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District Cooling Systems: Technology Integration, System Optimization, Challenges and Opportunities for Applications

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Abstract: District cooling system (DCS) has been widely used because of its low cost and high energy efficiency. Excessive studies have been done on DCSs, based on either actual projects or hypothesis. This paper presents a comprehensive review on the research and applications of DCSs. The characteristics and problems of DCS are introduced. The performance and progress of DCS integrated with sustainable energy technologies are summarized, including systems integrated with renewable energy systems, combined cooling, heating and power systems, and thermal storage systems. Efforts on the optimization of DCS are reviewed and categorized, including the efforts on district planning, DCS design, operation and control. An introduction on the existing typical DCS projects in China is presented. Challenges and opportunities for future application of DCS are discussed including the uncertainty issues at design stage, the control optimization and integration with smart gird.

Keywords: District cooling system; renewable energy; CCHP; thermal storage system; design and control optimization; smart grid

1. Introduction

District cooling system (DCS) becomes increasingly popular because of its high efficiency and high-class cooling, especially in the areas with high density of buildings. DCS is defined as a system that distributes thermal energy in the form of chilled water from a central source to residential, commercial, institutional, and/or industrial consumers for use in space cooling and dehumidification [1]. It typically consists of four parts: the heat rejection system, the central chiller plant, the distribution system and the end users as shown in Fig.1.

The first known DCS began to work at Denver's Colorado Automatic Refrigerator Company in 1889. In 1930s, large DCSs were used for Rockefeller Centre in New York city [2]. Approximately 20 cities and towns adopted DCSs till 1996 in US [3]. The earliest DCS in Europe appeared in Paris in 1960s. After that it began to be widely used in Germany, Italy, Sweden, Finland, etc. DCS began to be used in Japan since 1970 and then it has been developing very fast. The Japanese government encourages the development of DCS for its high efficiency and low pollution emissions. More than 154 district cooling systems in Japan had been in use by 2005 [4]. DCS was introduced in United Arab Emirates in 1999 and now it accounts for 10% of the cooling market [5]. In China, DCS is a relatively new system. The first well-known DCS located in Beijing and began to work since 2004. After that, several large DCSs began to appear such as the DCS in Guangzhou University Town.

A general introduction of DCS including its advantage and disadvantage, subsystems, classification, environment and economic effects can be found in the references [1, 6-9]. Although DCS has been used widely, there is still no systematic review on the studies that have been done from a technical viewpoint. This paper presents a review on the state-of-the-art of the studies of

DCS and its applications. In Section 2, DCSs integrated with various sustainable energy technologies are introduced. In Section 3, the studies on the district planning, DCS design and operation optimization are introduced. In Section 4, existing DCS projects in China are introduced. The challenges and opportunities for future application of DCS are discussed in Section 5. Conclusive remarks are given in the last section.

2. Integration with sustainable energy technologies

DCS can be integrated with many sustainable energy technologies. By integrating with the local renewable energy resources, the greenhouse gas emissions can be largely reduced. By coupling with the CCHP system, the energy efficiency of the fuels can be highly improved. The integration with thermal storage system helps to reduce energy consumption of DCS at peak hours. Integration of DCS with all these sustainable energy technologies can be illustrated in Fig. 2. Detailed review is introduced in the following sections.

2.1 Integration with renewable energy resources and use of waste cold energy

Usually the renewable energy resources include the energy from the surface water (such as the sea, river and lake), geothermal energy, solar energy, wind energy, biomass, etc. [10, 11]. The integration of DCS with renewable energy resources is summarized as follows.

