Applied Energy Symposium 2019: Low carbon cities and urban energy systems
October 16-18, 2019, Xiamen, China
Paper ID: 0041

NEW METHOD TO CALIBRATE THE CHILLED WATER PIPE NETWORK IN A HIGH-RISE BUILDING

Hai Wang[1], Hua Meng [3*], Guang Yang[1], Fengxia Wang[1], Feng Xue[2], Ting Li[2]

1 School of Mechanical Engineering, Tongji University, No. 1239, Siping Road, Shanghai 200092, China

2 China Construction Engineering Design Group Corporation Limited, No. 15, Sanlihe Road, Beijing 100044, China

3 School of Mechanical Engineering, Tongji University, No. 1239, Siping Road, Shanghai 200092, China (Corresponding Author)

ABSTRACT

To predict the energy performance of a chilled water system more accurately, the hydraulic resistances of its water pipe network should be calibrated before simulation. However, it is a challenge to calibrate the hydraulic resistance of such a complex pipe network that are compose of chillers, terminal units, variable-speed pumps, valves and many pipes installed in different floors of a high-rise building. In this study, a new calibration method is proposed elaborately to adapt the vertical structure of the water pipe network in a high-rise building. The proposed calibration method utilized an optimization model and a general pipe network hydraulic solver. To overcome the severe nonlinear characteristic of the pipe network, Genetic Algorithm (GA) is used to solve the optimization model. Then, the proposed calibration method is validated in a real-life chilled water system in a high-rise building. With the hourly measured data from the chilled water system in operation in a typical summer day, the hydraulic resistances of 200 terminal units, 46 valves and 912 pipes are calibrated in detail. The calibrated hydraulic resistances are used to predict pressures and flow rates of the chilled water system in the next day. Compared with the uncalibrated simulation results, the average pressure error between the calibrated simulation results and measured data from the 42 onsite pressure meters is reduced from 2.2% to 0.6%. The average flow rate error between the calibrated simulation results and measured data from the 3 onsite flow rate meters is reduced from 5.3% to 0.9%.

Keywords: chilled water system, high-rise building, hydraulic resistance calibration, optimization model, GA

1. INTRODUCTION

Central air-conditioning system contributes a significant proportion to the total energy consumed in buildings [1]. As the increasing number of high-rise buildings in future urban construction, the energy performance of the central air-conditioning system in a high-rise building can be a key issue for energy saving [2, 3]. Therefore, the efficiency of chilled water system that contributes the main part of the energy consumption of a central air-conditioning system should be enhanced. To conduct better operation strategies for a chilled water system, using simulation tools is one of the effective approaches. For a chilled water system in operation, the hydraulic resistances of its water pipe network should be calibrated to predict its energy performance more accurately.

The hydraulic model calibration methods had been discussed in many studies in term of water distribution network [4, 5]. Lingireddy and Ormsbee [6] presented a general calibration approach using genetic optimization. Sophocleous et al. [7] developed a new graph-theory based technique for clustering water distribution networks. Savic et al. [8] reviewed the water distribution network calibration problem and various solution approaches. Wang et al. [9] presented a method that hydraulic resistances of all the pipelines in the district heating network can be obtained. There are already many simulation models for energy efficiency of chilled water system or building heating system [10,

Selection and peer-review under responsibility of the scientific committee of CUE2019

11]. However, a practical calibration method for the chilled water system in a high-rise building is still rare in previous studies. To calibrate the pipe network in a high-rise building, a suitable hydraulic model is quite required to estimate the water pressure and flow rate at the location of the meters. Syed et al. [12] developed a numerical model for pumping system of an academic building. Energy savings with variable speed pumping systems is identified. Lee et al. [13] presented the performance model of variable speed chillers using standard regression techniques. Ma et al. [14, 15] improved energy efficiency by using variable speed pumps and bypass check valve in a chilled water system. Moore et al. [16] investigated the pump pressure differential set point position in a chilled water system. Fang et al. [17] proposed an evaluation method for optimal design for chilled water system. Though there are already some models for chillers, pumps and terminal units in term of energy performance in previous studies, the hydraulic model of chilled water pipe network is still too simplified to be qualified for the calibration approach in a high-rise building.

