Simulation and Optimization of Cooling Water Systems with Closed Wet Cooling Tower Based on Reduced Order Model

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This study presents a CFD (computational fluid dynamics)-assistant multi-scale modeling and optimization strategy for synthesizing cooling water systems which incorporates multiple closed wet cooling towers (CWCTs) installed with plain tubes. The utilization of CFD is capable of providing accurate and visual results with respect to complex thermal and fluid flow phenomena that can be used to explore the synergistic mechanism of multi-parameter for CWCTs. Based on CFD results, a systematic reduced order model (ROM) for CWCTs is developed by closely approximating the high-fidelity CWCTs models through integrating principal component analysis (PCA) with Kriging-based surrogate model. This ROM is accessible to the desired result through input data without accounting for the complex geometries and detailed thermal-hydraulics property models. The proposed CFD-assistant ROM for the CWCTs is applied to enhance solution convergence and obtain optimal results of cooling water systems. An industrial case study is used to demonstrate the superiority of the proposed CFD-assistant strategy for the cooling water system synthesis and optimization.

1. Introduction

Reducing freshwater consumption is critical to process industries toward sustainable development due to water scarcity (Zhu et al., 2017). In an industrial enterprise, the amount of circulating cooling water typically accounts for more than 70% of the plant-wide water load which leads to dramatic water consumption by evaporation loss especially in summer (Roundtable et al., 2004). The utilization of cooling water system has been recognized as a principal approach that allows more freshwater to be saved efficiently. Cooling water system mainly consists of interlinked cooling towers, heat exchangers, and pumps, in which cooling towers play the core role in cooling down circulating water and exchanging heat with environment. Recently, CWCTs have been proposed due to their remarkable advantages over conventional open wet cooling towers in water-saving, less plume generation, high thermal efficiency, and no pollution to the process fluid (Xie et al., 2017). Consequently, integrating cooling water systems equipped with CWCTs would lead to economic and environmental benefits for the design and operation of cooling water systems.

The interfacial heat and mass transfer involved in a typical cooling tower includes three complex sub-processes in series: from process fluid to tube wall, from tube wall to falling film, and from spray water to air. These complex transfer processes lead to a great number of challenges in model prediction, parametric analysis, mechanism investigation, and system optimization of cooling water system. Over the past decade, researchers have dedicated to these complicated processes and proposed multiform models for the cooling towers. Significant studies on cooling water systems have also been reported in the literature based on these models. Majozi et al. (2008) used an empirical model-based approach for synthesizing the cooling water systems consisting of multiple cooling supplies. This approach provides a fast computational speed but is difficult to offer accurate description for the complex heat and mass transfer behaviors. Gololo et al. (2011) used a wide-accepted mechanism, namely Merkel's method, to predict the performance coefficients of cooling tower and demonstrated that cooling water systems with multiple cooling towers can achieve the maximum cooling water reuse. Rubio-Castro et al. (2013) developed a novel approach for sizing the cooling towers based on the Merkel method and used for synthesis of cooling water systems with multiple cooling towers. However, the overwhelming majority of previous studies on cooling towers either employ empirical models that results in over-simplified and

unrealistic predictions, or relies on mechanism models like Merkel method that requires a huge computational burden due to their nonlinearity. Under these circumstances, the design and optimization of cooling tower systems become a challenging work especially when the CWCTs are involved in the cooling water systems.

To capture the phenomena of CWCTs and gain a more realistic and manageable model, this work takes advantage of the previous knowledge to develop a CFD-assistant modeling optimization strategy for synthesizing cooling water system which incorporates multiple CWCTs installed with plain tubes. CFD models are used for evaluating the performance of the CWCTs and providing accurate descriptions. The former models of CWCTs are substituted by a systematic ROM which develops by integrating PCA with Kriging-based surrogate model based on CFD results. The proposed CFD-assistant ROM for the CWCTs is embedded in the models of cooling water systems. The original model is updated in the light of the proposed models to enhance the solution convergence to the optimization.

