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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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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.

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

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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)

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 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 meet the specified requirements of stakeholders. 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 [10].

1.3 Outline and innovation of this study

In this paper, a new concept/approach of probabilistic optimal design and adaptive commissioning for constant water flow systems is proposed. The interaction between system design and commissioning is built to fully explore the energy saving potentials. The probabilistic optimal design concerning uncertainties can provide feasibility and flexibility for on-site adaptive commissioning. Apart from the basic requirement for conventional design condition, the projected possible actual conditions concerned are also considered during pump selection. Monte Carlo simulation is adopted to estimate probability distribution of actual pressure head by quantifying uncertainties in system design and construction to project the possible actual pressure head. Adaptive commissioning schemes with less/smaller pumps and minimized throttling are developed for different possible pressure heads that might be practically achievable eventually. Three case studies are conducted to test and validate this new design and commissioning approach.

2. Concept of probabilistic optimal design concerning uncertainties and on-site adaptive commissioning

Chilling water systems typically consist of two sub-systems (chilled water system and condenser cooling water system) as shown in Fig.1. The chilled water system including constant flow primary and variable flow secondary loops is the most common option for medium and large chilling systems today. As a common option, the pumps in each loop are grouped and connected in parallel to serve the chillers, which are also connected in parallel. This reduces the impact of pump/chiller failures and enhance the system reliability. The cooling/primary chilled water pump and chiller combination is conventionally designed on a one-to-one matching basis, i.e. one large pump to one large chiller, one small pump to one small chiller [30].

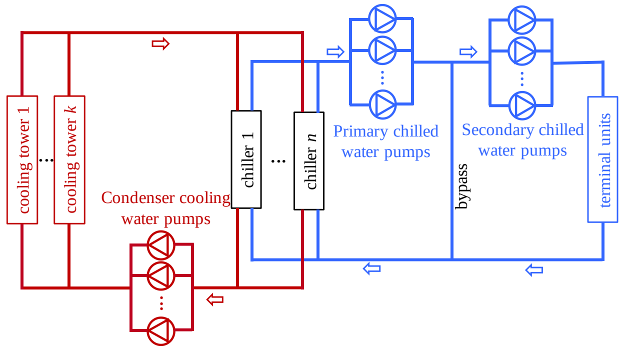

Fig 1. Schematics of a typical chilling water system

On-site adaptive commissioning proposed in this paper is the process of identifying the proper pump-load matching and balancing water flowrate in a water pump system 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.2.

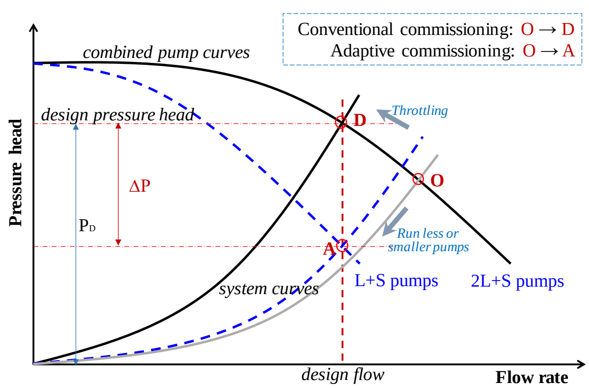

Fig 2. Flow balancing of conventional commissioning and adaptive commissioning

(Note: "L" refers to "large", "S" refers to "small")

On-site adaptive commissioning needs to be systematically considered and planned at design stage. The probabilistic optimal design for on-site adaptive commissioning proposed in this paper provides the pump systems with the capability and flexibility to achieve maximized energy saving together with associated adaptive commissioning schemes for different commissioning intervals.

Multiple commissioning intervals are considered in the possible oversizing range, in order to fully utilize the opportunities of energy saving and minimize the risk of achieving reduced pressure head. The pump design/selection takes the possibility and flexibility of commissioning into account by considering different possible pressure heads after the construction of a water pump system. The modeling and construction uncertainties are quantified in design stage and the possible commissioning intervals are selected accordingly. The adaptive commissioning schemes for selected commissioning intervals, as shown in Fig.3, are provided by 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.

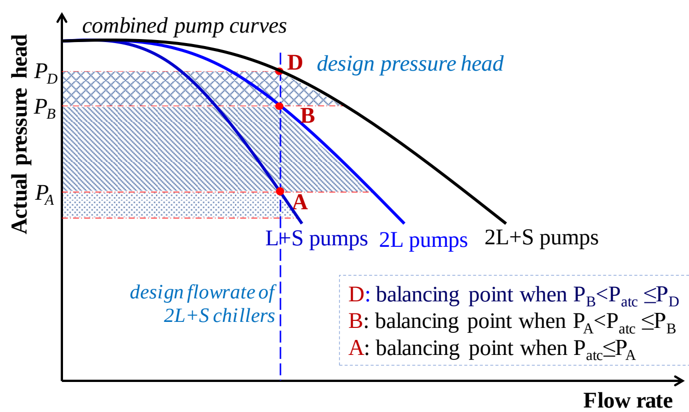

Fig 3. Adaptive commissioning schemes at different commissioning intervals

Compared to the conventional design and commissioning, which only contains one certain design condition for all potential circumstances, the probabilistic optimal design offers multiple balancing points to fulfill the flow requirement and achieve maximum energy saving at different possible pressure heads when the system is constructed and ready for test and commissioning. As lower throttling is made in the on-site adaptive commissioning, energy saving is achieved compared to the conventional design and commissioning.

3. Probabilistic optimal design for on-site adaptive commissioning

3.1 Design procedure

The optimal design follows the procedure as shown in Fig.4. The conventional design pressure head is calculated based on the conventional standard procedure [5-6]. Then all uncertainties in pressure head calculation model and system construction are identified and quantified. Monte Carlo simulation [31] method, as one of the most commonly used methods to treat uncertainties [32], is adopted to generate the actual pressure head probability distribution according to previous studies [27]. 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, i.e. 68%) and is therefore considered worth of being targeted by compromising the energy benefit and risk. The associated "target oversizing degree" of pumps is obtained accordingly. Then, pumps are selected for fulfilling the needs of both conventional design and the situation under the target oversizing degree. Various adaptive commissioning schemes are developed for the pressure head intervals associated to the selected balancing points between the design pressure head and the target pressure head.

