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AN ENERGY-EFFICIENT DECENTRALIZED CONTROL STRATEGY FOR MULTI-EVAPORATOR AIR CONDITIONING SYSTEMS

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ABSTRACT

Multi-evaporator air conditioning system has found increasing applications in buildings. Energy efficient control for this kind of system is a critical issue. The major challenge is the complicated coupling in operation parameters and strong nonlinearities. This paper proposes a novel energy-efficient decentralized control strategy for multi-evaporator air conditioning systems. In this strategy, the compressor speed is controlled to maintain the suction superheat, and the indoor expansion valve is controlled to maintain room temperature of each indoor unit. The command following test shows that the proposed strategy delivers more stable and smooth control performance compared with a conventional strategy. Moreover, simulation results show that the proposed strategy provides 8.6% energy savings. The proposed strategy is also found to be more robust against model error and actuator faults, compared with a model predictive controller.

Keywords: multi-evaporator, air conditioning system, decentralized control, energy saving, refrigeration

1. INTRODUCTION

Multi-split air conditioning system, also called as variable refrigerant flow (VRF) system, is widely used in residential and commercial buildings. VRF system accounts for a large portion of the total building energy consumption. Energy-efficient control for reducing energy consumption of VRF system is critically important.

In general, for a multiple variable system like VRF system, two typical control schemes, i.e. multi-input multi-output (MIMO) control and single-input single-output (SISO) control, are applicable. SISO control is also known as decentralized control. It has been conclusively shown that MIMO controller performs better than SISO controller [1, 2], since it is based on the knowledge about the overall system dynamic characteristics. Shah et al. [3] designed a linear quadratic regulator (LQR) for a dual-evaporator system based on its linearized dynamic model. Koeln et al. [4] found that centralized model predictive controller (MPC) provides better performance in controlling superheat and cooling capacity of each evaporator. Kang et al. [5] developed artificial neural network based control strategy for VRF systems to obtain optimal set-points of the control variables.

However, the design of MIMO controller usually requires a fairly accurate system dynamic model. Such a model is not easy to obtain for VRF system. Because VRF systems tend to operate at variable modes when indoor units are turned on and off. It requires elaborate efforts to develop system model considering all the possible operating modes. Besides, control performance of model based controllers is very sensitive to model error. In contrast, decentralized controller does not require such complicated dynamic model and thereby is easy to implement, also more robust to model error.

Extensive research has been carried out on decentralized control of VRF systems [6-11]. The primary control objective is to satisfy cooling demands of multiple rooms and realize safe and efficient operation of the system. The widely-used control variables include the compressor speed and the indoor expansion valve (EXV) openings. The indoor fan speed is usually set by users and thereby is not adjustable. A simple strategy was proposed which regulated the compressor speed to maintain constant suction pressure (p_s) and regulated the indoor EXVs openings to maintain room air temperature (T_{ea}) [6].

Constant suction pressure control may result that the system is unable to meet varied cooling demand and has a relatively low efficiency [7-9]. Tu et al. [7] proposed to modify the target suction pressure with the average pipe temperature leaving the indoor units. The suction pressure setpoint can also be determined by a supervisory controller to minimize energy consumptions [8], or using the load responsive method [9].

Another concern is that, refrigerant superheat at the suction port (T_{ssh}) of compressor is closely related with safe operation of the compressor and heat transfer efficiency of evaporators, and should be directly controlled for better performance. However, it was not considered in the strategy developed by Chen et al. [1]. Xu at el. [10] suggested that indoor EXV controlled T_{sh} when room air temperature T_{ea} was higher than its setpoint, and indoor EXV is fully closed when the setpoint was met. To avoid frequent switching on and off of indoor unit, a deadband of ±0.5°C in T_{ea} control loop was allowed. Similar control strategies were widely used in commercialized VRF products [12]. Yan et al. [11] amended this strategy for simultaneous temperature and humidity control. The strategy proposed by Xu at el. [10] aims to control the EXV openings using two signals, i.e. T_{sh} and T_{ea}, so as to simultaneously meet indoor cooling demand and prevent the compressor from liquid carryover. However, theories from functional controllability tell us that the number of inputs should be no less than that of outputs to impose effective control on all outputs [13]. Therefore, with only one input, i.e. the indoor EXV opening, it is difficult to control two variables, i.e. the indoor air temperature and the suction superheat. In other words, the strategy proposed in [10, 12] will probably cause T_{sh} and T_{ssh} being uncontrollable. It can be concluded from the literature review that existing control strategies hardly satisfy the primary control objective for multi-evaporator air conditioning systems.