In this paper, a new calibration method is proposed for a chilled water system considering the vertical structure of the chilled water pipe network. The proposed method uses an optimization model and a general pipe network hydraulic solver, which considers the water density difference between the supply and return water pipes. To overcome the sever nonlinear characteristic of the pipe network, Genetic Algorithm (GA) together with a local are used to solve the optimization model. The local optimizing algorithm can obviously accelerate the searching efficiency of GA in practice. Then, the proposed calibration method is validated in a real-life chilled water system in a high-rise building. The pressure meters for calibration are installed at the entrance of each floor. The simulation results are significantly improved by using the calibrated hydraulic resistances of the pipe network.

2. SYSTEM DESCRIPTION

The chilled water system is usually composed of chillers, terminal users (AHU or Coil), circulation pumps, valves and pipes, etc. A typical configuration of the chilled water system is shown in Fig.1 and Fig.2.

There are also heat rejection units for the chillers, which are not shown in Fig.1 and Fig.2 for simplicity. The primary pumps are usually operating at constant speed. The bypass pipe with check valve is used to guarantee the chillers in operation with a minimum water flow rate when there is not enough water returning from the terminal users. The secondary pumps are operating at variable speed according to the current cooling demand. In each floor, the throttle valves are installed to keep hydraulic balance among the terminal units. The terminal units, such as AHU or coil, provide cooling energy to the rooms as demand. The supplementary pump set the basic static pressure for the inlet of the primary pumps.

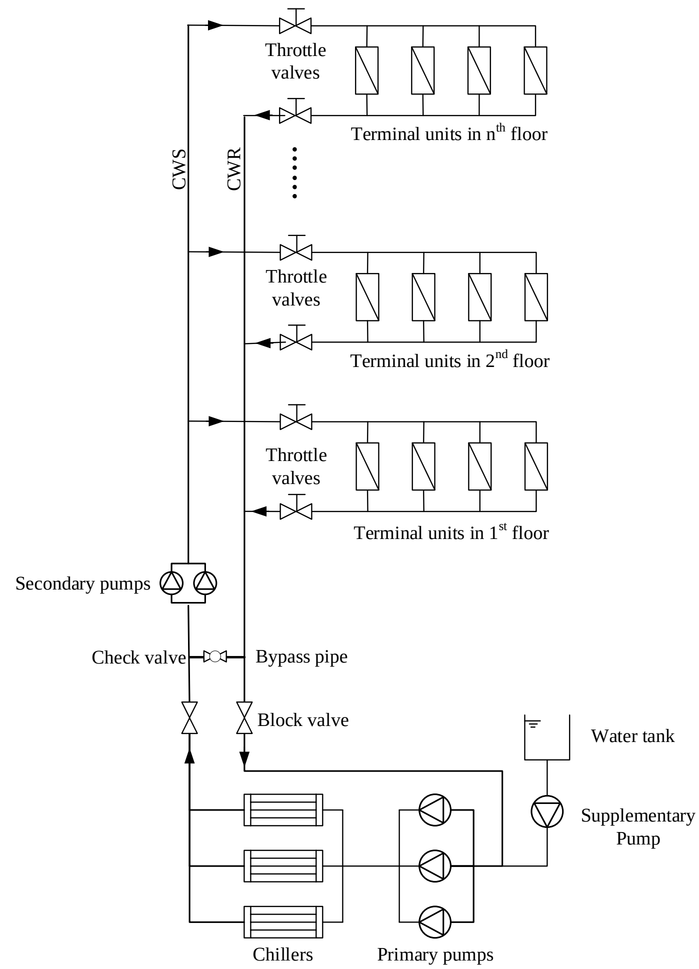

Fig.1 The configuration of a chilled water system

3. HYDRAULIC MODEL

In a chilled water system, the circulating pumps (both primary and secondary pumps) delivery water passing through chillers, valves, terminal units and pipes, etc. The hydraulic resistance of the pipes and its fittings can be calculated as [18],

$$R_{\text{pipe}} = \frac{8\rho}{\pi^2 d_n^4}\left(f\,\frac{l}{d_n} + \sum \xi_{\text{pipe}}\right)\dot{V}^2 \quad (1)$$

Where f is the Darcy friction factor; l is the length of the pipe; d_n is the inner diameter of the pipe; ξ_{pipe} are the local resistance factor of fittings, such as junctions and accessories; ρ is the density of chilled water; $\dot{V}$ is

