An Intelligent Control Strategy for the Intervals of Temperature in a Plate Heat Exchanger

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Abstract: The plate heat exchanger (PHE) is a strong nonlinear cascade process, where the input is the steam valve position and the outputs are the steam flow-rate of inner loop and the supply water temperature of outer loop. In general the PHE operation is subjected to the large random disturbances caused by the outdoor temperature and the water randomly discharged by users. These disturbances will make the temperature and the flow rate of return water fluctuate a lot. This causes the supply water temperature to fluctuate outside the targeted range and leads to the frequently changes of steam flow-rate. To solve this problem, an intelligent cascade control method for the temperature interval of PHE is proposed for such a nonlinear process. The proposed method combines a feed forward compensation, a range limitation unit, rule base reasoning (RBR) and cascade control together. The intelligent control for the intervals of supply temperature method is established that includes a PI-based feed forward control for the supply water and a PI-based upper bound constraint control for the steam flow. The successful application to a real PHE confirms the effectiveness of the proposed method. In particular, the real application has shown that the proposed method can ensure the supply temperature to be within its technically specified range and can realize a small fluctuation range of steam flow-rate when the system is subjected to the disturbances of outdoor temperature and the randomly discharged water by users.

Keywords: Plate heat exchanger process; feed forward compensation; interval cascade control; rule based reasoning (RBR);

1. INTRODUCTION

At present, PHE has become a main heating supply process because it has the advantages of high efficiency, energy saving and low pollution. The process exhibits a strong nonlinear and cascade nature, where the input is the steam valve position and outputs are the steam flow-rate of inner loop as well as the supply water temperature of outer loop. Since the indoor temperature is associated with the supply water temperature, it is a challenging issue on how the automatic control of the supply water temperature can be realized. In this context, a fuzzy PID was proposed by taking the steam valve opening as the input and the supply water temperature as the output, where a simulation experiment was carried out on the set-point control of supply water (Ge Nan, Li Tieying, & Wang Yuhui. 2012). Also, a cascade control method was developed that takes the steam valve opening as the input, the steam flow-rate as the inner loop output and the supply water temperature as the outer loop output (Andreas Rauh, Christina Dittrich, Harald Aschemann, Nedialko S. Nedialkovy, & John D. Pryce. 2013; Alexander Kharitonov, & Oliver Sawodny. 2006; Vladimír Bobá, Marek Kubalþk, & Petr Dostá. 2013). A feedback control method was established based on the state observer to realize the control of the set-point of supply water temperature (Andreas Rauh, Christina Dittrich, Harald Aschemann, Nedialko S. Nedialkovy, & John D. Pryce. 2013). For this group of methods, the outer loop uses a feed forward-feedback control and the on-line self-tuning prediction model, respectively (Alexander Kharitonov, & Oliver Sawodny. 2006; Vladimír Bobá, Marek Kubalþk, & Petr Dostá. 2013). However, only simulation studies have been carried out in these proposed methods. For the plate heat system where the variation outdoor temperature is significant, the system would be subjected to the random disturbances of the outdoor temperature and water emission. In these cases, adjusting the set-point of the supply water temperature alone cannot ensure the required level of control for the supply water temperature. In this context, a wide range of steam flow-rate fluctuations would occur. This leads to unexpected frequent changes of the steam valve opening, causing possible damage to the valve and affecting its safe operation.

To solve the above problems, an intelligent cascade control strategy is proposed here for the supply temperature when the system is subjected to the frequent changes of outdoor temperature and random water emission disturbances. This method has been successfully applied to a real PHE process in a mineral separation plant in China.

2. CONTROL PROBLEM DESCRIPTION

2.1 The PHE process description

The PHE process is shown in Fig. 1. When the compensating pressure P_b and the water supply pressure P_g are both in stable conditions, the valve opening $u(k)$ is adjusted to control the steam flow using the steam pressure P_1 and its temperature T_1 that are produced by the thermal power plant. Under this operating condition, the supply water temperature $y_2(k)$ can be controlled within its targeted range by applying the high temperature steam flow to heat the back-water, where steam flow $y_1(k)$ and back-water flow are applied into the plate heat exchanger. The supply water with temperature $y_2(k)$ runs through the water supply pipes so as to control the room temperature $T(k)$ into its targeted range.