DCS using energy from the surface water

Among all the renewable energy resources, surface water is frequently used in DCS as illustrated in Fig.3. Many DCS projects locating in coastline cities worldwide use seawater as the cold source. A district cooling and heating system (DCHS) using seawater heat pumps was installed in the north of China [12]. Results show that the system has lower annual cost, significant energy saving and environmental benefits compared with coal-fired heating system and traditional cooling system. Another DCHS with seawater heat pumps was studied and the results indicate that the economic performance of the system highly depends on the local tariff and policy [13]. A DCS using seawater as cold source was installed in Hong Kong to supply cooling for a new development area [14-16]. The DCS in Stockholm of Sweden is one of the largest DCSs in the world. The fast development of this project is encouraged by the political decision to phase out CFC and HCFC-based products, which are used as refrigerants and extremely aggressive to the ozone layer [17]. By sending the cold seawater from the Baltic Sea to the heat pump units, it can supply sufficient cooling to the users. Up to 2009, the cooling system serves over 600 buildings including offices, hospitals and universities, etc. [18]. Cold energy stored in the riverwater can also be used in DCS. For a DCS in Paris, seven chiller plants are used, of which four plants use cooling towers and the other three use water from Seine to produce cooling. When the water temperature is below 8℃, water from the Seine is used directly for cooling [19].

When the temperature of the surface water is low enough, free cooling technology can be used in DCS. By eliminating or bypassing chillers, the energy consumption of DCS can be largely reduced. A DCS using deep lake water was built in Canada in 2002 [20]. The cold water from a depth of 83 meters is pumped and transported to the Toronto Island Filtration Plant. The DCS serves 51 high-rise buildings in a high population density area of downtown Toronto, which has a sum cooling load of 54,493 RT. The chilled water is distributed to users after exchanging heat with the lake water [21]. Another DCS [22], which locates in the Conrell University in US, extracts cold lake water from a depth of 76 meters or more and circulates the lake water through heat exchangers to remove heat from a district (or campus) chilled-water loop. Auxiliary chillers are used to supply additional cooling when needed.

DCS using geothermal energy (aquifer)

Geothermal energy is another important cold source for the cooling system [23, 24], which mainly refers to energy from aquifer or groundwater in this paper. It is regarded to conserve about 90%~95% energy for DCS [25]. One of the largest groundwater reservoirs in Norway is used to serve the Gardermoen Airport as complemental heat sink and source for DCHS [26]. During cooling period, the chilled water is pre-cooled by the groundwater with a cooling capacity of 3MW. It is then post-cooled by a combined heat pump/refrigeration plant with a cooling capacity of 6 MW.

DCS using solar energy

Solar energy can be used in DCS. A DCS using solar energy in a hospital district was studied in Italy [27]. The solar energy is collected by thermal collectors and converted into hot water. The hot water exchanges heat with circulating water from the absorption chillers for cooling and district heating network for heating.

DCS using biomass

A DCS driven by thermal heat from municipal solid waste-fired power plant was studied in Thailand [28]. Instead of landfilling, the waste incineration is coupled with the power plant and heat is recovered for the absorption chillers. The system offers a great opportunity for primary energy saving, greenhouse gas reduction and contributions to biomass-based energy production. Rentizelas et al. [29] presented a optimization study for a place with multi-biomass. The optimization was condcuted to get the optimal bioenergy supply chain and conversion facility with a financial aim. Where, the biomass was used for a trigeneration plant which connected with a DCHS.

DCS using waste cold energy

Waste cold energy from industry can be recovered as cold source of DCS. Cold energy from the liquefied natural gas plant can also be one of the cold source. Before being sent to the customers, liquefied natural gas will be regasified and a large quantity of cold energy will be released. Wang et al. [30] compared two schemes that using the cold energy from the liquefied natural gas plant for DCS. One scheme uses the cold energy to produce ice and the ice is transported to the central plant. The other is to cool the chilled water directly via heat exchangers. The prior choice of the two schemes depends on the distrance from the central plant to the gasification station.

By coupling with renewable energy resources, the DCHS can achieve energy saving and greengas emission reduction [31]. The renewable energy has been widely used in the district heating system (DHS). Solar energy is widely used in DHS [32-34] and the benefit is promising. Geothermal energy is coupled with DHS to supply the users heating by pumping hot fluid from the underground [35, 36]. Biamass is often used as the heating source in DHS [37]. 14 % of gross energy consumption is met by straw in 2003 in Denmark. The biamass is used as the energy resource of the combined heat and power plant, where the electricity and heating are supplied to the surounding households [38]. However, the application of solar energy, geothermal energy and biomass in DCS is not as popular as that in DHS. The main reason may be that all the above energy resources can be used for heating with high efficiency. For cooling purpose, however, the renewable energy has to be converted into heat firstly and the heat is then transferred into electricity. Alternatively, the heat energy is convered into cold energy by absorption chillers. The efficiency for cooling applications is much lower compared with the heating applications, due to the heat loss and conversion efficiency.