Therefore, this paper proposes a new strategy that controls the compressor speed to maintain T_{ssh} and controls the indoor EXV opening to maintain T_{ea} of each indoor unit. The current paper attempts to test the performance of this strategy in meeting cooling demands of all indoor units and safety operation of the compressor. Its energy performance compared with the conventional control strategy [10, 12] will be numerically evaluated using a validated dynamic model. Besides, control performance of the proposed strategy will be compared with a model predictive controller under model error and actuator faults.

2. DYNAMIC MODELING

2.1 Model development

A physics-based dynamic model for a two-evaporator air conditioning system was developed by modeling each of its components and integrating them together.

Dynamic models of evaporators and condenser are developed based on the moving-boundary method. Taken the dynamic modeling of evaporator (Fig. 1) as an example, the governing equations include mass and (or) energy equations of refrigerant, tube wall and air in both two-phase and superheat regions.

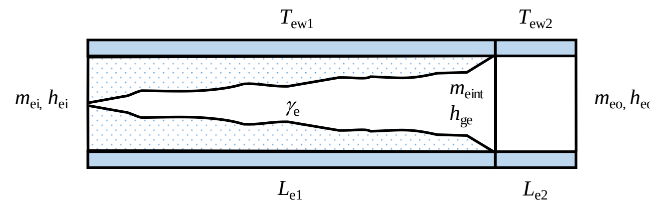


Fig. 1 Schematic of the evaporator model

Since the original conservation equations are partial differential equations, the time-invariant mean void fraction assumption is made to simplify the equations into ordinary differential equations. For example, energy conservation equation of refrigerant two-phase region is given by Eq. (1).

$$\frac{\partial\left(\rho A_e h - A_e p_e\right)}{\partial t} + \frac{\partial m h}{\partial z} = \alpha_{e1}\pi D_e L_{e1}\left(T_{ew1} - T_e\right) \qquad (1)$$

Based on the time-invariant mean void fraction assumption, we integrate Eq. (1) from $z = 0$ to $z = L_{e1}$ (i.e. the two-phase region), simplifying the partial differential equation as ordinary differential equation Eq. (2).

$$\begin{aligned}&\left(\rho_{le}h_{le} - \rho_{ge}h_{ge}\right)\left(1-\bar{\gamma}_e\right)A_e \dot{L}_{e1} \\ &+\left(\frac{\mathrm{d}\rho_{le}h_{le}}{\mathrm{d}p_e}\left(1-\bar{\gamma}_e\right) + \frac{\mathrm{d}\rho_{ge}h_{ge}}{\mathrm{d}p_e}\bar{\gamma}_e - 1\right)A_e L_{e1}\dot{p}_e \\ &= m_{ei}h_{ei} - m_{eint}h_{ge} + \alpha_{e1}\pi D_e L_{e1}\left(T_{ew1} - T_e\right)\end{aligned} \qquad (2)$$

Due to space limitations, details of the moving boundary method shall not be described in this paper, and can be found in [14].

Steady-state models are developed for compressor and EXV modeling considering that their dynamic responses are much faster than that of the two heat exchangers. First-order room model is developed based on the energy conservation equation. When integrating component models into a system model, the refrigerant mass conservation of the whole cycle, and the refrigerant mass flow distribution among multiple indoor units are carefully considered. The system model is further linearized into a 19-order state-space model, as given by Eq. (2), where input vector of the system includes compressor speed and EXV openings of the two indoor units, and output vector **Y** = [T_{ssh}, T_{ea1}, T_{ea2}], i.e., suction superheat and room air temperature of two indoor units.

$$\begin{cases} \dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BU} \\ \mathbf{Y} = \mathbf{CX} + \mathbf{DU} \end{cases} \tag{2}$$

2.2 Model validation

To validate the dynamic system model, simulation results are compared with experimental data. The compressor speed and EXV openings tested in the experiments, as shown in Fig. 2, are adopted as the inputs of the system model in validation tests.

