Jestr

Investigation of Operation Optimization of CCHP and Water Source Heat Pump Compound Energy Supply Systems

Zhang Wei[1,2,*], Lu Jun[1], Huang Ruolin[1], Li Weidong[3] and Huang Feng[4]

[1]College of Urban Construction and Environmental Engineering of Chongqing University, Chongqing, 400030, China
[2] Chongqing Technology and Business Institute, Hechuan Chongqing, 401520, China
[3] Chongqing Sino-French Energy Services Co. Ltd., Chongqing, 400060, China
[4]Universite Toulouse III – Paul Sabatier, Laboratoire PHASE, 118 route de Narbonne, Toulouse, 31062, France

___

Abstract

Several studies and applications have explored combined cooling, heating, and power systems (CCHP) and water source heat pump systems, but the compound operation of these systems have not been sufficiently investigated. The majority of investigations on CCHP system optimization are based on economic, energy quantity, or energy level perspectives. These different optimization objectives provided varied results. The author introduces an optimization method that takes exergetic cost as optimization objective to couple energy cost, energy quantity, and energy level into a comprehensive indicator that integrates optimization results. The quantities of import and export energy are calculated based on the mathematical models including exergetic cost, CCHP system, and water source heat pump system. The systems' exergetic cost is then compared and analyzed under the external constraint conditions to determine the operation strategy. Finally, the optimization method is applied to the compound energy supply system of Danzishi centre business district (CBD) CCHP plant station in Chongqing China. Results show that the exergetic cost of operation of the compound system is 0.103 US dollar/kWh in summer and 0.088 dollar/kWh in winter, which are lower than the water source heat pump and closer to that of the CCHP system. Primary energy utilization rate (PER) in summer is 1.40 and 0.92 in winter. These findings verify the capability of the method to help the CCHP and water source heat pump compound systems achieve good energy efficiency and economy performance. The investigation develops the theoretical method and reference for the practical application of operation optimization and performance research of CCHP and relative compound energy supply systems.

Keywords: CCHP, Water source heat pump, Compound energy supply system, Exergetic cost, Operation optimization

___

1. Introduction

The increasing severity of energy shortage, energy exploitation, energy production, and utilization efficiency are significant scientific issues in energy research. Combined cooling, heating, and power (CCHP) systems have the following advantages: 1) energy conservation and highly comprehensive utilization rate of energy; 2) peak load shifting, power shortage easing, and seasonal balance of energy consumption; 3) environmentally friendly; and 4) insurance of energy security. Distributed power system compound with state grid power supply an investment-saving, low energy consumption, and highly reliable international system. This system is a new direction for the development of the energy industry in the 21st century. Water source heat pump systems have sustainable operation performance under external climate changing conditions. Unlike air source heat pump, these systems are highly energy-efficient and free from defrosting. Thus, water source heat pump systems are regarded as a renewable energy utilization technology with positive application. The compound system can fully utilize the advantages of CCHP and water source heat pump systems. Water source heat pumps, which are auxiliary heating/cooling sources, can effectively balance heat/power requirement and enable energy supply to meet the energy requirement of the compound system thereby improving its operating effects. Moreover, the construction scale of the compound system is significantly lower than that of a single system. This feature can largely reduce investment cost. The price of uploaded power is lower than the power purchased from the grid, which means that the water source heat pump system of a compound system can help reduce operation costs. Moreover, CCHP and water source heat pump compound systems have more advantages than single systems in cities with rich natural gas and water sources.

However, existing research are mainly focus on the individual operation of CCHP and water source heat pump systems. Most studies on the compound system of CCHP discuss the combinations of CCHP and energy-storage devices [1-4]. The operation optimization of compound system became an urgent energy project given the rapid development of CCHP and water source heat pump systems. Studies on CCHP system optimization tend to select a single

objective, such as energy efficiency or investment cost [5-8]. This approach generates different results. A few studies [9-10] have integrated them into one comprehensive objective by weighting their impacts on the system, but they are still based on a single objective and degree of integration remains a constraint.

The present study investigates CCHP and water source heat pump compound systems that have internal combustion engine generators as core devices coupled with lithium bromide absorption water chiller. This study proposes an optimization method that integrates energy efficiency and economic factors as a comprehensive objective. The validity of the method is verified as well.

2. State of the art

Lots of studies explored the operation and application of water source heat pump systems. A considerable number of studies [5, 11-13] also achieved good results in exploring the optimization of CCHP system operation. Lin [14] analyzed the applying advantages and thermodynamics principle of the gas engine-driven heat pump (GEHP) combined cooling heating and power system, and discussed the primary energy utilization rate (PER) of GEHP at different combined supply energy modes, Zhang [15] set the criterion in predicting the energy saving level of CCHP systems and discussed the impacts of factors, such as heat-to-power ratio, thermal efficiency, and absorption chiller COP, on the energy consumption of the system. He et al. [16] proposed the criterion for evaluating the utilization rate of energy cascade. This criterion is the sum of energy utilization rates of generation, refrigeration, and heating after multiplying their weight coefficients. Some studies [14-16] selected optimization objectives related to energy efficiency; they considered energy quantity and energy level, but they did not relate these factors to the economy.