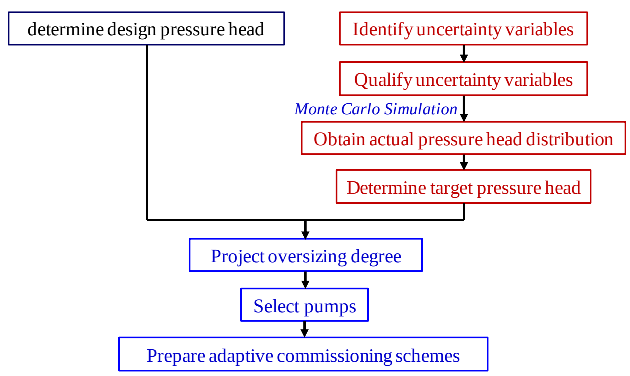

Fig 4. Procedure of probabilistic optimal design

3.2 Step 1: Determine design pressure head – conventional design

The conventional design condition is the fundamental requirement of the proposed optimal design in order to guarantee the capability of pumps to fulfill the local design standard/regulation. The design flow is the rated flow of chillers. The design pressure head is determined by the total pressure loss in the worst circuit, which can be obtained with Eq. (1). A safety factor (typical range: 1.1-1.3) is assigned to the calculated total pressure loss to finally determine the design pressure head according to the standard or regulation [5-6] as shown in Eq. (2). The reference values for most of the design inputs in Eq. (1) and Eq. (2) are given in the relevant standard/regulation, such as ASHRAE Handbook (HVAC Systems and Equipment) and CIBSE Guide C.

$$\Delta P_{tot} = \sum \left(\lambda_i \frac{l_i}{d_i} + \zeta_i\right) \frac{8000\rho {Q_i}^2}{\pi^2 {d_i}^4} + \sum \Delta P_{eq} + \Delta P_{noz} + 10 H_{ele} \quad (1)$$

$$P_D = a \Delta P_{tot} \quad (2)$$

where, P_D is design pressure head (kPa). ΔP_{tot} is total pressure loss of the worst circuit (kPa). a is safety factor. ρ is the density of water (kg/m^3). λ_i, ζ_i, l_i, d_i, and Q_i are friction coefficients, pressure loss factors of pipe fittings, length (m), inner diameter (mm) and flow rate (L/s) of pipe i, respectively. ΔP_{eq} is the pressure loss in system equipment such as condenser, evaporator and cooling coil (kPa). ΔP_{noz} is the pressure needed for nozzle spraying in cooling tower (kPa). H_{ele} is the elevated height of cooling water from water level in water tank to spraying nozzle in cooling tower (m). For chilled water systems, $\Delta P_{noz}=0$ and $H_{ele}=0$.

3.3 Step 2: Obtain actual pressure head probability distribution considering uncertainties

Uncertainties occur inherently at any stage from the calculation to system construction, which can cause rather large discrepancy between the actual pressure head (without throttling the commissioning valves) and the calculated pressure head. In order to determine the target pressure head, uncertainty analysis is conducted to quantify the probability distribution of pressure head actually achieved by system at the design flowrate when the system is constructed ready for test and commissioning.

3.3.1 Identification and quantification of uncertainties

Factors, which lead to the uncertainties, should be identified first, in order to quantify the uncertainties. Uncertainties can be caused by inaccurate formulation, lack or abundance of information, measurement tolerance, etc. [33]. In water pump systems, sources of uncertainties associated to the pressure head actually achieved can be classified into two categories, i.e. model uncertainties and construction uncertainties, as shown in Fig.5.

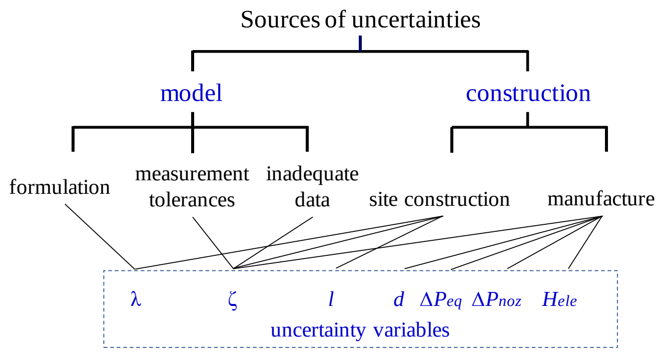

Fig5. Sources of uncertainties in pressure head prediction of water circulation loop

Model uncertainties: Model uncertainties refer to that exist in the parameters of models used for pressure loss calculation. Some model parameters are obtained from empirical formulas, such as friction coefficient, λ. The others are from experiment data directly, such as pressure loss factor, ζ. Uncertainties of formulas partially come from the processes of formulating themselves and partially come from the experimental data used. In all cases, the quality (tolerances) and quantity (adequacy) of experiment data cause uncertainties.

Construction uncertainties: Construction uncertainties refer to that caused by deviations of site-construction from design and the manufacturing tolerances of devices used. Manufacturing tolerances include pipe diameters and surface treatment, valves and other devices used in the water delivery circuits. For instance, the diameters (d) of pipes and the pressure drops of devices have tolerances from their design values. The tolerances of surface treatment and pipe fittings will cause the errors in selected parameters of models. Besides, modifications from design are often made in site construction due to various reasons or constraints such as unforeseen pipe collision and building structure modification, which can cause changes in the pipe length and use of fittings, etc.

It can be seen that the main uncertainty variables associated to the actual pressure head in water circulation systems are λ, ζ, l, d, ΔP_{eq}, ΔP_{noz}, and H_{ele}, as shown in Eq. (1). In order to quantify these uncertainty variables, distributions are used accordingly to describe the uncertainties based on uncertainty sources, as shown in Table 1. Normal distribution is used to describe uncertainties caused by model formulas, measurement tolerances and construction, such as friction coefficients, pipe size, pressure loss factors of various valves, etc. The uncertainties caused by inadequate data such as pressure loss factor of 90^o elbows, enlargement/reduction and flexible connectors are assumed to be subject to uniform distribution. It is worth noticing that each of the friction coefficient (λ) and pressure loss factors (ζ) has two sources of uncertainties, which are quantified separately and should be multiplied to quantify the overall uncertainties. The distribution types and values of uncertainties are determined referring to Ref. [27] and Ref. [28].