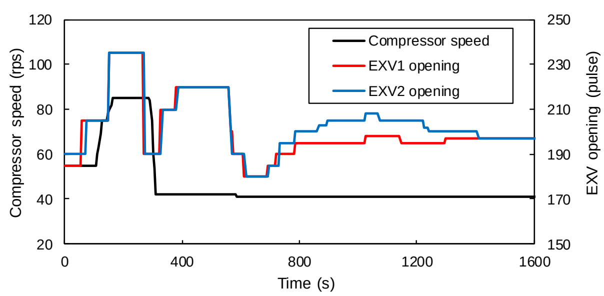
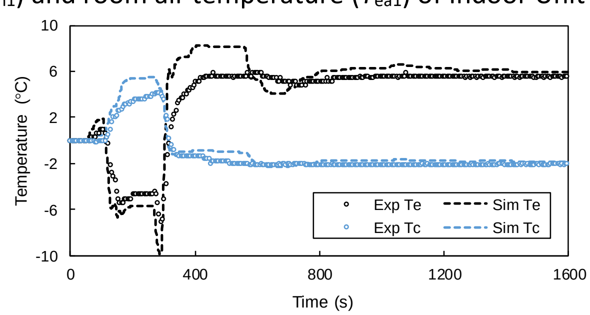
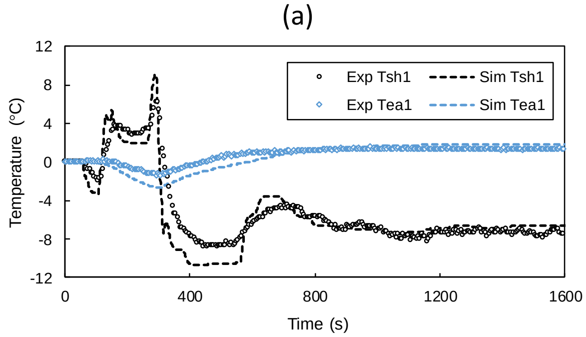


Fig. 2 Inputs in experiments and simulation

Fig. 3 compares simulation results of the key operation parameters with those obtained in experiments, including the evaporating temperature (T_e), condensing temperature (T_c), refrigerant superheat (T_{sh1}) and room air temperature (T_{ea1}) of Indoor Unit 1.



(a)



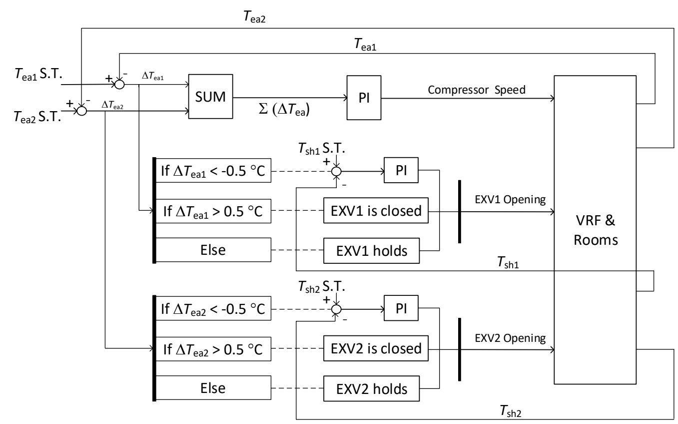
(b)

Fig. 3 Comparison of experimental and simulated outputs

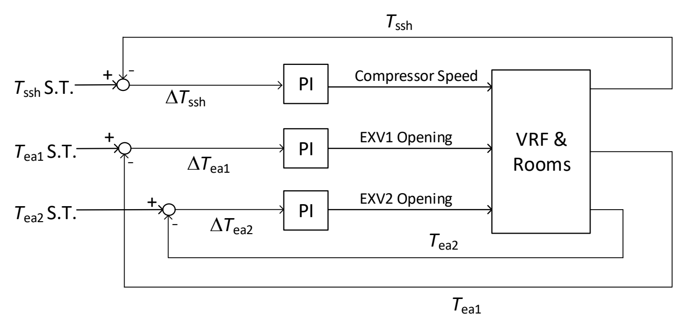
As observed from Fig. 3, the state-space model is able to reasonably track major dynamic response in the experiments. Although some deviations exist, the overall prediction accuracy is acceptable. Therefore, control performance analysis hereinafter will be conducted with the validated model.