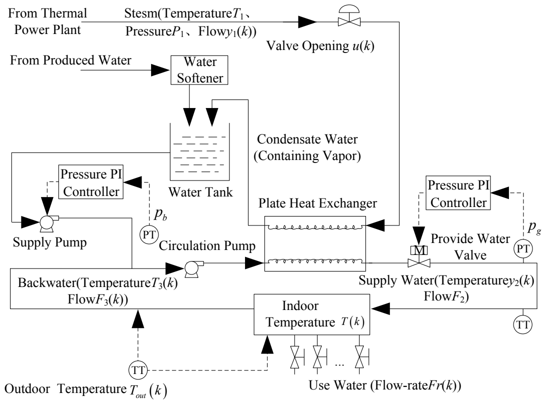

Fig. 1 The flowsheet of the PHE process

In this context, the main control objective that we need to ensure the following,

$$y_{2\min} \le y_2(k) \le y_{2\max} \tag{1}$$

where $y_{2\max}$ and $y_{2\min}$ are the technically specified upper and lower limits of the supply water temperature, respectively. Another control objective is shown that, i.e.,

$$y_{1\min} \le y_1(k) \le y_{1\max} \tag{2}$$

where $y_{1\max}$ and $y_{1\min}$ are the technically specified upper and lower limits of the stream flow-rate, respectively.

Therefore, the control task of the PHE process in factory is to design a controller with valve opening $u(k)$ as the input variable and with the flow-rate of steam $y_1(k)$ and supply water temperature $y_2(k)$ as inner and outer loop output variables. When the disturbances of outdoor temperature $T_{out}(k)$ are present and the water flow-rate $F_r(k)$ is randomly discharged by users, we need to ensure that control objectives (1) and (2) are both met.

2.2 The analysis of dynamic characteristics

Based upon the results presented in (J.P.Holman. 2011; LI Haibo, CHAI Tianyou, & ZHAO Dayong. 2013), a dynamic model is established using the Euler discretization method to give,

$$y_1(k) = (1-\frac{1}{\tau})y_1(k-1) + \frac{k_0}{\tau}u(k-1) \tag{3}$$

$$\begin{aligned} y_2(k+1) &= \left[1 - f(T_1, y_2, T_3, T_4)\left(F_3(k)+F_b\right)\rho_w c_w\right]y_2(k) + \\ & f(T_1, y_2, T_3, T_4)\left[H_v y_1(k) + F_3(k)\rho_w c_w T_3(k) + F_b \rho_w c_w T_b\right] \\ & - f(T_1, y_2, T_3, T_4)F_4(k)\rho_w c_w T_4(k) \end{aligned} \tag{4}$$

$$f(T_1, y_2, T_3, T_4) = \frac{\dfrac{1.15}{VK\beta\eta}\left[\ln\dfrac{T_1 - T_4(k)}{y_2(k)-T_3(k)}\right]^2}{\dfrac{T_1 - T_4(k) - y_2(k) + T_3(k)}{y_2(k)-T_3(k)} - \ln\dfrac{T_1 - T_4(k)}{y_2(k)-T_3(k)}}$$

where V is the volume of the heat exchanger plate; K is the coefficient of the heat transfer; β is the revise coefficient of the heat exchanger plate filth and η is the heat transfer efficiency. $H_v(T_1,P_1)$ is the stream heat content, Moreover, F_b is the compensation water flow-rate and T_b is the compensation water temperature, ρ_w and c_w are the density and the specific heat of the water, respectively.