Benonysson [17] investigated the optimization of CCHP systems in some areas in terms of operating cost, and analyzed the sensitivity of thermal management in relation to economic factors. Qin [18] established a mathematical model of the optimization of waste heat recovery boiler. The objective function of this model is the refrigeration cost of BCHP systems. The model is based on decision variables, namely, the exhaust gas temperature of the boiler, the number of spiral-finned tubes in the evaporator, and fuel economizer. This model suggests that the best structure of the boiler is concerned with the load characteristics of the BCHP system. Kong et al. [19] set up an economic optimization model to achieve the lowest operating cost while satisfying chilling, heating, and power needs. Liu [20] established a mathematical model for the coupling system of gas turbines and waste heat recovery boilers to achieve economic benefits. Results show that the system can achieve improved economic results when the load rate of generating was over 0.8. Hao et al. [21] established a mathematical optimization model that can minimize annual cost. The optimization results of CCHP system distribution and operation plan showed that the annual cost of the optimized plan is lower than that of a traditional plan, but their operating energy consumption is almost equal. A number of studies [18–21] used operating cost as optimization objective and considered energy quantity and the economy, but the impacts of energy quality on system energy efficiency were ignored.

Some studies explored several optimization objectives. Ren et al. [22] explored ways on how to minimize the cost rate of fuel and non-energy component, and investigated the operation optimization of three different CCHP systems. Fang [23] examined operation optimization of the CCHP system of the Central Hospital of Huangpu District, Shanghai to achieve energy efficiency and system economy. This study concluded that the load rate of units has a strong impact on energy efficiency, but heating cost played the most significant role on affecting profits. The operation objectives in Aaron Smith et al. [6] include primary energy consumption, operating costs, and carbon emissions of an office building in Atlanta. According to this study, changing the indexes of the internal part of the model will not significantly affect the operation strategy of the CCHP system, but external fuel prices are the decisive factor in choosing system operation strategy. Results from the group of objectives differed. Each objective has a different emphasis, thereby increasing the difficulty of choosing an operation strategy.

The studies mentioned selected a few factors only on energy efficiency or economic costs. Different objectives always led to different results [6, 22-23]. Feng [7] compared the most common evaluation criterion of CCHP systems and considered energy saving rate and economic efficiency as suitable criteria for evaluation. Yang et al. [8] achieved a similar conclusion. Some papers [9-10] chose a comprehensive index as optimization objective. Sun et al. [9] worked on a CCHP system of a hotel building in Tianjin and established separate multi-objectives function of annual costs, primary energy consumption, and carbon emission. They transformed multiple objectives into a comprehensive performance index by weighing coefficients and obtaining the best capacity of internal combustion engine and operation strategy from the various objective functions. Based on the analysis of optimization results, the comprehensive performance index was applied in the evaluation of CCHP systems. Wu [10] utilized the same method in examining an energy center in Shanghai and summarized the best distribution plan and operation strategy of CCHP system. Some comprehensive performance indexes [9-10] include total annual economic costs, but economic factor was added only as a weight coefficient; the limitation of using a single factor as optimization objective was not discarded to a certain extent in the analysis. The study examined fuel price and the level of import and export energy, selected exergetic cost as optimization objective, and studied the operation optimization of CCHP and water source heat pump compound systems.

The rest of this study is organized as follows. Exergetic cost and performance model of the compound system are discussed in Section 3. Section 4 introduces an operation optimization method for compound system and analyzes the applicability of the model and method through case study. Conclusions are summarized in Section 5.

3. Methodology

Two mainstream energy analysis methods can be used to examine CCHP systems. These methods are the analysis methods using the first and second laws of thermodynamics. The first law of thermodynamics analysis method is the fundamental rule of thermal efficiency. The effective utilization of energy-consuming devices and compound systems are analyzed and evaluated by heat balance theory.

This method reflects the conserved quantity of energy based on the main indexes, which consist of primary energy utilization rate, energy saving rate, and thermodynamic coefficient. The second law of thermodynamics analysis method involves analysis through exergy. This method combines the first and second laws of thermodynamics and comprehensively considers the quantity and quality of energy while analyzing exergy transfer, transition, utilization, and loss of the energy in the system or devices. Exergy efficiency is the major thermodynamic index. Exergy analysis can perform extensive investigations and more scientific and comprehensive than other methods because exergy is a theoretical scale of energy value evaluation. However, the overall thermodynamic process cannot be reflected through simple exergy analysis.

