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Research of cascade averaging control in hydraulic equilibrium regulation of heating pipe network

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Abstract

The heating pipe network system with such dynamic characteristics as nonlinearity and large time lag may cause hydraulic disorder. To solve this problem, this paper proposes a unit control-based hydraulic equilibrium control strategy, which constructs an equilibrium regulation system for heating pipe networks by optimising the inlet device of each unit and using a novel control theory. By developing a cascade control system to control the return water temperature and the pressure difference between supply and return water of the branches at each unit of the pipe network, we were able to stabilise the pressure and control the temperature. Then, we used the averaging control theory to set the parameters of regulation systems between each unit. The research results indicate that, compared to the traditional single-loop negative-feedback return water temperature control system, the cascade averaging controller has a better control effect than the single-loop PID controller. This is because it has a smaller overshoot and can cope with system interference factors quickly. Therefore, the temperature of return water between each unit can be coordinated and fluctuation is within a smaller range. This effectively eliminates the influence of static and dynamic hydraulic disorder on entire system stability.

Keywords: heating pipe network, hydraulic disorder, cascade control system, averaging control

1 Introduction

In an urban heating pipe network, intelligent regulation and equilibrium control are the core of the entire system operation [1], and the control condition will greatly affect the power and heat consumption of the entire heating system [2]. Currently, central heating still faces the problems that (1) in case of lack of effective regulation at the terminals of a heating system, hydraulic disorder may result in uneven indoor temperatures of

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different users; and (2) in order to maintain the heat supply of users with lower indoor temperature, the heat output from the heat source is increased, which leads to excessive heating and overall overheating loss [3–5]. Therefore, the pipe network flow should be controlled in a reasonable range so that it can satisfy heat consumers' needs and help to save energy and reduce consumption of the entire heating system.

To improve hydraulic disorder in the heating pipe network, a various types of research have been carried out in the industry, and a lot of hydraulic equilibrium regulation methods have been raised. Common regulation methods include a proportional regulation method, compensational regulation method, return water temperature method etc. [6]. Both proportional regulation method and compensational regulation method require the regulating staffs to perform a related heating theoretical calculation before regulation operation. Comparatively, the return water temperature method is simpler. It only takes return water temperature as a regulating target. However, the traditional return water temperature method has the weaknesses of regulating time delay and indoor temperature not fully represented by return water temperature. This paper puts forward an automatic levelling scheme that can remedy the demerits of the traditional return water temperature method.

2 Overall structure of equilibrium regulation system based on unit control and its control scheme

2.1 Equilibrium regulation system based on unit control

The secondary heating network system has strong thermal inertia and a larger time constant during the heat transfer process [7, 8]; so, traditional temperature regulation measures cannot provide precise control over the controlled object. Meanwhile, the heating system often adopts a branch-shaped pipe network [9, 10], which leads to hydraulic disorder in the system; see Figure 1 for the system diagram. Though a large number of studies and demonstrations on the hydraulic disorder of pipe networks have been conducted in the industry, problems exist to varying extents and these can be attributed to the practicality of operating effect, such as high cost and poor regulating effect [11]. In contrast with from previous strategies that a system needs to be regulated repeatedly by professional staffs according to their experience, this system proposes a unit control-based hydraulic equilibrium control strategy. It is a unit control-based equilibrium regulation system for heating pipe networks, which optimises the device at the unit inlet and applies the structure of novel control theories.

This system decomposes the controlled objects with larger delay, takes the pressure difference and return water temperature required by heat consumers of each unit as control parameters to design a cascade averaging control system and transmits the heating network data remotely by IoT technology and equipment to the remote monitoring centre of the heating company. The managing staffs of the company could regulate automatically according to various data of heating system, stabilise the pressures of each branch and meanwhile compare the measured return water temperature with the set value of return water temperature issued by the remote monitoring centre. Then, they can adjust the electric control valve installed at the unit entrance of each building and change the flow of the pipeline. When the re-measured return water temperature and real working pressure difference of all units are basically the same, it can be said that the hydraulic and thermodynamic equilibrium of the secondary network system is achieved.

At the same time, the indoor temperature data collectors are installed in the home as part of heat consumers in the building; this is done to monitor the indoor temperature of typical consumers in real time, which provides an indoor temperature reference for equilibrium regulation of secondary network and can ensure the heating quality [12, 13].

