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Probabilistic optimal design and on-site adaptive commissioning of building air-conditioning systems concerning uncertainties

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Abstract

Sizing of building air-conditioning systems is a critical issue in design practice concerning the building energy consumption in operation and risk of being undersized. In current practice, chillers and pumps are often oversized due to the rough consideration of uncertainties using safety factor to avoid the risk of being undersized, which results in significant energy waste in operation. In addition, the current design and commissioning do not provide means and flexibility for the air-conditioning systems to minimize their energy consumption when the systems are found oversized in operation. This paper presents a novel design and commissioning approach, consisting of probabilistic optimal design and on-site adaptive commissioning, for building air-conditioning systems to maximize their energy savings in operation. The probabilistic optimal design of an air-conditioning system involves two parts. One is probabilistic optimal design of chillers considering uncertainties, one is probabilistic optimal design of water circulation system considering uncertainties and the flexibility of on-site adaptive commissioning. Monte Carlo simulation is used to quantify uncertainties in system design and operation process. The on-site adaptive commissioning method has alternative commissioning schemes developed to maximize the energy saving based on the actual situation. A case study is performed to test and validate this new design and commissioning approach. Results show that about 20% energy saving could be achieved when the system is oversized by 20%, compared to conventional design and commissioning methods.

Keywords: Probabilistic optimal design; uncertainty analysis; adaptive commissioning; air-conditioning system; building energy saving

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1. Introduction

Buildings account for up to 40% of the energy end use in most developed countries. In Hong Kong, this percentage is even up to 80% (of the total energy consumption) [1-2]. Among the building energy consumers, the heating, ventilation and air-conditioning (HVAC) systems in buildings often take up over 50% [3]. Therefore, the air-conditioning system is one of the key targets for action to save energy and reduce carbon emissions in buildings.

1.1. Conventional design and commissioning

Conventional design of chillers: The conventional design of chiller plant, proposed by ASHRAE [4], is usually sizing the chillers to meet the peak load demand under the preset design condition (such as weather and internal gains). And a safety factor is usually assigned to the peak load demand to get a larger design capacity to reduce the risk of being undersized. This may result in significant oversizing of chiller plant and thus a large amount of energy wastes [5].

Conventional design and commissioning of water circulation systems: The conventional design of water circulation systems often follows standard procedures, as specified in CIBSE Guide C [6] and ASHRAE Handbook [4]. The pump with intersection of design flow and design head on pump curve at or close to the best efficiency point is usually chosen [7]. A larger value of design head is often considered by multiplying the pressure head of the worst circuit by a safety factor to avoid of being undersized. However, these systems are usually found oversized in practice, which leads to higher cost and energy consumption [8]. An important engineering practice to mitigate the oversizing problem is the use of commissioning valves, which are installed to ensure pumps work at the design condition (with rather high efficiency) [9]. Better design and commissioning method considering the uncertainties need to be developed to mitigate the oversizing problem and maximize energy saving.

1.2. Uncertainty analysis on buildings

Recently, simulation methods are studied by more and more researchers to size energy systems more precisely by quantifying uncertainties [10-12]. Sten de Wit and Augenbroe [10] analyzed the influence of uncertainties in building design. Cheng et al. [11] proposed a robust optimal design of pump systems by considering uncertainty and reliability. An optimal design method was suggested for district cooling systems by Gang et al. [12] by quantifying uncertainties in design inputs. Compared to conventional design methods that only consider a certain design state, the new design methods concerning uncertainties consider much more potential scenarios probabilistically, enabling risk-based decision rather than sizing systems blindly with large safety margin, which always leads to excessive oversizing [8].

1.3. Outline and innovation of this study

In this paper, a new concept/approach of probabilistic optimal design and on-site adaptive commissioning for air-conditioning systems is proposed. The probabilistic optimal design of an air-conditioning system consists of two parts. One is probabilistic optimal design of chillers considering uncertainties, the other is probabilistic optimal design of water circulation system considering uncertainties and the flexibility of on-site adaptive commissioning. Monte Carlo simulation is used to quantify uncertainties in system design and operation process. The on-site adaptive commissioning method has alternative commissioning schemes developed to maximize the energy saving based on the actual situation. A case study is conducted to test and validate this new design and commissioning approach.

2. Concepts of the proposed probabilistic optimal design and on-site adaptive commissioning

Concept of probabilistic optimal design: The aim of the probabilistic optimal design is to achieve the best design option that ensures the system with the capability to operate at relatively high efficiency at various possible conditions even though the working conditions deviate far away from design conditions. Unlike current design practices that simply use experience-based “safety factors” to handle uncertainty issues, the probabilistic design method considers the impact of uncertainty in a quantitative way.

