Energy performance evaluation of centralised ice-storage district cooling system

Yehong Li¹²*, Jiankun Yang¹ and Xiangyang Jiang¹

¹ Guangzhou Institute of Building Science Co. Ltd., Guangzhou, Guangdong, 510440, China
² Guangzhou Construction Engineering Co., Ltd., Guangzhou, Guangdong, 510030, China

*Corresponding author’s e-mail: yehongli_gibs@yeah.net

Abstract. Centralised district cooling system equipped with ice storage has substantial advantages in comprehensive energy utilization and cost effectiveness. It facilitates cutting peak and filling valley of power load and helps saving energy costs by using the peak-valley electricity price. Despite such advantages, energy performance of ice-storage district cooling systems is still a controversial topic, especially there is a lack of effective evaluation methods and relevant evaluation standards in China. Therefore, this paper establishes a thorough index system to evaluate energy performance of ice-storage district cooling system. The index system covers all aspects of ice-storage district cooling systems, including the gradual evaluation of each process from equipment, via subsystem to whole system. Afterwards, the index system is used to analyse a real case, focusing on the eight most important energy performance indexes. The results show that the index system can adapt well to the evaluation requirements, help to find energy performance problems and facilitate to improve energy efficiency. In view of existing insufficiency, further efforts are needed to make in formulating reasonable benchmarks of such energy performance indexes.

1. Introduction

District cooling system is normally applicable for building groups that have high density and need continuous cooling [1]. In this way, single building has no need for individual cold source and avoid setting cooling towers everywhere. This is especially important for places that have appearance requirements such as CBD (central business district). Since cooling demand of various building peaks at different time, the total installed capacity for chillers of district cooling system will be less than that when the chillers are installed separately. Thus, it can reduce the initial investment. District cooling system is especially feasible in hot summer and warm winter areas such as Guangzhou, Shenzhen and other southern cities in China, where cooling period is long [2]. In northern China, it is more suitable to combine centralised cooling with energy stations such as CCHP (combined cooling, heating, and power plant) [3]. When peak-valley price policy is implemented, ice storage scheme integrated with district cooling system will be considerable economical and is a highly preferred solution. Using valley electricity for ice storage and releasing the stored cold for air conditioning during the peak time can significantly reduce energy cost and cut peak power load.

Ice-storage district cooling system technologies have been increasingly mature in practical application, but still many problems need to be improved. The most important one is the evaluation of energy performance. It is found that ice-storage cooling systems have relatively lower energy...
performance than conventional cooling systems [4]. However, present studies mainly focus on economic evaluation of ice-storage systems. Few studies are related to energy performance evaluation [5]. For example, Dong and Wei [6] analysed incremental cost of cold storage system in Anhui television centre; Chen [7] introduced operational strategy of an ice-storage cooling system and evaluated its economy. Zhang [8] analysed energy efficiency of an ice-storage system but combined with ground-source heat pump. Bai and Zhang [9] put forward an evaluation system of combined water-source heat pump and thermal storage. The energy performance evaluation of ice-storage district cooling systems usually refers to the methods of conventional cooling systems. However, conventional evaluation indexed for ice-storage cooling systems also has applicability problems. Therefore, it is essential to establish a set of scientific energy performance indexes for energy diagnosis and analysis of ice-storage district cooling systems.

This paper puts forward a comprehensive index system for energy performance evaluation of ice-storage district cooling systems. The evaluation indexes are formulated based on the three levels of equipment, subsystems and whole system. A case study is demonstrated by using the proposed indexes.

2. Energy performance index system for ice-storage district cooling systems

2.1. Composition of ice-storage district cooling systems

Through investigation of the design of ice-storage district cooling systems in literatures and real cases, the composition of ice-storage district cooling systems is as follows (figure 1).

![Composition of an ice-storage district cooling system](image)

Differing from conventional cooling systems, there are two types of chillers in ice-storage systems, namely base-load chiller and dual-mode chiller. Base-load chillers are used for refrigeration when dual-mode chillers are working for ice making. Dual-mode chillers have two work conditions, namely air-conditioning and ice-making mode.

Additionally, there are three types of circulation systems in ice-storage systems, i.e. glycol solution, chilled water and cooling water circulation system. Glycol solution is used for dual-mode chillers instead of chiller water since the evaporation temperature of dual-mode chillers reaches to -5°C when making ice, while chilled water has a freezing point of 0°C. The glycol solution out from dual-mode chillers is supplied to the ice-storage tanks or heat exchangers depending on the various work modes.
While the chilled water flows through the tanks or heat exchangers for cold release or exchanging. The chilled water is then supplied to end users through water distribution network.