3.1 Exergetic Cost Model

Varied energy levels among different energy forms are considered in the exergetic cost model. Analyzing the exergy efficiency of system from economic aspect is conducive in the comparison of systems involving different energy forms. Exergetic cost is defined as the ratio of the cost of energy to export exergy:

$$C_{ep} = \frac{\sum Z}{\sum(W_s + E_h + E_c)} \tag{1}$$

where C_{ep} denotes exergetic cost in dollar/kWh; $\sum Z$ denotes total energy costs in dollar; W_s denotes the export power exergy of system in kWh; E_h denotes the export heat exergy of system in kWh; E_c is the export cold exergy of system in kWh.

As explained from refrigeration perspective, chilling capacity Q_c is conducted from the cold source of the system based on inverse Carnor circle. The external environment consumes considerable amount of work when chilling temperature T_c is lower than environment temperature T_o. Q_c and work are transferred into the environment. Cold exergy E_C is defined as the minimal work done by the external environment. The function is shown as:

$$E_C = Q_c \times (\frac{T_o}{T_c} - 1) \tag{2}$$

Heat exergy E_H means maximal work to the external environment that can be done through reverse thermodynamic engines when heat source temperature T_h is higher than environment temperature T_o. Heat Q_h is achieved from the source. This mathematical relationship is expressed as:

$$E_H = Q_h \times (1 - \frac{T_o}{T_h}) \tag{3}$$

The calculation of fuel exergy expression was given in Ghamarian and Cambel [24]:

$$E_x = e \cdot \beta \tag{4}$$

where E_x is fuel exergy in kWh; e is fuel energy in kWh; β, exergy coefficient which is defined as the ratio of energy source exergy value to energy value, which is a fixed value for a certain kind of energy source.

This study proposes exergetic cost as the optimization objective and analyzes the operation performance of CCHP and water source heat pump systems.

3.2 Hypothesis of the energy system model

Internal combustion engine coupling of lithium bromide absorption chiller is common in CCHP systems. This study discusses the operation optimization of CCHP of this type coupled with water source heat pumps.

Several studies explored the various working condition models of internal-combustion engines [25-28]. Based on the investigation results, the universal characteristic expressions below are summarized based on a large amount data:

$$\overline{T_{fg}} = T_{fg}/T_{fg,s} = 0.53 + 0.38\overline{N} + 0.09\overline{N}^2 \tag{5}$$

$$\overline{G_{fg}} = G_{fg}/G_{fg,s} = 0.968 + 0.029\overline{N} \tag{6}$$

where T_{fg} pertains to the exhaust gas temperature of internal combustion engine, °C; G_{fg} is the exhaust gas flow of the exhaust gas, Nm³/h; N is export power, kW; $\overline{N}$ is the load rate of units (superscript with a bar means the ratio of the actual working condition to the design, subscript with an s means the design working condition factor.)

The expression of COP (ξ) among the lithium bromide chiller with inlet water temperature of cooling water (T_{ci}) and exhaust gas temperature is obtained from existing studies [29-30]:

$$\xi = 1.0796 - 0.01789T_{ci} + 0.0009107T_{fg} \tag{7}$$

A mathematical model of water source heat pump was built on [31-33] and shown below.
Chilling mode:

$$\left. \begin{array}{l} EER = EER_b \cdot \phi_{c,t} \cdot \phi_{e,t} \\ EER_b = -18.369\varepsilon^4 + 54.827\varepsilon^3 - 59.895\varepsilon^2 + 28.542\varepsilon + 0.481 \\ \phi_{c,t} = 0.0004t_{c,i}^2 - 0.0448t_{c,i} + 1.8256 \\ \phi_{e,t} = -0.00011t_{e,o}^2 + 0.0356t_{e,o} + 0.7901 \end{array} \right\} \tag{8}$$

Heating mode:

$$\left. \begin{array}{l} COP = COP_b \cdot \phi_{c,t} \cdot \phi_{e,t} \\ EER_b = -23.548\varepsilon^4 + 62.369\varepsilon^3 - 57.732\varepsilon^2 + 22.481\varepsilon + 0.3423 \\ \phi_{c,t} = 0.00046t_{c,o}^2 - 0.06843t_{c,o} + 3.15548 \\ \phi_{e,t} = -0.0008t_{e,i}^2 + 0.0348t_{e,i} + 0.7538 \end{array} \right\} \tag{9}$$

where EER_b, COP_b is the basic performance coefficient. The characteristic expression of the units' COP changes with various load rates under different design working conditions; $\phi_{c,t}$ is the correction coefficient of condenser water temperature used to describe the units' EER and COP changes when the condenser water temperature is different from the working conditions; $\phi_{e,t}$ is the correction coefficient of the evaporator water temperature used to describe the units' EER and COP changes when the evaporator water temperature is different from the working condition; ε is the load rate of the units; $t_{c,i}$ is the inlet water temperature of condenser, °C; $t_{e,i}$ is the inlet water temperature of evaporator, °C; $t_{c,o}$ is the outlet water temperature of

condenser, °C; $t_{e,o}$ is the outlet water temperature of evaporator, °C.