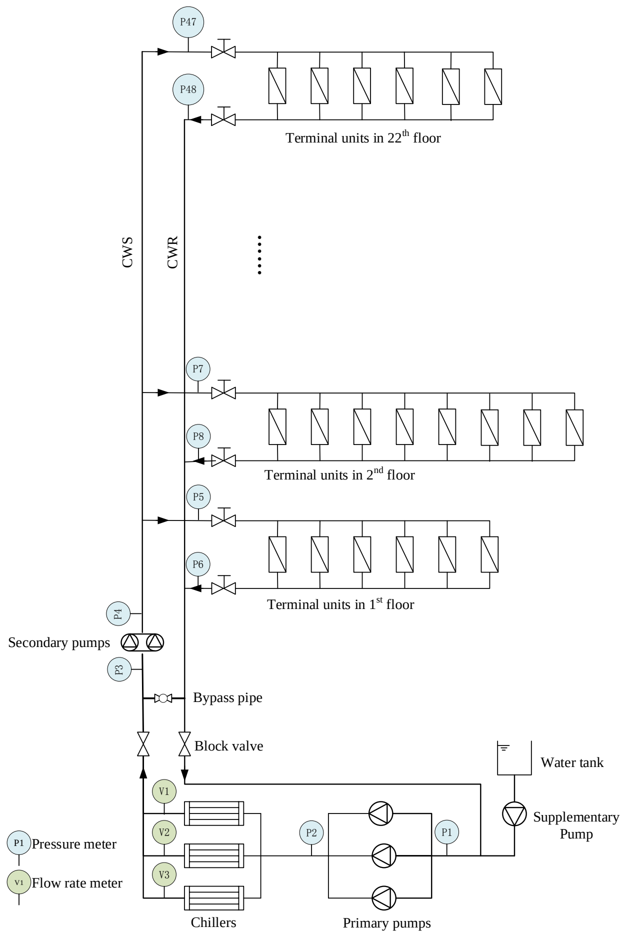

Fig.2 The configuration of a chilled water system in a high-rise building of 22 floors

the volume flow rate of the pipe. For simplicity, the fittings are treated as parts of the pipe. Then the local resistances can be treated as part of modified roughness of the pipe, Eq. (1) can be revised as,

$$R_{\text{pipe}} = f' \frac{8\rho l}{\pi^2 d_n^5} \dot{V}^2 \tag{2}$$

Where f' is the modified friction factor, which can be given as [19],

$$\begin{cases} f' = \frac{64}{Re} & laminar \\ \frac{1}{\sqrt{f'}} = -2\log_{10}\left(\frac{2.51}{Re\sqrt{f'}} + \frac{\varepsilon}{3.7d_n}\right) & fully\ turbulent \end{cases} \tag{3}$$

Where ε is the modified roughness of the inner pipe surface, which considers the fittings as parts of the pipe.

The chillers and terminal units can be treated as local resistances as,

$$\begin{cases} R_{\text{C}} = \xi_{\text{C}} \cdot \left(\dot{V}_{\text{C}}\right)^2 \\ R_{\text{T}} = \xi_{\text{T}} \cdot \left(\dot{V}_{\text{T}}\right)^2 \end{cases} \tag{4}$$

Where ξ_{C} and ξ_{T} are the local resistance factor of the chillers and terminal units, respectively. $\dot{V}_{\text{C}}$ and $\dot{V}_{\text{T}}$ are the volume flow rate of the chillers and terminal units, respectively.

The resistance of a throttle valve can also be simplified as a local hydraulic resistance,

$$R_{\text{v}} = k_{\text{v}} \frac{(\dot{V}_{\text{v}}/A_{\text{v}})^2}{2} \tag{5}$$

Where R_{v} is the resistance of a throttle valve; $\dot{V}_{\text{v}}$ is the volume flow rate through the valve; A_{v} is the opening area of the valve; k_{v} is characteristic coefficient of a valve, which is usually provide by the manufactory.