2. Methods and model formulation

This section presents the CFD-assistant ROMs for the CWCTs and the mathematical model incorporating the ROMs for cooling water systems optimization. The ROMs approach is described first followed by the application to the systems.

2.1 CFD-assistant ROMs

For a given CWCT in steady state, as shown in Figure 1, the relationships of the output variables corresponding to its input variables can be assumed and expressed by the following formulation.

$$y = \Psi x \tag{1}$$

where x is the input vector containing the output variables of interest in the fluid field, such as temperature, flow rate of the CWCT; y is the output vector corresponding to the input variable of interest; Ψ is coefficient matrices which can be derived using the approach of PCA-based ROM described in detail by Lang et al. (2009).
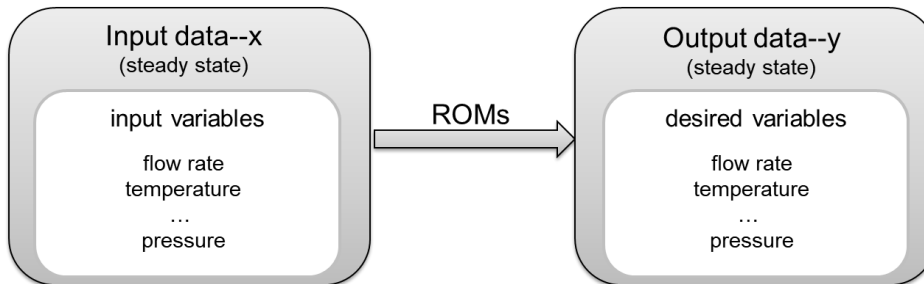

Figure 1: The diagram of the method

Considerable effort is required to work on CFD simulation designs, PCA and input-output mapping in order to obtain the ROMs with high fidelity for the CWCTs. PCA introduced and developed by Pearson and Hotellling (Jolliffe, 2002) is a powerful simplified data tool, which can use to reduce the number of variables in multidimensional data sets. The schematic framework of CFD-assistant ROMs for the CWCTs is shown in Figure 2 and can be summarized by the following steps:

Step I: Determine the variables of interest (temperature, flow rate, etc.) and the corresponding domain of the CWCTs.

Step II: The cases of CFD simulation are obtained from the combination of the interest variables through space-filling experimental designs. Herein, the Latin Hypercube Sampling (LHS) is adopted in this work.

Step III: Carry out the cases from Step II on the CFD software and extract the corresponding data set of the CWCTs via a series of CFD simulations.

Step IV: The data set from Step III is analyzed based on PCA. According to the required accuracy and criterion, the reduced rank and ranked principal component are determined.

Step V: Build the mapping from the input to the output of the CWCTs During this process, the Kriging method explored by Lophaven et al. (2002) is used for the developments of the ROMs. A first degree polynomial and Gauss correlation is choose for this method as follows.

$$x_i' = \frac{x_i - \bar{x}_i}{\sigma_i} - 1, \quad \forall i \in \{1,...,n\} \tag{2}$$

where x is the input vector of current trial point; $\bar{x}$ and σ are the mean and variance, respectively, among the design sites Ω; n is dimension of the input vector.

$$\lambda_j = \prod_{i=1}^{n} \exp\left[-\alpha_i\left(x_i' - \Omega_{j,i}\right)\right], \quad \forall i \in \{1,...,n\}, \quad \forall j \in \{1,...,m\} \tag{3}$$

where λ is the correlation between x' and Ω; α is parameter from the Kriging regression; m is number of design sites for the regression.

$$y_k' = \sum_{i=1}^{n+1} \beta_{k,i} f_i + \sum_{j=1}^{m} \gamma_{k,i} \lambda_j, \quad \forall i \in \{1,...,n\}, \quad \forall j \in \{1,...,m\}, \quad \forall k \in \{1,...,l\} \tag{4}$$

where y' is the original output vectors at the trail point x; f is the basis of the first degree polynomial with $f_1=1$,