2.2 Integration with CCHP systems

DCS is often combined with CCHP systems as shown in Fig.4, which supply cooling, heating and power simultaneously to users. Wu and Wang [39] presented a literature review on CCHP system. The work on the system configuration, operation and performance of DCS integrated with CCHP system is summarized in this section.

For DCS integrated with CCHP system, thermal driven chillers are usually employed to use the low grade heat from the CCHP system. Detailed review about the chillers can be found in the paper [40]. Lozano et al. [41] studied a CCHP system connected with DCS in Spain, which aimed to optimize the design of the system. The system serves 500 apartments in a district. Mixed integer linear programming method was used to find the optimal design of CCHP with thermal storage system. The integrated DCS and CCHP system using absorption chillers only may not be able to meet the cooling demand and electricity demand simultaneously. When the cooling demand is very high, the cooling produced by absorption chillers may be not sufficient and electrical (compression) chillers are required. Rodriguez-Aumente et al. [42] studied the economic performance of a DCHS coupled with a tri-generation plant under different pricing and using patterns. The absorption chillers are used as the basic units and back up with compression chillers and boilers. In CCHP systems, absorption chillers can only use saturated steam with the pressure of 0.4 MPa~0.8 MPa [43]. However, the steam produced by the power generator is usually superheated. A DCS integrated with CCHP was studied by Zhang et al. [43] , which uses an industrial turbine, driving the compression chillers, to cool down the superheated steam. Where, a combined compression refrigeration and absorption refrigeration system is adopted, which saves a large amount of steam consumption to meet the same amount of cooling demand.

For the hot water supplied to the absorption chillers in DCS with CCHP system, there is optimal supply and return temperature with the objective of lowest primary energy consumption of the chillers and pumps [44]. Nagae et al. [45] pointed out that the energy efficiency of DCS integrated with CCHP system could be improved by increasing the maximum chilled water flow rate of absorption chillers and compression chillers, decreasing the chilled water flow rate through the bypass between the supply and return pipes, and increasing the return chilled water temperature. Energy recovered from a coal-fired power plant can be used by DCHS as reported by Erdem et al. [46]. The authors also evaluated the energy saving potentials of using the heat from the condenser, stack gases, extracted steams for feed water heater and low-pressure turbine inlet steam.

Both energy and exergy efficiency were used to assess the performance of DCS with CCHP system [47, 48]. Three DCSs integrated with CCHP systems were compared, which use electrical chillers, single-effect absorption chillers and double-effect absorption chillers respectively. Results show that it is necessary to conduct exergy analysis to assess and compare the three options since the electricity, heating and cooling produced from three different systems have different natures and qualities. Hart and Rosen [49] compared the health and environment effects caused by DCHS integrated with CCHP system.

From the above studies, it can be observed that DCS integrated with CCHP system usually couples with DHS to meet the heating and cooling demand of the users. The integrated system is often used in the heating dominated areas, while the DCS serves as a supplemental system to meet the cooling demand of the area [12, 13]. In the cooling dominated areas, the application of DCS with CCHP system is rarely reported. One reason might be that the energy efficiency of CCHP system is not high when the primary aim is to meet the cooling demand. However, there is little quantitative and detailed study in the performance of DCS integrated with CCHP system in cooling dominated areas. Further study on this aspect is necessary.

2.3 Integration with thermal storage system

To reduce the operation cost and limit the power demand of the system at peak hours, DCS is integrated with thermal storage system. The integrated systems with different configurations are shown in Fig. 5. The concept of cool storage system is defined by the *Design Guide for Cool Thermal Storage*: Cool storage systems store cold energy during periods of low cooling demand. The stored cooling is later used to meet the air-conditioning cooling load [50]. By using the thermal storage system, the power utilities benefit from the reduction of the peak electricity generation and consumers benefit from lower electricity bills, by taking advantage of the lower off-peak rates and reducing peak demand billing charges [51].