A number of studies [34-36] verified parts of the models mentioned above; these studies argued that the high accuracy of the model can determine unit performance at specific load rate and the inlet and outlet temperatures of condenser and evaporator.

4 Result Analysis and Discussion

4.1 Analysis Implementation of Compound System Operation Performance

Compound systems must be established based on the optimization of system operation. CCHP and water source heat pump compound systems are aimed to suplly power, cool and heat for target districts. The import and export energy of sub-systems of CCHP system are different, as well as water heat pump system. The priority operating order of the units is a significant issue in their practical operation. The aim of this study is to determine priority operating order by comparing their exergetic cost during operation, and to determine the best operation strategy by considering economic combined with energy efficiency factors. The main optimization procedures based on exergetic cost are as follows.

(1) Calculate all kinds of energy sources inputs and outputs when system operates according to the external limitations, such as operation performance models of units, climate and weather, geologic and hydrologic characteristics, and energy requirement of the building.

(2) Analyze the exergetic cost of the operation of sub-systems in relation to economic factors, such as energy prices, and regulations in relevant laws and legislations.

(3) Determine the priority operating orders of the cooling/heating units based on exergetic cost to implement optimization.

Operation performance can be summarized according to the results.

4.2 Case Study
4.2.1 Project Introduction
Danzishi CBD Energy Station in Chongqing China is located at the confluence of Changjiang River and Jialingjiang River with the Nanshan Mountain on the background. The rest of the directions face the rivers. Chongqing Danzishi CBD Energy Station supplies energy to 15 buildings, including office buildings, hotel buildings, apartment buildings, conference center, commercials buildings, restaurants, and financial buildings. Specific indexes are shown in Tab. 1.

Table 1. Buildings areas

Total Area (m²)	Plot Ratio	Area Radios of Different Buildings								
		Office	Finance	Hotel	apartment	Conference	Commercials	Entertainment	Restaurant	Others
799, 900	4.71	43%	7%	8%	7%	5%	16%	7%	3%	4%

DeST energy consumption analysis software is used to conduct dynamic simulation calculation of annual cooling/heating load of buildings in Danzishi CBD. Comprehensive load considers the simultaneity usage coefficient. The coefficient of cooling load is 0.7 and heating load is 0.8. The annual hourly cooling and heating load is shown in Fig. 1.
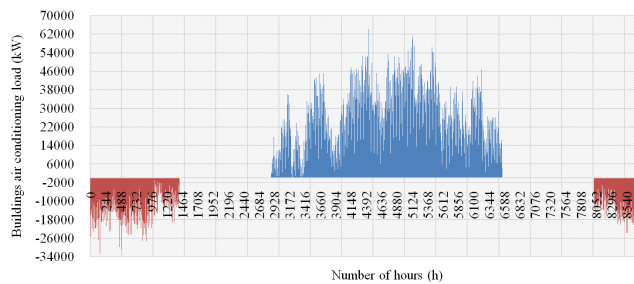

Fig. 1. Hourly cooling and heating load of buildings

The annual maximum cooling load of the buildings is 64264.12 kW; annual accumulative value is 71,479,700 kWh; maximum heating load is 33220.93 kW; and annual accumulative value is 22,265,900 kWh. CCHP and water heat pump compound systems supply energy to the project. Device plan is shown in Tab. 2.

Table 2. Compound system's cold and heat supply devices and capacities

Cold and heat supply devices	Index	Number	Design capacity of a unit (kW)
Internal combustion generation engine (JGS320)	Generation capacity	2	1063
Internal combustion generation engine (JGS616)	Generation capacity	2	2667
Gas-hot water absorption chiller 1 (BZHE100XD)	Waste heat recovery heating	2	1021
	Waste heat recovery heating		460
Gas-hot water absorption chiller 2 (BZHE200XD)	Waste heat recovery chilling	2	2088
	Waste heat recovery heating		1014
Water source chiller (LS10150)	Chilling capacity	3	10150
Water source heat pump 1 (RB5250)	Chilling capacity	2	5250
	Heating capacity		5800
Water source heat pump 2 (RB10050)	Chilling capacity	2	10050
	Heating capacity		10400

4.2.2 Analysis of Exergetic Cost
(1) Constrain Conditions

In this project, summer outdoor temperature is set to 36.3 °C; winter outside temperature is 3.5 °C; inlet/outlet water temperature of cold water is 13.5 °C/5.5 °C; supply/return temperature of hot water for air conditioning is 50 °C//42 °C; average cold water temperature is 9.5 °C; and average hot water temperature is 46 °C for exergetic cost calculation of system operation. The summer average temperature of Changjiang River is 24 °C and its winter average temperature is 13 °C based on hydrologic data. The sold price of natural gas for industrial, commercial, and group utilization in Chongqing is 0.320 dollar/m³; electric power is priced at 0.120 dollar/kWh for general industrial,

commercial and other usage in the range of 1 to 10 kV (based on local price information in September 1, 2016, and the Chinese RMB/US dollar exchange rate was 1:6.68).