2.2. An index system for energy performance evaluation of ice-storage district cooling systems

According to the above composition of ice-storage district cooling system, the indexes for energy performance evaluation are divided into three levels, namely the whole system, subsystem and equipment levels (figure 2). The whole system includes all subsystems and end users; while the subsystems are classified into base-load refrigeration systems (which use base-load chillers as cold source), ice-storage refrigeration systems (which use dual-mode chiller as cold source), and cooling medium distribution systems (which includes all pipelines and pumps). At each level, evaluation indexes are formulated corresponding various systems and equipment. The advantage of the index system is to comprehensively diagnose energy performance problems step by step.

![Diagram of energy performance indexes for ice-storage district cooling systems](image)

**Figure 2. Hierarchy of energy performance indexes for ice-storage district cooling systems.**

2.2.1. Energy performance indexes for equipment. For each process equipment, the indexes are as follows (figure 3):

- **COP (Coefficient of performance)** is the most important index for chillers. It represents the refrigerating output per unit power consumption. For dual-mode chillers, COP at air-conditioning mode and ice-making mode should be both evaluated, as well as overall COP for global efficiency, so as to compare the performance at different work conditions.

![Diagram of energy performance indexes for equipment](image)

**Figure 3. Energy performance indexes for equipment.**
• Distribution EER (energy efficiency ratio) and work efficiency are indexes for pumps. Distribution EER represents the power required to deliver unit cooling energy. Working efficiency refers to the ratio of effective power to shaft power.

• Cooling capacity and approximation degree are indexes for cooling towers. Cooling capacity refers to the ratio of measured and designed water temperature drop; and approximation degree represents the difference between cooling water temperature and ambient wet bulb temperature. Such indexes evaluate heat dissipation effect of cooling towers.

• Logarithmic mean temperature difference (LMDT) and exergy efficiency are used to evaluate heat exchangers. LMDT refers to the integral mean value of temperature difference between hot side and cold side of heat exchange. Exergy efficiency represents the ratio of effective output exergy to input exergy on both sides of heat exchangers.

• Cooling charging and discharging efficiency are two indexes for ice-storage devices. Cooling charging efficiency is the ratio of actual and nominal cold storage capacity of ice-storage devices in a working cycle. Cooling discharging efficiency refers to the ratio of cooling release and total cooling storage of ice storage devices in a working cycle.

2.2.2. Energy performance indexes for subsystems. The evaluation of subsystems includes the indexes for base-load refrigeration system, ice-storage refrigeration system, and cooling medium distribution system (figure 4). Base-load refrigeration system contains base-load chiller and its related primary chilled water pumps, cooling water pumps, and cooling towers. Ice-storage refrigeration system comprises dual-mode chiller and its related glycol pumps, primary chilled water pumps, cooling water pumps, and cooling towers. Cooling medium distribution system includes all pipelines and pumps. COP is an important index for base-load and ice-storage refrigeration systems, which represents the ratio of total refrigerating output and power consumption of the overall system. Ice-storage rate is another index for ice-storage refrigeration system. It refers to the proportion of refrigerating output for ice storage to the total refrigerating output provided by chillers. For cooling medium distribution system, the evaluation indexes include chilled water and cooling water delivery coefficient. Such delivery coefficients represent the cooling energy transported by unit power consumption of the distribution system. Temperature rise of pipe network is an index used to evaluate insulation performance of pipelines. The temperature rise is also related to the distance of end users and may be different in different seasons.

2.2.3. Energy performance indexes for whole system. The indexes for whole system include COP for centralised refrigeration plant and COP for district cooling system. COP for centralised refrigeration plant represents the cooling output from the plant divided by the total power consumption of the plant. Meanwhile, COP for district cooling system refers to the cooling arrived at end users divided by the total power consumption of the system. The difference of these two COPs is mainly caused by cold loss of distribution network. Therefore, cold loss rate is also selected as energy performance index, including cold loss rate of refrigeration plant, cold loss rate of distribution network, and total cold loss.
rate of district cooling system. Other important indexes for ice-storage district cooling system include maximum clipped peak load, annual shifted peak electricity and annual peak electricity shifting rate.

The above indexes cover different aspects of the ice-storage district cooling systems, which can facilitate a comprehensive evaluation and analysis of energy performance of the system.

