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Analysis of combined cooling, heating, and power systems under a compromised electric–thermal load strategy

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ABSTRACT

Following the electric load (FE) and following the thermal load (FT) strategies both have advantages and disadvantages for combined cooling, heating and power (CCHP) systems. In this paper, the performance of different strategies is evaluated under operation cost (OC), carbon dioxide emission (CDE) and exergy efficiency (EE). Analysis of different loads in one hour is conducted under the assumption that the additional electricity is not allowed to be sold back to the grid. The results show that FE produces less OC, less CDE, and FT produces higher EE when the electric load is larger. However, FE produces less OC, less CDE and higher EE when the thermal load is larger. Based on a hybrid electric–thermal load (HET) strategy, compromised electric–thermal (CET) strategies are innovatively proposed using the efficacy coefficient method. Additional, the CCHP system of a hotel in Tianjin is analyzed for all of the strategies. The results for an entire year indicate the first CET strategy is the optimal one when dealing with OC, CDE and EE. And the second CET is the optimal one when dealing with OC and EE. Moreover, the laws are strictly correct for different buildings in qualitative terms.

1. Introduction

Based on the graded use of energy, a combined cooling, heating and power system (CCHP system is also called tri-generation system) can supply electricity and recover waste heat for space heating, cooling, and domestic hot water. The main difference between CCHP systems and conventional methods of electricity generation is the utilization of the waste heat rejected from the prime mover to satisfy the thermal demand of a facility [1]. The employment of clean gaseous fuel results in a lower discharge of exhaust gas, which is of great significance to the environment. Considering CCHP systems with natural gas as an example [2], the consumption of electricity and natural gas in one year can be adjusted to ease the peak-electricity demand. In addition, the difference in energy consumption in the winter and summer seasons is reasonably balanced.

Thus far, many researchers have investigated different aspects of CCHP systems using mathematical models [3–5], optimization of operation strategies [6–9], analysis of different systems [10–13] and evaluation criteria [14–16] to take full advantage of such systems. To obtain better economic, thermodynamic, environmental and social benefits, all of the aspects above must be considered together in the employment and analysis of CCHP systems.

A CCHP system is mostly composed of dynamic (prime mover), supplementary, heating and cooling systems. In addition to the configuration, operation strategies play an important role in the design of equipment and operational benefits. The most distinctive operation strategies are the following [17,18]:

(1) Following the electric load (FE): the electricity generated by the prime mover is equal to the electric load at any moment. There is no need to purchase electricity from the electric grid if the electricity generated is enough. And, if the recovered waste heat is not enough to handle the thermal load, additional heat must be provided by the supplementary system. Otherwise, the prime mover can meet both the electric and thermal load independently.
(2) Following the thermal load (FT): the recovered waste heat from the prime mover is equal to the thermal load at any moment. There is no need to run the supplementary system if the recovered heat is enough. And, if the electricity generated by the prime mover is not enough to meet the electric load, additional electricity must be purchased from the grid. Otherwise,

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Nomenclature

CCHP	combined cooling, heating and power
FE	following the electric load
FT	following the thermal load
HET	hybrid electric–thermal load
CET	compromised electric–thermal load
COP	coefficient of performance

Symbols

OC	operation cost (¥)
CDE	carbon dioxide emission (kg)
EX	exergy
EE	exergy efficiency
ECF	electric conversion factor (kg-CO_2/kW h)
FCF	fuel conversion factor (kg-CO_2/kW h)
LHV	lower heating value (MJ/m^3)
P	Price (¥/kW h or ¥/m^3)
F	fuel (kW h)
E	Electricity (kW h)
Q	heat (kW h)
T	temperature (T)
V	volume (m^3)
η	efficiency
φ	compromised degree to the electric load
ρ	compromised degree to the thermal load

Subscripts

pgu	power generation unit
grid	electricity grid
tran	grid transmission efficiency
req	required
e	electricity
g	gas
o	the environment
h	heat
c	cool
rec	recovery system
f	fuel
r	recovered waste heat
b	supplementary boiler

the prime mover can meet both the electric and thermal load independently.