(2) Comparison of Exergetic Cost

Based on the fundamentals of indexes above and exergetic cost model of the compound system, the exergetic cost of system operation can be calculated when each of the sub-systems supplies energy independently.

The exergetic cost curves of CCHP sub-system operation are shown in Figs. 2 and 3 when lithium bromide absorption chillers supply chilling or hot water using waste heat from generators.
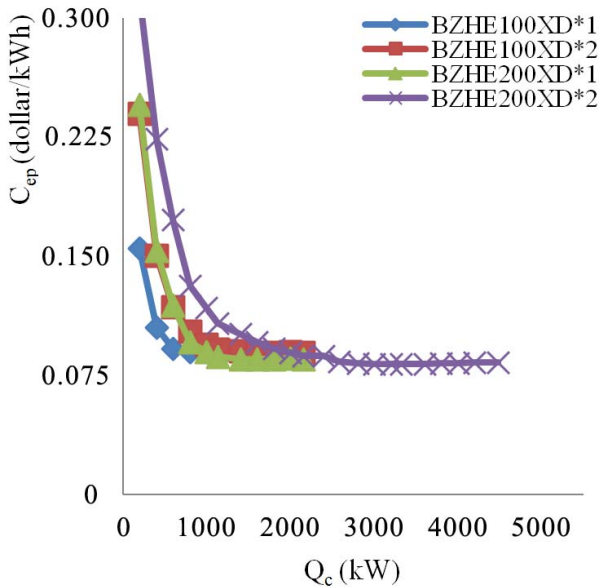

Fig. 2. Exergetic cost of CCHP sub-system when the absorption chiller supplies cold water
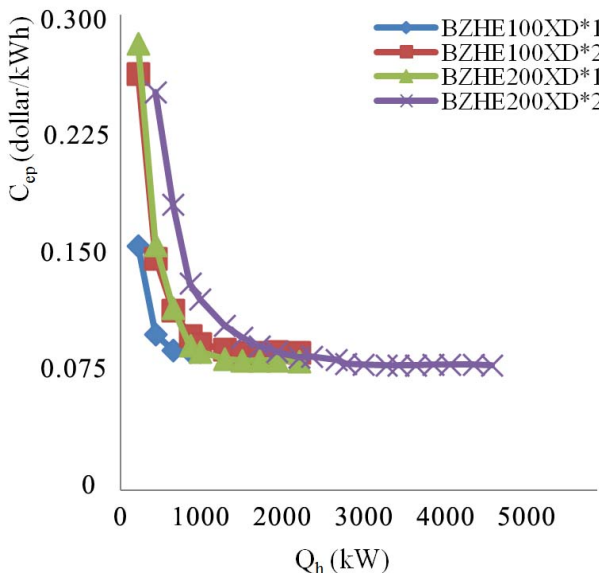

Fig. 3. Exergetic cost of CCHP sub-system when the absorption chiller supplies hot water

Figs. 4 and 5 show the exergetic cost curves of the water source heat pump sub-system, which consists of heat pumps and chillers, when supplying chilled or hot water.
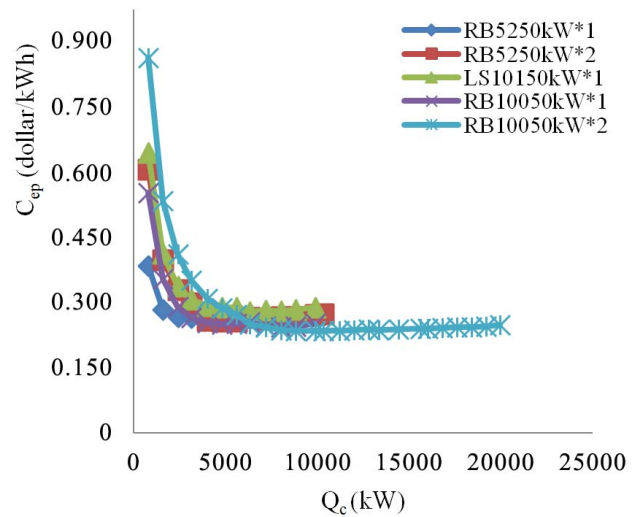

Fig. 4. Exergetic cost of water source heat pump sub-system when it supplies cold water
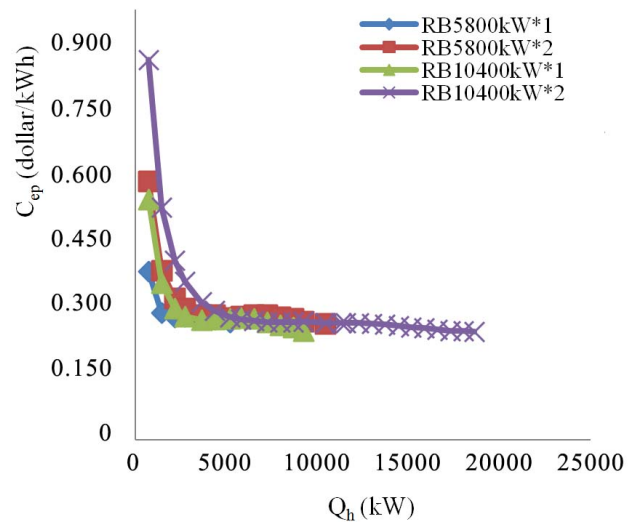

