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Comparison of combined cooling, heating and power (CCHP) systems with different cooling modes based on energetic, environmental and economic criteria

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ABSTRACT

Combined cooling, heating and power (CCHP) system is drawing great attention due to its energy-saving, environmentally friendly and cost-saving characteristics. Conventionally, CCHP system uses the water–LiBr absorption chiller to meet the cooling demand. In this paper, comparison of exhaust-gas-and-hot-water-driven absorption chiller (AC) and another three cooling modes, including AC combined with electric chiller (EC), AC combined with gas-fired absorption chiller (GFC), and AC combined with ground source heat pump (GSHP), is made. Optimization models for the four CCHP systems following the electric load (FEL) and following the thermal load (FTL) are proposed. The evaluation criteria include primary fossil energy saving rate (PFESR), carbon dioxide emission reduction rate (CDERR) and annual total cost saving rate (ATCSR) compared with the separation production (SP) system. Genetic algorithm (GA) is used to achieve the optimal solutions. A case analysis of a hypothetical commercial building in Shanghai is performed. Results show that the CCHP system with GSHP under FEL strategy has the best comprehensive performance, with PFESR of 0.2990, CDERR of 0.5278 and ATCSR of 0.1582. Finally, sensitivity analysis of climate, natural gas price and pool purchase price are performed.

1. Introduction

Combined cooling, heating and power (CCHP) is drawing great attention due to its energy-saving, environmentally friendly and cost-saving characteristics. CCHP system generates power and heat simultaneously in a single process. A typical CCHP system consists of a power generation unit (PGU), a waste heat recovery system, an auxiliary gas boiler, an absorption chiller and a heat exchanger. The waste heat from the electricity generation is provided for the absorption chiller and the heat exchanger to satisfy the cooling and heating demand of the users. Compared with the conventional separation production (SP) system where power demand is met by electricity purchased from the grid and thermal demand is met by fuel burning, CCHP system has higher energy efficiency and lower pollutant emission. Besides, CCHP system is often located close to the end users, which reduces the electricity and heat transmission losses and further improves the system energy efficiency. Its overall energy efficiency can be 70–90% [1]. CCHP system can be used as a small-medium scale energy supply system for various kinds of users, including industrial parks, campuses, commercial buildings, hospitals, hotels, etc. The high efficiency, the low contamination and the flexibility make CCHP system a promising way to deal with building energy related issues.

The equipment capacity and the operation strategy have great influence on the performance of CCHP system [2]. In order to meet the power and heat demand of the users, and to make CCHP system energy-saving, environmentally friendly and cost-saving, the capacities of the equipment should be determined appropriately. According to Ref. [2], the capacity of PGU is a key variable to determine the capacities of other facilities including the waste heat recovery system and the auxiliary gas boiler. However, the capacity of PGU depends on the system operation strategy. There are two basic operation strategies for CCHP system: following the electric load (FEL) and following the thermal load (FTL) [3]. Under FEL strategy, the system meets the power demand first, and uses the by-product heat to meet the heat demand. If the by-product heat is insufficient, an auxiliary boiler will be implemented. While under FTL strategy, the system meets the heat demand first. If the by-product electricity cannot satisfy the power demand, additional electricity will be purchased from the grid. Mago et al. [4,5] optimized and analyzed the performances of CCHP and combined heat and power (CHP) systems under FEL and FTL strategies. Wang et al. [6] compared

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Nomenclature

Abbreviations

AC	exhaust-gas-and-hot-water-driven absorption chiller
AS	annual saving
ATCSR	annual total cost saving rate
CCHP	combined cooling, heating and power
CDE	carbon dioxide emission
CDERR	carbon dioxide emission reduction rate
CHP	combined heat and power
CO	comprehensive objective
COP	coefficient of performance
DPP	discounted payback period
EC	electric chiller
FEL	following the electric load
FHL	following the hybrid electric-thermal load
FTL	following the thermal load
GA	genetic algorithm
GFC	gas-fired absorption chiller
GSHP	ground source heat pump
ICE	internal combustion engine
IRR	internal rate of return
NPV	net present value
PFESR	primary fossil energy saving rate
PGU	power generation unit
SP	separation production

