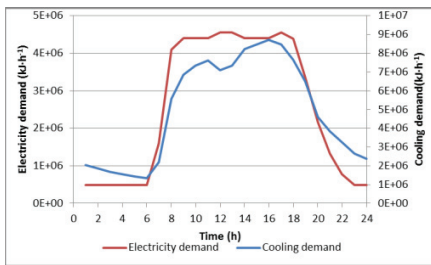


Fig. 2. Electricity and cooling demands on design day.

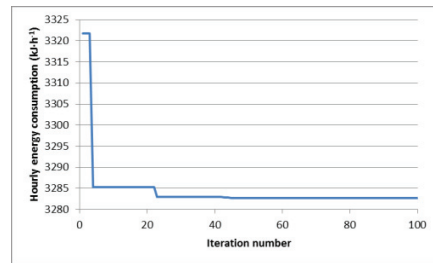


Fig. 3. PSO convergence in control optimization on design day.

3.2 Performances of control strategy

Fig. 3 illustrates the effectiveness of the control strategy to optimize the operation of SOFC-GT CCP system during the peak cooling demand on the design day. It is seen that the PSO can determine the minimum energy consumption effectively and the search convergence is found after about the 40 iterations. Fig. 4 summarizes the hourly results of the decision variables *a*, *b* and *c* of SOFC-GT CCP and SOFC CCP systems on the design day. It is seen that the operating time for *a* of SOFC-GT CCP system set at 1 was less than that of SOFC CCP system. It was because part of the electricity load could be supplied by GT in SOFC-GT CCP system. On the other hand, it is noted that *b* was generally equal or close to 1 in SOFC-GT CCP system. This showed that it was preferable for GT to operate around the full load condition due to its inherently low part-load efficiency. It is also observed that the operating time for *c* of SOFC-GT CCP system set at 1 was longer than that of SOFC CCP system. Actually, the yearly average values of *c* of SOFC-GT CCP and SOFC CCP systems were 0.910 and 0.629, respectively. It is because more electricity was produced in SOFC-GT CCP system, hence the compression chiller could handle more cooling load rather than the absorption chiller.

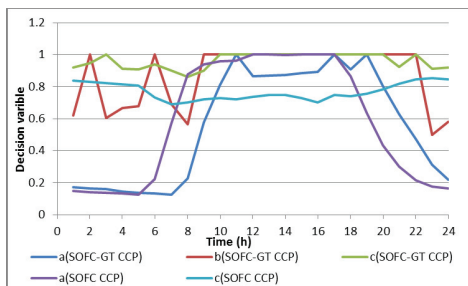


Fig. 4. Decision variables of SOFC-GT/SOFC CCP systems on design day.

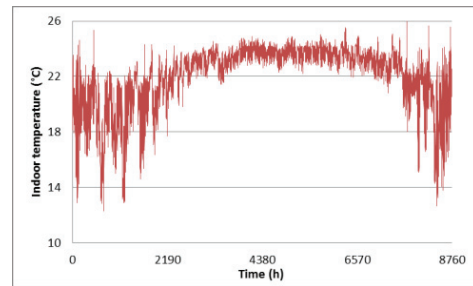


Fig. 5. Indoor temperature in office with SOFC-GT CCP system.

3.3 Year-round performance analysis

With the implementation of the control strategy, it was found that the yearly energy consumption of the SOFC-GT CCP system was 5.133×10^{10} kJ·year⁻¹. Compared to those of the two reference cases, 5.378×10^{10} kJ·year⁻¹ of the SOFC CCP system and 5.513×10^{10} kJ·year⁻¹ of the sole SOFC system, the yearly energy savings of the SOFC-GT CCP system would be 4.6% and 6.9%, respectively. By using GT as bottoming cycle, the overall electrical efficiency of the SOFC-GT CCP system would be increased. Besides, since the compression chiller could share more cooling load, it had better utilization, thus higher COP operation.

In order to demonstrate the effectiveness of control strategy implemented in the SOFC-GT CCP system, the year-round profile of the indoor dry-bulb air temperature of the building zone is shown in Fig. 5. It is seen that the temperature could be kept well below 26 °C, in particular the summer period between 2,881 and 6,552 hours (i.e. from May to September in the subtropical Hong Kong). This shows that the control strategy is useful to deploy the prime mover and the bottoming cycle, as well as the absorption the compression chillers, in providing electricity and cooling for the office building.

4. Conclusion

In this study, a control strategy for the SOFC-GT CCP system was developed for office building application in the subtropical climate. Dynamic simulation model was built in TRNSYS 17 and coupled with PSO in MATLAB for control optimization. It was found that the yearly energy saving of the SOFC-GT CCP system would be 6.9% against the sole SOFC system, as well as 4.6% against the SOFC CCP system. The 3 decision variables, the capacity ratio of cells in operation; the ratio of exhaust heat delivered to GT; and the ratio of cooling load shared between absorption and compression chillers, are useful in control optimization of the SOFC-GT CCP system.

Acknowledgements

This work described in this paper is fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CityU 11200315).

References

- [1] Ondeck AD, Edgar TF, Baldea M. Optimal operation of a residential district-level combined photovoltaic/natural gas power and cooling system. *Applied Energy* 2015;**156**:593-606.
- [2] Han W, Chen Q, Lin RM, Jin HG. Assessment of off-design performance of a small-scale combined cooling and power system using an alternative operating strategy for gas turbine. *Applied Energy* 2015;**138**:160-8.
- [3] Wang J, Wang J, Zhao P, Dai Y. Thermodynamic analysis of a new combined cooling and power system using ammonia–water mixture. *Energy Conversion and Management* 2016;**117**:335-42.
- [4] Wu DW, Wang RZ. Combined cooling, heating and power: a review. *progress in energy and combustion science* 2006;**32**:459-95.
- [5] TRNSYS 17: A Transient System Simulation Program. Solar Energy Laboratory University of Wisconsin, Madison, USA.
- [6] MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.
- [7] Jüdes M, Vigerske S, Tsatsaronis G. Optimization of the design and partial-load operation of power plants using mixed-integer nonlinear programming. *Optimization in the Energy Industry* 2009:193-220.
- [8] Baghernejad A, Yaghoubi M, Jafarpur K. Optimum power performance of a new integrated SOFC-trigeneration system by multi-objective exergoeconomic optimization. *International Journal of Electrical Power & Energy Systems* 2015;**73**:899-912.
- [9] Fong KF, Lee CK. Investigation on zero grid-electricity design strategies of solid oxide fuel cell trigeneration system for high-rise building in hot and humid climate. *Applied Energy* 2014;**114**:426-33.
- [10] Wang LF, Singh C. Stochastic combined heat and power dispatch based on multi-objective particle swarm optimization. *International Journal of Electrical Power & Energy Systems* 2008;**30**:226-234.



Biography

X. J. Luo is a Ph.D candidate studying in Department of Architecture and Civil Engineering of City University of Hong Kong. Her research interest is trigeneration system, dynamic modeling and control strategy development. She aims at developing an effective and efficient control strategy for complex trigeneration systems.



Dr. K. F. Fong is Associate Professor of the Division of Building Science and Technology, City University of Hong Kong. He has the academic interest in renewable cooling and heating, sustainable trigeneration and evolutionary computation. Through exercising both the academic and professional knowledge, Dr. Fong aims at developing the zero carbon building technologies for sustainable urbanization.