Fig.5. Exergetic cost of water source heat pump sub-system when it supplies hot water

Figs. 2 to 5 show that when the system supplies chilled water and the curves are stable (load rate is about 0.35), the exergetic cost of CCHP systems with different units range from 0.082 to 0.091 dollar/kWh; the exergetic cost of the water source heat pump systems range from 0.234 to 0.265 dollar/kWh. When hot water is supplied, the costs of CCHP system range from 0.079 to 0.087 dollar/kWh and the costs of water source heat pump system range from 0.244 to 0.281 dollar/kWh.

The curves of exergetic cost goes down sharply at first stage along with the increase of load rate of the units before stabilizing at a load rate of about 0.35 on both chilling and heating working conditions regardless of whether CCHP or water heat pump systems are involved. Thus, the units should not operate under the load rate of 0.35. The exergetic costs of absorption chillers or water source heat pumps with small capacity is comparatively lower than the larger ones when they can satisfy the same amounts of chilling loads. This finding is attributed to the fact that the units with small capacity works in higher load rate faced with the same requirements. Moreover, small units spend less exergetic cost at the same load rate, which fits with the basic rule of unit performance.

4.2.3 Determination of Operation Strategy

The operation strategy of the CCHP and water source heat pump compound system in summer and winter is determined based on the lowest exergetic cost of system operation as shown in Figs. 6 and 7.
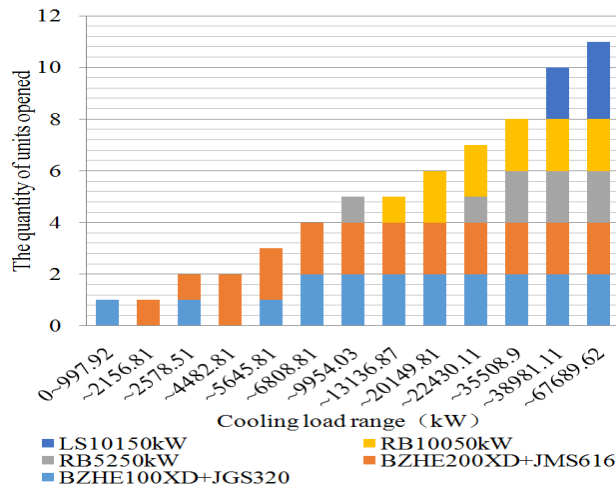

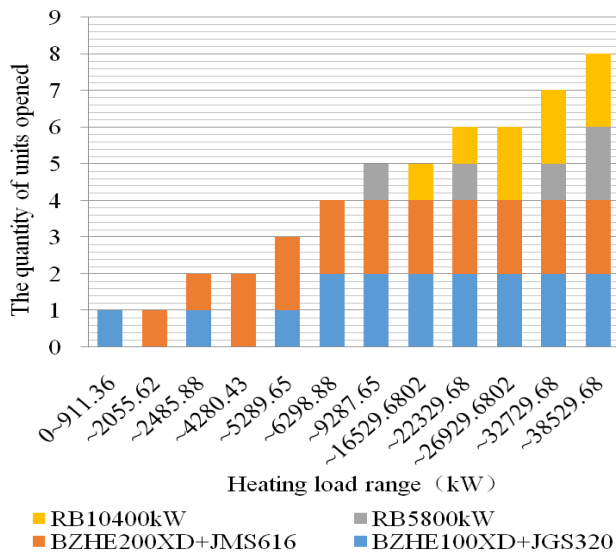**Fig. 6.** Compound system's operation strategy in summer

Fig. 7. Compound system's operation strategy in winter

The exergetic cost curves always have intersecting tendency during operation when the small and large units with the equal total capacity are separated in groups. For example, the curves of two BZHE100XD units in a group and two BZHE100XD units in another group show intersecting appearance when the former's load rate is 0.89. The exergetic costs of the system decreases as the load rate of the large units increases. However, the energy consumption of transmission system may go down and then go up along with the cooling/heating load increases in a certain range. For example, the frequency conversion of water intake pumps (1 stage), which have large power consumption, operate in fixed frequency when the quantity of intake water is small and in conversing frequency when the quantity of water intake is large. The energy consumptions of water pumps differ even when transmitting the same amounts of water. Thus, the basic rule of unit performance cannot be the sole basis for operation optimization, but the comparisons among the exergetic cost of kinds of the unit combination to achieve best results.