Concept of on-site adaptive commissioning: On-site adaptive commissioning is the process of identifying the proper pump-load matching and balancing water flowrate based on the actual on-site situation in order to maximize the pump energy saving while achieving the expected design flow. Unlike the conventional commissioning to make pumps to work at the design condition by throttling, on-site adaptive commissioning keeps throttling as little as possible to reduce the addition of unnecessary pressure head. Pump-load matching with fewer or smaller pumps are identified and adopted to meet the flow requirement at the reduced pressure head, as shown in Fig.1.

Concept of probabilistic optimal design for on-site adaptive commissioning: The probabilistic optimal design for on-site adaptive commissioning proposed provides the pump systems with the capability and flexibility to achieve maximized energy saving. Multiple commissioning intervals are considered in the possible oversizing range quantified by uncertainty analysis, in order to fully utilize the opportunities of energy saving and minimize the risk of achieving reduced pressure head. The adaptive commissioning schemes, as shown in Fig.2, can be provided by designing (selecting) the pumps properly. When the actual pressure head (P_{act}) is within the interval between P_D and P_B (not including P_B), conventional commissioning is conducted and the system is balanced at point D. When the actual pressure head is within the interval between P_B and P_A (not including P_A), lower throttling can be made and the system is balanced at point B to maximize energy saving. If the actual pressure head is at or lower than the estimated pressure head P_A, the best adaptive commissioning point is point A.

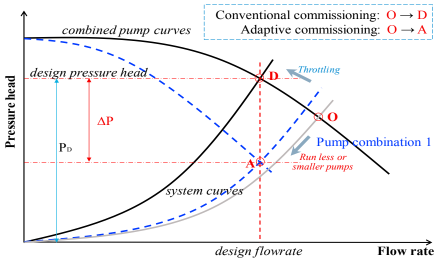

Fig. 1. Flow balancing of conventional commissioning and adaptive commissioning

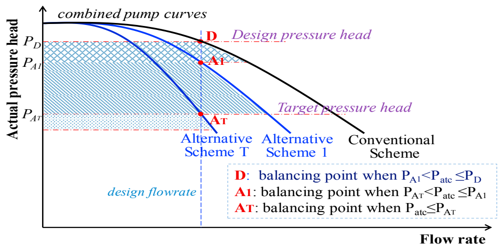

Fig. 2. Adaptive commissioning schemes at different commissioning intervals

3. Probabilistic optimal design and on-site adaptive commissioning for air-conditioning systems

3.1. Outline of the proposed probabilistic design and adaptive commissioning

As shown in Fig.3, the main differences between the current procedure and the proposed procedure for system design & commissioning are their different methods to handle uncertainties. In the current practices, uncertainties are considered in the design stage using experience-based “safety factors” and “standbys”. Test & commissioning (T&C) is only a “fixed” stage to realize the design conditions. In the proposed “design & commissioning” procedure, T&C and design are integrated as a whole process. Uncertainties are considered at the design stage with quantitative analysis and the design of pump systems considers the flexibility of T&C. In the T&C stage, the best T&C scheme among all possible design options is identified and then implemented.

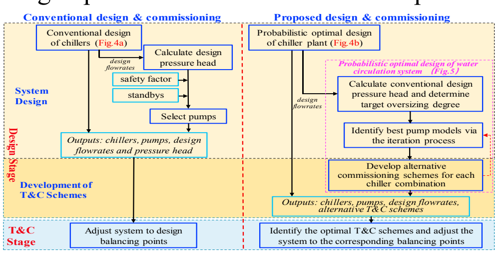

Fig. 3. Comparison of current and proposed “design & commissioning” procedures

3.2. Probabilistic optimal design of chillers concerning uncertainties

The proposed probabilistic design method for chillers can be implemented according to the procedures as shown in Fig. 4. First, uncertainties in design inputs are identified and quantified using Monte Carlo method [13]. The distribution of cooling load is obtained. Then the searching range of total cooling capacity of chiller plant is determined based on the cooling load distribution. Finally, different numbers/sizes of chillers are tried to obtain the optimal capacity and configuration of chiller plants with the minimum life cycle cost.

3.3. Probabilistic optimal design for on-site adaptive commissioning of water circulation systems

The probabilistic optimal design of water circulation/pump systems follows the procedure as shown in Fig.5. The conventional design pressure head is first calculated based on the conventional design method [4,6]. Then all uncertainties in pressure head calculation model and system construction are identified and quantified. Monte Carlo method is adopted to generate the actual pressure head probability distribution. According to the probability distribution of the actual pressure head, a “target pressure head” is determined, which has a probability above a preset level (within a given confidence level, such as 68% in this study). The associated “target oversizing degree” of pumps is obtained accordingly. Then, suitable pumps are selected for fulfilling the needs of both conventional design condition and the situation under the target oversizing degree. Among the suitable pumps, the pump with the minimum average energy consumption under presumed commissioning intervals/conditions are finally identified as the optimal one.