3. CONTROLLER DESIGN AND IMPLEMENTATION

Decentralized PI controllers for the conventional strategy [10, 12] and proposed strategy are respectively designed and implemented in the validated dynamic model. Control block diagrams of the two strategies are shown in Fig. 4(a) and Fig. 4(b).



(a) Conventional strategy



(b) Proposed strategy

Fig. 4 Block diagrams of the conventional control strategy (a) and proposed strategy (b)

To properly handle loop interactions, control parameters are tuned using the effective open loop transfer function (EOTF) method [15]. EOTF of loop *i* is defined as the transfer function relating input u_i with output y_i while loop *i* is open and all other loops are closed. Using EOTF, the design of multi-loop controller could be reasonably converted into the design of single-loop controller. After obtain EOTF of individual loop, control parameters, i.e., proportional and integral coefficients (k_p and k_i) can be derived by assigning appropriate bandwidth and phase margin to each closed control loop.

For comparison, a model predictive controller is also designed using Simulink Toolbox. Inputs rate weight is determined by trial and error so that maximum control inputs using PI controller equal to that using MPC controller.

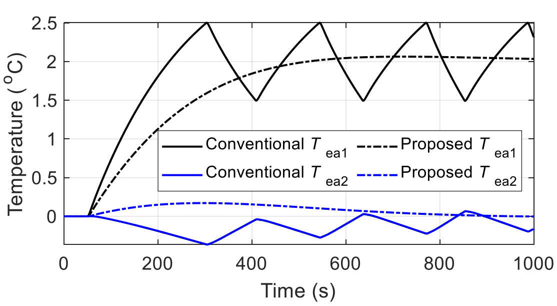
4. CONTROL PERFORMANCE COMPARISON

A virtual testbed is developed in Simulink by integrating the dynamic model and the controllers. Control performance of the proposed strategy is compared with the conventional decentralized strategy and advanced model predictive controller using this testbed.

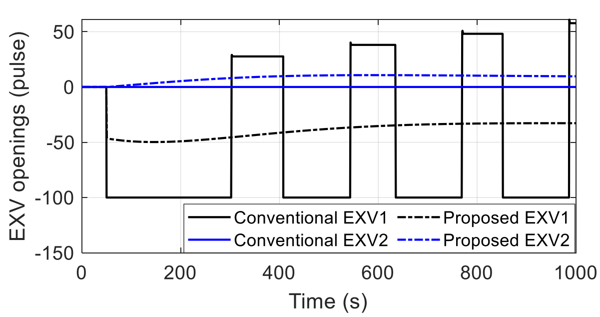
4.1 Compared with conventional decentralized *strategy*

Fig. 5 presents command following performance of the proposed control strategy and conventional decentralized strategy, where the setpoint of indoor room air temperature T_{ea1} increases by 2°C and the other operation parameters remain unchanged. Note that inputs and outputs shown in Fig. 5 are deviations from the original conditions.

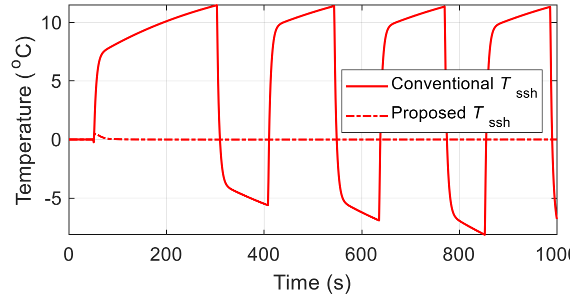
As shown in Fig. 5(a), there exist severe fluctuations in T_{ea} using the conventional strategy, which agree with the results reported in Xu's work [10]. The main reason for this is that the room air temperatures are actually controlled by switching on and off of the indoor EXVs, as shown in Fig. 5(b).



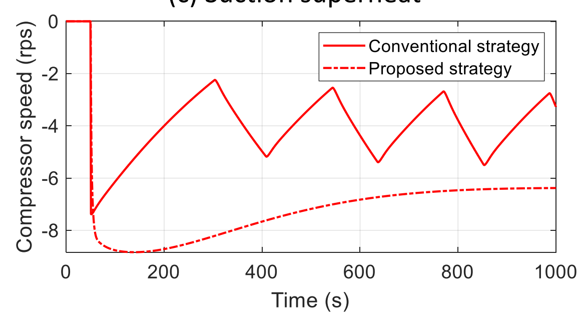
(a) Room air temperature



(b) EXV opening



(c) Suction superheat



(d) Compressor speed

Fig. 5 Command following performance

The conventional strategy also results in unstable suction superheat, as shown in Fig. 5(c), because the control of T_{sh} is overridden by T_{ea} in each indoor unit. Unstable suction superheat should be avoided considering that drastic reduction in T_{ssh} increases the risk of liquid carryover to the compressor, while increase in T_{ssh} indicates poor heat transfer efficiency at the evaporators.

