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Robust optimal design of chilled water systems in buildings with quantified uncertainty and reliability for minimized life-cycle cost

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ABSTRACT

Conventional design of chilled water systems is typically based on the peak cooling loads of buildings, while the cooling load reaches its peak level for only a small proportion of time in a year. This results in that design flow of chilled water system could be significantly oversized in actual operation and it thus causes significant energy wastes. In this paper, a robust optimal design based on minimized life-cycle cost is proposed to optimize the design of chilled water pump systems while concerning the uncertainties of design inputs and models as well as the component reliability in operation. Monte Carlo simulation is used to generate the cooling load distribution and hydraulic resistance distribution by quantifying the uncertainties. Markov method is used to obtain the probability distribution of the system state. Under different control methods, this proposed design method minimizes the annual total cost. A case study on a building in Hong Kong is conducted to demonstrate the design process and validate the robust optimal design method. Results show that the system could operate at a relatively high efficiency and the minimum total life-cycle cost could be achieved.

1. Introduction

The building sector is the largest energy consumer in most countries and regions worldwide, especially in the metropolis such as Hong Kong [1–3]. Building central chilled water systems, which are the major sub-systems in heating, ventilation and air-conditioning (HVAC) systems, accounts for a significant proportion to the total electricity used in buildings [4,5].

1.1. Conventional design of chilled water system

The sizing and selection of chilled water pump systems is one of the most important aspects in determining the energy performance of the HVAC systems [6,7]. The conventional design of chilled water pump systems, proposed by ASHRAE Handbook [8], mainly concerns the design flow required and design pressure head required. The intersection of the required head and flow on the pump curve should occur close to or perhaps a little to the left of best efficiency point (BEP), which may maintain the pumps operating at high efficiency and thus minimize the electricity cost of operating the pumps [9]. Considering that pumps are only manufactured in certain sizes, selection range between 66% and 115% of design flow at the BEP are suggested [10]. In a central air-conditioning system, the designer tends to use identical pumps in parallel to share the system flow [10]. In addition, a standby or backup pump of equal capacity and pressure installed in parallel to the main pumps is recommended to operate to ensure continuous operation when a pump fails to operate or needs to be maintained [11].

Oversizing of chilled water pump systems, which is a common problem in HVAC fields [12], may result in high capital cost, high operation cost, and increased maintenance problems over the system life-cycle when compared to properly sized systems [9]. Oversizing of pump systems contain the oversizing of design flow and oversizing of design pressure head. Due to the inevitable uncertainty of input parameters (e.g., weather condition, occupancy) on cooling load calculation [13], designers tend to select a larger design cooling capacity than the peak duty (e.g., multiply a safety factor) in order that the design cooling capacity can fulfil the cooling demand for safety [14,15]. This may result in significant oversizing of cooling capacity and thus the design flow [16]. Based on the design flow rate and actual design information of the chilled water loop, component pressure drop information is utilized to calculate the assumed pump head. Then additional design safety factors are added on the assumed pump head to get the design pump head to allow the changes of system load and to cover unknown or unforeseen pressure drop factors [12]. Sometimes an artificial aging factor

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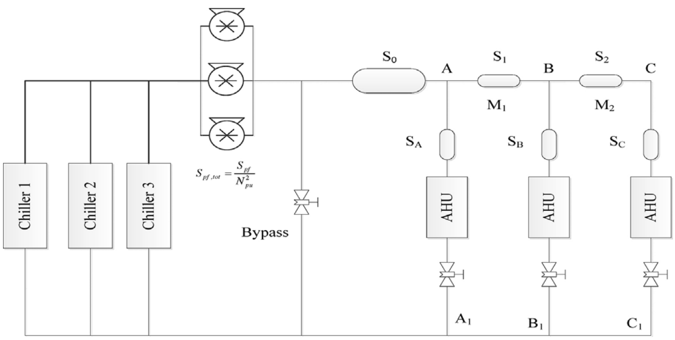

Fig. 1. Scheme of primary only pump system.

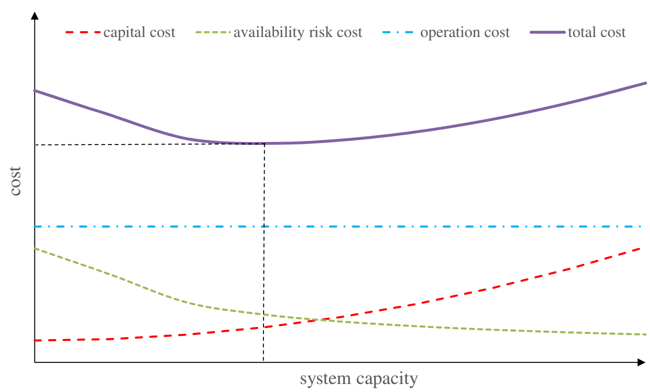

Fig. 2. Total cost *vs* system capacity.