Water is used for the thermal storage due to its low cost and high thermal capacity. Temperature of water storage system is compatible with evaporation temperature of conventional chillers, making it easier to be connected with DCS. Typical water-storage tanks stratify to a water temperature of 4℃ [3], at which water density is at its maximum. Majid and Waluyo [52] studied the temperature distribution at different depths of stratified thermal energy storage tank during charging process. Thermocline thickness was evaluated for two cases with different water flow rates. Tanaka et al. [53] investigated the DCHS using water tanks for daily thermal storage and seasonal water thermal storage. Where, the daily heat and cold storage charges were realized by a heat pump. Results show that the DHCS with seasonal and daily thermal storage system consumed much less primary energy. One DCS with aquifer thermal energy storage was studied by Andersson [54]. The storage system was used to increase the capacity of the DCS plant aiming to connect more customers. It stores cold at night and recovers during the daytime. Results show that the aquifer storage system has very good economic performance.

Ice stores cold in the form of latent heat. It fits best in tight downtown areas because it requires smaller storage volume. The DCS with ice storage system has been used in many projects, which are summarized in the reference [1]. A DCS in Paris uses both water and ice storage systems [19]. Three cold storage units having capacity of 140 MWh are used, of which two are ice storage units and one is chilled water storage unit. In China, most of the DCS projects are integrated with ice storage system. Chan et al. [51] conducted a parametric study to evaluate the performance of DCS with ice storage system at different partial storage capacities, control strategies, and tariff structures in Hong Kong. Results show that DCS with ice storage system is not economic feasible because the local tariff has trivial price difference between the peak time and off peak time.

Phase change material (PCM) is another popular group of cool storage medium. Most of PCM for cool storage are inorganic salt hydrates or mixtures of them. They are used due to their high latent heat during phase change, high density and low cost. A commercial salt hydrate PCM is used in DCS with a phase change temperature of 13°C [55]. The performance of the storage system was compared with systems with auxiliary chillers and stratified chilled water storage system. Results show that the latent heat thermal storage system is more economically viable. The major problem in using salt hydrates is that most of them melt incongruently. It is because they have poor nucleating properties resulting in super cooling of the liquid salt hydrate prior to freezing. Another problem is corrosion, which means short service life, high packing and maintenance costs. Paraffin wax can also be used for cool storage for DSC application. Bo [56] attempted to determine the thermal properties of paraffin waxes and their binary mixtures to demonstrate the potential of using these materials for cool storage. The experimental results indicate that laboratory-scale tetradecane and hexadecane and their mixtures could be used as PCMs for cool storage. However, applications in real projects are not practical due to its high cost.

Proper treatment of the thermal storage systems is necessary. It is crucial to maintain the systems within acceptable limits for corrosion, scale deposition and microbiological growth. Walicki et al. [57] discussed the treatment of large thermal storage systems in DCS, particularly in maintaining proper biological control. It included proper biocide selection and the implementation of side-stream filtration to control microbiological growth within the systems while mitigating corrosion and other effects.

All these mediums have been used in DCS applications. Ice storage systems require smaller volumes due to the large latent heat of water. However, chillers with lower evaporation temperature have to be used resulting in lower efficiency. For the thermal storage system using chilled water, conventional chillers can be used but the required volume to store equivalent cooling is much larger. Comparison of different technologies and their pros and cons are summarized in the literature [58]. The use of thermal storage system is based on electricity price policy, i.e. different electricity price at different time of the day. For example, the current tariff structure in Hong Kong is not so advantageous for using thermal storage system. To reduce the peak electricity demand and connect more users, promotion of appropriate electricity price is necessary. The existing literatures only mentioned the use of thermal storage system in DCS but few addressed the design and control optimization of the integrated system. Problems including the sequence control of the base load chillers and the storage system, the optimal size of the storage system, the amount of energy to be stored, etc., need to be further investigated.

3. Optimization of DCS planning, design and operation

DCS can perform well only when the system is well planned, designed and operated. The work in the planning, design and operation of DCS is categorized in Fig.6 and reviewed in this section.