In contrast, the proposed strategy obviously improves the control performance. As shown in Fig. 5(a) and Fig. 5 (c), the controlled variables reach their setpoints smoothly and stably, which indicates the cooling demand of each room is well satisfied. Meanwhile, safe operation of the compressor is guaranteed as shown in Fig. 5 (c).

The proposed strategy also exhibits higher energy efficiency. The average COP using the conventional strategy is 3.5, while the average COP using the proposed strategy is 3.8. Up to 8.6% energy savings is achieved using the proposed strategy. The reason is that frequent switching on and off of indoor EXV in conventional strategy results in discontinuous cooling supply. As a result, the conventional strategy needs to operate the compressor at higher speed, as shown in Fig. 5(d), and consumes more energy when delivering same cooling capacity.

4.2 Compared with model predictive controller

The intention of this section is to examine the robustness of PI controller and MPC under model error and actuator faults.

Fig. 6 presents command following performance of the PI controller (based on the proposed control strategy) and MPC. As seen, MPC responses faster than PI controller, and fluctuation in T_{ea2} caused by loop coupling is weaker than PI controller. This is, however, not surprising considering model based controller requires detailed system model, and also imposes high computation load.

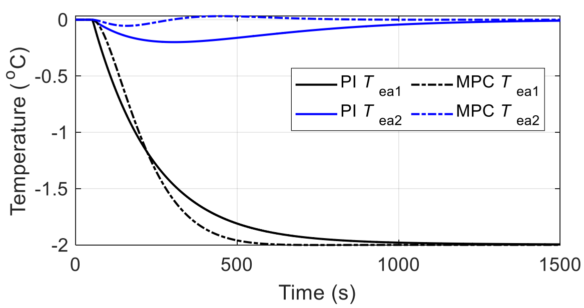


Fig. 6 Control performance of PI controller and MPC under design conditions

Fig. 7 presents settling time in T_{ea1} control loop in a command following test under off-design conditions, in which the setpoint of T_{ea1} is decreased by 2°C. The x axis represents different operation conditions where the system model is linearized. The controller was designed at the condition when compressor speed operates at 40 rps. As seen, settling time using MPC drastically increases when the operation conditions get far away with design conditions. By contrast, settling time using PI controller is quite stable. Therefore, the PI controller developed in this research is more robust against model error, compared with MPC controller.

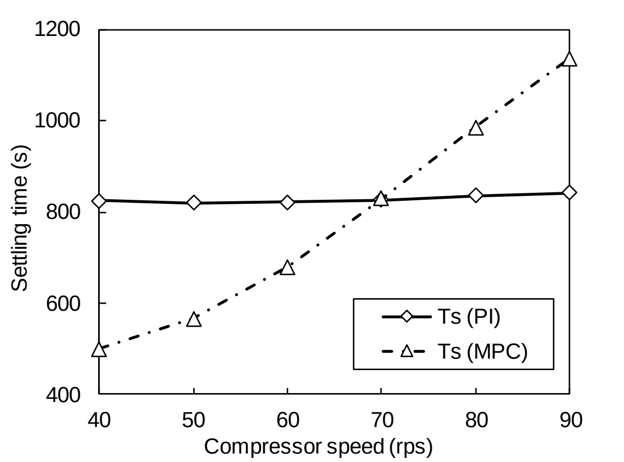


Fig. 7 Control performance of PI controller and MPC under off-design conditions

Fig. 8 compared control performance of PI controller and MPC with actuator fault in EXV1 opening. A case with EXV1's opening unchangeable is simulated. In such a case, the output T_{ea1} is undoubtedly difficult to control. Fig. 8 shows how the other two outputs response. Setpoints for T_{ssh} and T_{ea2} change by 1°C and -2°C, respectively. As seen, T_{ssh} and T_{ea2} using MPC shows steady-state deviations with the setpoint. By comparison, PI controller delivers accurate control of T_{ssh} and T_{ea2}. Therefore, the PI controller developed in this research is more robust against actuator faults, compared with MPC controller.