$f_i = x_{i-1}'$; β and γ are parameters from the Kriging regression; l is dimension of output vector.

$$y_k = \bar{y}_k + y_k' \hat{\sigma}_k, \quad \forall k \in \{1,...,l\} \tag{5}$$

where y is the scaled output vectors at the trail point x; $\bar{y}$, $\hat{\sigma}$ are the mean and variance vectors of the output matrix corresponding to Ω.
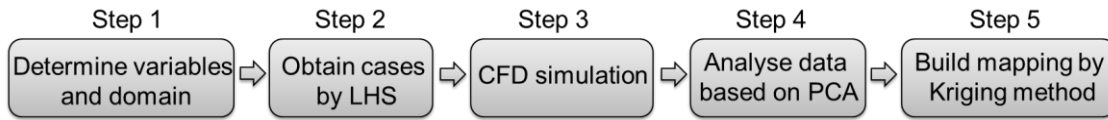

Figure 2: Schematic framework of CFD-assistant ROMs

2.2 Model formulation of cooling water systems

It is assumed that the following information are given before systems modelling: (1) a set of hot process streams, and their inlet/outlet temperature and flow rates, (2) a freshwater source and its temperature, but with variable and unlimited flow rate, (3) multiple CWCTs and their ROMs, (4) constant heat capacities for hot process streams and cooling water, (5) a wastewater sink with maximum allowable properties and unlimited flow rate, (6) constant overall heat transfer coefficients for countercurrent coolers. The goal of the model is to find the optimal interconnection for the cooling water systems to determine the minimum total annual cost.
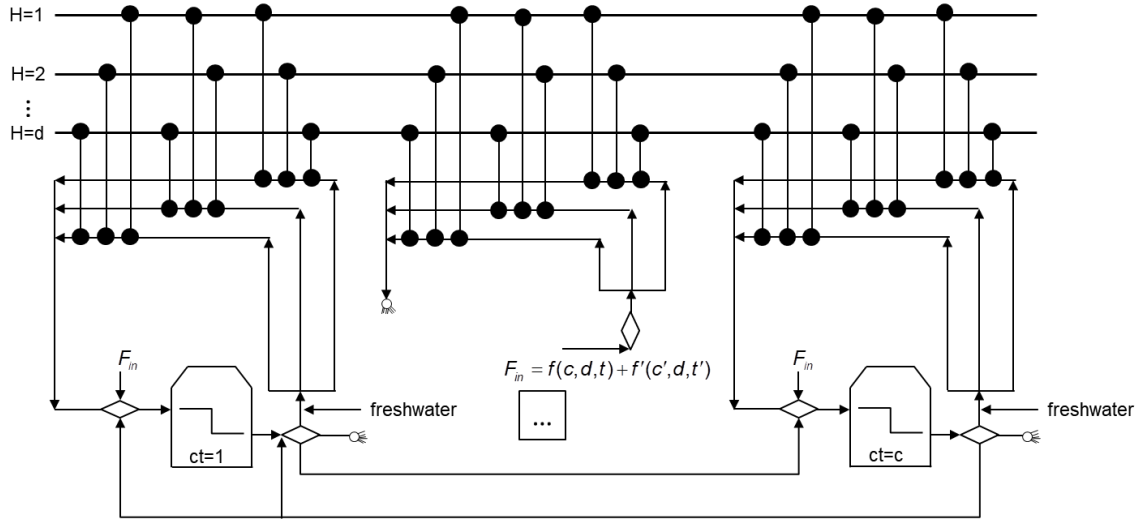

Figure 3: The superstructure network for cooling water systems

The superstructure network for cooling water systems is shown in Figure 3. Mathematical formulations proposed in this work include the mass and heat balances in this superstructure. The aforementioned developed ROMs are involved in these formulations. The mathematical models based on the superstructure are presented in the following equations.

