ARTICLE IN PRESS

Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Probabilistic approach for uncertainty-based optimal design of chiller plants in buildings ☆

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HIGHLIGHTS

- A wide range of uncertainties is generated by Monte Carlo simulation.
- A new method is proposed to determine the minimum simulation number.
- An optimization is conducted to select the best configuration of chiller plant.
- The total cost is reduced significantly compared with the conventional design.
- This method can be automatically conducted with computation efficiency.

ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form 12 October 2015
Accepted 13 October 2015
Available online xxxx

Keywords:
Probabilistic approach
Uncertainty-based optimal design
Chiller plant
Simulation number
Energy efficiency

ABSTRACT

Conventional design of chiller plant 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 even a perfectly designed chiller plant could be very significantly oversized in actual operation and it thus causes significant energy wastes. In this paper, an uncertainty-based optimal design based on probabilistic approach is proposed to optimize the chiller plant design. It ensures that the chiller plant operate at a high efficiency and the minimum annual total cost (including annual operational cost and annual capital cost) could be achieved under various possible cooling load conditions, considering the uncertain variables in cooling load calculation (i.e., weather conditions). On the premise of determining the minimum sufficient number of Monte Carlo simulation, this method maximizes the operating COP (coefficient of performance) and minimizing the annual total cost. A case study on the chiller plant of a building in Hong Kong is conducted to demonstrate the design process and validate the uncertainty-based optimal design method.

1. Introduction

The building sector is the largest energy consumer in most countries and regions worldwide, especially in the metropolis such as Hong Kong [1,2]. In commercial buildings, about 40–60% of the total electricity consumption is consumed by the heating, ventilation and air-conditioning (HVAC) systems [3]. Among all HVAC components and equipment, chiller plant is usually the major energy consumer, accounting for up to 50% of the total energy consumption of the entire HVAC systems [4]. It is found that a significant saving of chiller energy can be achieved by optimal design and energy efficient operation [5,6].

The sizing and selection of chiller plants play the most important role in determining the energy performance of the HVAC systems [5]. The conventional design of chiller plant, proposed by ASHRAE [7], is usually based on sizing the components individually to meet a peak duty at a nominal operating point. Due to the inevitable uncertainty of weather data, indoor occupants and internal heat gain, designers tend to select a larger capacity 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 [8,9]. This may result in significant oversizing of chiller plant and thus a large amount of energy wastes because the actual operating conditions are seldom the same as the design condition [10]. Oversizing of chiller plants is usually encountered as a result of cooling load calculation method, predefined weather data, and internal heat-gain criteria [11,12]. Some measures, such as using a detailed

☆ This paper was presented at the 7th International Conference on Applied Energy (ICAE2015), March 28–31, 2015, Abu Dhabi, UAE (*Original paper* title: "Robust optimal design of chiller plants based on cooling load distribution" and *Paper No.:* ***447***).

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http://dx.doi.org/10.1016/j.apenergy.2015.10.097
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simulation method, statistic weather data, model calibration and even the experiments, have been recommended to reduce the oversizing problems to a certain degree caused by uncertainties [8]. However, these methods cannot help to minimize the oversizing due to the adoption of conservative criteria for estimating the cooling loads of buildings.

Different from the early design methods which only address the peak cooling load of selected design day, some studies also have taken part load conditions into account in order to achieve a high efficiency in most of operating time of chiller plants [13,14]. There are several approaches available to improve the energy performance of chiller plants under part load conditions since such conditions frequently occur throughout the entire cooling season [15]. In order to improve the systems PLR (part load ratio) that impacts the COP strongly, optimal sequence control is considered as an effective approach for the chiller plant with multiple chillers [16–19]. When the actual cooling load falls down from the peak duty, some of the chillers can be shut down so that each of the operating chillers can operate at a relatively higher PLR. Another important approach to ensure the performance of a chiller plant at high level is to use high efficiency chillers, particularly the chillers having good performance characteristics even under part load conditions [20]. For instance, variable-speed chillers may be employed to improve the energy efficiency when the chiller plant operates at part loads [21–24]. In addition, some studies show that the high COP of chiller plants can also be achieved by using hybrid chillers with different types of compressors or different energy sources, which can ensure all operating chillers within the optimum loading ranges [25].