2.2 System structure

The equilibrium regulation system collects such signals as supply and return water pressure difference and returns water temperature at heat inlet of all units in the community through PLC controller of all buildings. Then, it communicates with the remote control centre, controls the designated electric regulating valve through a novel algorithm and adjusts valve opening to affect the pipeline flow, enabling the return water temperature

Fig. 1 Diagram of heating system structure.

to reach a stable value. The structure of the entire heating network equilibrium system is divided into three layers: a bottom layer, a network layer and a remote control layer. The bottom layer is the on-site control part, in which PLC control cabinets are installed in each building to collect the return water temperature and supply and return water pressure data of each unit. Moreover, a new control algorithm is run in PLC's CPU (through PLC's new control strategy) to adjust corresponding electric regulating valves and to transmit collected data into the system's network layer. In the network layer, various parameters of the system in the PLC host are transmitted via an optical fibre conversion device in the control cabinet to the exchanger of the heat exchange station in the community. Then, through connecting to WAN via a router, by way of port mapping, the summarised heating network data is interacted to the host computer, to realise remote transmission. After that, in the remote control layer, the data is displayed in the Supervisory Control And Data Acquisition (SCADA) system, and a self-designed operation interface makes it possible to monitor the bottom layer data in real time and to manually set and automatically adjust valve opening. The overall structure of the system is shown in Figure 2.

2.3 Control system scheme

In a heating pipe network system, the different distance between different heat consumers and the heat source centre leads to the discrepancy of the residual pressure heads in the pipelines of different heat consumers. Different residual pressure heads make the flow into each heat consumer not conform to the designed value, and thus, hydraulic disorder generates [14]; when the secondary pipeline is well heat-preserved, that is, if the supply water temperature is the same, the temperature of return water in the pipeline can accurately reflect the heat disorder of the pipe network [15, 16].

The heating pipe network has strong thermal inertia and a larger time constant during heat transfer, and so traditional temperature regulation means could not provide precise control over the controlled object. In order to satisfy overall heat consumers' demand for indoor temperature, a unit-specific regulation scheme is designed and reasonable temperature and pressure observation points are set at the heat inlet of each unit in the community. In this way, the controlled objects with larger delay are decomposed, and a disturbance variable with frequent and large-range changes is found from the return water temperature of originally controlled objects. That is, the temperature T_H of the return water pipeline in the unit is taken as the main parameter and the actual working pressure difference ΔP_L of heat consumer in this unit is considered as a minor parameter to design a cascade control system. In the system, the output signals of the controller in the primary loop are taken as the set value of the controller in the minor loop, and the output signals of a minor control system are taken as the input signals of the main controlled object, to regulate the electric valve of each unit accurately and in real time. The working pressure difference ΔP_L of the heat consumer in each unit can pre-reflect the disturbance condition in the network. By effectively suppressing the disturbance, the system is enhanced in quick response

Fig. 2 System structure chart.

and self-adaptive capability. In this cascade control system, the effect of disturbance f_1 on the network will affect ΔP_L first, followed by T_H . By dividing the pipe network temperature with a longer nonlinear control channel into two levels, ΔP_L can be measured preferentially and controlled, which ensures that most of the disturbance is overcome basically in the minor loop, and the residual influence and the overall influence from other disturbance are then overcome by the primary loop. Thereby, compared to the situation prevailing before introducing the pressure difference ΔP_L of the minor loop, the design of cascade control scheme will greatly weaken the disturbance in the minor network system, so as to shorten the regulation time and accelerate the system equilibrium. The control system diagram is shown in Figure 3.

Fig. 3 Unit branch cascade control system.

3 Development of equilibrium regulation system based on unit control

3.1 System control strategy

The control system principle diagram is shown in Figure 4. Let us suppose that pipeline clogging or household valve lockup occurs at the heat consumer side. If such an influential condition will act on a minor object, then it can be categorised as disturbance f_1 in the figure. This results in the decrease of pressure required by the heat consumer side and the increase of residual pressure difference in this unit branch. Thus, when other influential factors remain unchanged, the flow and temperature provided by the heat exchange station will also be kept the same. Immediately, at the measuring points of this project, the working pressure difference ΔP_L of monitored unit rises, resulting in increased Z_L , which then leads to reduced e_L , decreased output p of the minor controller and declined flow q_R into this unit. Finally, ΔP_L falls back, and this demonstrates the control effect.