It can be seen from (4) that there is a nonlinear function $f(T_1,y_2,T_3,T_4)$, where $y_2(k)$ was mainly affected by $y_1(k)$. Indeed, $y_2(k)$ and $y_1(k)$ are heavily nonlinearly related. Such nonlinear characteristics are also affected by $T_3(k)$, $F_3(k)$, $T_4(k)$, $F_4(k)$. It can be obtained from (Tu Guangbei. 2003) that,

$$T_3(k) = y_2(k) + \varphi_1\left[T - T_{out}(k)\right]^{\frac{1}{1+B(k)}} - \frac{\varphi_2}{C(k)}\left[T - T_{out}(k)\right] + v(T_{out}, h) \tag{5}$$

where $C(k)$= $F_3(k)/C$ is the relative flow-rate; $B(k)$ is the heat exchanging parameter; C, φ_1 and φ_1 are the design parameters of the PHE process; $v(T_{out},h)$ is the unknown nonlinear function related to the outdoor temperature $T_{out}(k)$, the structure and parameter h of the pipeline.

As shown in Fig. 1, the backwater flow-rate $F_3(k)$ can be expressed as,

$$F_3(k) = F_2 - F_r(k) \tag{6}$$

It can be seen from (5) that when the design parameters of PHE process are determined, $T_3(k)$ is not only affected by $y_2(k)$ and T, but also significantly depends on the variation of $T_{out}(k)$. The system considered here is located in the northwest region of China, where $T_{out}(k)$ also changes and such variations can be around 20℃. From equation (6) it can be seen that when F_2 is in a steady state, $F_3(k)$ can exhibit large variations because of the random discharge of the water. In fact, such fluctuations of $F_3(k)$ can be up to 25% of its designed capacity. When $k\to+\infty$, and equation (4) becomes,

$$\begin{aligned} y_1(k) = \frac{\rho_w c_w y_2^*}{H_v}\left(F_3(k)+F_b\right) - \frac{\rho_w c_w}{H_v}F_3(k)T_3(k) - \\ \frac{F_b \rho_w c_w T_b}{H_v} + \frac{\rho_w c_w}{H_v}F_4(k)T_4(k) \end{aligned} \tag{7}$$

From equation (7) it can be seen that when the supply water temperature is in a steady state, $y_1(k)$ is mainly affected by the disturbances. When such disturbances are large and frequent, $y_1(k)$ would exceed its technically specified range. When $k\to+\infty$ it can be obtained from (3) that,

$$u(k) = \frac{y_1(k)}{k_0} \tag{8}$$

From equation (8) it can be observed that if $y_1(k)$ exceeds its the technically specified range, the valve opening $u(k)$ would vary a lot. This would lead to unexpected serve vibration of the stream pipeline and thus reduce the lifespan of the valve, causing concerns of operational safety. To avoid the above situation, it is imperative that the stream flow-rate is controlled within its technically specified range. However, when large disturbances occur, $y_2(k)$ will fluctuate in a wide range and can be outside its technically specified range.

At present, the set-point control of the supply water temperature in the heat exchanger of the urban houses mainly uses PI control method (Xiong Xin-min, & Cao Yi. 2009) or PI cascade control method (Liang Yuanyuan. 2011). However, it is difficult to use such control strategies for the PHE process, the manual operation is widely used as shown in Fig. 2.

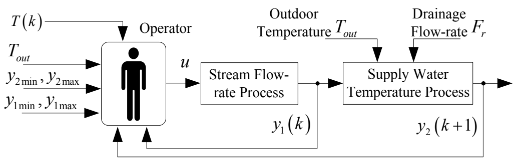

Fig. 2. The existing manual-based control status of the PHE process in factory

For these manual control strategies, the operator generally combines the outdoor temperature $T_{out}(k)$ and indoor temperature $T(k)$ together so as to empirically adjust the steam flow-rate valve opening $u(k)$ according to the supply water temperature $y_2(k)$, the stream flow-rate $y_1(k)$ and its technical required limits $[y_{2\min}, y_{2\max}]$ and $[y_{1\min}, y_{1\max}]$. When the random disturbance of outdoor temperature $T_{out}(k)$ are present and the water flow-rate $F_r(k)$ is discharged by users in factory, large fluctuations of the backwater flow-rate $F_3(k)$ and its temperature $T_3(k)$, would take place. Under such circumstances, the manual operation cannot adjust steam valve opening $u(k)$ timely and accurately. This would often cause the supply water temperature and the stream flow-rate to exceed their specified range.

