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Analysis of tri-generation system in combined cooling and heating mode

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ABSTRACT

Tri-generation system is efficient in supplying thermal energy and electricity. But it is very difficult to satisfy multiple load demands simultaneously in real applications. Therefore, the benefit of tri-generation system is not so easy to realize. If the electric load is separated from the thermal load, difficulty of control would be avoided. In this work, combined cooling and heating (CCH) mode of tri-generation system is proposed. The generated electricity is only used to power the HVAC device, which converts all the electricity into thermal energy. Namely, there is only thermal output in this kind of mode. As for the rest electric load of user, it can be ensured by the public grid. Considering 20% of total energy consumption and 50% of building energy consumption may come from the HVAC system in developed countries. The CCH mode of tri-generation system would be potential in energy saving. The influences of system capacity, HVAC performance, public grid efficiency, and energy prices on system performances are analyzed. Results show that the CCH mode of tri-generation system can be much better than an independent HVAC system. For a system with generator capacity over 100 kW, the payback period could be less than 4 years.

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1. Introduction

Tri-generation system, which is also named as combined cooling, heating and power (CCHP) system, is a kind of important distributed energy resource system [1,2]. The thermal and electric output of tri-generation system usually interact with each other which results in difficulty in satisfying thermal and electric load demand simultaneously [3]. Although many design, control and operation optimization methods are proposed [4–7], they are usually too complex to realize. As complex operation strategy may make the system unstable, the quality and security of electricity would be hard to ensure. Actually, in a developed country, 20% of total energy consumption and 50% of building energy consumption come from the HVAC system [8]. So, there would still be a huge energy saving potential if tri-generation systems work only for air conditioning. If tri-generation systems work only for the air conditioning, not only the burden of public grid can be relaxed, but also the control problem of tri-generation system can be simplified. It is named as combined cooling and heating (CCH) mode in this work. As we know, combined heating and power mode (CHP) and combined cooling, heating and power mode (CCHP) are two kinds of general working modes of tri-generation system [9,10]. But seldom researches directly relate to CCH mode of tri-generation system.

CCH mode of tri-generation system is similar to a gas engine heat pump system in function. Both of them are based on combusting fuels directly. Gas engine heat pumps have already been proposed and studied by some researchers [11–14]. Lazzarin et al. [15] studied a typical gas engine heat pump system, in which the compressor is powered by the internal combustion engine (ICE) directly for air conditioning. They concluded that there is a strong energy saving. Sanaye et al. [16] analyzed the economic performance of a gas engine heat pump system in various climate regions. Brenn et al. [17] compared natural gas driven heat pumps and electricity driven heat pumps for heating purpose without considering waste heat recovery and refrigeration. But there are huge differences between CCH mode of tri-generation system and gas engine heat pump in structure and operation. For gas engine heat pump system, a compressor is powered by the shaft power of gas engine. For CCH mode of tri-generation system, the shaft power of gas engine is used to drive a generator to generate electricity, and then the electricity is used to power any HVAC devices. Besides, the waste heat of gas engine is also recovered. So, the CCH mode of tri-generation system would be more efficient and more compatible with the existing HVAC system.

In this work, the CCH mode of tri-generation system is analyzed. The waste heat of the ICE is recovered for house heating or powering a single-effect absorption chiller (SAC). And the

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Nomenclature

B	annual benefit (RMB/year)
C	annual cost (RMB/year)
CCHP	combined cooling, heating, and power
CCH	combined cooling and heating
CDE	carbon dioxide emission
CHP	combined heating and power
COP	coefficient of performance
CRR	carbon dioxide reduction ratio
CSR	cost saving ratio
ESR	primary energy saving ratio
F	carbon dioxide emission factor (g/(kW h))
f	polynomial fitting function
HE	heat exchanger
HVAC	heating, ventilation and air-conditioning
I	investment (RMB)
ICE	internal combustion engine
N	payback period (year)
NG	natural gas
P	electric power (kW)
PLR	part load ratio
Q	thermal power (kW)
Pr	price of energy (kW/(kW h))
R	interest rate
SAC	single effect absorption chiller
t	operation time

Subscripts

grid	public grid
ref	reference system
fuel	fuel consumption of ICE
el	electricity
rec	recovery efficiency
r	cooling mode
h	heating mode
waste	waste heat
output	energy output
i, j	index numbers

Greek symbols

η	efficiency
ξ	energy price ratio

generated electricity is only used to power the HVAC device. Namely, the tri-generation system is only used to satisfy the demand of the air conditioning load. In order to evaluate this mode, the independent HVAC system is chosen as the reference system. Firstly, system principle and structure are introduced. Secondly, the methodologies are described. Thirdly, the investigation results are detailed discussed. At last, some main conclusions are summarized.

