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Operation strategy and suitability analysis of CHP system with heat recovery

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ABSTRACT

In order to coordinate and balance the demand of combined heat and power (CHP) system, a solution of optimal operation strategy of CHP system with heat recovery in a distributed energy system has been presented. This paper will discuss more deeply the suitability of the CHP system under different operation strategies. The selections of electricity determined by heat load (EDHL) and heat load determined by electricity (HLDE) are actualised by Aspen Plus and formula computing. In addition, the performance difference of the CHP system operating in EDHL and HLDE is analysed by comparing thermoelectric output and fuel consumption. The result shows that the optimal heat to power ratio (HPR) is 1.75 and is derived when the electric output is approximately equal to the electric demand and the heat output is approximately equal to the heat demand. EDHL is the optimal selection when the HPR is greater than or equal to 1 and less than 1.75, and HLDE is adopted suitably when the HPR is greater than 1.75 and less than or equal to 2.5. Additionally, the total thermal efficiency does not vary with increasing or decreasing regenerative temperature or variable HPR on CHP system, maintaining 87–88% thermal efficiency, meanwhile, the total exergy efficiency is about 24.7%–28.8% when the CHP systems operate in EDHL, and 23.1%–31.4% when the CHP systems operate in HLDE. The final research results show that, it has great significance in operation strategy and suitability analysis of the CHP system.

1. Introduction

At present, distributed energy systems (DES) have been receiving increased attention because they are a good option for future energy systems with respect to sustainable development and low-carbon society development. A DES is currently an important method to solve the global energy crisis that has received attention from both researchers and the public [1,2].

Combined heat and power (CHP) systems refer to the simultaneous generation of electricity and useful heat from the combustion of a fuel that is an important mode in DES applications [3–7]. In recent years, many domestic and foreign researchers have been researching and developing “the Second Generation Energy System” [8,9], and the system is provided with a distributed CHP system as its core, which uses natural gas as its main fuel. The improved system is equipped with the most advanced modern environmentally-friendly energy systems which are integrated with innovative technologies and devices, such as gas turbines, gas engines, steam turbines, internal combustion engines, absorption chillers, compression refrigerating machines and energy comprehensive control systems and realise the coupling and high efficient utilization of many kinds of energy, thus raising the degree of energy utilization and environmental protection criterion to a new level. The improved system has already obviously shown many features such as security, stability, high energy efficiency, environmental friendliness, good social benefits and economic advantages [10,11]. In China, with the adjustment of energy structures, such as clear fuel, the proportion of applications of natural gas in urban energy consumption will increase to a great scale; in the meantime, the CHP system carries out an advanced technology to achieve high efficient utilization of gas as well. The pilot projects of CHP were constructed first in Beijing and Shanghai, e.g., the Gas Group’s dispatching building and the Ciqu CHP program in Beijing, as well as the Huangpu Central Hospital and the Pudong International Airport in Shanghai. Furthermore, many industrial parks have adopted the independent generation system in Guangdong Province, within which thousands of megawatt (MW) class internal combustion engines are configured. The CHP systems with small-scale gas turbines or internal combustion engines are usually adopted for these programs [12–14].

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Nomenclature

Abbreviations

CHP	Combined heat and power
DES	Distributed energy system
HPR	Heat to power ratio
PE	Providing electricity
pH	Providing heat
LHV	Lower heating value, kJ/Nm3
TDM	Thermal demand management
EDM	Electrical demand management
HLDE	Heat load determined by electricity
EDHL	Electricity determined by heat load

Latin letters

W	Work, kW
M	Fuel consumption, kg/h
c_p	Specific heat at constant pressure, kJ/(kg K)
T	Temperature, K
f	Mass fuel-air ratio
Q	Heat demand, kW
k	Adiabatic index
m	Mass flow, kg/s
E_x	Absolute exergy, kW
$E_{x,L}$	Exergy loss, kW
H	Enthalpy, kJ
S	Entropy, kJ/K

Greek letters

ρ	Density, kg/Nm3
π	Turbine pressure ratio
γ	Compressor pressure ratio
η	Efficiency