3 CONTROL METHOD

3.1 The proposed control structure

Based upon the analysis of dynamic characteristics, and taking into account the fact that the control objectives of the supply water temperature and the stream flow-rate are basically intervals control problem, a new method is proposed as shown in Fig. 3, where the control strategy combines together the feedforward compensation, rule base reasoning and interval limiting control with the cascade control. The functionalities of each part is described as follows,

The PI-based feedforward control for the supply water temperature: This unit consists of the feedforward compensation and the PI controller, where the feedforward path is used to eliminate the influence of the disturbance. On the other hand, the PI controller for the temperature is used to ensure that the actual temperature $y_2(k)$ follows its set-point y_{2ref}.

The PI-based limiting control for steam flow-rate: This unit consists of the interval limiting compensation controller of the rule base reasoning (RBR) and the PI controller of the stream flow-rate, the purpose of such a RBR is to prevent the valve opening $u(k)$ from a large range of variation when the stream flow-rate $y_1(k)$ exceeds its technically required range. It should also prevent the fluctuation of the supply water temperature caused by the limiting control for steam flow-rate. The PI controller for the stream flow-rate is used to ensure that the actual flow-rate $y_1(k)$ follows its set-point $y_1^*(k)$, so that the temperature and the flow-rate are all controlled well within their target ranges.

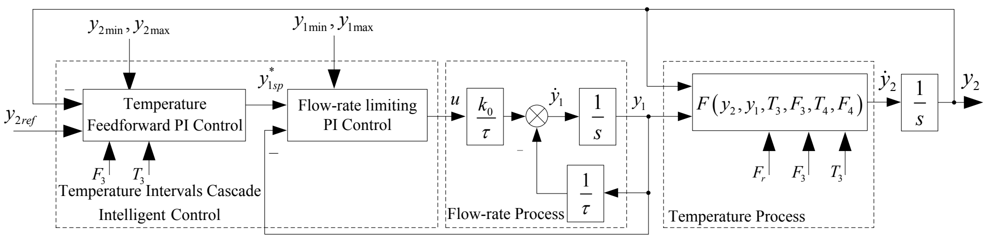

Fig. 3 The intelligent cascade control method for the intervals of temperature of the PHE process