$$F_n = \sum_i F_i \qquad \forall i, n \in m_{out}, m \in \text{heat exchange} \tag{6}$$

$$F_n T_n = \sum_i F_i T_i \qquad \forall i, n \in m_{out}, m \in \text{heat exchange} \tag{7}$$

$$F_n = \sum_j F_j \qquad \forall j, n \in m_{in}, m \in \text{heat exchange} \tag{8}$$

$$F_n T_n = \sum_j F_j T_j \qquad \forall j, n \in m_{in}, m \in \text{heat exchange} \tag{9}$$

$$Q_n^{cw} = Q_n^{ps} \qquad \forall n \tag{10}$$

$$F_n = \sum_{ct} F_{ct} \qquad \forall ct, n \in m_{in}, m \in \text{CWCTs} \tag{11}$$

$$F_n T_n = \sum_{ct} F_{ct} T_{ct} \qquad \forall ct, n \in m_{in}, m \in \text{CWCTs} \tag{12}$$

$$F_n = \sum_{ct} F_{ct} \qquad \forall ct, n \in m_{out}, m \in \text{CWCTs} \tag{13}$$

$$F_n T_n = \sum_{ct} F_{ct} T_{ct} \qquad \forall ct, n \in m_{out}, m \in \text{CWCTs} \tag{14}$$

$$\begin{bmatrix} Y_t \\ T_n \geq T_{min} \\ T_n \leq T_{max} \\ CC_{ct} = f_1(F_n) \\ OC_{ct} = f_2(F_n, C_n) \end{bmatrix} \qquad Y_{ct} \in \{\text{Ture,False}\}, \forall ct, n \in m_{in}, m \in \text{CWCTs} \tag{15}$$

In the above equations, F_i, F_j and F_{ct} are the flow rates (m^3/h) of any stream (i, j, ct) in the superstructure. T_i, T_j, and T_{ct} are the temperature of any stream (i, j, ct) in the superstructure. Q_n^{cw} and Q_n^{ps} are the total exchanged heats of cooling water and process stream, respectively. In the disjunctive formulation, Y_{ct} indicates whether cooling tower ct is chosen for the system or not, and the temperature of streams inlet the cooling tower ct must fall between the minimum value and the maximum value. CC_{ct} and OC_{ct} represent the capital cost and operating cost of cooling tower ct.

3. Results and discussion

MATLAB is employed to obtain CFD-assistant ROMs and convert them into simulation modules for the cooling water systems optimization. The contours of the steady state for cooling tower can be obtained by the CFD simulation and the input-output mapping, as shown in Figure 4. These two methods identify with the CFD models and the developed ROMs, respectively. Comparing these contours, it can be found that the contours maintain high accuracy and the distortions are even hardly observed. These results offer reasonable and sufficient confidence that the ROMs of the cooling tower can be further used to integrate within the cooling tower systems models for optimization.

A case study is used to demonstrate the applicability and advantages of the proposed method. In this case, a traditional design with a single CWCT, which exchanges heat with process streams in parallel, is used to establish a comparison with the proposed design considering the CFD-assistant strategy. The basic data for the case study is collected from the previous study (Rubio-Castro et al., 2013). The MINLP problem associated with the case study was implemented using GAMS 24.7.1 and solved on a computer with an Intel Core i7 at 3.60 GHz with 8 GB memory. The BARON solver in a GAMS 24.7.1 modelling environment was employed to solve the MINLP problem. The optimality gap of the MINLP problem was 10^{-9} at each iteration in order to ensure the validity of the solution.

In this case, five hot process streams and four cooling towers are considered in the cooling tower systems superstructure. The process stream data of this case study is detailed in Table 1.