3.1 Planning of buildings in a district

Generally, DCS is financially beneficial for densely populated urban areas, high-density building clusters and industrial complexes. For low-density areas, the economic advantages are less apparent because of the cold transportation loss [6]. The buildings served by a DCS may have different functions, as shown in Fig. 7. The combination of different types of buildings in a district will affect the performance of DCS. A more uniform cooling load profile is regarded to be suitable for DCS because it would minimize the start and stop counts of chillers and ensure the system to work with a high stability. Chow et al. [59] conducted a study to find the optimal percentage shares of different types of buildings in a DCS, aiming to get the most uniform cooling load profile. The performance of DCS is not only related to the load profile but also the system design. The optimal combination should be obtained by taking the energy consumption of DCS as the objective, especially when compared with the traditional cooling systems at the planning stage.

In Eastern Asian countries like China and Japan, most DCS users are commercial and public buildings. In Middle East, the residential buildings are included because DCS usually serves entire resort areas [60, 61]. For European countries and US, both commercial buildings and residential buildings are involved as the users and DCSs couple with DHS to both supply cooling and heating to the entire districts or cities. Actually residential buildings and commercial buildings can complement each other and combination of these two types of buildings may achieve better performance. The performance of DCS with and without the residential buildings needs to be assessed and compared. The main barriers and corresponding solutions to include the residential buildings need to be figured out. It is easy to understand that DCS can be used in the areas where the climate is hot and the cooling load is dominated, especially in the tropical and subtropical area. However, many well-known DCSs are developed in European countries where the climate is cold. The performance of DCS in different climate areas needs to be studied and compared with the traditional cooling system.

3.2 DCS design

DCS design involves cooling load calculation, system selection, system and component sizing, etc. The design optimization of DCS is reviewed in this section from two viewpoints: the global system design optimization and the subsystem optimization. The global optimization aims to optimize the DCS overall system configuration. The subsystem optimization aims to improve the performance of the component or subsystem. This section pays special attention to the chilled water network subsystem.

Global system design optimization

For the system selection, Li et al. [12] conducted performance comparisons of cooling and heating systems using different energy resources. A DCHS using seawater heat pumps was compared with the coal-fired heating system and conventional air conditioning system in the north of China. After the system scheme is determined, design optimization of the subsystems needs to be done to get the optimal global performance. Soderman et al. [62, 63] used a mixed integer linear programming model to optimize the DCS design in an urban area. The issues concerned included the location of cooling plants, the cooling capacity of the plants, the cold storage location, the storage capacity, the routing of distribution pipe-lines to individual consumers, optimal operation of cooling plants in different periods of the year, the charge and discharge of the storages and the cold medium flow rates in the district cooling pipelines. The optimization was conducted at seasonal level in that study. Design optimization of DCS based on daily or hourly-scale would be more precise and more reliable.

Subsystem design optimization

Most existing studies on DCS subsystem design optimization address chilled water distribution networks. The central plants and the users are connected by the chilled water networks. The connection can be direct or indirect by isolating with heat exchangers [64]. For systems using direct connection, chilled water is pumped from the central plant to the in-building air-conditioning systems. The direct connection is more economic efficient due to the elimination of heat exchangers and associated equipment, water treatment systems and equipment maintenance [1]. The main limitation is that it is easy to get cross-contamination between different users. For systems using indirect connection, the cross-contamination can be avoided and the responsibilities of different parties are clear. However, the efficiency becomes lower and the capital cost is increased because of the heat exchangers. In fact, indirect connection is used by most of the projects.

The chilled water network can be organized in radial and/or tree shaped networks, as illustrated in Fig.8. Genetic algorithm is frequently used to get the optimal layout and size of the chilled water network [65-67]. The objective can be the piping cost plus pumping energy cost [65], or annual equivalent cost including the overall investment, annual operating cost, maintenance and amortization expense, and annual cooling loss cost [66, 67]. Sometimes the depreciation cost of the pumps and pipes is also included [68, 69]. The selection of pipe material should consider the pipe strength, durability, corrosion resistance and cost [14]. The placement of the pipes was studied

[70-72]. The recommended configuration for both the DCS and DHS is to place the two pipelines one above the other in the trench with the hotter pipe being the upper one. This differs radically from the traditional arrangement (the pipes being placed side by side) and leads to at least 4% additional energy saving. Narrower trenches are required also and the cost would also be lower eventually.