Table 1. Uncertainty quantification for variables associated to pressure loss calculation

Uncertainty variables			**Reference values for conventional design [5]**	**Uncertainty sources**	**Uncertainty description**	
					distribution	*values*
λ	friction coefficient		based on Haaland Equation	formula	normal	N(1,0.05)
				manufacture	normal	N(1,0.02)
ζ	enlargement		0.05-0.80	inadequate data	uniform	based on the case
				construction	normal	N(1,0.02)
	reduction		0.05-0.55	inadequate data	uniform	based on the case
				construction	normal	N(1,0.02)
	flexible connector		0.02-0.11	inadequate data	uniform	based on the case
				construction	normal	N(1,0.02)
	regulating valve		2.0	measurement tolerance	normal	N(1,0.05)
				construction	normal	N(1,0.02)
	check valve		2.0	measurement tolerance	normal	N(1,0.05)
				construction	normal	N(1,0.02)
	butterfly valve		0.1-0.8	measurement tolerance	normal	N(1,0.05)
				construction	normal	N(1,0.02)
	90^o elbow		0.2-1.0	inadequate data	uniform	based on the case
				construction	normal	N(1,0.02)
	tee	branch	4.5(d<20mm) / 3.0(d≥20mm)	measurement tolerance	normal	N(1,0.05)
				construction	normal	N(1,0.02)
		main passage	3.0	measurement tolerance	normal	N(1,0.05)
				construction	normal	N(1,0.02)
l	length		based on the design	site construction	normal	N(1,0.05)
d	inner diameter		based on the design	manufacture	normal	N(1,0.02)
ΔP_{eq}	pressure loss in equipment		offered by manufacturer	manufacture	normal	N(1,0.05)
ΔP_{noz}	pressure needed for nozzle spraying		offered by manufacturer	manufacture	normal	N(1,0.05)
H_{ele}	elevated height		offered by manufacturer	manufacture	normal	N(1,0.05)

3.3.2 Prediction of actual pressure head distribution

In principle, the actual pressure head of a water pump system is determined by the total pressure loss of the critical circuit, which is calculated using Eq. (1) in design. For cooling water systems, the overall pressure loss includes pressure drops in pipelines, pressure drops in pipe fittings, pressure drop in condenser, the pressure needed for nozzle spraying and the elevated height of cooling water from water tank to the nozzle. In chilled water systems, as close cycle systems, no height is increased after a complete circulation and no nozzles are needed. The pressure losses of pipelines, pipe fittings and equipment (i.e. evaporator and cooling coil or air handling unit) are the elements contributing to the overall pressure drop.

For a new water pump system, the pressure head is determined by the flow rate, friction coefficients of pipes, pressure loss factors of pipe fittings, pipe sizes, etc. In this study, the selection of chillers and design of pipeline systems are assumed to be completed, thus the flow rate in pipelines are fixed. The pressure head is then only influenced by uncertainties in the friction coefficients, pressure loss factors of pipe fittings (including enlargement, reduction, flexible connector, elbows, tees and valves), pipe sizes and pressure losses of devices. The uncertainties are quantified by different distributions according to their sources as described in Table 1. After sufficient sampling from the distribution of uncertainty variables being input into Eq. (1), the actual pressure head distribution can be generated by the Monte Carlo simulation [31].

3.4 Step 3: Estimate oversizing degree

The designer can then make risk-based selection of the target pressure head (P_A) using the predicted actual pressure head distribution. The estimated oversizing degree (d_{os}) can be then calculated with Eq. (3). The less risk stakeholders are willing to take, the larger the target pressure head and the smaller the possible oversizing degree would be selected, and less energy saving potential is taken into account.

$$d_{os} = \frac{P_D - P_A}{P_D} \times 100\% \tag{3}$$

where, P_A is the target pressure head (kPa). d_{os} is the estimated oversizing degree (%).

3.5 Step 4: Optimal selection of pumps considering possible oversizing

The optimal selection of pumps is achieved by two sub-steps: selection of potential pumps and selection of the best pump model among the potential pumps. The potential pumps should satisfy the needs of two operating conditions, and the best pump model is the one that offers the least average energy consumption at all possible commissioning points of concern.

Selection of potential pumps

In order to explore the maximum energy saving potential with adaptive commissioning, the pumps should satisfy two operating conditions. One is the conventional design condition, which is the basic requirement in case that the system is not oversized. The other one is the condition associated to the estimated oversizing degree. Besides, potential pumps selected should have relatively high pump efficiency over the range between the design pressure head and the target pressure head. In particular, the efficiency at the conventional design point should not be sacrificed significantly to ensure that the optimal design does not consume obviously more energy over that of the conventional design at the conventional design pressure head. The types, capacities and number of suitable pumps can be determined based on the following rules as shown in Table 2 and Table 3. It can be observed that one more pump is needed for the proposed design method compared to the conventional design. The optimal design method with "more" pumps can offer higher backup opportunities but might not significantly affect the capital cost as the total pump design capacities are the same. It is worth noticing that multiple pump models will usually be found in most cases.

Table 2. Rules for pump selection of probabilistic optimal design for adaptive commissioning

		Type	**Number**	**Capacity**	
				when $P=P_D$	*when* $P=P_A$
System with large and small chillers	Large pump	CSD	As recommended in Table 3	$Q=Q_{1L\ chiller}$	$Q=Q_{L+S\ chillers}$
	Small pump	CSD & VSD		$Q=Q_{1S\ chiller}$	$Q=Q_{1L\ chiller}$
System with identical chillers	Large pump	CSD & VSD	CSD: n-1 VSD:1	$Q=Q_{1\ chiller}$	$Q=Q_{2\ chillers}$
	Small pump	CSD	1	$Q=0.5Q_{1\ chiller}$	$Q=Q_{1\ chiller}$

Table 3. Recommended number of pumps for different chiller combinations using optimal design *vs* that using conventional design

Chiller combinations	Pumps by optimal design	Pumps by conventional design
3L+2S	2L+2S+2S(VSD)	3L+2S
4L+2S	3L+2S+2S(VSD)	4L+2S
5L+2S	3L+3S+2S(VSD)	5L+2S
5L	4L+1L(VSD)+1S	5L

Note: both back-up for chillers and pumps are considered, i.e. 3L+2S chillers have 1L+1S chillers for back-up.