When the part load conditions are considered in conventional optimal chiller design methods, they are typically based on the annual cooling load under the predefined conditions, which is commonly subject to a deterministic model-based simulation [26,27]. The system may achieve a satisfactory performance when the actual operating conditions are the same or similar as the predefined conditions. However, when the actual conditions are different from predefined conditions caused due to various uncertain factors, the chiller plant is very likely to operate at a low efficiency [27,28]. In order to address the problem caused by uncertainties, many researchers attempted to make the design to be more flexible, resilient and sustainable to achieve high operating performance under various load conditions [29,30]. Several studies have taken the impact of uncertain variables into account when evaluating the chiller plant performance throughout the entire cooling season. Aaron and Li presented an analysis on a CCHP (combined cooling, heating and power) system model considering uncertainties of inputs and models [31,32]. Case studies under different operating strategies were conducted to investigate the significance and sensitivity of uncertainties in predicting the CCHP system performance. Zhou [33] proposed a two-stage stochastic programming model for the optimal design of distributed energy systems, which uses genetic algorithm to perform the search in the first stage and Monte Carlo simulation to deal with uncertainties in the second stage. Burhenne [34] developed a Monte Carlo based methodology for uncertainty quantification to combine the building simulation and the cost-benefit analysis. However, the above studies have recognized and analyzed the impact of uncertainties on system performance, but they did not consider or propose effective approaches to overcome or reduce these impacts, which is the most important for improving the operating efficiency and robustness since uncertainties exist inevitably.

In order to achieve more flexible, resilient and sustainable design of the chiller plants, a cost related uncertainty-based optimal design method is proposed in this paper. It can ensure high chiller performance and achieve the minimum operation cost under various possible cooling load conditions, even though the load conditions deviating from the design conditions significantly due to various uncertainties of design information (i.e., weather conditions and number of occupants). In contrast to previous research, a probabilistic approach, which contains a wide range of so-called uncertainty "scenarios" generated by Monte Carlo simulation, is used for evaluating the performance of uncertainty-based optimal design. A statistical method is proposed to determine the number of Monte Carlo simulation for computational efficiency and accuracy. This design is based on two statistical principles, i.e., a maximization of the expected COP and a minimization of the expected value of the annual total cost. Meanwhile, an uncertainty-based optimization is conducted to identify the best configuration of number, sizes and types of chillers to achieve high operating efficiency and minimum total cost (including the operational cost and capital cost) under any cooling load conditions. Section 2 describes the concept of uncertainty-based optimal design in the HVAC domain. Section 3 presents the method of the uncertainty-based optimal design for chiller plants. Section 4 shows a case study on the uncertainty-based optimal design of the chiller plant of a building in Hong Kong. The last section draws the conclusion.

2. Concept of uncertainty-based optimal design

2.1. Uncertainties in HVAC field

Uncertainty is a term used to encompass many concepts [35]. It has been defined as a degree of ignorance [36], a state of incomplete knowledge [37], insufficient information [38], or a departure from the unattainable state of complete determinism [39]. In structure field, the various sources and categories of uncertainty identified in the literature can be classified into four categories [40]: epistemic uncertainty, variability, linguistic uncertainty [41] and decision uncertainty [42]. Epistemic uncertainty is the uncertainty associated with imperfect knowledge, which could be reduced by additional research and observation, i.e. model calibration and realistic data [43]. Variability is the uncertainty associated with diversity or heterogeneity, which cannot be minimized or even eliminated with additional research or observation [44,45]. Considering the classification in structure field [40], HVAC fields contain epidemic uncertainty and variability only, and linguistic uncertainty and decision uncertainty are not considered in this study.

According to engineering practice, the uncertainties in the HVAC field could be divided into two types, including design uncertainties and operation uncertainties. Fig. 1 presents an outline of uncertainties in the HVAC domain. Operation uncertainties mainly consist of information uncertainty and system reliability. This paper considers the design uncertainties only. Design uncertainties are mainly related to the cooling load uncertainty since the selection and sizing of HVAC subsystems (i.e., chillers, pumps, AHUs and cooling towers) mainly depend on the distribution of the annual cooling load. Cooling load uncertainty consists of the epidemic uncertainty and variability only. Variability mainly consists of the number of occupants and weather conditions, which cannot be minimized or even eliminated with additional research or observations. As for epidemic uncertainty, it concerns heat transfer performance of building envelopes and efficiency of air-conditioning equipment, which could be minimized and narrowed with additional research and observations, i.e. model calibration, realistic data and even correction factor.

2.2. Concept of uncertainty-based optimal design

Optimal design in HVAC field guarantees the optimization over predefined conditions (without considering the uncertainties)