If we assume that the supply and return water pressure difference at the heat inlet of the original unit is under the effect of regulated flow q , then the transfer function is $G_{02}(s)$. And the entire minor loop of the unit cascade control system is equivalent to a controlled process, whose equivalent transfer function is represented by $G'_{02}(s)$. Then,

$$G'_{02}(s) = \frac{P_L(s)}{g_L(s)} = \frac{G_{c,P}(s)G_v(s)G_{02}(s)}{1 + G_{c,P}(s)G_v(s)G_{02}(s)G_{m2}(s)} \quad (1)$$

According to the existing experiments, if the output characteristic of the electric regulation valve is set as $G_v(s)$, the transfer function of pressure difference measuring transmitter at the minor side is $G_{m2}(s)$; then the transfer functions of each link in the minor loop are

$$G_{02}(s) = \frac{K_{02}}{T_{02}s + 1}, \quad G_{c,P}(s) = K_{c2}, \quad G_v(s) = K_v, \quad G_{m2}(s) = K_{m2}$$

Eq. (1) is converted to

$$G'_{02}(s) = \frac{K_{c2}K_vK_{02}/(T_{02}s + 1)}{1 + K_{c2}K_vK_{m2}K_{02}/(T_{02}s + 1)} = \frac{K'_{02}}{T'_{02}s + 1} \quad (2)$$

in which K'_{02} and T'_{02} are the amplification coefficient and time constant of equivalent process, respectively, and it is obtained that

$$G'_{02}(s) = \frac{K_{c2}K_vK_{02}/(T_{02}s + 1)}{1 + K_{c2}K_vK_{m2}K_{02}/(T_{02}s + 1)} = \frac{K'_{02}}{T'_{02}s + 1} \quad (3)$$

In a normal-operation condition of heating network, $K_{c2}K_vK_{m2}K_{02} \gg 1$; so, when the regulation process of the minor loop causes amplification coefficient K_{02} or K_v to change with network load, K'_{02} scarcely changes. Therefore, there is no need to reset regulator parameters [17]. In addition, the rise of the unit working pressure difference ΔP_L directly affects the return water temperature T_H of this unit to rise, z_H to rise and e_H to fall, which make the set value g_L of the minor loop to decline. At this time, the minor loop will further suppress the change of unit working pressure difference ΔP_L caused by the change of disturbance pressure at the heat consumer end of each unit. From above, the added minor loop will enhance the speed and stability of such control effect during the equilibrium process of the network system and relieve the systemic pressure disturbance.

When the influential conditions act on the primary object, for example, the supply water temperature at the heat exchange station of a community fluctuates, or in-station valve disturbance causes flow fluctuation, as shown as f_2 in the figure. The in-station valve fluctuation may lead to the rise of supply water temperature in minor network and the unit working pressure difference ΔP_L may suffer weak impact. However, the rising unit return water temperature T_H makes z_H to increase and e_H to fall, causing the minor loop to give effect and bringing down the set value g_L of the minor loop. As a result, the output ΔP_L of the minor loop will undoubtedly

Fig. 4 Control system's principle diagram.

lower, eventually bringing T_H down back to the set temperature and overcoming disturbance conditions. When the whole control system reacts, the unit working pressure difference value ΔP_L is lower than that of the original working condition. This is a necessity to prevent overheating at heat consumers when the supply water temperature of the secondary network rises at the heat exchange station – because the set value g_L of the minor loop has decreased during the control process, and the minor loop will not give effect to adjust ΔP_L to the original value. To sum up, when the disturbance condition acts on the primary object, the cascade control system designed under each unit of the total system will effectively overcome the impact of the disturbance.