<u>*Selection of the best pump model*</u>

Considering possible commissioning optimization in the range of pressure head between the design pressure head and target pressure head, several commissioning intervals and commissioning points are presumed, which is used for the final optimized pump selection. The pressure increment between the commissioning points is presumed to be 5% of the design pressure head starting from 10% of oversizing, typically in this study. Such assumption is made based on two facts:

- Conventional commissioning is a proper choice when oversizing degree is within about 10% because of significant energy saving is hard to be achieved by proposed adaptive commissioning method based on the authors' experience.
- The pump system with a reduction of pressure for about 5% normally has another optimal commissioning scheme (e.g. one smaller pump less).

The best pump model can be selected by comparing the mean energy consumptions of selected potential pump models at the presumed commissioning points, as described in Eq. (4).

$$E(N) = wN_{nov} + \frac{(1-w)(\sum N_{ov})}{n-1} \quad (4)$$

where, *E(N)* is the mean pump energy consumption (kW). N_{nov} is the pump energy consumption at the conventional commissioning point (kW). N_{ov} is pump energy consumption at the presumed commissioning point when system is oversized (kW). *n* is the number of the presumed commissioning intervals. *w* is the weighting of pump energy consumption at the conventional commissioning point, which can be selected based on the preference of the stakeholders. A large weighting indicates the high pump efficiency at the conventional commissioning point is more important in pump selection. In this study, w is selected as 0.4.

The energy consumption of pumps can be calculated by Eq. (5) – Eq. (9) [34-35]. Where, *N, g, P, and Q* are pump energy consumption (kW), acceleration of gravity (m/s^2), pressure head (kPa), and flow rate (L/s) respectively. x is the fraction of nominal speed. $d_0 - d_3$ and $e_0 - e_3$ are coefficients, which are obtained by polynomial regression based on manufacturers' pump performance data at the full speed operation. η_{pump} and η_{VFD} are the pump efficiency (%) and variable frequency driver efficiency (%), respectively. η_{motor} is the motor efficiency (%), which is regarded as a constant value of 93% in this study as used in Ref.[36].

$$\mathrm{N} = \frac{\rho g P Q}{10^7 \eta_{pump} \eta_{motor} \eta_{VFD}} \tag{5}$$

$$\mathrm{P} = d_0 + d_1 Q + d_2 Q^2 + d_3 Q^3 \tag{6}$$

$$\eta_{design} = e_0 + e_1 Q + e_2 Q^2 + e_3 Q^3 \tag{7}$$

$$\eta_{pump} = 1 - \frac{1-\eta_{design}}{x^{0.1}} \tag{8}$$

$$\eta_{VFD} = 0.451 + 1.6577x - 2.0869x^2 + 0.9334x^3 \tag{9}$$

3.6 Step 5: Development of on-site adaptive commissioning schemes

As described before, using the pumps finally selected, water flow requirements can be satisfied with fewer pumps and minimized throttling if pumps are oversized. Multiple commissioning points are considered between the design pressure head and target pressure head, in order to fully utilize the opportunities of energy saving and minimize the risk of achieving reduced pressure head. Corresponding multiple commissioning schemes are developed for different commissioning intervals, which are further optimized based on performance curves of selected pumps and the cooling load profile. The presumed commissioning intervals are fine-tuned and optimized to provide maximum energy savings under all operating chiller combinations while satisfying the requirement of the water flowrate. For instance, two commissioning intervals (i.e. 0%-10% and10%-15% oversizing) are pre-determined for optimal pump selection. With the selected optimal pumps, all or most of the operating chiller combinations are provided with more water flow than what are needed with the adaptive commissioning method at the commissioning points corresponding to 10% oversizing. If the system is commissioned to the points corresponding to 8% of oversizing, all chiller combinations are provided with water flow equal or close to what are needed. In this case, in order to maximize the energy savings of pumps, the commissioning intervals are fine-tuned to be 0%-8% and 8%-15% oversizing. Different pump combinations suitable 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 studies and results

4.1 Optimal design and adaptive commissioning of cooling water system - Case 1

The central chilling plant of a building in The Hong Kong Polytechnic University campus is under retrofitting, which is chosen as the system for this case study. This case study, involving the design of the condenser cooling water pump system, is conducted to test and validate the proposed probabilistic optimal design and on-site adaptive commissioning method. The condenser cooling water system serves five large chillers (one stand-by), each requesting 100 L/s of cooling water flow, and two small chillers (one stand-by), each requesting 50 L/s of cooling water flow, as shown in Table 4. At first, the design pressure head is calculated using the conventional approach. Then Monte Carlo simulation is adopted to generate the actual pressure head probability distribution profile. The target pressure head and associated oversizing degree are determined accordingly. Pumps are selected based on the conventional design pressure head and the target pressure head. The adaptive commissioning schemes are prepared for different possible oversizing degrees. Finally, the comparisons between the energy consumptions of the proposed design and the conventional design (all using CSD pumps) as well as the design all using VSD pumps are made to evaluate the feasibility of the optimal design and adaptive commissioning as well as the energy saving potentials.

Table 4. General information of water systems and chiller plants concerned in three case studies

Case	Water system	Chiller cooling capacity (kW)	Chiller number	Design flowrate (L/s)
1	Cooling water system	1800 (Large) 900 (Small)	5 (4+1) 2 (1+1)	100 50
2	Primary chilled water system	2286 (Large) 1190 (Small)	5 (4+1) 3 (2+1)	109.2 56.67
3	Cooling water system	1800 (Large)	5 (4+1)	100

4.1.1 Results of optimal design

Based on the required cooling flow rates of chillers, the design pressure head is calculated to be 239kPa with Eq. (1) and Eq. (2) by considering a safety factor of 1.1. Monte Carlo simulation is then used to generate the actual pressure head probability distribution profile by considering uncertainties in the inputs of Eq. (1) as shown in Table 1. By repeatedly sampling from uncertainty variables and inputting into the calculation model, the actual pressure head probability distribution is obtained as shown in Fig. 6. The target pressure head is determined as 179kPa at the cumulative probability of 0.4 and with 25% oversizing degree.