The work on the design optimization of DCSs is summarized into Table 1. The design of DCS is important because it affects the performance of DCS over the entire life cycle. The study on DCS system design optimization is not sufficient yet, such as the chiller capacity and combinations considering partial cooling load, pump connection, the number and location of the chiller plants, etc. In addition, the DCS installation is usually separated into several stages. Corresponding design considering multiple stages should be further studied.

3.3 DCS operation and control

The operation and control of DCS is more complex compared with traditional cooling system. The considerable energy consumption requires stricter management and better operation. In this section, studies on DCS operation and control are reviewed.

Operation and optimization of DCS plants

To improve the energy performance of DCS, many efforts have been paid on various aspects of DCS, including the cooling load prediction, the optimization of system operation, the waste heat recovery, etc., besides the efforts on chilled water distribution systems discussed later.

Cooling load prediction is necessary for the control of DCSs, especially for the systems with thermal storage. Artificial neural networks were used to predict the cooling load of the buildings by Sakawa et al. [73], where a three-layer artificial neural network model was used to predict the cooling load of next day using latest data available. Results show that this method can predict the cooling load accurately. Several types of buildings were surveyed including the office buildings, retail shops, restaurants and hotels [16]. The surveying ratios of occupancy, lighting and fresh air supply at different time of a day were obtained, which were used in cooling load perdition using HKDLC, HTB2 and BECON as the tool. Results show that the sum of loads for each type of buildings can be predicted accurately but for each individual building, the prediction is not accurate.

Many optimization techniques have been used in DCHS, which was reviewed by Ortiga et al. [74]. The common approach used for DCHS was mathematical programming, genetic algorithms, neural networks and fuzzy logic systems. Multi-criteria optimization was used because of conflicting and non-comparable criteria existed in optimization. Sakawa et al. have done a lot of work on the optimization of DCS. In their early work, the operational planning problem of district cooling and heating plants is regarded as a mixed 0–1 linear programming problem and it involves hundreds of variables [75, 76]. Genetic algorithm is adopted to get the optimal result. In their later work, the operation optimization is regarded as nonlinear 0-1 programming problems [77]. An interactive fuzzy satisfying method through genetic algorithms is adopted. Considering the state of the components in the DCHS as continuous operating ratio instead of just on-off, the operation planning problem of an actual district cooling and heating plant is taken as a nonlinear programming problem in their latest work [78]. To reduce the energy consumption and minimize the running cost, a multi-objective nonlinear programming formulation is used. An interactive fuzzy satisfying method through particle swarm optimization was introduced. The feasibility and efficiency of the proposed method was tested on an actual district cooling and heating plant in Tokyo.

The use of energy efficiency measures helps to improve the benefits to the operators of DCSs when the users pay fixed total amount for the cooling received [79]. Results show the following measures are effective for reducing the energy consumption of DCS: 1) to circulate the chilled water with a large differential temperature; 2) to use the outdoor air directly for free cooling when the outdoor temperature is even lower; 3) to reduce the outdoor air intake based on ventilation demand; 4) to reset the indoor temperature set-point. In order to assess the risk of the pricing strategy, the ratio that users who signed the contract and the changes of weather conditions were investigated. Results show that higher ratio would bring the operator more benefits while the higher outdoor air temperature would reduce the benefits.

Waste heat from DCSs is regarded as low class energy. However, by introducing heat recovery measures, the system energy efficiency can be improved. In a hybrid system that coupled DCS with distillation system, waste heat from the condensers of DCS plants is used to power the desalination system [80]. Two kinds of water treatment technologies in the desalination processes were compared, including multiple effect distillation and reverse osmosis. Results show that both the hybrid systems were more cost effective than the individual systems. District cooling business in Helsinki started in 2000 [81]. There were about 200 buildings connected with DCS with a cooling demand more than 100 MW by 2010. One special character of the DCS in Helsinki is that the distribution network delivers the heat collected/removed from the buildings to the DHS.

Operation and control optimization of chilled water distribution system

The cold loss is a very important factor resulting in bad performance of the DCS. It consists of two parts: the transportation loss and the cold loss resulting from the pumps. Research shows that the transportation cold loss can be controlled within 1% if the insulation and construction of pipes is good. The main cold loss is caused by the secondary chilled water pumps [82]. To reduce the energy consumption of the chilled water pumps, available alternative methods are classified as follows:

1) *To reduce the resistance of the pipelines*. Specific surfactants in DCHS could reduce the friction attributed to a formation of an additional viscous sub-layer along the pipe internal surfaces [83]. Some additives were tested and could be used in the DCHS without serious technical problems. However, slight toxicity limited the application and they could only be used in primary system.

