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Quantitative evaluation of the impact of building load characteristics on energy performance of district cooling systems

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HIGHLIGHTS

- Building load characteristics affect the energy performance of DCSs significantly.
- Gini coefficient is used for quantifying the inequality of building cooling load.
- Grouping coefficient is used to evaluate the spatial distribution characteristic.
- Key energy performance indicators of district cooling systems are proposed.
- DCS can save 14% energy when grouping coefficient and Gini coefficient are low.

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ABSTRACT

With the rapid increase of research and application of district cooling systems (DCS), the controversy whether DCS is really energy-efficient is intensifying. Building load characteristics of DCS may be a main reason for this controversy. However, how building load characteristics affect the energy performance and which load characteristics can ensure a high performance? To answer such critical questions and improve the energy performance of DCS, this paper presents a systematic method for quantitative analysis and evaluation of the impact of building load characteristics on the energy performance of DCS. Key energy performance indicators are proposed. The load characteristics of DCS are described and quantified by introducing the concept of Lorenz curve and Gini coefficient. “Grouping coefficient” is proposed to evaluate the rationality of grouping different buildings into the same branch of chilled water distribution system. Case studies are conducted to investigate the performance of DCS under different load characteristics and to compare with conventional cooling systems. The impact of Gini coefficient and grouping coefficient on the energy performance of chiller plant, chilled water distribution system and the whole DCS are analysed. Recommendations are provided for future’s application of DCS and individual cooling systems.

1. Introduction

District cooling system (DCS) is a type of cooling system where the chilled water from a central plant is delivered through a distribution network to groups of individual buildings in a district [1,2]. There are many studies on system modelling [3], energy performance assessment [4], optimum design and optimum operation of DCS [5]. A large number of DCSs have been applied in many countries such as in US, in Germany, Italy, Sweden, Japan and China [6].

With the rapid increase of research and application of DCS, however, the controversy whether DCS is really energy-efficient is intensifying. On one hand, high energy efficiency is considered as one of the most attractive features of DCS, which has been declared and verified in many studies and practical projects, particularly in high density areas such as Hong Kong, Singapore and Tokyo [7–9]. Gang et al. [10] conducted a performance assessment of DCSs by comparing with conventional cooling systems. Results show that the DCS has a higher efficiency. Appraised technological, environmental, and economical advantages of district energy systems are discussed by Rezaie and Rosen in a review paper [2]. Zhen et al. [11] compared a district cooling and heating system using sea water heat pumps with a coal-fired heating system & a conventional air conditioning system. Their

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Nomenclature

COP	coefficient of performance of chillers
C_0-C_3	correlation coefficients
G	chilled water flowrate of pumps
H_{Pump}	pump head
Q	total cooling supply of the chiller plant
Q_{eff}	effective cooling supply to all end-users
T_{Con}	chiller condensing temperature
$W_{chiller}$	energy consumption of chillers
W_{distri}	energy consumption of distribution systems
$W_{p,\ cw}$	energy consumption of condenser pumps
$W_{P,\ sec}$	energy consumption of secondary pumps
W_{plant}	energy consumption of the DCS plant
X	cumulative share of buildings
χ	share of number of buildings
n	number of buildings
η	overall energy efficiency of pumps
COP_{Plant}	coefficient of performance of the chiller plant
DCS	district cooling systems
$Gini$	Gini coefficient
PLR	part load ratio of chillers
Q_{Avail}	available cooling capacity of chillers
$SCOP$	system coefficient of performance of DCSs
T_{Eva}	chiller evaporating temperature
Wct	energy consumption of cooling towers.
$W_{p,\ con}$	energy consumption of concentrated system
$W_{p,\ pri}$	energy consumption of primary pumps
$W_{p,\ sep}$	energy consumption of separate systems
WTF_{distri}	water transport factor of distribution systems
Y	cumulative share of normalized cooling load
γ	share of normalized cooling load
$\eta_{Grouping}$	grouping coefficient
λ	normalized cooling load of buildings

study shows that the district cooling and heating system is more efficient and has a lower annual cost. Shimoda et al. [8] summarized the reasons attributing to the high efficiency of DCSs, including employing more efficient equipment, the cooling load concentration effect, easy integration with local renewable energies, etc. On the other hand, the actual performance of some DCS projects in operation are reported to be not satisfactory, which causes the cooling prices much higher than the that of using individual cooling systems or packaged air-conditioners [12]. Some researchers have conducted energy consumption surveys in residential buildings in several cities of China. Survey results have shown that the energy consumption of DCS in residential buildings is usually larger than that of split air-conditioners by as much as ten times [13]. These two opposite results indicate that the energy performance of DCS varies greatly and the energy efficiency of DCS is not necessarily higher than that of conventional cooling systems.