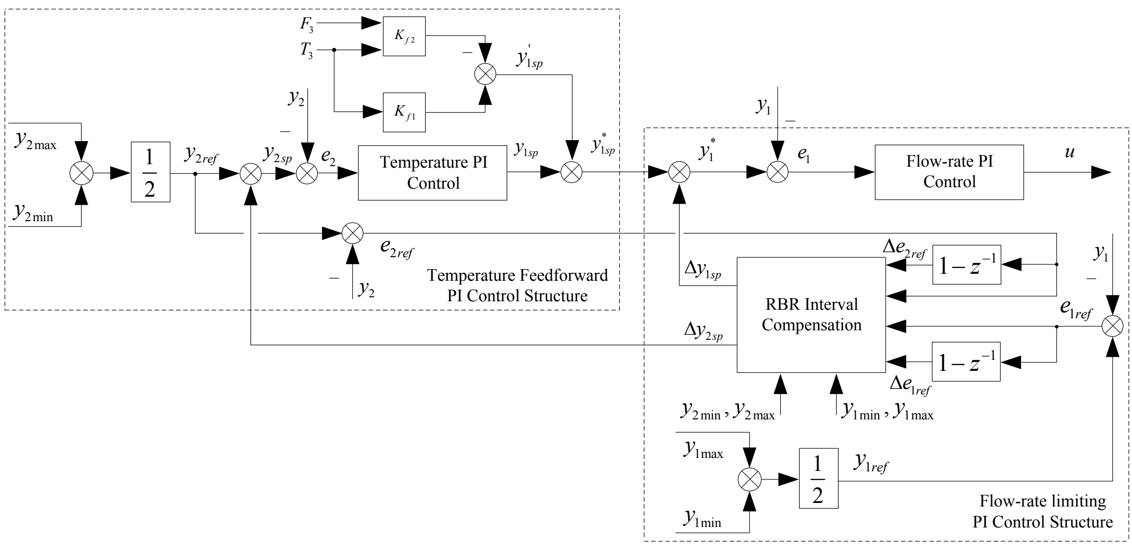

Fig. 4 The intelligent cascade control structure for the intervals of temperature of the PHE process

3.2 The intelligent intervals control of supply temperature control algorithms

1). The PI-based feedforward control algorithm of the supply water temperature

As shown in Fig. 4, the stream flow-rate set-point $y_{1sp}{}^{*}(k)$ can be expressed as,

$$y^{*}_{1sp}(k) = y_{1sp}(k) + y^{'}_{1sp}(k) \tag{9}$$

The supply water temperature is realized by incremental PI controller as follows.

$$y_{1sp}(k) = k_{2p}\Delta e_2(k) + k_{2i}e_2(k) \tag{10}$$

where $e_2(k)=y_{2sp}(k)-y_2(k)$, $\Delta e_2(k)=e_2(k)-e_2(k-1)$

In order to eliminate the influence of the supply water temperature cause by $F_3(k)$ and $T_3(k)$, the compensated value $y_{1sp}{}^{'}(k)$. i.e.,

$$y^{'}_{1sp}(k) = K_{f1}F_3(k) - K_{f2}F_3(k)T_3(k) \tag{11}$$

where K_{f1} and K_{f2} are the feedforward compensation coefficients.

In this paper, the FOPDT approximation model (Jin Yihui. 2006) is established to determine parameters k_{2p} and k_{2i} of PI controller for supply water temperature as follows,

$$G_2(s) = \frac{K_2}{T_2 s + 1}e^{-\tau_2 s} \tag{12}$$

The parameters of the PI controller are tuned by adopting the well-known Z-N method (Lequin, Gevers, Mossberg, & Bosmans, 2003) as follows,

$$k_{2p} = \frac{0.9T_2}{K_2\tau_2} \qquad k_{2i} = \frac{k_{2p}}{3.33\tau_2} \tag{13}$$

Using (8)-(10), the feedforward compensation coefficients (K_{f1} and K_{f2}) can be obtained from:

$$y^{*}_{1sp}(k) = k_{2p}\Delta e_2(k) + k_{2i}e_2(k) + K_{f1}F_3(k) - K_{f2}F_3(k)T_3(k) \tag{14}$$

Substituting (13) into the closed loop system equation, it can be seen that the error signal $e_2(k)\rightarrow 0$ when the control system for supply water temperature is in a steady state. Therefore, the closed loop system can be expressed by the following,

$$K_{f1}F_3(k) - K_{f2}F_3(k)T_3(k) = \frac{\rho_w c_w y^{*}_2}{H_v}F_3(k) - \frac{\rho_w c_w}{H_v}F_3(k)T_3(k) \tag{15}$$

The feedforward compensation coefficients can be obtained using (15) to read,

$$K_{f1} = \frac{\rho_w c_w}{H_v}y^{*}_2 \qquad K_{f2} = \frac{K_{f1}}{y^{*}_2} \tag{16}$$

where the specific heat of the water, respectively, H_v is the heat content of the stream which can be obtained from the table of the heat content.

2). The PI-based limiting control algorithm of the steam flow-rate

As shown in Fig. 4，this unit consists of interval limiting compensation controller using RBR and the PI controller. In this context, the reference values y_{2ref} of the supply water temperature and y_{1ref} of the stream flow-rate are selected as $y_{2ref}=(y_{2\max}+ y_{2\min})/2$ and $y_{1ref}=(y_{1\max}+ y_{1\min})/2$. The permitted maximum deviation of the supply water temperature and the stream flow-rate are expressed by $\delta=(y_{2\max}- y_{2\min})/2$ and $\gamma=(y_{1\max}- y_{1\min})/2$, respectively.