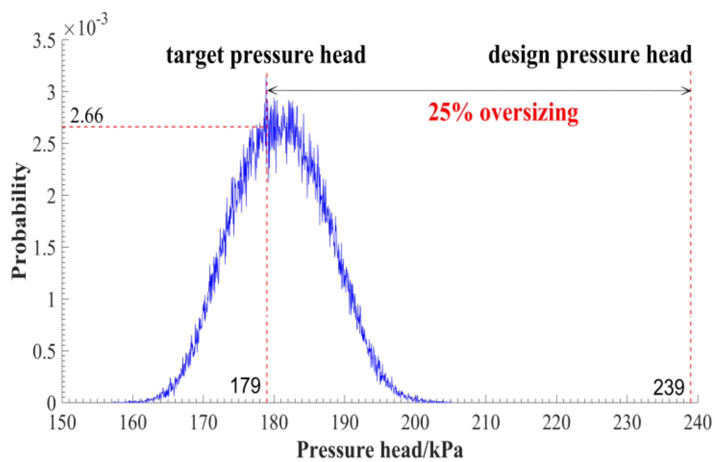

Fig 6. Probability distribution of actual pressure head and projected oversizing degree

Pumps which meet the requirements introduced in Section 3 are searched from the available pump data base from a manufacturer [37]. 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%. Detailed performance data of all the suitable CSD pumps at the presumed commissioning points are shown in Table 5. Mean energy consumption at the presumed commissioning points for each pump option is calculated and compared. From Table 3, it can be seen that the Option 1 for both large and small pumps consumes the least energy, and this option is therefore selected for both of them. Three large CSD pumps, five small pumps (including three CSD pumps and two VSD pumps) are selected for the condenser cooling water system. The pump curves of selected CSD pumps are shown in Fig.7.

Table 5. Suitable pump models for large and small pumps

	Option	Operation points				
		P (kPa)	Q (L/s)	η (%)	N (kW)	E(N)(kW)
Large pump	1	239	100	80	29.9	33.6
		215	138	85	34.9	
		203	150	84.5	36.0	
		191	161	84	36.6	
		179	169	82.5	36.7	
	2	239	100	77	31.0	34.9
		215	139	83	36.0	
		203	147	82	36.4	
		191	164	80.5	38.9	
		179	172	79	39.0	
Small pump	1	239	50	77.7	15.3	19.6
		215	80	82	21.0	
		203	89	81.8	22.0	
		191	98	81.6	23.0	
		179	105	79.6	23.6	
	2	239	50	73.5	16.2	20.3
		215	82	82.4	21.4	
		203	92	81.4	23.0	
		191	97	79.9	23.2	
		179	104	76.5	24.4	
	3	239	50	72.5	16.5	19.8
		215	81	82	21.2	
		203	87	82	21.5	
		191	94	81	22.2	
		179	100	78	22.9	

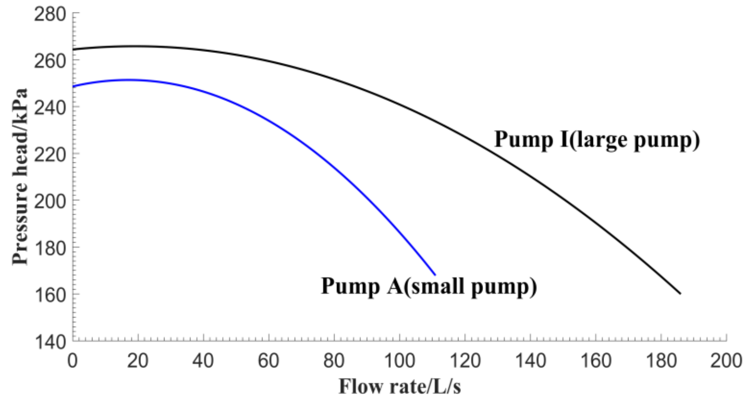

Fig 7. Pump performance curves of selected pumps

4.1.2 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 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 6. The second best schemes are also identified and listed in the table, which can be used in case of pump failure.

Table 6. Adaptive commissioning schemes for different oversizing degrees

operating chiller combinations	Oversizing degree (OD)			
	0% ≤OD<10%	10%⩽OD<15%	15%⩽OD<20%	20%⩽OD
1S	1S	1S(VSD)	1S(VSD)	1S(VSD)
1L	1L/2S	2S(VSD)	2S(VSD)	1S
L+S	L+S/3S	2S	1L/2S	1L
2L	2L/L+2S	L+S	L+S	2S
2L+S	2L+S/L+3S	2L	3S/2L	L+S/3S
3L	3L/2L+2S	L+2S/4S	2L/L+2S	3S/2L
3L+S	3L+S/2L+3S	2L+S/L+3S	4S/2L+S	L+2S/2L+S
4L	3L+2S/2L+4S	3L/2L+2S	L+3S/3L	4S/2L+S
4L+S	3L+3S/2L+5S	L+4S/3L+S	3L/2L+2S	L+3S/3L

When the system is less than 10% oversized, the conventional commissioning measure, throttling to the conventional design point, is adopted. When the system is oversized for 20% or more, the best commissioning point is 191kPa (corresponding to 20% oversizing) as shown in Fig. 8. In this case, one small CSD pump can provide the flow of one large chiller. Similarly, two small CSD pumps can provide the flow of two large chillers. One small chiller need one small VSD pump. One large chiller and one small chiller need one large CSD pump. The pumps used for all other operating chiller combinations can also be found in the table.