Table 1: Date of Cooling Water Systems for the Case Study

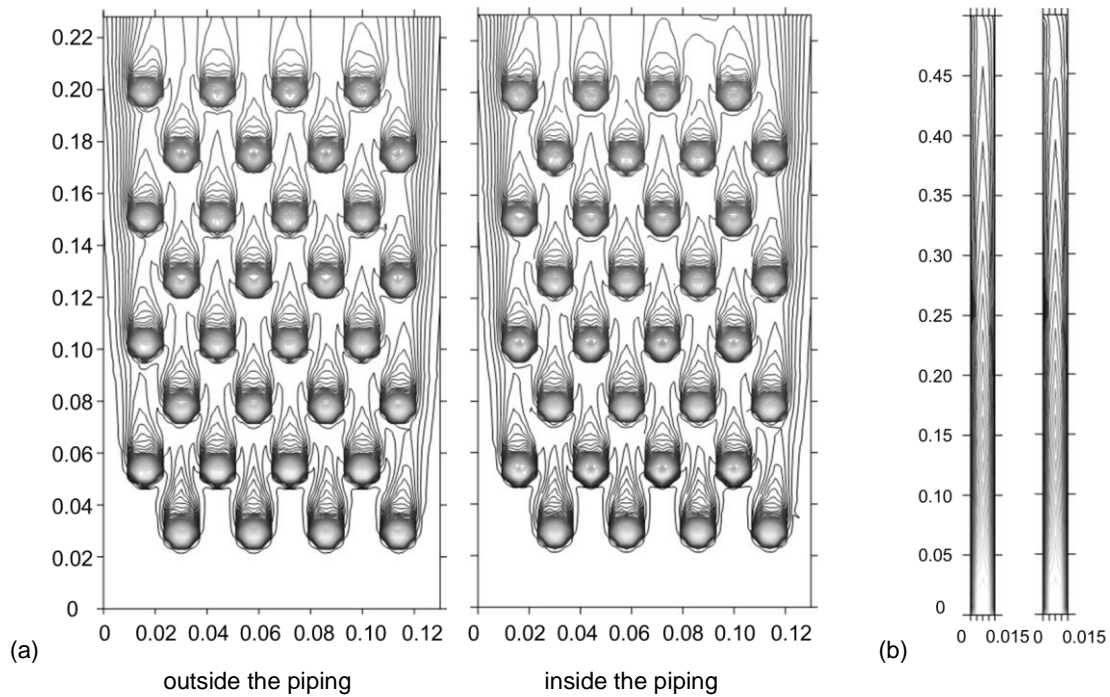| Streams	T_{in} (K)	T_{out} (K)	F_{cp} (kW/K)	Q (kw)	h (kw/m^{2}K)
1	353	333	500	1.0×10^4	1.089
2	348	301	100	4.7×10^3	0.845
3	393	313	450	3.6×10^4	0.903
4	363	318	300	1.35×10^4	1.025
5	383	313	250	1.75×10^4	0.750