By introducing the reference error signals $e_{2ref}(k)$ and $e_{1ref}(k)$ together with its rate of changes denoted by $\Delta e_{2ref}(k)$ and $\Delta e_{1ref}(k)$, a set of rules can be obtained in the form of "If <*premise*> then <*conclusion*>" (Li Shue, & Shiue. 2000; Lin Tseng, & Teng. 2008). This leads to the following rules,

rule 1: IF $e_{2ref}(k)>\varepsilon$ and $e_{2ref}(k)\Delta e_{2ref}(k)>0$ THEN $\Delta y_{1sp}(k)= \Delta y_{1sp}(k-1)+\alpha\leq y_{1\max}- y_{1sp}{}^{*}(k)$;

rule 2: IF $e_{2ref}(k)<-\varepsilon$ and $e_{2ref}(k)\Delta e_{2ref}(k)>0$ THEN $\Delta y_{1sp}(k)= \Delta y_{1sp}(k-1)-\alpha\leq y_{1\min}- y_{1sp}{}^{*}(k)$;

rule 3: IF $|e_{2ref}(k)|\leq\varepsilon$ or $|e_{2ref}(k)|>\varepsilon$ and $e_{2ref}(k)\Delta e_{2ref}(k) <0$ THEN $\Delta y_{1sp}(k)= \Delta y_{1sp}(k-1)$;

rule 4: IF $e_{1ref}(k)>0.8\gamma$ and $e_{1ref}(k)\Delta e_{1ref}(k)>0$ THEN $\Delta y_{2sp}(k)= \Delta y_{2sp}(k-1)+\beta\leq y_{2\max}- y_{2ref}$;

rule 5: IF $e_{1ref}(k)<-0.8\gamma$ and $e_{1ref}(k)\Delta e_{1ref}(k)>0$ THEN $\Delta y_{2sp}(k)= \Delta y_{2sp}(k-1)-\beta\leq y_{2\min}- y_{2ref}$;

rule 6: IF $|e_{2ref}(k)|\leq\varepsilon$ and $|e_{1ref}(k)|\leq 0.8\gamma$ and $y_{2sp}(k)= y_{2ref}$ THEN $\Delta y_{2sp}(k)=0$;

rule 7: IF $|e_{2ref}(k)|\leq\varepsilon$ and $|e_{1ref}(k)|\leq 0.8\gamma$ and $y_{2sp}(k) > y_{2ref}$ THEN $\Delta y_{2sp}(k)= \Delta y_{2sp}(k-1)-0.5\beta$;

rule 8: IF $|e_{2ref}(k)|\leq\varepsilon$ and $|e_{1ref}(k)|\leq 0.8\gamma$ and $y_{2sp}(k) < y_{2ref}$ THEN $\Delta y_{2sp}(k)= \Delta y_{2sp}(k-1)+-0.5\beta$;

where ε is determined by the production specifications, α and β are the rule compensation coefficients obtainable from experiments.

The stream flow-rate is realized by an incremental PI controller expressed as follows.

$$\Delta u(k) = k_{1p}\left[e_1(k) - e_1(k-1)\right] + k_{1i}e_1(k) \tag{17}$$

$$e_1(k) = y^{*}_1(k) - y_1(k) \tag{18}$$

Substituting (18) into (17) yields,

$$\Delta u(k) = k_{1p}\left[\Delta y^{*}_1(k) - \Delta y_1(k)\right] + k_{1i}\left[y^{*}_1(k) - y_1(k)\right] \tag{19}$$

where k_{1p} and k_{1i} are the parameters of the PI controller of the stream flow-rate. where the PI controller parameters can be obtained using again the well-known Z-N method.

