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Optimization of capacity and operation for CCHP system by genetic algorithm

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ABSTRACT

The technical, economical and environmental performances of combined cooling, heating and power (CCHP) system are closely dependent on its design and operation strategy. This paper analyzes the energy flow of CCHP system and deduces the primary energy consumption following the thermal demand of building. Three criteria, primary energy saving (PES), annual total cost saving (ATCS), and carbon dioxide emission reduction (CDER) are selected to evaluate the performance of CCHP system. Based on the energy flow of CCHP system, the capacity and operation of CCHP system are optimized by genetic algorithm (GA) so as to maximize the technical, economical and environmental benefits achieved by CCHP system in comparison to separation production system. A numerical example of gas CCHP system for a hotel building in Beijing is given to ascertain the effectiveness of the optimal method. Furthermore, a sensitivity analysis is presented in order to show how the optimal operation strategy would vary due to the changes of electricity price and gas price.

1. Introduction

Combined cooling, heating and power (CCHP) system is broadly identified as an alternative for the world to meet and solve energy-related problems, such as increasing energy demands, increasing energy cost, energy supply security, and environmental concerns [1–6]. A good CCHP system must yield economical savings, but more importantly must yield real energy savings as well as reducing the emission of pollutants. The performance of CCHP system is closely dependent on its design and operation. Aiming to maximize the benefits from CCHP system in comparison to traditional separation production (SP), it is necessary to optimize the design and operation strategy.

Many studies have been reported on this topic. Better performances (e.g. operations cost, carbon dioxide emission reduction (CDER), and primary energy consumption (PEC)) can be obtained when the optimization was applied to design and/or operate CCHP systems. The optimized CCHP systems have different components. For example, the prime mover includes gas turbine [7–9], steam turbine [10,11], gas engine [12,13], a steam Rankine process using biomass fuels [14], and the cooling system adopts compression [15], absorption [7,15], and ejector refrigeration cycle [11], etc.

The typical optimization algorithms used in CCHP systems are usually divided to linear programming and non-linear programming. The linear algorithm is easily applied to CCHP system optimization [16–19]. The mixed integer non-linear programming model is another common optimization method [9,10,14,15,20,21], which considers the non-linear characteristic and solves the non-linear problems. There are other optimization methods such as sequential quadratic programming [8], tri-commodity simplex algorithm [17], extended power simplex algorithm [18], Lagrangian relaxation [22] and genetic algorithm (GA) [23,24]. More importantly, the objective function in optimization process guides and determines the optimal result in some extent. Usually, the objective function is expressed in different terms of net cash flow, primary energy saving [25], total cost rate [8], annual total cost [9], energy cost [7,26], exergetic efficiency and gross benefit [27], as well as carbon dioxide emissions costs [17]. Generally, the benefits achieved by CCHP system are maximized from economy, energy consumption and environment.

This paper presents the general energy flow model of CCHP system and the evaluation criteria including technology, economy and environment. Then the objective function of the integrated performance of CCHP is constructed and GA is employed to optimize its design capacity and operation. This paper is organized as follows. Section 2 presents the mathematical analysis of the CCHP system and the evaluation criteria of CCHP systems in comparison to SP. Section 3 proposes the optimization problems and constructs the GA optimization method. Section 4 applies GA to optimize the CCHP system providing three products to a commercial building in Beijing, China. Some comments are concluded in the last section.

2. CCHP system

2.1. Energy flow of CCHP system

The CCHP system consists of a power generation unit (PGU), a waste recovery system, a back-up boiler, cooling system and

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Nomenclature

ATCS	annual total cost saving
CCHP	combined cooling heat and power
CDE	carbon dioxide emission
CDER	carbon dioxide emission reduction
COP	coefficient of performance
GA	genetic algorithm
PGU	power generation unit
PES	primary energy saving
SP	separation production

Symbols

C	cost
E	electricity
F	fuel
N	installation capacity
Q	heat
R	capital recovery factor
η	efficiency
μ	CO_2 emission conversion factor