Figure 4: Contours of temperature for the cooling tower. The left picture in each set is from the CFD model, while the right is predicted by ROMs.
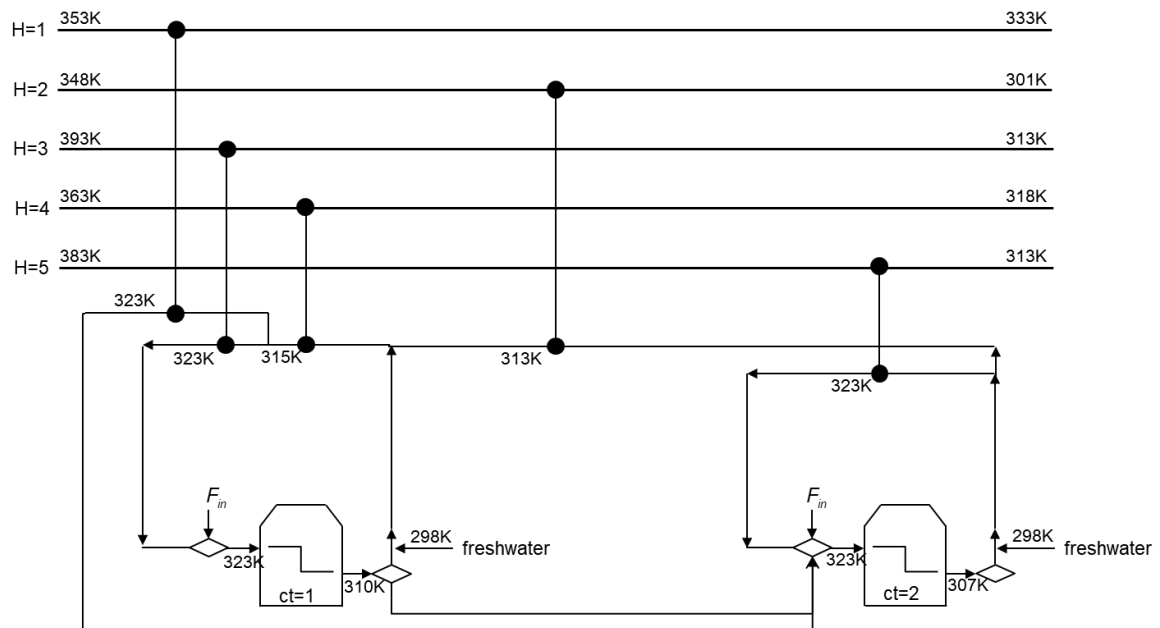

Figure 5: The optimal network of cooling water systems for case study

It can be found that the optimal design considering the proposed CFD-assistant strategy shown in Figure 5 features distributed cooling water network and heat exchange network which segregate and dispatch hot/cold streams for their appropriate units. This design involves a more complex configuration of network than the traditional design. The cooling water in this optimal design exchanges heat with more than one process streams and the heated water streams are split and then mixed before they are fed to the CWCTs. Moreover, in this figure, two CWCTs in a series-parallel arrangement are required to cool down the heated water streams. In this way, the high-efficient removal of heat by circulating cooling water can be achieved. Finally, the proposed CFD-assistant strategy design results in remarkable reductions in freshwater consumption, operating cost, and total

annual cost as listed in Table 2. The freshwater consumption drops from $1.20{\times}10^5$ m^3/y for the traditional design to $1.00{\times}10^5$ m^3/y for the proposed design, while the total annual cost can be accordingly curtailed from $1.10{\times}10^6$ $/y to $7.50{\times}10^5$ $/y, respectively, which proves the superiority of the proposed network design.

Table 2: Optimal Results of Cooling Tower Systems for the Case Study

	Traditional design	Proposed design
Freshwater, m^3/y	$1.20{\times}10^5$	$1.00{\times}10^5$
Freshwater cost, $/y	$5.40{\times}10^5$	$4.50{\times}10^5$
Operating cost, $/y	$2.82{\times}10^5$	$1.55{\times}10^5$
Total annual cost, $/y	$1.10{\times}10^6$	$7.50{\times}10^5$

4. Conclusion

In this work, an optimization-based method was developed for designing of the cooling water systems network with multiple CWCTs to make full use of the cooling water. Importantly, a systematic PCA-based ROM obtained from the CFD simulation results was proposed to replace the corresponding conventional models for CWCT, which was further embedded with the cooling water system models to overcome the burden of excessive computational requirements. The proposed CFD-assistant strategy for cooling water systems synthesis was demonstrated using a case study which determines the optimal configuration on minimum total annual cost. The results in this work showed that integrating CFD-assistant ROMs in a cooling system models can lead to a decrease in the total annual cost of the system from $1.1{\times}10^6$ $/y for the traditional one to $7.5{\times}10^5$ $/y for the proposed one. Moreover, the models based on the proposed method are easy to achieve the thermal-hydraulics performance of the CWCTs and the optimal solution of the network, which were practically reliable and manageable.

Acknowledgement

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