3.2 Controller design

The unit control-based hydraulic equilibrium regulation system is composed of a PLC controller, electric regulating valve, temperature sensor, pressure sensor, optical fibre converter and so on. The system structure is designed briefly, with clear control equipment, to ensure the regulation performance of valves. Therefore, the controller adopts SIEMENS S7-200 SMART type. The pressure and temperature sensors are connected with the PLC controller by shield cables to transmit signals, while the PLC controller supports open user communication protocol, which guarantees signal transmission in the whole process. This system takes return water temperature and supply and return water pressure difference as a basis of hydraulic equilibrium regulation, designs reasonable temperature and pressure measuring points in the heating network, installs temperature and pressure transmitter and measures return water temperature and supply and return water pressure difference in different unit pipelines. The PLC controllers allocated in buildings upload the measured return water temperature and supply and return water pressure difference to the remote control centre. Then the remote control centre will summarise return water temperature and supply and return water pressure difference in the unit pipeline of different buildings as well as outdoor temperature change to figure out the appropriate set value of return water temperature, and deliver it to the PLC controller. Later, each controller adjusts the electric regulating valve of each unit entrance by running a built-in control algorithm, ultimately enabling the return water temperature of each unit to reach an equilibrium value. Take a PLC controller designed in Building #1 as an example; see its design drawing in Figure 5.

According to the real monitored point number of hydraulic equilibrium regulation system based on unit control, in order to ensure that PLC terminal number accounts for 10–20% margin of total point number, the S7-200 SMART PLC's CPU module is selected as SR30, the on-off input/output is 18 points/12 points and input/output form is DC 24 V input/AC 220 V relay output. On account of this, the system needs multi-path analogue input and output points, and so the analogue module needs to be extended. Take a building with two units as an example and extend two analogue modules EM AE08 of eight-module input selected in the input combination and one analogue module EM AQ04 of four-module output. The I/O point address assignment of

3.3 Application of averaging control

Table 1 I/O point address assignment.

Input		Output	
I0.0	System On	Q0.0	Automatic operation indicator
I0.1	System Off	Q0.1	Comprehensive alarm indicator
I0.2	Manu/Auto switchover	Q0.2	Out-of-control valve in unit #1 higher zone
I0.3	Emergency cut-off	Q0.3	Out-of-control valve in unit #1 lower zone
AIW16	Return water temperature in unit #1 higher zone	Q0.4	Out-of-control valve in unit #2 higher zone
AIW18	Return water temperature in unit #1 lower zone	Q0.5	Out-of-control valve in unit #2 lower zone
AIW20	Return water temperature in unit #2 higher zone	Q0.6	Return water temperature alarm in unit #1
AIW22	Return water temperature in unit #2 lower zone	Q0.7	Return water temperature alarm in unit #2
AIW24	Supply water pressure in unit #1 higher zone	Q1.0	Supply and return pressure difference alarm in unit #1
AIW26	Return water pressure in unit #1 higher zone	Q1.1	Supply and return pressure difference alarm in unit #2
AIW28	Supply water pressure in unit #1 lower zone	AQW48	#1 Higher valve opening instruction
AIW30	Return water pressure in unit #1 lower zone	AQW50	#1 Lower valve opening instruction
AIW32	Supply water pressure in unit #2 higher zone	AQW52	#2 Higher valve opening instruction
AIW34	Return water pressure in unit #2 higher zone	AQW54	#2 Lower valve opening instruction
AIW36	Supply water pressure in unit #2 lower zone		
AIW38	Return water pressure in unit #2 lower zone		
AIW40	Valve feedback in unit #1 higher zone		
AIW42	Valve feedback in unit #1 lower zone		
AIW44	Valve feedback in unit #2 higher zone		
AIW46	Valve feedback in unit #2 lower zone		

the overall regulation procedure in Figure 7.

4 Engineering application

4.1 Profile of engineering

Application research was conducted in Dihao Community, Shijiazhuang city, and was carried out in accordance with standardised engineering practices. This community was built early in 2018, including nine high-rise residential buildings, with a total construction area of 118,435 m² and a heating supply area of 43,188.62 m². The tail-end network path has an unreasonable route due to on-site construction conditions and unit load estimation deviation, and hydraulic disorder is obvious in near-end and tail-end heat consumers; owing to these

Fig. 6 Program design flow chart.

reasons, it is necessary to improve the system. See detailed community information in Table 2.

Table 2 Statistics of building condition in the community.