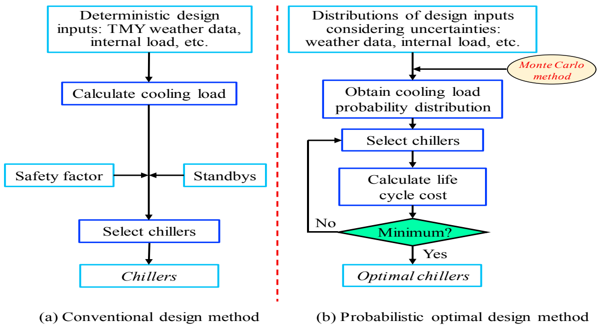

Fig. 4. Probabilistic optimal design method and conventional design method for chillers

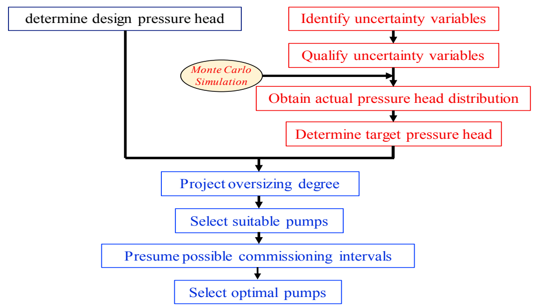

Fig. 5. Procedures of probabilistic optimal design method for water circulation systems

3.4. Development of on-site adaptive commissioning schemes

The presumed commissioning intervals are fine-tuned and optimized based on performance curves of selected optimal pumps and the cooling load profile, in order to provide maximum energy savings under all possible actual conditions while satisfying the requirement of water flowrate. Different pump combinations for different commissioning intervals are prepared and ranked at design stage, based on the flow requirement and pump energy consumption. The suitable combinations are selected, at the commissioning stage, based on the actual pressure head of the water loops concerned. Then, the pump-chiller combinations keep unchanged and are controlled automatically during operation stage.

4. Case study and results

A building in The Hong Kong Polytechnic University is chosen as the reference building for the case study. The design of its chillers and cooling water system is used to demonstrate and validate the proposed method.

4.1. Results of probabilistic optimal design for chillers

The uncertainties in weather data, occupancy density and infiltration flow rate are quantified. After 780 times of Monte Carlo simulations, the distribution of the cooling load at the peak hour is obtained as shown in Fig.6, together with the design capacities corresponding to different unmet hours as shown in Fig.7. Based on “50 unmet hours” specified in ASHRAE, the total design capacity of chillers is determined as 10.8 MW, corresponding to 600L/s of cooling water flow rate. Different sizes and numbers of chillers are tried. Eventually, the configuration of 5 large chillers (1800kW) and 2 small chillers (900kW) is identified as the optimal chiller option with the minimum life cycle cost.

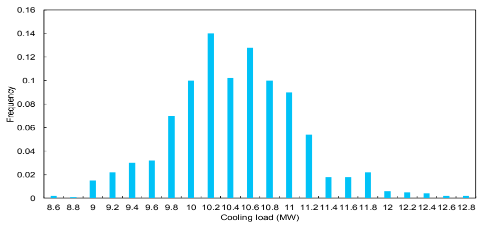

Fig. 6. Distribution of cooling load at the peak hour

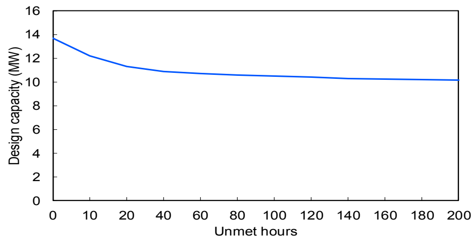

Fig. 7. Design capacity of cooling system at different unmet hours

4.2. Results of probabilistic optimal design for cooling water system

Based on the required cooling flow rates of chillers, the conventional design pressure head is calculated to be 239kPa by considering a safety factor of 1.1. Monte Carlo simulation is then used to generate the actual pressure head probability distribution profile as shown in Fig.8. The target pressure head is determined as 179kPa at the cumulative probability of 0.4 and with 25% oversizing degree. Pumps which meet the requirements introduced in Section 3 are searched from the available pump data base from a manufacturer [14]. Two models meet the selection requirements for the large pump, and three models meet the selection requirements for the small pump. 5 commissioning intervals are presumed based on the determined oversizing degree, i.e. 0%-10%, 10%-15%, 15%-20%, 20%-25% and over 25%. Mean energy consumption at the presumed commissioning points for each pump option is calculated and compared. At last, the optimal models for the large pump and the small pump are identified, respectively, as shown in Fig.9. Three large CSD pumps, five small pumps (including three CSD pumps and two VSD pumps) are eventually selected for the cooling water system.