In addition, the valve is necessary to evaluate the output of steam flow controller as follows,

$$\begin{cases} u(k) = u(k-1) + \Delta u(k) & |\Delta u(k)| > \phi \\ u(k) = u(k-1) & |\Delta u(k)| \leq \phi \end{cases} \tag{20}$$

where ϕ is the incremental value of valve which is determined by its only parameters.

4. INDUSTRIAL APPLICATION

4.1 Parameter selection of the controller

The proposed control method has been applied to the PHE process in China as displayed in Fig. 5.

Fig. 5. The heat transfer process

The process requirements of the supply water temperature is $y_{2\min}$=45℃, $y_{2\max}$=55℃, then the purpose is to required to achieve the following,

$$45 \le y_2 \le 55 \tag{21}$$

Based on the analysis of actual operation of the system, the maximum fluctuate of the supply water temperature is given as δ=5.0℃, and the temperature deviation limiting is defined as ε=2.0℃, The coefficients of the proposed rule based reasoning compensation, namely α and β, are set to 0.5t/h and 2.0t/h, respectively. The upper and lower limitations of the stream flow-rate are given as $y_{1\min}$=1.5t/h and $y_{1\max}$=4.0t/h, respectively.

$$1.5 \le y_1 \le 4 \tag{22}$$

In practice, the feedforward action factor is given by K_{f1}=0.09 and K_{f2}=0.015, the temperature PI controller parameters being set to k_{2p}=5.0 and k_{2i}=0.05, the stream flow-rate PI controller parameters is set to k_{1p} =5.0, k_{1i}=0.15. Moreover, the sampling period is selected as 1 second; the supply water temperature set-point period is 3mins. In this context, the stream flow-rate set-point period is 1min, its control period is of 1 second and the valve incremental value is selected as 2%.

4.2 Industrial application effectiveness analysis

The controller of the supply water temperature and the stream flow-rate intervals is designed by adopting the proposed control method. The hardware of control system is shown in Fig. 6.

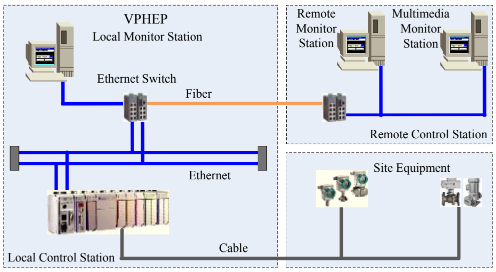

Fig. 6. Control system hardware platform for the PHE process

The human machine interface of the PHE process is shown in Fig. 7.

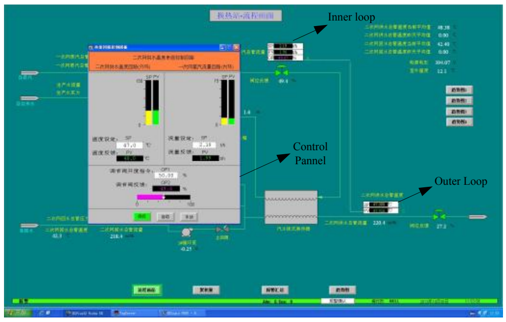

Fig. 7. Human machine interface of the PHE process

Using the proposed method, the control effect is shown in Fig. 8.