Subscripts

gt	Gas turbine
ac	Air compressor
gc	Natural gas compressor
b	Combustion chamber
g	Combustion gas
a	Air
n	Natural gas
e	Regenerator combustion-gas-side outlet
d	Terminal exhaust
c	Preheated air
tot	Total thermal
in	Inupt
out	Output
s	Saved
dem	Demand
act	Actual
HEX	Regenerator
HE	Heat exchanger
1-6	Intlet and outlet state point

The CHP system requires both power generation equipment and thermally activated components, while the proportion of product output will heavily influence the performance of the whole system. Currently, EDHL and HLDE are two kinds of typical operating strategies of CHP systems. EDHL determines electricity demand by heat demand; on the contrary, HLDE will determine heat demand via electricity demand [15,16].

Some scholars have done research and analysis with respect to EDHL and HLDE [17–20]. Y.Y. Jing developed a multi-objective optimization design method based on life cycle assessment, in which several objectives (energetic and environmental goals) are combined into a single objective by a weighted method [21]. J.G. Yu noted that: the rationality of EDHL is not absolute, but depends on some conditions. As a result, lopsided views cannot be used for instructing the overall situation. Consequently, to adopt EDHL as the principle of thermoelectricity development is not scientific [22]. X.L. Huo proposed that EDHL could save more energy than the mode of HLDE; however, because of the influence on the price of electricity and natural gas, EDHL is not always better with respect to the economy [23]. J.J. Wang studied corresponding primary energy consumption in thermal demand management (TDM) and electrical demand management (EDM) operation modes. The results indicate that a CCHP system in TDM mode in a cold area, where the building requires more heating during the year, achieves more benefits over a separate system while a CCHP system in an EDM mode is applicable to the building having a stable thermal demand in a mild climate zone [24]. Meanwhile, the calculation results conclude that a CCHP system in winter under EDM achieves more benefits than in summer [25]. W.L. Ma noted that EDHL should be adopted when the thermoelectric demand is less than the rated HPR, while HLDE should be adopted when the thermoelectric demand is higher than the rated HPR [26]. F. Fang studied a complementary CCHP-ORC system, and proposed the electricity to thermal energy output ratio, which is an important impact factor for the operating modes and performance of CCHP. It showed that the electricity to thermal energy output ratio can be adjusted by changing the loads of the electric chiller and organic Rankine cycle (ORC) dynamically [27]. Q.Y. Gu studied a CCHP system based on a gas engine and a fuel cell. The selection of a heat tracking mode, an electricity tracking mode and an energy island mode is of vital importance for the adoption of the CCHP system [28]. Additionally, foreign scholars, such as G. Han, P.J. Mago and A.D. Smith, also discussed the above problem. In the literature [29–31], related research and analysis have been discussed. Above all, there are some controversies concerning the "electricity is determined by heat load" mode or the "heat load is determined by electricity" mode. A.D. Smith studied a CHP system and presents two basic load-following methods, namely following the thermal load and following the electric load. The results showed a higher total efficiency than that of either a mode of following the thermal load or a mode of following the electric load, with CHP system efficiency values ranging from 71% to 87% [31]. A.L. Facci demonstrated that an optimised strategy would reduce the total daily cost, from 8% to approximately 100%, depending on seasonal load, with respect to rule-based control strategies, such as heat-tracking and electrical tracking [32]. S. Sanaye analysed and optimised CCHP according to both priority of providing electricity (PE) and priority of providing heat (pH) operation strategies. The optimisation results indicated that two gas engines (with nominal powers of 3780 and 3930 kW) in an SELL-PE scenario, two gas engines (with nominal powers of 5290 and 5300 kW) in an SELL-pH scenario, and one gas engine (with nominal power of 2440 kW) in a Non SELL-PE scenario provided the maximum value of the objective function [33].

In conclusion, the previous research was analysed qualitatively with extensive experience, but had less quantitative analysis. This paper will discuss more deeply the selection of EDHL and HLDE. The main contributions of this paper can be outlined as follows:

(1) A selection of optimal operation strategies of CHP is presented and calculated. The total thermal efficiency is employed in order to evaluate the system performance.
(2) The optimal HPR could be acquired when thermoelectric output meets demand. The operation strategies are selected respectively when the value of HRP is within the range.