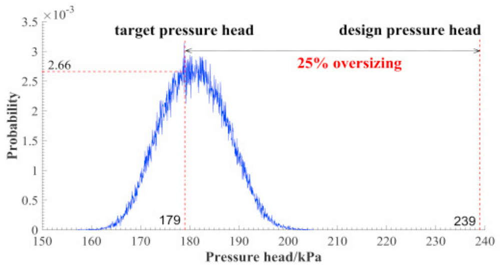

Fig. 8. Probability distribution of actual pressure head and projected oversizing degree

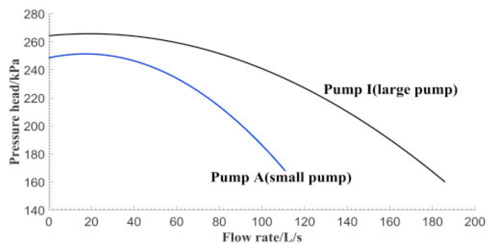

Fig. 9. Performance curves of selected optimal pumps

Table 1. Adaptive commissioning schemes and maximum energy saving (%) for different oversizing degrees.

Operating chiller combinations	Oversizing degree (OD)							
	0% ≤OD<10%		10%≤OD<15%		15%≤OD<20%		20%≤OD	
1S	1S	-1.3	1S(VSD)	3.9	1S(VSD)	8.8	1S(VSD)	14.4
1L	1L/2S	-2.4	2S(VSD)	0.6	2S(VSD)	5.7	1S	21.2
L+S	L+S/3S	-2.0	2S	5.2	1L/2S	18.7	1L	17.4
2L	2L/L+2S	-2.4	L+S	4.3	L+S	0.7	2S	21.2
2L+S	2L+S/L+3S	-2.2	2L	5.0	3S/2L	10.2	L+S/3S	18.9
3L	3L/2L+2S	-2.4	L+2S/4S	12.2	2L/L+2S	17.8	3S/2L	16.4
3L+S	3L+S/2L+3S	-2.2	2L+S/L+3S	11.6	4S/2L+S	14.3	L+2S/2L+S	19.6
4L	3L+2S/2L+4S	-3.0	3L/2L+2S	10.4	L+3S/3L	12.7	4S/2L+S	21.2
4L+S	3L+3S/2L+5S	-2.8	L+4S/3L+S	9.9	3L/2L+2S	18.1	L+3S/3L	19.9

4.3. Adaptive commissioning schemes

0%-10%, 10%-15%, 15%-20% and over 20% oversizing are proven to be the best commissioning intervals which can be satisfied by the optimal pumps selected based on the available pumps. Only oversizing up to 20% can be considered properly. For different combinations of operating chillers, the best commissioning schemes for different pressure head intervals can be identified to satisfy the flow requirements and achieve maximized energy saving as shown in Table 1. The second best schemes are also identified and listed in the table, which can be used in case of pump failure. The energy savings of the proposed design within different commissioning intervals are also analyzed and compared with the conventional design as shown in Table 1. It can be seen that significant energy savings (14.4%-21.2% corresponding to over 20% of oversizing degree) can be achieved using the proposed design and commissioning method except the case when conventional commissioning needs to be conducted.

5. Conclusions

A novel design and commissioning approach, consisting of probabilistic optimal design method and an on-site adaptive commissioning, is developed for building air-conditioning systems in this study. The probabilistic optimal design of an air-conditioning system consists of two parts. One is probabilistic optimal design of chillers considering uncertainties, the other is probabilistic optimal design of water circulation system considering uncertainties and the flexibility of on-site adaptive commissioning. The on-site adaptive commissioning method has alternative commissioning schemes developed to maximize the energy saving based on the actual situation. A case study is conducted to test and validate this new design and commissioning approach.

Based on the results of the case study, conclusions can be made as follows. The probabilistic optimal design method for chillers can determine the design capacity based on users' requirements and size the chillers to achieve minimum total cost, while the conventional design method has large probability of oversizing. The probabilistic optimal design and on-site adaptive commissioning approach for water pump systems are practically applicable and can achieve significant energy saving (about 20% maximum saving corresponding to over 20% oversizing degrees) compared to conventional design and commissioning.

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