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Sequential Monte Carlo simulation for robust optimal design of cooling water system with quantified uncertainty and reliability

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A B S T R A C T

Conventional design of cooling water systems mainly focused on the individual components of cooling water system, not the system as a whole. In this paper, a robust optimal design based on sequential Monte Carlo simulation is proposed to optimize the design of cooling water system. Monte Carlo simulation is used to obtain the cooling load distribution of required accuracy, power consumption and unmet cooling load. Convergence assessment is conducted to terminate the sampling process of Monte Carlo simulation. Under different penalty ratios and repair rates, this proposed design minimizes the annual total cost of cooling water system. A case study of a building in Hong Kong is conducted to demonstrate the design process and test the robust optimal design method. The results show that the minimum total cost could be achieved under various possible cooling load conditions considering the uncertainties of design inputs and reliability of system components.

1. Introduction

A typical centralized heating, ventilation and air conditioning (HVAC) system is comprised of cooling water loop, chilled water loop and indoor air loop [1]. A cooling water loop consists of condensers of chillers, pumps, cooling towers and fans [2]. The condensers of chillers transfer the indoor cooling load and the heat generated by the compressors of chillers into the cooling water. The cooling water pumps circulate cooling water from the chiller condensers to the cooling towers. The heat load is finally rejected to the ambient through heat transfer and evaporation by cooling towers.

The sizing and selection of cooling water systems is one of the most important aspects in determining the energy performance of the HVAC systems [3–7]. According to ASHRAE Handbook [8], the thermal capacity of a cooling tower might be determined by following parameters, i.e. return and supply cooling water temperatures, inlet air wet-bulb temperature and design cooling water flow rate [9–13]. Design cooling water flow rate depends on the total heat rejection of condensers under given working conditions. The total heat rejection contains the design cooling capacity and heat of compression [11]. Due to the inevitable uncertainty of weather data, indoor occupants and internal heat gain, designers tend to select a design cooling capacity much larger than the peak duty (e.g., multiply a safety factor) in order that the plant can fulfil the cooling demand under any uncertain conditions for safety [14,15]. At the same time, additional cooling tower capacity is added in case that the ambient temperature is off-design or heat rejection varies from the design condition [9]. This may result in significant oversizing of design cooling capacity and cooling tower capacity and thus a large amount of energy wastes. In selecting the pumps for a cooling water system, considerations are mainly given to the static pressure and the system friction loss [8]. The pump inlet must have an adequate net positive suction pressure [16]. In addition, continuous contact with air introduces oxygen into the water and concentrates minerals that can cause scale and corrosion on a continuing basis [8]. Fouling factors and an increased pressure caused by aging of the piping must be taken into account in the design of cooling water pump [17]. However, research on cooling water systems has focused on the individual components of cooling systems, not the system as a whole [18]. Picón-Núnez et al. [19] proposed a methodology for designing coolers in the context of both process needs and cooling water system behavior. It considers the design of cooling systems in the context of piping costs, exchanger costs, pumping costs and its hydraulic and thermal performance. In addition, little attention has been placed to the interactions among cooling towers, cooling water pumps and condensers of chillers [20], even though changes to operating conditions of cooling water systems frequently happen.

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Conventional optimal design of building energy systems is typically based on the annual cooling load under the predefined conditions, which is commonly subject to a deterministic model-based simulation [15,21]. However, many researchers had taken the impacts of uncertainties and reliability into account when calculating cooling loads and evaluating the performance of building energy systems [22–24]. Eisenhower et al. [25] conducted an uncertainty study in the intermediate processes by performing decomposition, aiming to find the most important subsystem in modeling. Sun et al. [15] proposed a design method to size building energy systems considering uncertainties in weather conditions, building envelope and operation. Cheng et al. [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 can operate at a high efficiency and the minimum annual total cost could be achieved under various possible cooling load conditions. Myrefelt [27] used actual data collected from buildings of seven large real estate operators to analyze the reliability of the HVAC systems. Gang et al. [28,29] 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. Au-Yong et al. [30] investigated the maintenance characteristics of HVAC systems that affect the satisfaction of occupants, subsequently established a relationship between the characteristics and the satisfaction of occupants through questionnaire surveys and interviews and finally develop a regression model for prediction purpose. Peruzzi et al. [31] 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.