The hydraulic characteristic of the primary pumps, which are usually paralleled to operation in constant speed, is given by

$$\begin{cases} \Delta P_{\text{pp}} = \rho g \left[k_2\left(\dot{V}_{\text{pp}}\right)^2 + k_1\left(\dot{V}_{\text{pp}}\right) + k_0\right] \\ W_{\text{pp}} = \frac{\Delta P_{\text{pp}} \cdot \dot{V}_{\text{pp}}}{3600\eta_{\text{pp}}} \end{cases} \tag{6}$$

Where ΔP_{pp} is the pressure increment of the primary pump; $\dot{V}_{\text{pp}}$ is the volume flow rate of the pump; k_0, k_1 and k_2 are fitting coefficients which are usually provided by the pump manufactory. W_{pp} is the total power consumption of the pump; η_{pp} is the efficiency of the pump.

The hydraulic characteristic of the secondary pumps, which are paralleled to operation in the same rotation speed, is given by

$$\begin{cases} \Delta P_{\text{sp}} = \rho g \left[k_2\left(\dot{V}_{\text{sp}}\right)^2 + k_1\left(\dot{V}_{\text{sp}}\right)\left(\frac{Fr}{Fr^{rate}}\right) + k_0\left(\frac{Fr}{Fr^{rate}}\right)^2\right] \\ W_{\text{sp}} = \frac{\Delta P_{\text{sp}} \cdot \dot{V}_{\text{sp}}}{3600\eta_{\text{sp}}} \end{cases} \tag{7}$$

Where ΔP_{sp} is the pressure increment of the secondary pump *n*; $\dot{V}_{\text{sp}}$ is the volume flow rate of the pump; k_0, k_1 and k_2 are fitting coefficients which are provided by the pump manufactory. Fr is the operation frequency of the pump. Fr^{rate} is the rated frequency of the pump. W_{sp} is the total power consumption of the pump; η_{sp} is the efficiency of the pump.

The hydraulic modeling of the pipe network is treated as a conventional fluid network based on the Graph Theory, which have been elaborated in the previous studies [20, 21]. The chillers, terminal units and junctions are aggregated as nodes of the network. With respect to the Kirchhoff's current and voltage laws, the basic incidence matrix ***A*** and basic circuit matrix ***B*** of the pipe network can be used from the topology structure of a pipe network layout. From the Kirchhoff's current law, it can be written as,

$$\boldsymbol{A} \cdot \dot{\boldsymbol{V}}_{\text{b}} = 0 \tag{8}$$

where $\dot{\boldsymbol{V}}_{\mathrm{b}}$ is the flow rate column vector of each branch in the pipe network.

From the Kirchhoff's voltage law, it can be written as,

$$\boldsymbol{B}\cdot\left(\boldsymbol{R_b}-\rho g\boldsymbol{H_p}+\rho g\boldsymbol{Z_b}\right)=\mathbf{0} \tag{9}$$

where $\boldsymbol{R}_{\mathrm{b}}$ is the resistance column vector of each branch in the pipe network. $\boldsymbol{H}_{\mathrm{p}}$ is the pump head column vector of each branch in the pipe network. $\boldsymbol{Z_b}$ is the height difference column vector for each branch.

4. CALIBRATION METHOD

For such a chilled water system, the hydraulic calibration is to determine the actual resistance coefficients of these chillers, terminal units and pipes, i.e., the values of ε and ξ. Based on the measured data from the pressure meter and flow rate meter, an optimization model can be developed to calibrate chilled water pipe network, as shown in Table.1.

Table.1 The optimization mode

Object function	$\min\left\{\omega_p\sum_{i=1}^{I}\sum_{t=1}^{T}(p_{it}^{\mathrm{m}}-p_{it}^{\mathrm{e}})^2+\omega_{\dot{V}}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(\dot{V}_{jt}^{\mathrm{m}}-\dot{V}_{jt}^{\mathrm{e}}\right)^2\right\}$ (10)
Decision Variable	$\varepsilon_m,\ \xi_n$
S.t.	$\varepsilon_m^{min}\le\varepsilon_m\le\varepsilon_m^{max}$ $\xi_n^{min}\le\xi_n\le\xi_n^{max}$ $\omega_p=[100/\mathrm{Max}(p_{it}^{\mathrm{m}})]^2$ for $i=1,\cdots,I;t=1,\cdots,T$ $\omega_{\dot{V}}=\left[100/\mathrm{Max}\left(\dot{V}_{jt}^{\mathrm{m}}\right)\right]^2$ for $j=1,\cdots,J;t=1,\cdots,T$