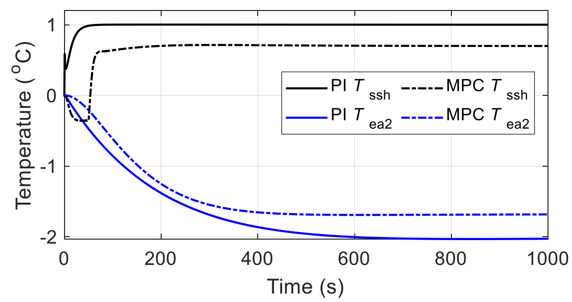


Fig. 8 Control performance of PI controller and MPC with actuator fault in EXV1 opening

5. CONCLUSIONS

In this study, an energy-efficient decentralized control strategy for multi-evaporator air conditioning system is proposed. Different from previous work, this strategy regulates the compressor speed to maintain the suction superheat, and regulates the indoor expansion valve to maintain room temperature of each indoor unit. Decentralized controllers are designed and tested using a validated system dynamic model. Through extensive numerical analysis, the proposed strategy is found to be able to improve performance in controlling room temperature and suction superheat. Moreover, simulation results show that the proposed strategy provides 8.6% energy savings than conventional strategy in the command following test compared with a conventional decentralized strategy. The proposed strategy is also found to be more robust against model error and actuator faults, compared with a model predictive controller.

REFERENCES

[1] Shah R, Alleyne AG, Bullard CW. Dynamic Modeling and Control of Multi-Evaporator Air-Conditioning Systems. ASHRAE Transactions. 2004;110:109-19.

[2] Lee IH, Choi JW, Kim MS. Studies on the heating capacity control of a multi-type heat pump system

applying a multi-input multi-output (MIMO) method. International Journal of Refrigeration. 2011;34:416-28.
[3] Shah R, Alleyne A, Bullard C, Rasmussen B, Hrnjak P. Dynamic modeling and control of single and multi-evaporator subcritical Vapor Compression Systems. ACRC TR-2162003.
[4] Koeln JP, Alleyne AG. Decentralized controller analysis and design for multi-evaporator vapor compression systems. Proceedings of the American Control Conference. Washington2013. p. 437-42.
[5] Kang I, Lee K, Lee J, Moon J. Artificial Neural Network–Based Control of a Variable Refrigerant Flow System in the Cooling Season. Energies. 2018;11:1643.
[6] Chen W, Zhou X, Deng S. Development of control method and dynamic model for multi-evaporator air conditioners (MEAC). Energy Conversion and Management. 2005;46:451-65.
[7] Tu Q, Zhang L, Cai W, Guo X, Yuan X, Deng C, et al. Control strategy of compressor and sub-cooler in variable refrigerant flow air conditioning system for high EER and comfortable indoor environment. Applied Thermal Engineering. 2018;141:215-25.
[8] Elliott MS, Rasmussen BP. Decentralized model predictive control of a multi-evaporator air conditioning system. Control Engineering Practice. 2013;21:1665-77.
[9] Yun GY, Lee JH, Kim HJ. Development and application of the load responsive control of the evaporating temperature in a VRF system for cooling energy savings. Energy and Buildings. 2016;116:638-45.
[10] Xu X, Pan Y, Deng S, Xia L, Chan M. Experimental study of a novel capacity control algorithm for a multi-evaporator air conditioning system. Applied Thermal Engineering. 2013;50:975-84.
[11] Yan H, Xia Y, Deng S. Simulation study on a three-evaporator air conditioning system for simultaneous indoor air temperature and humidity control. Applied Energy. 2017;207:294-304.
[12] Daikin. Maintenance handbook for VRV series: RUXYQ8-66AB. Shanghai: Daikin Air Conditioning Cooperation; 2014 (in Chinese).
[13] Rosenbrock HH. State-Space and Multivariable Theory. London: Nelson; 1970.
[14] Zhang W-J, Zhang C-L, Ding G-L. Transient modeling of an air-cooled chiller with economized compressor. Part I: Model development and validation. Applied Thermal Engineering. 2009;29:2396-402.
[15] Vu TNL, Lee M. Independent design of multi-loop PI/PID controllers for interacting multivariable processes. Journal of Process Control. 2010;20:922-33.