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Thermodynamic boundaries of energy saving in conventional CCHP (Combined Cooling, Heating and Power) systems

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ABSTRACT

In this research, an improved calculational method of ESR (energy saving rate) considering energy adjustments caused by climate effects is presented based on international standards or regulations regarding energy management. The indicator of "general heat-to-electricity ratio" (R) is proposed to illustrate the energy configurations of CCHP (Combined Cooling, Heating and Power) systems and their potential users. Theoretical calculations of "thermodynamic boundaries" incorporating the general heat-to-electricity ratio as well as the maximum of ESR have been discussed in the mode of "priority of providing cooling" to find the most suitable users for CCHP systems and to envision the energy saving potentials of CCHP systems. Moreover, investigation of CCHP systems in China in terms of ESR distribution has been undertaken to corroborate the theoretical calculations. Theoretical results show that the most suitable CCHP users should have their general heat-to-electricity ratios valued in the range of 0.9–2.8 (without heating demand) or 0.65–1.3 (with heating demand). Furthermore, particularly in Beijing, the maximums of ESR of CCHP systems without and with heating demand cases are 32.5% and 38%, respectively. Deviations between the investigation and theoretical calculations can be partially attributed to the assumptions, which have also been discussed.

1. Introduction

With the rapid growth of global energy demand [1], efficient energy use has become a hot topic in the current energy research field. CCHP (Combined Cooling, Heating and Power) systems, which produce electricity and use waste heat to provide cooling and heating for users [2], are generally energy saving [3] and environmentally friendly [4]. Thus, CCHP systems are considered to be potential substitutes for some conventional energy systems [5].

FESR (Fuel energy saving ratio) is one of the mostly often used indicators to evaluate the amount of energy savings in CCHP systems [6–9]. For example, Ebrahimi M et al. proposed a multi-criteria sizing function which incorporated FESR to design the optimum size and operating strategy of the prime mover of a residential micro-CCHP system [10]. Balli O et al. dealt with the thermodynamic and thermoeconomic methodology in which FESR was a crucial index of a trigeneration system [11], and the methodology had been applied in a CCHP system in Turkey [12]. Though FESR is prevailing in evaluation of energy savings in CCHP systems, incongruity with international standards or regulations regarding energy savings still exists. The conventional FESR method neglects the effects of climate differences among various places when CCHP systems are compared with separated energy systems. However, the international standards or regulations regarding energy management, such as IPMVP [13], M&V Guideline [14] and ASHREA Guidelines [15], emphasize that weather or climate corrections should be considered to correct the calculation of energy savings [16]. Actually, weather is a key issue in energy conversion and management. Weather cannot be controlled and changes in the weather are more likely to increase or decrease the energy use, which may trigger calculation deviations of energy savings. Therefore, the neglected climate effects would lead to an unfair comparison between CCHP and separated energy systems.

Meanwhile, an increasing number of studies have been ongoing to discuss the climate or weather effects on designing CCHP systems, since the weather would strongly affect the performance of CCHP systems. For either a gas turbine or a reciprocating engine, the

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Nomenclature

C	cooling provided for users
CCHP	Combined Cooling, Heating and Power
COP	coefficient of performance
E	energy
ESR	energy saving rate
FESR	fuel energy saving rate
GT	Gas Turbine
H	heat provided for users
P	electricity provided for users
R	general heat-to-electricity ratio
RE	Reciprocating Engine

Symbols

α	proportion of waste heat use
Δ	change of energy amount
η	efficiency

Subscripts

aver	average
ab	adjusted baseline
c	cooling from CCHP
C	cooling provided for users
cold	coldest month
e	electricity
h	heating from CCHP
H	heating
p	power from CCHP
r	reported energy consumption
ref	reference value
user	CCHP users
W	waste heat

power efficiency varies with temperature [17], which changes the energy use of CCHP systems. Several studies have investigated the effect of weather on CCHP systems. Fumo et al. [18] analysed the performance of CCHP systems at different areas to determine how to assess the performance of individual components at various altitudes. Basrawi et al. showed a detailed performance evaluation of a micro gas turbine cogeneration system under various regions with different annual average temperatures [19] as well as at different ambient temperatures [20]. Ebrahimi et al. studied the effect of weather on the prime mover size [3] and the design of CCHP systems for residential buildings due to temperature variations in Iran [10]. The results showed that for the same CCHP system, the yearly average fuel energy saving rates were quite different in different areas. Therefore, weather corrections to correct performance from baseline conditions to actual operating conditions need to be clearly specified and understood [14].

Furthermore, it is still debatable that the CCHP systems are capable of replacing all the traditional separated systems due to unsuccessful designs or failures in parameter settings. For CCHP systems, failure of a component may result in failure of a subsystem or of the whole system [21]. Also, the mismatching between energy demand from users and the producing abilities of CCHP systems tends to trigger more energy consumption. That is to say, either too much supplementation from traditional energy systems or redundancy of energy produced by CCHP systems may contribute to the failure of CCHP systems.

Therefore, it is imperative to propose an improved method in accordance with the international standards to comprehensively assess energy savings of CCHP systems, especially in China where the climate effects seem prominent due to the vast latitude span. Besides, the relationship between energy use of customers and energy provision from CCHP systems is expected to be discussed and quantified.

In this research, based on international standards or regulations regarding energy management, an improved calculational method of ESR (energy saving rate) considering energy adjustments caused by climate effects is presented. To illustrate the energy features of CCHP systems and their potential users, the indicator of "general heat-to-electricity ratio" is proposed. Theoretical calculations of "thermodynamic boundaries" incorporating the general heat-to-electricity ratio as well as the maximum of ESR of CCHP systems will be discussed in the mode of "priority of providing cooling" to find the most suitable users for CCHP systems and to envision the energy saving potentials of CCHP systems. Moreover, an investigation, including field trip and data collection, of CCHP systems in China in terms of ESR distribution will be presented to corroborate the theoretical calculation. Also, discussions about assumptions used in this research will be conducted.

2. Assumptions and system description

In this research, the mode of "priority of providing cooling" [18] is discussed due to the easy access of electricity [22]. The configurations of the CCHP systems being investigated in this research are shown in Fig. 1. Besides, assumptions are also established to simplify the study.

2.1. Assumptions

Assumption 1: Cooling and electricity are indispensable outputs of CCHP systems, while heating is not essential.

Assumption 2: CCHP systems are capable of satisfying all the energy demands from their users without redundant energy being thrown nor supplementation from traditional energy systems.

Assumption 3: Fossil fuel (e.g. natural gas), rather than sustainable or renewable energy (e.g. solar [23] and geothermal energy [24]), serves as the main energy source of CCHP systems. Also, facilities of energy storage [25] are out of the scope of this article.

Assumption 4: If heating is included in the energy demand from CCHP users, a RE (Reciprocating Engine) is selected as the power generator to drive the CCHP system (Fig. 1a) due to the convenience of using hot jacket water from the RE to provide heat for the users. By contrast, if CCHP users have no heating demand, GT (Gas Turbine) is selected as the power generator (Fig. 1b), because there will be no concerns about energy waste from hot jacket water.

2.2. System description

This research mainly concerns two configurations of the CCHP systems: (a) with heating unit (Fig. 1a) and b) without heating unit (Fig. 1b).

2.2.1. System with heating unit

In Fig. 1a, a CCHP system with heating unit is presented. A portion of the thermal energy generated from the fuel combustion in the RE is converted to electricity. When the RE is operating, hot exhausted gas and hot jacket water are generated. The hot exhausted gas is used to drive the absorption refrigerator to provide cooling for the