The object function is formulated to minimize the square of the difference between measured and estimated values of the pressures and flow rates. In Eq. (8), p_{it}^{m} and p_{it}^{e} are measured and estimated pressures at location of meter *i* at time *t*; $\dot{V}_{jt}^{\mathrm{m}}$ and $\dot{V}_{jt}^{\mathrm{e}}$ are measured and estimated flow rates at location of meter *j* at time *t*; *I* is number of pressure meters; *J* is the number of flow rates meters; *T* is the number of data collection times for all meter readings. ω_p and $\omega_{\dot{V}}$ are normalized weights for pressure and flow rate, respectively. ε_m and ξ_n are decision variables. ε_m is the modified roughness of the pipe inner surface, *m* is the index of the pipe, *m*=1, … , *M*. ξ_n is the local resistance factor of the chillers and terminal units, *n* is the index of the chillers and terminal units, *n*=1, … , *N*.

To solve the optimization model, GA is used as basic solution. The decision variables are edited as chromosomes for processing, i.e., each decision variable can be expressed as a binary string. For instance, the minimum value ε_m is set as 1 (μm) and the maximum value of ε_m is 4000 (μm). Then the feasible region of ε_m is discretized into 4096 values as {1, 2, 3, ⋯, 4096}, the resolution is 0.976 (μm). Such a resolution has already met the requirement of roughness of a pipe inner surface in most circumstances. The value of ε_m is then expressed as a binary string with 12 bits. For its sophisticated mechanisms, the detail of GA is not studied here [6].

5. CASE STUDY

The chilled water system in a hotel with 22 floors is demonstrated to validate the proposed calibration method. The schematic diagram of the chilled water system is shown in Fig.2. There are 4 identical chillers and primary pumps in the underground floor of the building. The primary pump's rated volume flow rate is 164.0 m^3/h and its rated water head is 15.3 H_2O m. There are 8 identical secondary pumps with rated volume flow rate as 82.0 m^3/h and rated water head as 16.6 H_2O m. There are usually 3 primary pumps and 6 secondary pumps in operation. The static pressure at the outlet of the supplementary pump is 0.9 MPa.

There are 48 water pressure meters and 3 flow rate meters installed as shown in Fig.2. Then, *I*=48 and *J*=3. The resolutions of water pressure meters and flow rate meters are 0.1 kPa and 0.1m^3/h, respectively. The hourly measured data (pressure meter P1-P48, flow rate meter V1-V3) in a day in summer are used to calibrate ε_m and ξ_n. Then, *T*=24 (from 0:00 AM to 23:00 PM). There are 3 chillers, 202 terminal units and 904 pipes in operation. Then, *M*=904 and *N*=205. The initial values of all modified roughness of the pipes are set as 100 (μm). The initial values of local resistance factor of all chillers are set as 0.80 ($\mathrm{Pa\cdot h^2/m^6}$). That of all terminal units are set as 8.0 ($\mathrm{Pa\cdot h^2/m^6}$). By solve the optimization model, the modified calibrated roughness values of all pipes are obtained as shown in Fig.3. The average calibrated roughness value of all pipes is 141.1 (μm). The calibrated local resistance factor values of all terminal units are shown in Fig.4. The average calibrated local resistance factor value of all terminal units is 25.8 ($\mathrm{Pa \cdot h^2/m^6}$). The calibrated local resistance factor values of 3 chillers are 0.940, 0.949 and 0.958 ($\mathrm{Pa \cdot h^2/m^6}$), respectively.