(3) Hybrid electric–thermal load (HET): this is a hybrid strategy of FE and FT. The CCHP system operates under FE when the thermal load is comparatively larger than the electric load, and under FT when the electric load is larger. The excess need for electricity or heat can be met by the grid or the supplementary system. The main feature of the HET strategy is lowered waste of electricity and heat, which helps to enhance the overall energy efficiency.

From the previous studies, some conclusions have been gotten about the operation strategies. When the electric load is comparatively larger, much heat from the prime mover is wasted under FE and buying electricity from the grid is necessary under FT. When the thermal load is larger, the supplementary system has to run under FE and much electricity generated may get no benefit under FT. These all lower the energy efficiency and are inevitable. HET is a hybrid strategy and also has the problems. So this paper mainly analyzes the benefits of different operation strategies and puts forward a novel operation strategy to adjust the problems.

The criteria for analyzing the performance of different operation strategies in this paper are operation cost (OC), carbon dioxide emission (CDE) and exergy efficiency (EE). The analysis is performed under two load conditions: one is that the electric load is larger, and the other is that the thermal load is larger. And a compromised electric–thermal load strategy (CET) is proposed with optimization using the efficacy coefficient method. Based on the loads of a hotel in Tianjin, China, the laws of OC, CDE, and EE are determined and discussed.

2. Mathematical model

The model is built based on the CCHP system of a hotel in Tianjin, China, to calculate the consumption of electricity and natural gas under various loads.

2.1. CCHP system

The CCHP system employed by the hotel is shown in Fig. 1. From this figure, it can be observed that natural gas is supplied to the power generation unit (PGU-internal combustion engine generator) to produce the electricity needed for the building (lights, equipment, etc.). The waste heat in the jacket and exhaust gas is recovered in the heat recovery system and used to produce cooling by a Li–Br absorption chiller or heating by the heating coil to meet the thermal demands. A supplementary boiler is used to replenish heat if the recovered heat is not sufficient.

To analyze the performance of PGU alone in this paper, the cooling and heating loads are converted to thermal loads by COP_c and η_h. Thus, the thermal load is located at the entrance of the heat transmission system rather than the building load as:

$$Q_{req} = \frac{Q_{c.req}}{COP_c} + \frac{Q_{h.req}}{\eta_h} \tag{1}$$

where COP_c refers to the refrigerating coefficient of performance of the absorption chiller, η_h is the efficiency of the heating coil, $Q_{c.req}$ and $Q_{h.req}$ are the cooling and heating load of the building per hour, and Q_{req} is the thermal load at the entrance of the heat transmission system.

Based on the principle of electricity generation [19], the relation between electricity generated by PGU and waste heat recovered is:

$$\frac{E_{pgu}}{Q_r} = \frac{\eta_{pgu}}{\left(1 - \eta_{pgu}\right) \times \eta_{rec}} \tag{2}$$

where η_{pgu} is the generating efficiency, η_{rec} is the efficiency of the heat recovery system, E_{pgu} is the electricity generated by PGU, and Q_r is the recovered waste heat.

$m = \eta_{pgu}/((1 - \eta_{pgu}) \times \eta_{rec})$ is set as the performance parameter of the PGU. It is used to distinguish whether the electric load or the thermal load is larger (and this contains almost all of the conditions of the building loads).

The evaluation is performed on the basis of one-hour loads, so that all of the symbols except efficiencies refer to the corresponding sum over one hour. To analyze the performance of the different strategies, some assumptions are made as below:

(1) all of the equipment can be operated from 0% to 100% continuously. And their capacities are chosen to be greater than the building loads;
(2) the efficiencies of the equipment are constant values;
(3) the CCHP system is 100% reliable;
(4) the extra electricity generated is assumed to not be sold back to the grid because the relevant policies and prices in China are not clear.