In reliability evaluation studies of substations, there are two main approaches applied: the analytical approach (a steady approach) and the Monte Carlo simulation approach. In HVAC fields, the analytical approach, such as Markov processes, is usually utilized for reliability modeling of aging equipment. Gang et al. [28,29] proposed the Markov method to quantify the system reliability on the design of cooling systems. Cheng et al. [32] proposed a robust optimal design based on minimized life-cycle cost 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. The advantages of the analytical approach include high accuracy and relatively fast computation speed. Its disadvantages are the inability to provide more detailed reliability information. For example, only the average steady probability distribution of states can be provided. Moreover, in some situations, transitions between some states do not have Markovian characteristics and therefore cannot be modeled by standard Markov processes [33,34]. Compared to analytical methods, the Monte Carlo simulation is a powerful tool that can handle more conditions related to reliability evaluation (i.e., impact of severe weather, load variation) of systems [35,36]. Moreover, the Monte Carlo simulation approach is capable of providing more comprehensive results.

In order to achieve the minimum total life-cycle cost under various possible cooling load conditions considering the uncertainties of design inputs and reliability of the components in operation, a sequential Monte Carlo simulation-based robust optimal design method is proposed in this paper. In order to achieve the minimum total cost, trials of simulations on different cooling water flows and different number/size of cooling water pump and cooling tower are conducted to obtain the optimum cooling water system. A series of so-called uncertainty "scenarios" generated by Monte Carlo simulation, is used to obtain the average cooling load distribution of required accuracy and average "unmet cooling load". Several indices are developed for the convergence assessment of average cooling load and average "unmet cooling load". Average cooling load is used to evaluate the operation cost of the cooling water system. "Unmet cooling load" is used to evaluate the availability risk cost of the cooling water system.

2. Optimization objective of the robust optimal design method

Fig. 1 shows the schematic of a cooling water loop. Identical constant-speed pumps are used to circulate the cooling water through the entire system and the pumps are assumed to work at the rated power. Identical cooling towers are used to reject the heat load to the ambient. Variable speed fans are used in the cooling towers.

In the cooling water loop, the energy balance is shown in Equations (1) and (2).

$$CL + Q_{compression} = \sum_{i=1}^{n} m_{fluid} \cdot c_{fluid} \cdot \left(T_{fluid,in} - T_{fluid,out}\right) \quad (1)$$

$$Q_{compression} = CL/COP_{chiller} \quad (2)$$

where, CL is cooling load, $Q_{compression}$ is heat of compression, m_{fluid} is the cooling water flow rate, c_{fluid} is the specific heat of water, $T_{fluid,in}$ is the return cooling water temperature, $T_{fluid,out}$ is the supply cooling water temperature.

The total heat load rejected by cooling towers is determined by building cooling load and the COP of chillers. Under a given range (i.e. the temperature difference between the supply cooling water temperature and return cooling water temperature) and approach (i.e. the temperature difference between supply cooling water temperature and wet-bulb temperature of inlet air), the design cooling flow rate is determined by the total heat load.

The objective of the proposed method is to ensure that the cooling water system operates at high efficiency over the entire cooling season and achieve the minimum total cost considering uncertainties of inputs and reliability of system components in operation. The total cost (TC_n) consists of annualized capital cost (CC_n), annual operation cost (OC_n) and annual availability risk cost (RC_n). Annualized capital cost includes the expense in purchasing/

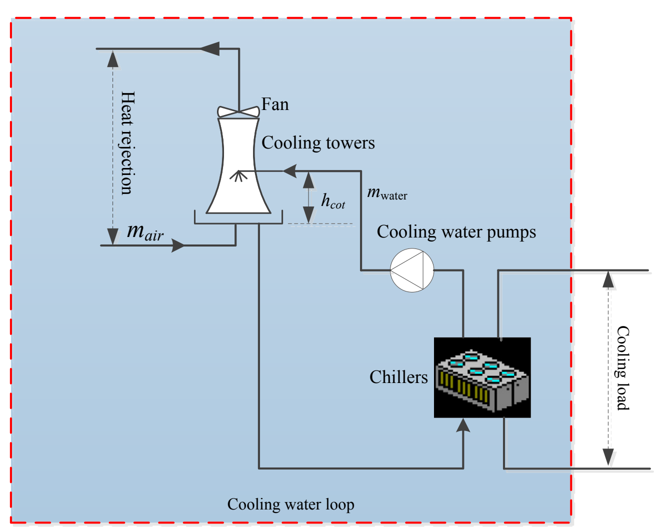

Fig. 1. Schematic of a cooling water loop.

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