4.2.4 Results of Operation Optimization

Energy consumptions and energy yields of the compound system in summer and winter is shown in Tab. 3.

4.2.5 Analysis of Operation Performance

Based on the calculation results, the SEER of the compound system is 1.42 in summer and 0.93 in winter; the primary energy utilization rate is 1.40 in summer and 0.92 in winter; exergy efficiency is 0.35 in summer and 0.40 in winter; operation exergetic cost is 0.103 dollar/kWh in summer and 0.088 dollar/kWh in winter.

The chilling capacities of water source heat pump system takes 91% of the total compound system's chilling capacity and the percentage is 92% when it comes to heating capacity. The exergetic cost of operation of the compound system after optimization is much lower than the water source heat pump system when it operating alone, but close to the CCHP system, and with a high primary energy utilization rate. This finding shows that the optimization method with exergetic cost is applicable to CCHP and water source heat pump compound systems.

Table 3. Energy Import and Export of the System

Data	Water consumption(10⁴ m³)	Power consumption (10⁴ kWh)	Gas consumption (10⁴ Nm³)	Power generation (10⁴ kWh)	Power purchased (10⁴ kWh)	Power updated (10⁴ kWh)	Chilling/heating (10⁴ kWh)	Heat for domestic water (10⁴ kWh)
Summer	1368.54	1173.53	603.70	2359.53	50.27	1236.28	7147.97	29.30
Winter	510.63	410.61	365.87	1438.61	0.16	1028.16	2226.59	31.73

5. Conclusions

To optimize the operation of CCHP and water source heat pump compound system and avoid the differences of the results caused by different optimization objective, this study coupled energy price, quantity, and level with exergetic cost and applied it into the compound energy-supply system operation optimization of Chongqing Danzishi CBD Energy Station. The following conclusions were obtained:

(1) The mathematical models of exergetic cost, internal combustion engines, lithium bromide absorption chillers, and water source heat pumps can accurately reflect the operation performance of units. Performance indexes fit into the actual operation condition.

(2) Optimization of compound systems through minimal exergetic cost attains improved performance, especially in improving the SEER and primary energy utilization rate.

Overall, the optimization method can optimize the CCHP and water source heat pump compound system and achieve good results, which can be used as reference for compound system operation.

However, this study only takes the CCHP with internal combustion engine and lithium bromide chillers and water source heat pumps compound system as example to verify the models. The method can be used in other CCHP

compound system plans with different device arrangement and coupling forms by establishing the models of the relative units and sub-systems. However, accuracy might differ in other forms of compound system because of the presence of complex and varying devices and sub-systems. Thus, the relative models should be corrected according to operation data from actual projects to guarantee accuracy. This area may be explored in future studies.