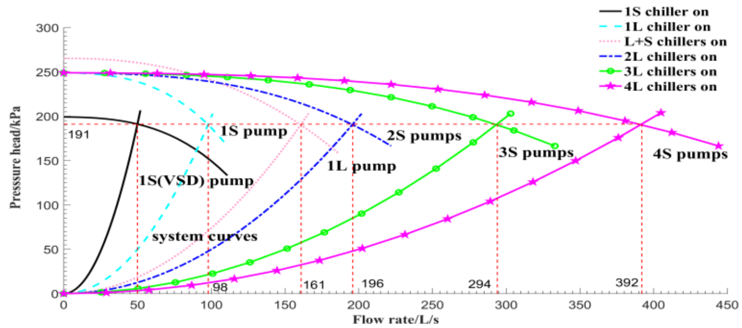

Fig 8. Flow balancing when system is oversized for 20% or more

When the oversizing degree is less than 20% but not less than 15%, the best commissioning point is 203kPa (corresponding to 15% oversizing). One large CSD pump just meets the flow requirement of one large chiller and one small chiller, and two large CSD pumps provide the flowrate of 300L/s, just meeting the need of three large chillers. Two small VSD pumps are needed for one large chiller since the increased flow of one small CSD pump is inadequate to satisfy the flow requirement while one large CSD pump consumes more energy with flow more than what is required. For four large chillers, one large CSD pump and three small CSD pumps is the best option as they consume least energy.

When the pump system is oversized for 10%-15% (not including 15%), the best commissioning point is 215kPa (corresponding to 10% oversizing) as shown in Fig. 9. One small VSD pump is the best option for one small chiller since one small CSD pump consumes more energy with more flow at the reduced pressure head. Two small VSD pumps are the best option for one large chiller. Two small CSD pumps are enough to provide the cooling water when one large and one small chillers are in operation. One large and one small CSD pumps can fully satisfy the need of two large chillers.

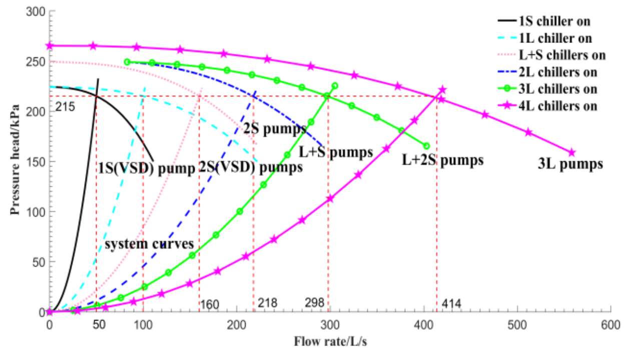

Fig 9. Flow balancing when system is oversized between 10%-15% (not including 15%)

Table 7 presents the energy savings of the proposed design within different commissioning intervals compared to conventional design using all CSD pumps as well as the design using all VSD pumps. Significant energy savings of the optimal design can be achieved except the case when conventional commissioning needs to be conducted. The larger the oversizing degree is, the more energy can be saved compared with conventional design due to that more pressure head is reduced. Compared to the conventional design using all VSD pumps, 14.4%-21.2% of energy can be saved when the system is commissioned to the commissioning point corresponding to 20% oversizing. Even 0.6%-12.2% of energy can be saved when the system is commissioned to the commissioning point corresponding to 10% oversizing. The optimal design also has advantages in energy saving compared to the design using all VSD pumps in most cases due to the decrease of VSD pump efficiency at reduced speed and significant efficiency loss of variable frequency drivers. In a few cases, the proposed design consumes more energy than the design using all VSD pumps. It is caused by the lower pump efficiency as a result of compromising to guarantee relatively high efficiency at other possible pressure heads. For instance, in the case the conventional commissioning is adopted on the system, 1.3%-3.0% more energy is used by the proposed design compared to conventional design. However, in this case, compared to the design all using VSD pumps, 1.6%-3.2% of pump energy is saved by the proposed design due to the efficiency loss of VSD driver.

Table 7. Energy saving (%) of optimal design compared to conventional all CSD and VSD designs

Operating chiller combinations \ benchmark	Oversizing degree (OD)							
	0% ≤OD<10%		10%≤OD<15%		15%≤OD<20%		20%≤OD	
	CSD	VSD	CSD	VSD	CSD	VSD	CSD	VSD
1S	-1.3	3.2	3.9	-1.7	8.8	-1.6	14.4	0.0
1L	-2.4	2.2	0.6	-7.5	5.7	-7.3	21.2	5.5
1L+1S	-2.0	2.6	5.2	-2.0	18.7	8.1	17.4	1.5
2L	-2.4	2.2	4.3	-3.6	0.7	-13.1	21.2	5.3
2L+1S	-2.2	2.4	5.0	-2.4	10.2	-1.9	18.9	3.1
3L	-2.4	2.2	12.2	5.0	17.8	6.4	16.4	5.3
3L+1S	-2.2	2.4	11.6	4.6	14.3	2.7	19.6	3.7
4L	-3.0	1.6	10.4	3.0	12.7	0.5	21.2	5.4
4L+1S	-2.8	1.8	9.9	2.7	18.1	7.0	19.9	4.1

4.2 Adaptive commissioning for the existing design of a primary chilled water loop - Case 2

This case study is based on the existing design of the primary loop of the chilled water system in another building in the same campus, which was designed by the consultant using conventional design approach. The design is chosen for this case study in order to test and evaluate the energy saving potential of the adaptive commissioning on the system using conventional design. The chilling plant consists of five identical water-cooled chillers (one stand-by) with the design chilled water flow rate of 109.2L/s each and three identical air-cooled chillers (one stand-by) with the design chilled water flow rate of 56.67L/ each, as shown in Table 4. The air-cooled chillers are installed for the case of failure in water supply. Therefore, the energy efficient operation only concerns the water-cooled chillers. The design pressure head of the primary loop for water-cooled chillers is 330kPa, five identical large CSD pumps are selected to serve the water-cooled chillers, each providing 109.2L/s of water flow at 330kPa. Three identical small CSD pumps are selected to serve the air-cooled chillers, each providing 56.67L/s of water flow at 330kPa. One large CSD pump is converted to VSD pump by adding a frequency inverter according to the suggestion of the authors who act as the energy advisors in this retrofitting project. The pump curves are shown in Fig.10.