3. Case study

This section demonstrates a case which used the proposed indexes to analyse energy performance of an ice-storage district cooling system. This system is located at hot summer and warm winter zone in China. It contains one base-load chiller and seven dual-mode chillers. The total capacity of chillers is 17400 RT. The nominal COP of the base-load chiller is 5.6, while the nominal COP of the dual-mode chillers at ice-making mode is 4.5 and at air-conditioning mode is 5.3. The cooling system also includes seven glycol pumps, eight primary chilled water pumps, eight secondary chilled water pumps, eight cooling water pumps, seven cooling towers and seven plate heat exchangers with a total heat exchanging area of 7406 m². Two ice storage tanks contain multiple coils, whose total cold storage capacity reaches to 80910 RTH. The end users of the cooling system include office buildings, shopping malls, hotels and so on, which have cooling demand throughout the year.

According to the annual monitoring data, eight indexes were selected for analysis, mainly focusing on COP at different levels. Figure 5 shows the daily refrigerating output and power consumption of the base-load chiller, and Figure 6 presents its daily COP. It can be seen that the base-load chiller run from May to October. Its average daily refrigerating output was 65064 kWh. Meanwhile, its average daily power consumption was 11841 kWh. The daily average COP of the base-load chiller was 5.49.

Figure 5. Daily refrigerating output and power consumption of the base-load chiller.

Figure 6. Daily COP of the base-load chiller.

Figure 7 shows the daily refrigerating output and power consumption of a dual-mode chiller, and figure 8 presents its daily COP. It can be seen that the dual-mode chiller run throughout the year. From November to April, the chiller only worked at ice-making mode during the night and the daily refrigerating output was about 45000 kWh. From May to October, the chiller worked at both mode, making ice during the night and providing air conditioning during the day in order to meet the cooling demand. The average daily refrigerating output in this period was 67322 kWh. It can be seen from figure 8 that the daily COP of the chiller at air-conditioning mode was higher than that at ice-making mode. The curve of daily COP at ice-making mode is concave, which is lower in summer and higher in winter. This is because the lower outdoor temperature in winter helped reducing condensation temperature of the chiller and improving the efficiency of the chiller. The daily average COP of the dual-mode chiller was 4.73 at ice-storage mode, 5.01 at air-conditioning mode and 4.80 as a whole.
Figure 7. Daily refrigerating output and power consumption of a dual-mode chiller.

Figure 8. Daily COP of a dual-mode chiller.

Figure 9 shows the daily COP of the base-load and ice-storage refrigeration systems. It can be seen that the daily COP of the base-load system was higher than that of the ice-storage system. The daily average COP of the base-load system was 4.43. The curve of daily COP of the ice-storage system was also concave, the average was 3.89. Figure 10 shows the daily COP of the centralised refrigeration plant and the whole district cooling system. It can be seen that the daily COP of the whole cooling system was slightly lower than that of the refrigeration plant due to cold loss of pipelines. The daily average COP of the district cooling system was 3.11, and that of refrigeration plant was 3.41.

Figure 9. Daily COP of base-load and ice-storage refrigeration systems.

Figure 10. Daily COP of centralised cooling plant and district cooling system.

In summary, COP of the base-load chiller was higher than that of the dual-mode chiller, and COP of the dual-mode chiller at air-conditioning mode is higher than that at ice-storage mode. Also, COP of the base-load refrigeration system is higher than that of the ice-storage refrigeration system, and COP of centralised cooling plant is higher than that of the district cooling system.

4. Conclusions
Ice-storage district cooling systems have good economic performance when applied to groups of buildings which have high density, require continuous cooling and use peak-valley electricity price. However, there is still a lack of systematic, comprehensive indexes for energy performance evaluation.
of ice-storage district cooling systems. This paper proposes a hierarchical index system for energy performance evaluation of ice-storage district cooling systems, which helps making thorough diagnosis of energy performance problems and facilitates making decisions in improvements.

The proposed index system considers carefully the specific characteristics of ice-storage district cooling systems compared to conventional cooling systems. The formulated indexes are demonstrated to be well adaptable to the requirements for energy performance evaluation of ice-storage district cooling systems. It helps analysing energy performance problems at different levels, i.e. equipment, subsystem to whole system levels. The systems and chillers in the case study generally have good performance when comparing to the specifications of relevant conventional systems and industry experience data. Due to the distinctiveness of ice-storage systems and conventional systems, however it is not suitable to use current benchmarks of conventional systems to determine energy performance of ice-storage systems. Benchmarking of the energy performance indexes is very important. This paper at present proposes the list of energy performance indexes for ice-storage district cooling systems. Our future work will focus on the benchmarking of such indexes.

Acknowledgments
This paper is one of the phased achievements of the following funded project: China Postdoctoral Science Foundation project (2018M643044), the science and technology progress fund project of Guangzhou Institute of Building Science Co., Ltd. (2019Y-KJ08) and the science and technology plan project of Guangzhou Construction Engineering Co., Ltd. (2019-KJ024).

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