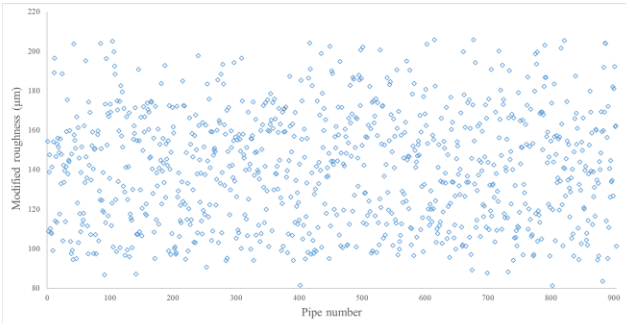

Fig.3 The calibrated value ε_m of all pipes

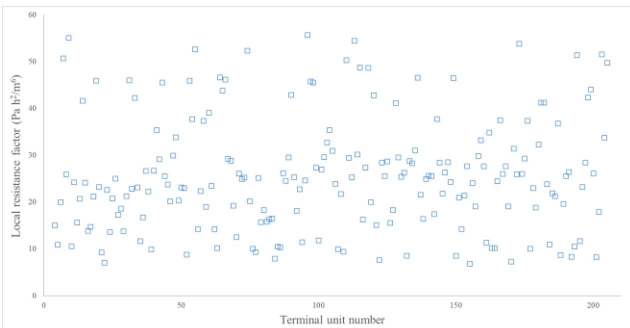

Fig.4 The calibrated value ξ_n of all terminal units

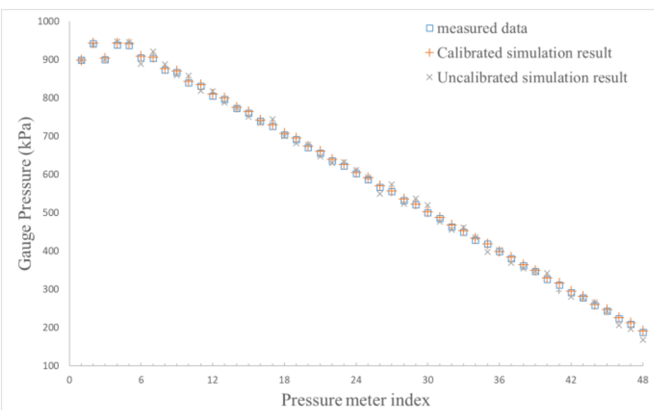

Fig.5 The estimated pressure results and measured data

The calibrated values are used to predict the pressures and flow rates in the next day. The simulation results are compared with the corresponding measured data in the next day as shown in Fig.5 and Fig.6, respectively. Compared with the uncalibrated simulation results, the average pressure error between the calibrated simulation results and measured data from the 42 onsite pressure meters is reduced from 2.2% to only 0.6%. The average flow rate error between the calibrated simulation results and measured data from the 3 onsite flow rate meters is reduced from 5.3% to only 0.9%. The number and locations of the meters are also very important for the calibration results, which would be discussed in future's work.

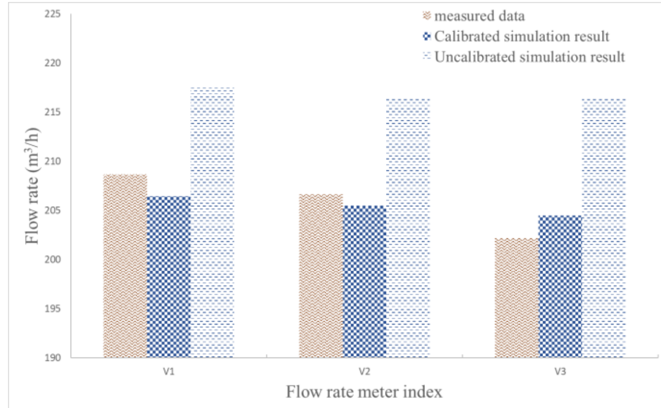

Fig.6 The estimated flow rate results and measured data

6. CONCLUSIONS

The chilled water system is vital important to enhance efficiency of a central air-conditioning system. To predict the hydraulic behavior or evaluate the performance of the chilled water system, the hydraulic resistance of the chillers, terminal units and pipes should be calibrated in advance. In this study, a new calibration method is proposed for the chilled water system in a high-rise building. The main conclusions are summarized as follows.

(1) A hydraulic model is proposed to adapt the vertical structure of the water pipe network in a high-rise building. The chilled water density variation between the supply and return pipes and flow regimes are considered in the proposed model.

(2) A new calibration method is proposed using an optimization model and a general pipe network hydraulic solver. Genetic Algorithm (GA) is used to solve the optimization model, which can effectively overcome the severe nonlinear characteristics of the pipe network.

(3) The proposed calibration method is validated in a hotel of 22 floors. In the case study, the roughness of all pipes' inner surface, the local resistance factor of all chillers and terminal units are calibrated by the measured data. And the calibrated values are used to predict the pressures and flow rates in the next day. Compared with the uncalibrated simulation results, the average pressure error between the calibrated simulation results and measured data from the 42 onsite pressure meters is reduced from 2.2% to 0.6%. The average flow rate error between the calibrated

simulation results and measured data from the 3 onsite flow rate meters is reduced from 5.3% to 0.9%.