2) *To increase the thermal capacity of the fluid in the chilled water network.* A DCHS coupled with dynamic-type ice storage system was proposed [84-86]. The ice-slurry is transported to the substations from the ice storage tanks at the central plant. The aim is to reduce the transportation power and costs of pipelines. By adding 25% volume of pentadecane into the chilled water, the volumetric thermal capacity of heat transfer fluid undergoing at a temperature difference of 15℃ is increased by almost 40%. With a larger thermal capacity, the flow rate and pump energy consumption can be decreased significantly [87].

3) *To limit the pipe distance and enlarge the difference between the supply and return chilled water temperatures.* Shou and Chen [88] suggested that the load density (average cooling load carried by one meter of pipeline) should be over 14 kW/m for DCS. The difference between the supply and return chilled water temperatures should be about 8~10℃ and 10℃ for the system with thermal storage system. The chilled water network radius should be around 1~2km considering the heat transportation loss. Kang et al. [89] also studied distance for the economic cooling using DCS considering the cooling load density and differential temperature between the supply and return chilled water. Results show that the distance for economic cooling could be longer for areas of higher cooling load density. The supply and return differential

temperature should not be less than 5℃.

In most of the operation studies, the central plants and the users (cooling systems in buildings) are operated separately, which is the result of separate management. The coordinated operation of users and central plants will benefit both sides. In the operation optimization of chilled water system, the dynamic performance is usually neglected such as the response delay caused by the chilled water network of long distance. Control optimization of the entire chilled water systems including DCS and users, considering the dynamic character and interactions, needs to be studied.

4. Existing projects in China

A summary on the worldwide projects except China can be found in [1, 90]. Several typical projects worldwide are summarized in Table 2. There are also many DCS projects in the last decade in China but there is little introduction which can be found in English literatures. In this section, reported existing projects in China are therefore summarized based on the climate zones of the country, which is shown in Fig. 8. The details for the projects are summarized in Table 1.

Table 3 shows that more DCS projects in China locate in the *Hot Summer and Warm Winter* zone, where cooling is required most of time in a year and heating demand can be ignored. In *Hot Summer and Cold Winter* and *Cold* zones, DCS is usually coupled with DHS. In the *Severe Cold* and *Temperate* zones, there is still no reported DCS project yet. It can be found that most of the projects are for commercial and public buildings. All the projects are located close to the sea or river, where seawater and river water can be used as the cooling source. However, the performance of DCS in China has been rarely reported.

DCS is expected to achieve good performance in urban areas of China due to high density of buildings. However, the development of DCS is not fast and it is not popular in application. That is partly because of the negative outcomes reported about the existing projects. For two large and well-known projects in the *Hot Summer and Warm Winter* area, the price for cooling taken from DCSs is too expensive [109]. It is almost the same with, or even higher than the local electricity price. However, the price for cooling from the traditional cooling system is only half or one third of the electricity price. Too high price drives some users to quit from using DCSs and install traditional cooling systems in their buildings. Two reasons can be found to explain the high price. One is that the capital cost for the DCS is too large and the investors try to get the money back quickly by increasing the price, the other is that the DCS is not well designed or operated and the energy efficiency is lower than that expected [110]. To promote the applications of DCS, the design, operation and management still needs to be improved.

5. Challenges and opportunities for future applications

DCS has been widely used due to its outstanding advantages compared with the traditional cooling systems. However, there is still much work to be done for the systems to achieve the expected or optimal performance and to integrate with new technologies such as smart grid. Three main points are summarized in this section.

5.1 Design optimization considering uncertainties

Various uncertainties exist in the data used at system planning and design stages. These uncertainties will cause system performance to deviate from what expected. For example, the capital cost of one DCS project in Hong Kong has to be increased again and again because installation cost of the chilled water pipelines is much higher than that of the original budget. There are also some DCSs that are oversized too much caused by the large difference of actual cooling load and estimated cooling load. All these are caused by the uncertainties existing in information and data available and used at the planning and design stages.