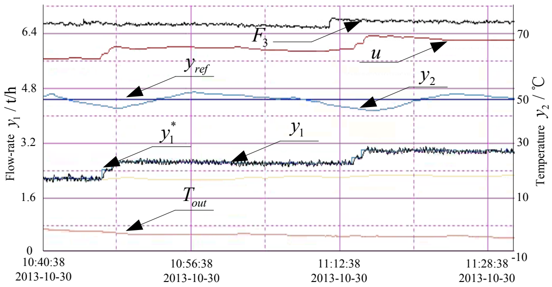

Fig. 8. The responses of y_1 and y_2 using the proposed method

Fig. 8 shows that the supply water temperature $y_2(k)$ can be steadily controlled around 50℃. At time of 10:40am, the outdoor temperature $T_{out}(k)$ dropped in the range of 0℃ ~-5℃. In order to ensure that the supply water temperature $y_2(k)$, the set-point of the steam flow-rate target $y_1^*(k)$can be increased by the feedforward controller, the set point of the steam flow-rate target y_1^* has been changed from 2.0t/h to 2.6t/h. The supply water temperature rises at 10:48am; the set-point of the steam flow-rate is not adjusted. Because the role of the RBR controller is subjected to the error value $e_2(k)$ which is lower than 2. At 11:10am, the users randomly discharge the water that led to the reduction of the flow-rate. The flow-rate $F_3(k)$ of backwater is increased from 160m^3/h to 180m^3/h, then the steam flow-rate was increased from 2.6t/h to 3.0t/h. Meanwhile, the supply water temperature has not appeared to be largely fluctuated. As can be seen from these operating curves, when the temperature in the plant is affected by the outdoor temperature and hot water users, supply water temperature and steam flow-rate will be controlled within the range prescribed in the process effectively by adopting the proposed control method. Indeed, it can be seen that the water temperature fluctuation range is 47℃ ~ 52℃ and the steam flow fluctuation range of 2.0t/h ~ 3.2t/h.

Before the computer control system is applied, this process has been under a manual control mode. The control effects are shown in Fig. 9.

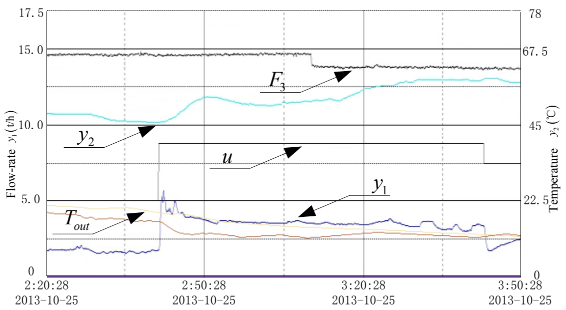

Fig. 9. The responses of y_1 and y_2 using manual control

It can be seen in Fig. 9 that the supply water temperature $y_2(k)$ is around 50℃. At 2:30am, as the outdoor temperature has dropped from -1℃ to -4℃, the temperature of backwater $T_3(k)$ and supply water $y_2(k)$ begin to decrease. The operator then increased the steam control valve opening manually at 2:40am, which makes the steam flow-rate go up to 5t/h and the temperature of supply water tend to ascend. At 3:10am, the backwater flow-rate $F_3(k)$ decreased from 200m3/h to 170m3/h as the users increased the water consumption. At this moment no action from operator was made. This leads to the temperature of supply water begins to rise to 60℃. At the time of 3:40am, the operator decreased the steam control valve opening to avoid a wide range of fluctuations of the temperature of supply water $y_2(k)$. As the manual control cannot adjust the system correctly and timely, the temperature of supply water and the steam flow-rate exhibited sever oscillation: from the period of 2:20am to 3:50am. In this case it can be seen that the temperature of supply water changed from 45℃ to 60℃, and the steam flow-rate varied from 1.2t/h to 5.5t/h. It can be seen that the temperature of supply water and the steam flow-rate present large fluctuations.

After the control system is put into operation, comparative end-effect data between the proposed control and manual control methods are shown in table 1.

Table1. Contrastive date of the proposed control and manual control methods

	y_2(℃)	y_1(t/h)	u(%)
This Paper	±3	±0.6	20
Manual	±8	±2	40

From the data in Table 1, it can be seen that proposed control method is superior to the manual control on $y_2(k)$, $y_1(k)$ and $u(k)$ when $T_{out}(k)$ and $F_3(k)$ changed between -0℃ ~5℃ and 160m^3/h ~200m^3/h, respectively.

5. CONCLUSIONS

This paper has presented a new intervals cascade intelligent control method. The real industrial application result has shown that the proposed method can control the supply water temperature and the stream flow-rate fluctuation within their targeted ranges and its rate of small fluctuations when the process is subjected to the outdoor temperature and the water flow-rate random disturbance caused by users. This proposed control method provides a novel framework that can be used to control nonlinear cascaded systems which are subjected to large random disturbances.

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