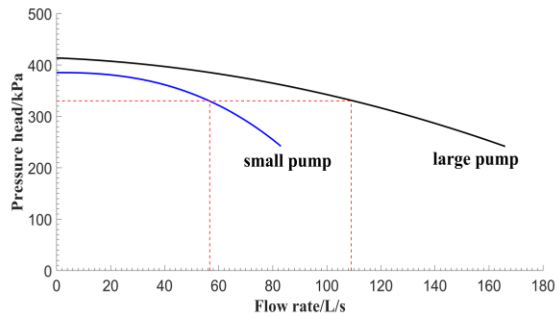

Fig 10. Pump performance curves of selected pumps

4.2.1 Adaptive commissioning schemes

The small pumps, which are designed to serve air-cooled chillers initially, are included in the adaptive commissioning schemes to be used also in the primary water loop of water-cooled chillers. Based on the uncertainty analysis results (as shown in Fig.11) and the working range limitation of selected pumps, 264kPa (corresponding to 20% oversizing) is selected as the target pressure head for developing the adaptive commissioning schemes. According to the performance curves of the available pumps, the proper commissioning intervals are selected to be 0%-11.8%, 11.8%-20% and over 20%.

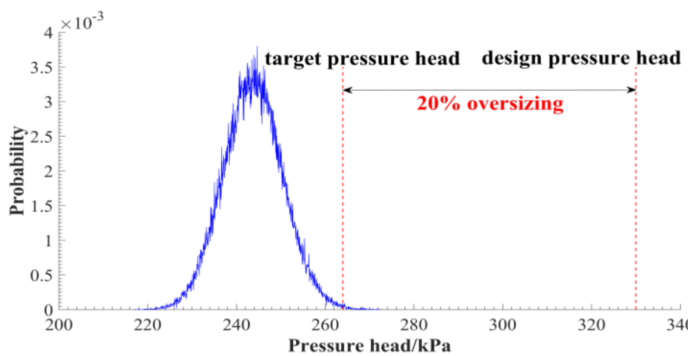

Fig 11. Probability distribution of actual pressure head and selected oversizing degree

When the oversizing degree is within 11.8%-20% (not including 20%), the best commissioning point is 291kPa (corresponding to 11.8% oversizing). In this situation, one large CSD pump and one small CSD pump can provide the water flowrate needed by two water-cooled chillers. Two large CSD pumps and one small CSD pump can provide the water flowrate needed by three water-cooled chillers. Three large CSD pumps can provide the water flowrate needed by four water-cooled chillers. When the oversizing degree reaches 20% or more, the system balancing is commissioned at 264kPa (corresponding to 20% oversizing), as shown in Fig. 12. Two large

CSD pumps are sufficient to serve three water-cooled chillers. When one water-cooled chiller is in operation, one large VSD pump is needed if the pumps are oversized, as shown in Table 8.

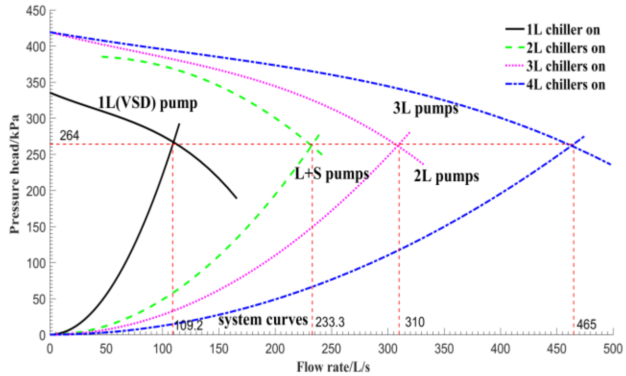

Fig12. Flow balancing when pump system oversizing is at or above 20%

Table 8. Adaptive commissioning schemes for different oversizing degrees

Operating chiller combinations	Oversizing degree (OD)		
	0%⩽OD<11.8%	11.8%⩽OD<20%	20%⩽OD
1L	1L	1L(VSD)	1L(VSD)
2L	2L	L+S/3S	L+S/3S
3L	3L	2L+S/L+3S	2L/L+2S
4L	4L	3L/2L+2S	3L/2L+2S

From Table 9, it can be seen that significant pump energy saving can be achieved by on-site adaptive commissioning even pumps are selected using conventional design approach without special consideration for adaptive commissioning. Significant energy saving can also be achieved by comparing with the system all using VSD pumps when pump system is oversized.

Table 9. Energy saving (%) of optimal design compared to conventional all CSD and VSD designs

benchmark / Operating chiller combinations	Oversizing degree (OD)			
	11.8%⩽OD<20%		20%⩽OD	
	CSD	VSD	CSD	VSD
1L	5.4	0.0	9.1	0.0
2L	15.8	11.0	11.6	2.8
3L	7.1	2.0	22.5	14.8
4L	17.2	12.0	12.8	4.1

4.3 Optimal design and adaptive commissioning of a cooling water pump system with low degree of oversizing - Case 3

This case study is a hypothesized case, being conducted to verify the feasibility of pump selection for the optimal design and development of adaptive commissioning schemes for a pump system of low oversizing degree. The cooling water pump system concerned serves identical chillers, which is also a very common situation in engineering practice. The number of chillers are 5 (one stand-by) as shown in Table 4. The flow rate and design pressure head are 100L/s and 320kPa respectively, and oversizing degree is assumed as 16% (269kPa).

4.3.1 *Results of optimal pump design*

Four large CSD pumps, one large VSD pump and one small CSD pump are selected from the same available pump database, meeting the needs of on-site adaptive commissioning schemes. The pump curves are shown in Fig.13.