In fact, both the advantages and disadvantages of DCS in terms of energy efficiency are caused by the "concentration effect", which refers to the concentration of the cooling loads of multiple buildings connected to the same DCS [8]. The concentration effect can result in energy saving of chiller plants by selecting large-capacity chillers with higher COPs [3] and improving the PLR (Part load ratio) of the plant through optimal chiller sequencing control [8]. On the other hand, the cooling energy needs to be delivered to multiple buildings through a complicated chilled water distribution network. The long-distance transmission and the complex configuration of the distribution network lead to higher energy consumption of chilled water pumps and larger cooling loss. The superiority of DCS over conventional individual cooling system (ICS) is eventually determined by the trade-off between the energy saving of the chiller plant and the extra energy use of the cooling distribution systems.

Compared to the concentration effect, building load characteristics provide much more details about the load composition of a DCS and have been identified as one of the most important factors affecting the energy efficiency of DCS by researchers. The load characteristics reflect the load variation features on both space and time dimensions, and describe how load distributes among different buildings and how load changes along time. Zhou et al. proposed to use the Lorenz curve and Gini indexes in the analysis of load characteristics in centralized HVAC systems [14]. Results have shown that Lorenz cure can describe the load distribution among zones or times graphically in a clear and straightforward way, and Gini index can reflect the unevenness of load distribution and its impact on energy performance effectively. Chow et al. developed a GA-based optimization method to determine the optimal mix of building types in the district in order to achieve the least cooling demand fluctuation of the chiller plant [5]. Zhu et al. pointed out that the most important preconditions of successful DCS projects are sufficient concentration of cooling users and enough low-cost natural cold sources [15,16]. Liew et al. presented a Total Site Energy Integration concept to integrate district cooling systems with local industrial clusters with power and heat generations. By addressing the economic trade-off between amounts of chilled water generated, cooling water and power consumed, a new framework has been proposed to guide users in selecting the most economical waste heat-to-cooling technology for DCS applications [17]. Peng et al. reported that the unsatisfactory load conditions of DCS lead to a large energy consumption by cooling transmission and distribution, and may offset the benefits due to the concentration effect of cold source. They also identified four load characteristic indexes, including the largest long-distant pipe, district cooling peak load, time weighted average load rate and total pipe length, as the necessary load characteristics conditions for achieve energy saving when compared to individual cooling systems [18].

In summary, previous studies have identified the importance of load characteristics and have provided some qualitative guidelines for improving the performance of DCS from the perspective of load characteristics. However, there is lack of a systematic method that can fully characterize the load characteristics of DCSs and can establish a quantitative relationship between load characteristics and energy performance of DCS. Some critical issues addressing the planning and design of DCS, including why the energy performance of DCS varies so greatly, how to select the best combination of buildings with diversifying cooling-load patterns and how to optimize the chilled water distribution system considering the different locations of end-users, are worth of in-depth research.

To answer above critical questions and improve the energy performance of DCS, this paper therefore presents a comprehensive method for quantitatively assessing the impact of load characteristics on the energy performance of DCSs. Key performance indicators, including "System Coefficient of Performance" of DCS, "Water Transport Factor" and "Coefficient of Performance" of the chiller plant, are proposed to evaluate the energy efficiency of the DCS and its main subsystems. Lorenz curve and Gini coefficient are introduced to describe building cooling load characteristics in quantitative ways. "Grouping coefficient" is proposed to evaluate the rationality of grouping different buildings into the same branch of chilled water distribution system. Case studies are conducted to investigate the energy performance of a DCS under different load characteristics in a new development area in Hong Kong. The impact of Gini coefficients and grouping coefficients on the energy performance of the chiller plant, the chilled water distribution system and the entire DCS are quantitatively analysed, which can be used for the optimal design and operation of future's district cooling systems.