2. System descriptions

The schematic diagram of CCH mode of tri-generation system is shown in Fig. 1(a). The studied tri-generation system mainly consists of ICE (including generator unit), HVAC device, heat exchanger (HE) and SAC. Fuel is fed into ICE. The shaft work output of ICE powers the generator to generate electricity. The entire electric output is used to power the HVAC device. In heating mode, the heating output comes from the HVAC device and HE. In cooling mode, the cooling output comes from the HVAC device and SAC. Waste heat of jacket water and exhaust gas is recovered for house heating in winter or for powering the SAC in summer. Considering that the

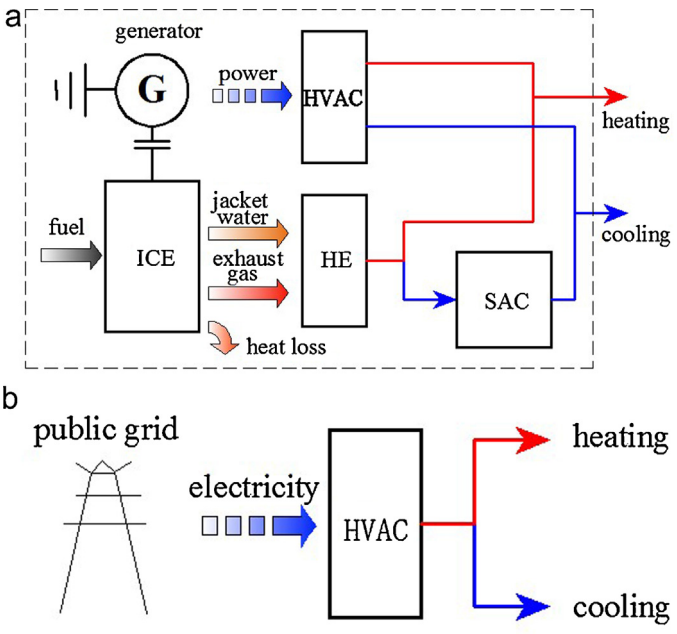

Fig. 1. Schematic diagrams of CCH mode of tri-generation system, and independent HVAC system.
(a) CCH mode of tri-generation system
(b) Independent HVAC system

jacket water temperature is lower than 95 °C, and the exhaust gas temperature can be over 500 °C, they can be recovered by HE in a cascade way [9,10]. The recovered hot water can reach 95 °C, which is high enough to efficiently power a SAC [18].

In order to analyze the performance and feasibility of CCH mode of tri-generation system, the independent HVAC system is used as the reference system. Fig. 1(b) shows the diagram of the independent HVAC system. The heating or cooling loads are all satisfied by the HVAC system, and the HVAC system is powered by the electricity from the public grid.

3. Methodologies

3.1. Evaluation criteria

Primary energy saving ratio (ESR) is a criterion evaluating system energy saving performance [19]. Cost saving ratio (CSR) is a criterion evaluating the economical performance in operation [20]. Carbon dioxide reduction ratio (CRR) is a criterion evaluating the environmental performance [20]. In order to evaluate the feasibility of this CCH mode of tri-generation system, these three commonly used criteria, as well as the payback period are used in the analyses.

The fuel consumption of tri-generation system comes from the ICE. The fuel consumption of ICE depends on the electric output and electric efficiency. So, the fuel consumption is:

$$Q_{\mathrm{ICE,fuel}} = \frac{P_{\mathrm{ICE,el}}}{\eta_{\mathrm{ICE,el}}} \tag{1}$$

In heating mode, the energy output of tri-generation system is:

$$Q_h = \eta_{\mathrm{rec}} \times Q_{\mathrm{waste}} + P_{\mathrm{ICE,el}} \times \mathrm{COP}_{\mathrm{HVAC}} \tag{2}$$

In cooling mode, the energy output of tri-generation system is:

$$Q_r = \mathrm{COP}_{\mathrm{SAC}} \times \eta_{\mathrm{rec}} \times Q_{\mathrm{waste}} + P_{\mathrm{ICE,el}} \times \mathrm{COP}_{\mathrm{HVAC}} \tag{3}$$

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