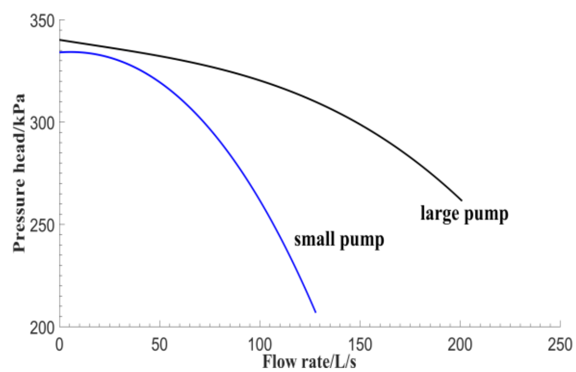

Fig 13. Pump performance curves of selected pumps

4.3.2 Adaptive commissioning schemes

The appropriate commissioning intervals are chosen as 0%-7.2%, 7.2%-16% and 16% (or more) based on the performance curves of selected pump. The best commissioning schemes at different commissioning intervals are shown in Table 10 as well as second best commissioning schemes. The best commissioning point is 297kPa (corresponding to 7.2% oversizing) when system oversizing is between 7.2% and 16% (not including 16%). In this case, a large VSD pump is needed when only one chiller is in operation. One large CSD pump and one small CSD pump can provide the flow needed by two chillers. Two large CSD pumps can fulfill the flow requirement of three chillers. Two large CSD pumps and one small CSD pump can meet the flow need of four chillers. When system is oversized for 16% or more, the system commissioning point is 269kPa (corresponding to 16% oversizing) as shown in Fig.14. The small CSD pump is able to provide the flow of one chiller, one large CSD pump can satisfy the flow requirement of two chillers, and two large CSD pumps are enough for four chillers. The flow needed by three chillers can be provided by one large CSD pump and one small CSD pump. Table 11 shows the energy saving potential of the optimal design. Significant energy can be saved in most cases compared to the conventional design. When oversizing degree reaches 16% or more, the optimal design saves about 14.5% to 19.4% energy compared with the all CSD design, and it saves about 2.3% to 14.3% compared with the all VSD pump design.

Table 10. Adaptive commissioning schemes for different oversizing degrees

Operating chiller combinations	Oversizing degree (OD)		
	0%⩽OD<7.2%	7.2%⩽OD<16%	16%⩽OD
1L	1L	1L(VSD)	1S/1L(VSD)
2L	2L	L+S	1L
3L	3L	2L	L+S
4L	4L	2L+S	2L

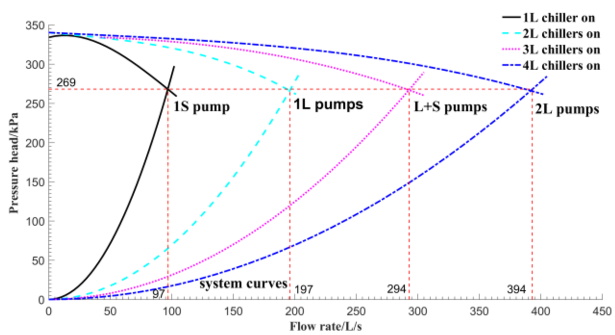

Fig 14. Flow balancing when system is oversized for 16% or more

Table 11. Energy saving (%) of optimal design compared to conventional all CSD and VSD designs

Operating chiller combination \ benchmark	Oversizing degree (OD)					
	0%≤OD<7.2%		7.2%≤OD<16%		16%≤OD	
	CSD	VSD	CSD	VSD	CSD	VSD
1L	-3.3	1.3	0.0	-4.8	19.4	14.3
2L	-3.3	1.3	0.0	-4.8	14.5	2.3
3L	-3.3	1.3	8.6	4.3	16.1	4.2
4L	-3.3	1.3	14.5	10.5	14.5	2.3

The pump energy savings achieved in the above three case studies are summarized in Fig.15 for the convenience of comparison. It can be observed that energy saving increases with the oversizing degree, a maximum energy saving of about 20% can be achieved using the optimal design and adaptive commissioning method compared to the conventional design all using CSD pumps corresponding to about 20% of oversizing. The average energy saving can be around 13% corresponding to about 15% of oversizing.

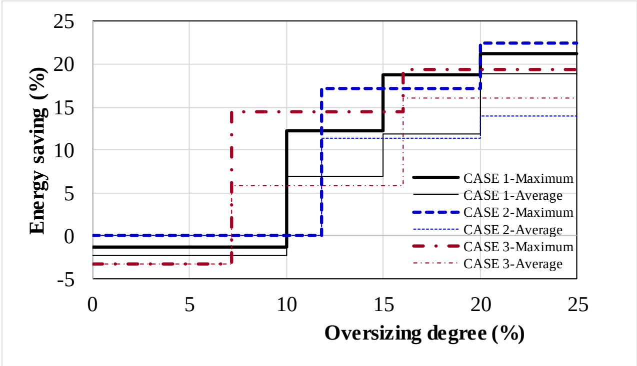

Fig 15. Maximum and average energy savings of optimal design compared to conventional design all using CSD

5 Conclusions

A probabilistic optimal design method and the corresponding on-site adaptive commissioning approach are developed in this study, which is based on quantifying the uncertainties in the pressure head calculation and system construction. Minimized throttling is achieved by adopting the on-site adaptive commissioning to maximize pump energy saving. Pumps are selected to facilitate the on-site adaptive commissioning based on the conventional design pressure head and the target pressure head. The target pressure head is determined on the basis of the predicted pressure head probability distribution. Adaptive commissioning schemes are developed for different commissioning intervals at design stage. Three case studies are conducted to test the application of the proposed method and approach with different practical constraints, and to verify the energy savings that can be achieved in practice.

Based on the validation tests and the test results, conclusions can be made as follows. The probabilistic optimal design and on-site adaptive commissioning approach are practically applicable and can achieve significant energy saving (about 20% maximum saving and about 13% average saving corresponding to about 20% and 15% of oversizing degrees respectively in the studied cases compared to conventional designs) for air-conditioning water pump systems, compared to the conventional design and even compared to the design all using VSD pumps. Significant energy saving could also be achieved by adopting on-site adaptive commissioning for the system designed using conventional methods, in cases where there is a smaller pump available and/or one VSD pump.

The case studies also show that it is practically feasible to find proper pumps from pump database available in the market, which can satisfy the operating conditions, i.e. the requirements of conventional design condition and alternative target condition based on the estimated oversizing degree while the efficiencies of selected pumps can be reasonably high in the whole possible operation ranges. In selecting pumps for different operating chiller combinations, VSD pumps are typically needed for situations when one chiller of the smallest capacity is in operation. When a central chilling system consists of a few identical chillers, having one small CSD pump is usually a preferred choice for on-site adaptive commissioning, which can provide half of the flowrate needed by an individual chiller at the conventional design pressure head.

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