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Probabilistic optimal design concerning uncertainties and on-site adaptive commissioning of air-conditioning water pump systems in buildings

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HIGHLIGHTS

- An optimal design and commissioning approach is proposed for constant flow systems.
- The optimal design concerns uncertainties of design calculation and construction.
- The optimal design provides the feasibility for on-site adaptive commissioning.
- Multiple commissioning schemes are developed for possible oversizing degrees.
- About 20% energy saving can be achieved under 20% pump oversizing.

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ABSTRACT

Sizing of air-conditioning water pump systems in buildings is a critical issue in design practice concerning the pump energy consumption in operation and risk of being undersized. As a result, significant energy is often wasted in operation due to oversizing to avoid the risk of being undersized. In current practice, throttling of commissioning valves are commonly adopted to push water flowrate (and pressure head) back to the design point no matter how much oversizing exists in a system. That partly mitigates the oversizing problem. This paper presents a novel approach consisting of probabilistic optimal design concerning uncertainties and on-site adaptive commissioning to further maximize energy savings of constant water flow pump systems. Minimized throttling is achieved by on-site adaptive commissioning, which reduces unnecessary pressure head and significant energy consumption. Pumps selected by the probabilistic optimal design can operate under both conventional design conditions and the projected possible off-design (oversized) conditions. The projection is based on the probability distribution of actual pressure head, which is estimated using Monte Carlo simulation by quantifying uncertainties in pressure loss calculation and system construction. Three case studies are conducted 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. The proposed approach also offers better energy performance in general compared to the designs all using variable speed pumps.

1. Introduction

Buildings account for up to 40% of the final energy in most developed countries, and the heating, ventilation and air-conditioning (HVAC) systems in buildings often take up over half of their total energy consumption [1]. In Hong Kong, buildings contribute over 80% of the total energy consumption and over 90% of electricity consumption respectively. The proportion of building energy consumption worldwide even keeps growing in response to the warmer climate, higher expectations for thermal comfort and more applications of computing and communication systems [2,3]. In typical air-conditioning systems of office buildings, the pumps contribute to the energy consumption of air-conditioning systems significantly, two to three times of their shares at design condition [4]. Therefore, the water pump system

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Nomenclature

a	safety factor
d	inner diameter of pipe (mm)
d_{os}	estimated oversizing degree (%)
d_0–d_3	coefficients
e_0–e_3	coefficients
$E(N)$	mean pump energy consumption (kPa)
g	acceleration of gravity (m/s^2)
H_{ele}	elevated height of cooling water from water level in water tank to spraying nozzle in cooling tower (m)
l	pipe length (m)
n	number of presumed commissioning intervals
N	pump energy consumption (kW)
N_{nov}	pump energy consumption at the conventional commissioning point (kW)
N_{ov}	pump energy consumption at the presumed commissioning point when system is oversized (kW)
P	pressure head (kPa)
P_A	target pressure head (kPa)
P_D	design pressure head (kPa)
ΔP_{eq}	pressure loss in system equipment (kPa)
ΔP_{noz}	pressure for nozzle spraying in cooling tower (kPa)
ΔP_{tot}	total pressure loss of the worst circuit (kPa)
Q	flow rate (L/s)
w	weighting of pump energy consumption at the conventional commissioning point
x	fraction of nominal speed
ζ	pressure loss factors of pipe fittings
η_{pump}	efficiency of pump (%)
η_{motor}	efficiency of motor (%)
η_{VFD}	efficiency of variable frequency drive (%)
λ	friction coefficients
ρ	density of water (kg/m^3)

is one of the key targets for action to save energy and reduce carbon emissions in buildings.

1.1. Conventional design and commissioning

The conventional design of water pump systems or water circulation systems often follows standard procedures, as specified in CIBSE Guide C [5] and ASHRAE Handbook (HVAC Systems and Equipment) [6], which normally involves determining design flow required, calculating design pressure head and selecting pumps. The design flow is determined by cooling load under the design condition and design temperature difference across the air-conditioning terminals or through the chillers. The design pressure head is determined by the total pressure loss through the critical water circuit, which is obtained by summing the pressure losses, together with a safety factor. The specific friction coefficients of pipes and pressure loss factors of typical pipe fittings as well as the range of safety factor are recommended in ASHRAE Handbook (HVAC Systems and Equipment) and CIBSE Guide C. Pumps are then selected from pump performance curves based on the design flow and design pressure head. Apart from the flow and pressure head required, pump efficiency is another factor to which designers will devote considerable attention. A good pump efficiency is very important to ensure a minimized pump energy consumption and, in many cases, to assure a minimized life cycle cost of buildings [7,8]. Therefore, the pump with intersection of design flow and design head on pump curve at or close to the best efficiency point would be chosen for minimized energy consumption and operating cost [9]. An important engineering practice for water pump systems is the use of commissioning valves, which are installed to balance the flow among chillers and to increase pressure resistance to ensure pumps work at the design condition, i.e. design flowrate [4].

However, these water pump systems, designed using the conventional approach, are usually oversized in practice to reduce the risk of being undersized. More water flow can be provided by pumps than what needed in almost all practical systems which are designed properly according to design standards. This is mainly due to the needs to address the inherent uncertainties existing in the processes of system design and construction. Oversized pumps not only cost more initially, but also lead to significantly higher operating cost. It is reported that pump oversizing is estimated to account for 15% of the energy consumption of HVAC systems in UK [10]. In Hong Kong, the oversizing degrees of pumps in real systems are often as high as 30% based on the investigation of authors. Pumps with variable speed drive (VSD) can offer good energy saving potential to mitigate the problem caused by pump oversizing when the operation condition changes over a large range, such as the typical secondary chilled water loops. For a system with steady flow rates and pressure heads in operation (constant flow systems), pumps with constant speed drive (CSD) are preferred due to the higher maintenance costs/efforts and inherent efficiency losses of VSD pumps. According to common engineering practices and commissioning standards [11,12] for constant water flow systems with CSD pumps, commissioning valves are closed to some extent to create additional pressure resistance necessary to resume the design operating condition of pumps. It reduces the pump energy consumption but cannot avoid the energy waste due to the overestimated design pressure head. Some common modification measures for oversized CSD pumps were summarized by Mansfield [13] based on practical field experiences. For instance, if the design pressure head is more than 10% higher than the actual pressure head, remedying the oversized pumps by impeller trim could be considered. However, it might be very costly and impractical in practice. The best the designers can do at design stage is to make the best prediction by considering the uncertainties to mitigate the oversizing problem and enhance system efficiency.

1.2. Uncertainty analysis on buildings

Recently, simulation methods are studied by more and more researchers to size energy systems more precisely by quantifying uncertainty factors in the uncertain practical situations [14–25]. Sten de Wit and Augenbroe [26] analyzed the potential influence of uncertainties in building design. Cheng et al. [27] proposed a robust optimal design of pump systems to address the oversizing issue by considering uncertainties of models and design inputs as well as the reliability of system components in operation to achieve the minimized life cycle cost. As a commonly used method, Monte Carlo simulation method was adopted to treat the uncertainties. An optimal design method was suggested for district cooling systems by Gang et al. [28] by quantifying uncertainties in design inputs including outdoor weather, building construction and indoor conditions. Sun et al. [29] explored a novel HVAC system design method under uncertainties, which supported risk-based sizing to