The potential uncertainties at the plan and design stages can be classified into several categories:

1) *Uncertainties in districts.* It includes the building types and numbers, building sizes, building layout, building orientation, etc.
2) *Uncertainties in cooling load calculation.* Outdoor weather condition including the outdoor air temperature, relative humidity, solar radiation, etc.; indoor environment such as the temperature set-point, relative humidity; ventilation, occupants, equipment and lighting heat gains; the materials of the envelop; the calculation method of cooling load, etc.
3) *Uncertainties in DCS.* The performance of the chillers and pumps, numbers and locations of the central chiller plants, the number and combination of chillers and pumps, resistances and layout of the chilled water networks, etc.

Nowadays the design of a DCS usually gives deterministic results based on fixed parameters without considering the uncertainties. Because of the uncertainties, the conventional design method may result in system performance deterioration and/or cost increase. How to handle these uncertainties and ensure the system to perform well is vital. Robust optimal design considering the uncertainties at plan and design stages needs to be studied.

5.2 Operation and control optimization of DCS

From the above review it can be found that the current research on operation and control of DCS mainly concentrates on the chilled water distribution system. For the global system level control, the research work is not sufficient. One characteristic of DCSs is that it has multiple buildings as users. If taking each building as an agent, multi-agent concept can be implemented in the DCS to improve the operation of the DCS from global view point. Multi-agent has been widely used in the building energy system [111-113]. Its implement in DCSs is worth to be studied.

As the main components of DCSs, chillers consume large percent of energy. The control of chillers in DCSs has hardly been mentioned. For the cooling water pumps and cooling towers, the control strategy can rarely be found also in the literature. The control of thermal storage systems and their coordination with chiller plants need to further study.

5.3 Smart DCS integrated with smart grid

In response to the increasing environmental challenges, dramatic growth of power demand, depletion of fossil fuels, integration of renewable energies, smart grid is considered as a promising solution concerning its improvements and benefits in power reliability, energy efficiency, economics and sustainability. By conducting efficient acquisition of energy information and optimal controls of operation, smart grid can achieve better power reliability and higher overall energy performance. Many countries like USA, Canada, China, South Korea, Australia, and European countries have started national programs or plans to adopt or implement smart grid.

With the development of smart grid, new concepts like smart poly-generation micro-grid, smart energy network, and smart thermal grid emerge [114-116]. All these systems try to integrate with the smart grid. As a large cooling supply system for a district or even a city, DCS has outstanding advantages to integrate with smart grid as illustrated by Fig.10. The integration of DCS and local renewable energy resources and thermal storage systems has been widely used, which is consistent with the development of the smart grid. Buildings play an important role in the smart grid because the building energy system occupies a large percent of the total electricity consumption in urban areas [117, 118]. This results in the necessity to develop smart DCS to be integrated with smart grid. The technologies to integrate DCS with smart grid and problems faced need to be studied.

6. Summary

This paper presents a review on the existing research and applications of DCS including the integration of DCS with different energy technologies, design and operation optimization and the further work needed. A few conclusions can be summarized as follows.

1. DCS can be easily integrated with the local renewable energy. The use of renewable energy is not as common as used in DHS. The integration with CCHP systems usually appears in the heating dominated areas. Such integration in cooling dominated areas and areas requiring similar amount of cooling and heating, needs to be studied. Water, ice and PCMs are used in DCSs for cool storage. The design and control optimization of DCSs with thermal storage system needs to be further studied.
2. Users for DCSs are mainly commercial and public buildings in Asian areas. Residential users usually are included when the DCS is couples with the DHS. The combination of buildings should be optimized concerning the energy cost.
3. The work on DCS design is reviewed from the global and subsystem viewpoints. The subsystem design optimization mainly focused on the chilled water distribution system. Design optimization of the other parts of DCSs and design optimization concerning multiple stage construction in practical applications need to be further studied.
4. Control optimization of DCSs at system level mainly can be realized by using various optimization algorithms. For the chilled water system, the energy consumption can be reduced by reducing the resistance of pipelines, increasing the thermal capacity of the fluid and increasing differential temperature of the supply and return water. Operation optimization

considering the dynamic response of DCS and the interaction between users and operators needs to be studied.

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