Symbols

C	cost
E	electricity
F	fuel consumption
f	load rate
I	interest rate
L	service lifetime
N	nominal capacity
P	operating power
Q	thermal energy
R	revenue
x	cooling or heating ratio
η	efficiency
λ	on-off coefficient
μ	carbon dioxide emission factor
ω	weight coefficient

Subscripts

ac	absorption chiller
C	carbon emission trading
c	cooling mode
CCHP	combined cooling, heating and power system
cd	cooling demand
E, e	energy, electricity
ec	electric chiller
ed	electricity demand
ex	excess electricity or thermal energy
gas	natural gas
gb	gas boiler
gfc	gas-fire absorption chiller
grid	grid, coal
gshp	ground source heat pump
h	heating mode
hd	heating demand
he	heat exchanger
I, i	annual investment
ice	internal combustion engine
II	initial investment
M, m	maintenance
nom	nominal capacity
SP	separation production system
t	power grid transmission

CCHP systems under FEL and FTL strategies in five different climate zones. However, the two basic strategies both lead to energy waste [7]. To avoid the excess power or heat, there have been some improved operation strategies. Mago et al. [8] proposed a following the hybrid electric-thermal load (FHL) strategy, which will switch between FEL and FTL strategies, for a micro-CCHP system. Han et al. [9] proposed compromised electric-thermal strategies based on FHL strategy. Zheng et al. [10] proposed a novel operation strategy based on minimum distance and compared it with FEL, FTL and FHL strategies.

To determine the equipment capacities and the operation strategy for CCHP system, an optimization model is needed [2]. Since the goals of implementing CCHP system are to achieve low energy consumption, low contamination and low cost, the evaluation criteria for CCHP system can be energy consumption, pollutant emission, cost, or a combination of them. Refs. [4,5,11,12] are all evaluated based on primary energy consumption, carbon dioxide emission (CDE) and operation cost. Ren and Gao [13] considered two operating modes including minimum-cost and minimum-emission operation for two residential micro-CHP systems. Wang et al. [14] compared the CCHP systems for four building categories in five climate zones in China based on energy, economy and environment criteria. With the objectives of minimizing energy consumption, contamination and cost, optimization models for CCHP systems are proposed. Li et al. [15] presented a two-stage optimal planning and design method for CCHP to minimize the total net present cost and CDE in life circle. To optimally design and operate small-size CHP plants connected by a heat distribution network, Bracco et al. [16] developed a mixed-integer linear programming model where a multi-objective function considering capital and operating costs, as well as CO_2 emissions was optimized. To determine the optimal size and operation strategy of the PGU for a residential micro-CCHP system, Ebrahimi and Keshavarz [17] proposed a multi-criteria sizing function that integrated fuel energy saving rate and exergy efficiency as the thermodynamic parameters, net present value (NPV), internal rate of return (IRR) and payback period for the economic criteria, and CO_2, CO and NO_x reduction for the environmental evaluations.

In addition to the research of PGUs and operation strategies of CCHP system, there are also some studies on the cooling modes. Conventionally, CCHP system uses the water–LiBr absorption chiller to satisfy all the cooling demand. However, a combination of the absorption chiller and the electric chiller (EC) can be an alternative way to meet the cooling demand, which can help match the ratio of the power and heat generated by PGU with the user demand better [7]. Wang et al. [18] set the ratio of electric cooling to total cooling load to be fixed, and optimized the capacity of PGU, the ratio of electric cooling to total cooling load, as well as other variables, to maximize the energy, economy and environment benefits achieved by CCHP system. Liu et al. [3] proposed a structural configuration of the CCHP system with combined electric and absorption chillers. The ratio of electric cooling to total cooling load varied with the electric and thermal loads every hour. Hajabdollahi et al. [19] compared the variable electric cooling ratio strategy with the constant electric cooling ratio strategy for different climates. Li and Hu [20] compared absorption chiller and EC in terms of exergy efficiency of cooling system in CCHP and energy efficiency of CCHP system. Jiang et al. [21] proposed a novel scheme of