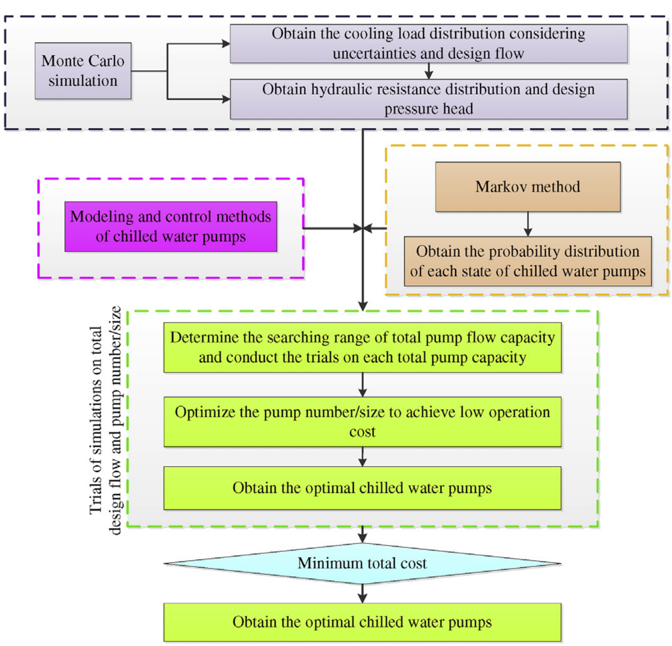

Fig. 3. Procedure of the proposed robust optimal design.

(e.g., an extra 15%) is included to account for the decrease in pipe diameter as deposits build up on the inside surfaces of the pipes due to aging [9]. Since part load conditions frequently occur throughout the entire cooling season [17], some engineers think they can grossly oversize a pump system and then use variable speed drives to maintain high efficiency and reduce operation cost during the part load period [18]. However, the capital cost and operation cost are still high while the variable speed drives are used.

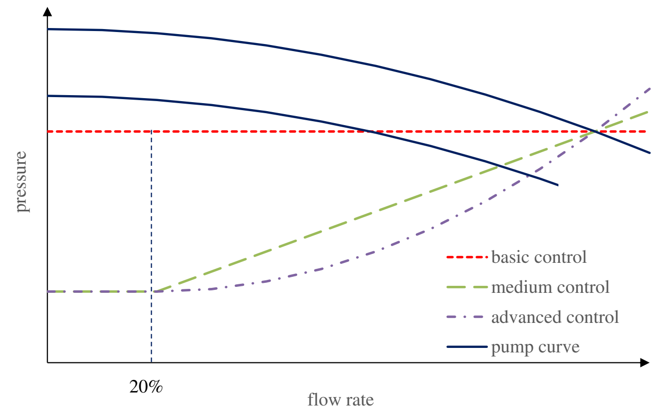

Fig. 4. Pressure set-point of chilled water loop *vs.* flow rate.

1.2. Uncertainty and reliability study on building energy system

Conventional optimal design of building energy systems are typically based on the annual cooling load under the predefined conditions, which is commonly subject to a deterministic model-based simulation [13,15]. However, many researchers had taken the impacts of uncertainties into account when calculating cooling loads and evaluating the performance of building energy systems [19–23]. The peak cooling load distribution was studied by Domínguez-Muñoz et al. [24] considering the uncertainties in the building material, heat transfer coefficients of external and internal wall, internal sources, etc. Eisenhower et al. [25] conducted an uncertainty study in the intermediate processes by performing decomposition, aiming to find the most important subsystem in modelling. Sun et al. [15] proposed a design method to size building energy systems considering uncertainties in weather conditions, building envelope and operation. Cheng [26] proposed a probabilistic approach for uncertainty-based optimal design to size the chiller plant considering uncertainties of input parameters, which ensures that the chiller plant operate at a high efficiency and the minimum annual total cost could be achieved under various possible cooling load conditions.

Reliability can be defined as the probability of successful operation or performance of systems and their related equipment, with minimum risk of loss or disaster [27]. Reliability analysis or assessment is necessary to avoid/reduce losses caused by both the normal situations and abnormal situations such as the failure of some components [28]. Myrefelt [29] used actual data collected from buildings of seven large real estate operators to analyze the reliability of the HVAC systems. Peruzzi et al. [30] emphasized the importance of the reliability parameters considering financial (reduction of energy and maintenances costs), environmental and resources managing (both concerning the energy and staff) profits. Au-Yong et al. [31] investigated the maintenance characteristics of HVAC systems that affect occupants' satisfaction, subsequently established a relationship between the characteristics and occupants' satisfaction through questionnaire surveys and interviews and finally develop a regression model for prediction purpose. Gang et al. [32,33] proposed a robust optimal design of cooling systems considering uncertainties of inputs and system reliability, which could obtain the optimal cooling systems with low cost and high robustness and provide a promising means for designers to make their best design decisions.

In order to achieve more flexible, resilient and cost effective design of the chilled water pump systems, a life-cycle based robust optimal design method is proposed in this paper. It can ensure that the chilled water system could operate at high energy performance and the minimum total life-cycle cost could be achieved under