Subscripts

ac	absorption chiller
b	boiler
c	cool
e	electricity
ec	electric chiller
f	fuel
grid	electricity grid
h	heat
p	pump
pgu	power generation unit
r	recovery heat
rc	the part of recovery heat for cooling
rec	waste heat recovery system
rh	the part of recovery heat for heating
x	ratio of electric cooling to cool load

Superscript

SP	separation production

heating system, which is shown in Fig. 1. Here the cooling system adopts the combination of electric chiller and absorption chiller because the excess electricity may be usually produced by CCHP system following thermal demand and the excess electricity is not allowed to be sold back to grid in China. The CCHP system operates following thermal demand, which is a common and simple operation strategy [28]. The PGU is driven by natural gas and produces the electricity to building. The high-temperature exhaust gas of PGU is recovered to accommodate the thermal load for cooling in summer and heating in winter. If the heating does not completely satisfy the application needs, a supplementary boiler can be used. Similarly, when the amount of generated electricity by PGU is not enough, the additional electricity comes from the local grid. On the contrary, when there are excess heat or electricity produced by CCHP system, the excess energy products are dissipated from CCHP system. Consequently, the operation of PGU must reduce the excess products when it satisfy one energy demand of building.

The balance of the electric energy in CCHP system is expressed as

$$E_{grid} + E_{pgu} = E + E_p + E_{ec} \tag{1}$$

where E_{grid} is the electricity from grid in CCHP system (when PGU generates the excess electricity, E_{grid} is negative and its value is equal to the excess electricity. The treatment of the excess electricity is explained in the last assumptions of Section 2.1), E_{pgu} is the generated electricity by PGU, E is the electric energy use (lights and equipments) of building, E_p is the parasitic electric energy consumption of CCHP system, and E_{ec} is the electric energy consumption for electric chiller providing cool to building.

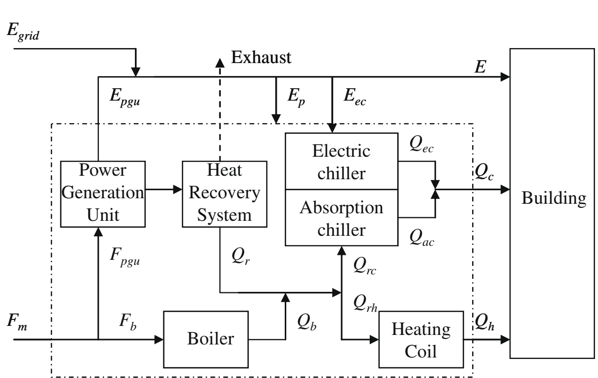

Fig. 1. Energy flow diagram of CCHP system.

The electricity used by electric chiller is calculated as

$$E_{ec} = \frac{Q_{ec}}{COP_e} \tag{2}$$

where Q_{ec} is the cooling produced by the electric chiller, and COP_e is the electric chiller's coefficient of performance (COP).

The PGU fuel energy consumption, F_{pgu}, can be estimated as

$$F_{pgu} = \frac{E_{pgu}}{\eta_e} \tag{3}$$

where η_e is the PGU generation efficiency.

The recovered waste heat from the prime mover, Q_r, can be calculated as

$$Q_r = F_{pgu}\eta_{rec}(1 - \eta_e) \tag{4}$$

where η_{rec} is the heat recovery system efficiency.

The heat supplied to the cooling system and heating coil is

$$Q_r + Q_b = Q_{rc} + Q_{rh} \tag{5}$$

where Q_b is the supplementary heat from the boiler, Q_{rc} and Q_{rh} are the heat supplied to absorption chiller and heating coil, respectively.

The heat required by the absorption chiller and heating coil to handle a part of cooling load and all heating load are estimated respectively as

$$Q_{rc} = \frac{Q_{ac}}{COP_{ac}} \tag{6}$$

and

$$Q_{rh} = \frac{Q_h}{\eta_h} \tag{7}$$

where COP_{ac} is the absorption chiller's COP, Q_{ac} is the cool produced by absorption chiller, Q_h is heat demand for space heating and domestic hot water, and η_h is the efficiency of heating coil (here to simplify the calculation, it is assumed that the transmission efficiency of domestic hot water is equal to η_h).