References

1. Hu, W. B., Hua, B., Guo, H. Q., "Analysis of building combined cooling, heat and power system with cold storage". *Gas & Heat*, 24(12), 2004, pp.670-674.
2. Li, Y. H., Fu, L., "Optimized operation analysis of building combined cooling, heat and power system with energy storage". *HV&AC*, 38(Supplement), 2008, pp.87-91.
3. Liu, A. G., Zhang, S. J., Xiao, Y. H., "Optimized distribution of distributed combined heat and power system with energy storage device". *Thermal Power Generation*, 39(6), 2010, pp.14-20.
4. Qian, H., Yang, M., Chen, D., Cui, C. G., "Optimization strategies for the operation of CCHP system in distributed energy station". *Journal of Engineering for Thermal Energy & Power*, 31(6), 2016, pp.74-79.
5. Chang, Y. J., Wang, C. C., "Air side performance of brazed aluminum heat exchangers". *Journal of Enhanced Heat Transfer*, 3(1), 1996, pp.15-28.
6. Aaron, S., Rogelio, L., Pedro, J. M., "Analysis of a combined cooling, heating and power system model under different operating strategies with input and model data uncertainty". *Energy and Buildings*, 42(11), 2010, pp.2231-2240.
7. Feng, Z. B., Jin, H. G., "Evaluation criteria of combined cooling, heating and power system". *Journal of Engineering Thermophysics*, 26(5), 2005. pp. 725-728.
8. Yang, C., Yang, Z. L., Cai, R. X., "Efficiency indexes comparison of combined cooling, heating and power system based on overall working condition performance". *Proceedings of The Chinese Society for Electrical Engineering*, 28(2), 2008, pp.8-13.
9. Sun, P., You, S. J., Zhang, H., Li, X., "Study of the applications of the method for evaluating the comprehensive performance of a trigeneration system". *Journal of Engineering for Thermal Energy & Power*, 30(2), 2015, pp. 187-192.
10. Wu, L. H., Yang, H. H., Wu, Z. H., "Multi-objectives optimization analysis of CCHP system distribution and operation strategy". *Building Energy & Environment*, 31 (1), 2012, pp.16-18.
11. Aoki, H., Shinagawa, T., Suga, K., "An experimental study of the local heat transfer characteristics in automotive louvered fins". *Experimental Thermal and Fluid Science*, 2(3), 1989, pp.293-300.
12. Sahnoun, A., Webb, R. L., "Prediction of heat transfer and friction for the louver fin geometry". *Journal of Heat Transfer, Transactions ASME*, 114(4), 1992, pp.893-900.
13. Suga, K., Aoki, H., "Numerical study on heat transfer and pressure drop in multilouvered fins". *Journal of Enhanced Heat Transfer*, 2(3), 1995, pp.231-238.
14. Qiu, L., "PER of gas engine-driven heat pump systems at different combined supply energy modes". *HV&AC*, 36(6), 2006, pp.44-46.
15. Zhang, X. H., Chen, Z. S., "Energy consumption characteristics of combine cooling, heating and power system". *Proceedings of The Chinese Society for Electrical Engineering*, 27(5), 2007, pp.93-98.
16. He, B. B., Duan, L. Q., Yang, Y. P., "New evaluation criterion research on CCHP system". *Journal of Engineering for Thermal Energy and Power*, 24(5), 2009, pp.952-596.
17. Benonysson, A., "Operational optimization in a district heating system". Energy conversion and management, 36(5), 1995, pp.297-314.
18. Qin, Z. H., Liu, F. Q., Cao, J. C., "Thermo-economic analysis of a cooling, heating and power generation system for buildings". *Energy Research and Information*, 19(2), 2003, pp.117-122.
19. Kong, X. Q., Li, Y., Wang, R. Z., Huang, X. H., "Optimization and energy saving economic performance research of gas turbine CCHP system". *HV&AC*, 35(7), 2005, pp. 4-8.
20. Liu, X. D., "Operation optimization of CCHP System". *Heilongjiang Science and Technology Information*, (19), 2007, pp.68.
21. Hao, X. J., Wang, L., et al., "Optimization of BCHP system of a large scale public building in Beijing". *HV&AC*, 39(1), 2009, pp.33-36.
22. Ren, H. S., Optimal analysis of thermal economy of micro-gas turbine combined heating and power system". *University of Shanghai for Science and Technology*, 26(5), 2004, pp.443-446.
23. Fang, H., Cao, J. C., Liu, F. Q., "Investigation into optimal operation of BCHP systems in the air-conditioning season". *Gas turbine Technology*, 19(1), 2006. pp. 43-49.
24. Song, Z. P., Wang, J. X., "*The principle of energy conservation*". Beijing: Water Resources and Electric Power Press, 1985, pp.63-90.
25. Ajav, E. A., Bachchan, S., Bhattacharya, T. K., "Performance of a stationary diesel engine using vaporized ethanol as supplementary fuel". *Biomass and Bioenergy*, 15(6), 1998, pp.493-502.
26. He, X. H., Cai, R. X., "Typical off-design performance of internal combustion engine and its CHP system". *Journal of engineering thermophysics*, 29(2), 2008, pp.191-194.
27. Wang, X., Yang, Y. P., Song, Z. P., Xu, E. S., "Sensitivity and Changeable Working Conditions Characteristics of Internal Combustion Engine Combined Double-Sources and Power System". *Proceedings of the Chinese society for electrical engineering*, 30(20), 2010, pp.22-27.
28. Chuang, C. C., Sue, D. C., "Performance effects of combined cycle power plant with variable condensor pressure and loading". *Energy*, 2005, 30 (30), pp.1973-1801.
29. Zhang, Q., "*Study on Properties of the Composite System of CCHP and River Water Source Heat Pump*". Master thesis of Chongqing University, China, 2015, pp.47-51.
30. Shan, H. H., "*Characteristic Research and Optimum Operation of the Water Intake System of Absorption refrigerator Installation*". Master thesis of Chongqing University, China, 2015, pp.58-64.
31. Kavanaugh, S. P., Woodhouse, J. G., Carter, J. R., "Test results of water-to-air heat pumps with high cooling efficiency for ground-coupled applications". *ASHRAE Transactions*, 97, 1991, pp.895-901.
32. Snijders, A. L., "Aquifer Seasonal Cold Storage for Space Conditioning: Some Cost-effective Applications". *ASHRAE Transactions*, 98, 1992, pp.1015-1022.
33. Jarvis, P., Jefferson, B., Parsons, S. A., "Floc structural characteristics using conventional coagulation for a high doc, low alkalinity surface water source". *Water Research Abbreviated*, 40(14), 2006, pp. 2727–2737.
34. Fan, Y. Q., "*Performance Study and Software Development of Lake Water Source Heat Pump System*". Master thesis of Chongqing University, China, 2010, PP.58-66.
35. Wu, D., "*Model study of heat pump units*". Master thesis of Huazhong University of Science and Technology, China, 2012, pp.52-60.
36. Zhu, S. M., "Application of water heat pump in the hotel building central air conditioning system". *Refrigeration and air-conditioning*, 4(2), 2004, pp.42-44.