ACKNOWLEDGEMENT

The authors sincerely acknowledge the Support of the National Key Research and Development Program of China (Project No. 2017YFC0702900).

REFERENCE

[1] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on building energy consumption information, Energy and Buildings 2008; 40 (3):394-398.

[2] E. Mathews, C. Botha, D. Arndt, A. Malan, HVAC control strategies to enhance comfort and minimize energy usage, Energy and Buildings 2001; 33 (8):853-863.

[3] S. Wang, Z. Ma, Supervisory and optimal control of building HVAC systems: a review, HVAC&R Research 2008; 14 (1):3-32.

[4] Ormsbee, L.E., Lingireddy, S. Calibrating hydraulic network models. Journal American Water Works Association 1997; 89(2):42-50.

[5] Massimo Greco, Giuseppe Del Giudice. New approach to water distribution network calibration. Journal of Hydraulic Engineering 1999;125(8):849-854.

[6] Lingireddy, S, Ormsbee, L.E. Hydraulic network calibration using genetic optimization. Civil. Eng. and Env.Syst. 2000;19(1):13-39.

[7] Sophocles Sophocleous, Dragan Savic, Zoran Kapelan, Yibo Shen, Paul Sage. A graph-based analytical technique for the improvement of water network model calibration. 12th International Conference on Hydroinformatics, HIC 2016. Procedia Engineering 2016;154:27-35.

[8] D. Savic, Z. Kapelan, P. Jonkergouw, Quo vadis water distribution model calibration? Urb. W. J. 2009:6 (1):3-22.

[9] Na Wang, Shijun You, Yaran Wang, Huan Zhang, Qingwei Miao, Xuejing Zheng, Leiyang Mi. Hydraulic resistance identification and optimal pressure control of district heating network. Energy & Buildings 2018:170:83-94.

[10] Abdul Afram, Farrokh Janabi-Sharifi, Alan S. Fung, Kaamran Raahemifar. Artificial neural network (ANN) based model predictive control (MPC)and optimization of HVAC systems: A state of the art review and case study of a residential HVAC system. Energy and Buildings 2017:141:96–113

[11] Hai Wang, Haiying Wang, Haijian Zhou, Tong Zhu. Modeling and optimization for hydraulic performance design in multisource district heating with fluctuating renewables. Energy Conversion and Management 2018;156:113-129.

[12] Syed A. Tirmizi, P. Gandhidasan, Syed M. Zubair. Performance analysis of a chilled water system with various pumping schemes. Applied Energy 2012;100:238-248.

[13] Lee TS, Liao KY, Lu WC. Evaluation of the suitability of empirically-based models for predicting energy performance of centrifugal water chillers with variable chilled water flow. Appl Energy 2012; 93:583-95.

[14] Ma ZJ, Wang SW. Energy efficient control of variable speed pumps in complex building central air-conditioning systems. Energy and Buildings 2009;41:197–205.

[15] Ma Z, Wang S. Enhancing the performance of large primary-secondary chilled water systems by using bypass check valve. Energy 2011; 36:268-76.

[16] Moore BJ, Fisher DS. Pump pressure differential set point reset based on chilled water valve position. ASHRAE Transactions 2003;109(1):373-279.

[17] Xing Fang, Xinqiao Jin, Zhimin Du, Yijun Wang, Wantao Shi. Evaluation of the design of chilled water system based on the optimal operation performance of equipments. Applied Thermal Engineering 2017;113:435-448.

[18] American Society of Heating, Refrigerating and air-conditioning engi neers, ASHRAE Handbook: Fundamentals, ASHRAE, Atlanta, GA, 2009.

[19] Vinko Jovic. Analysis and modelling of non-steady flow in pipe and channel networks. First Edition. Published by John Wiley& Sons, Ltd. 2013.

[20] Hai Wang, Haiying Wang, Tong Zhu. A new hydraulic regulation method on district heating system with distributed variable-speed pumps. Energy Conversion and Management 2017;147: 174-189.

[21] Hai Wang, Haiying Wang, Zhou Haijian, Tong Zhu. Optimization modeling for smart operation of multi-source district heating with distributed variable-speed pumps. Energy 2017;138:1247-1262.