SN	Building No.	Unit qty.	Floor qty.	Construction area (m ²)	Heating supply area (m ²)
1	#1	3	18	23086.5	7632.46
2	#2	2	18	9781	2337.86
3	#3	2	18	15309.36	5181.87
4	#4	2	18	16465.4	4188.8
5	#5	2	12	10113.6	4194.52
6	#6	2	18	16465.4	7502.58
7	#7	2	18	9558.21	4501.11
8	#8	2	11	9279.6	4254.63
9	#9	2	16	8431.84	3394.79

The community adopts central heating. Municipal high-temperature hot water will exchange heat with the minor network after being conveyed to the heat exchange station in the community, and then low-temperature hot water will be conveyed into each building. Indoor heating adopts floor radiation, and the courtyard pipe network is laid by lifting at the top of the garage. See network laying in Figure 8.

After electrical engineering network-route design, system hardware installation, controller programming and system communication test, the summarised heat network data is interacted to the operation environment of the host computer to realise remote transmission and to display in the SCADA system in the remote control layer. By self-designing an operation interface, it is possible to monitor the bottom layer data, manually set

Fig. 7 System operation flow chart.

Fig. 8 Community network laying drawing.

and automatically adjust valve opening in real time. Then, the averaging cascade controller and PID parameters are optimised and debugged; finally, the levelling control system is ready to accept input, after which it can be operated stably in the long run. This effectively improves the control quality of the network system on temperature and pressure difference parameters. See SCADA system's human-machine exchange interface in Figure 9.

Fig. 9 SCADA system's human-machine exchange interface. SCADA, supervisory control and data acquisition.

4.2 Control process and result analysis

After the heating system was completed in this community, the heating season had come, but the levelling system had not been installed yet. After water injection, multiple households of Unit 1 and one household of Unit 3 at the tail end of Building 1 complained about supercool indoor temperature. As the levelling system was not installed yet, the thermal power company performed a preliminary debugging, such as manually regulating valves, but showing poor effect. Afterwards, when the levelling system was completed, the heating system of the community was examined and debugged. The pre-debugging system data of that day is shown in Table 3. On December 27, it was sunny and the outdoor temperature was $6^{\circ}\text{C}/-7^{\circ}\text{C}$; the supply water temperature of minor side of heat exchange station in the community was 40°C , the return water temperature of minor side of higher/lower zone was $37^{\circ}\text{C}/36.1^{\circ}\text{C}$ and the operating frequency of circulating pump in higher/lower zone was 36 Hz/39 Hz. Further, the heat preservation of the minor network had not been finished.

From Table 3, it is observed that the valve opening of the heat inlet at each unit is very different and the supply and return water temperatures are varied between 1.8°C and 6.4°C . It indicates that hot water flow into each unit differs greatly and the hydraulic disorder is severe, resulting in uneven indoor temperatures between heat consumers of different units. The heat preservation work of the minor network was completed within the same week. The measured supply water temperature of the network in the tail end of building 1 was the same as the measured supply water temperature of the minor side. The same time period with similar weather data was selected for running the levelling system. On 4 January 2021, the regulation was performed. On that day, the supply water temperature of the minor side was 40°C and in-station operating parameters were stable. See pre-regulation and post-regulation data in Figure 10.

Table 3 Valve opening and supply and return water temperature at heat inlet of each unit before regulation.

Heat inlet (lower zone)	Valve opening (%)	Supply/return water temp. (°C)	Heat inlet (higher zone)	Valve opening (%)	Supply/return water temp. (°C)
Unit 1 Building 1	97	35.8/32.6	Unit 1 Building 1	97	37.2/31.2
Unit 2 Building 1	97	35.5/31.5	Unit 2 Building 1	97	35.2/33.6
Unit 3 Building 1	97	35.5/33.7	Unit 3 Building 1	97	37.6/35.6
Unit 1 Building 2	62	37.2/34.4	Unit 1 Building 2	65	36.8/34.6
Unit 2 Building 2	57	36.2/34.4	Unit 2 Building 2	97	37.4/34.8
Unit 1 Building 3	13	37.4/35.3	Unit 1 Building 3	31	37.1/34.7
Unit 2 Building 3	32	37.5/35.1	Unit 2 Building 3	31	37.4/34.1
Unit 1 Building 4	22	37.6/35.5	Unit 1 Building 4	27	36.4/34.8
Unit 2 Building 4	22	37.6/36.1	Unit 2 Building 4	20	36.4/34.2
Unit 1 Building 5	34	38.8/36.1	Unit 1 Building 6	52	37.1/35.5
Unit 2 Building 5	55	38.5/34.7	Unit 2 Building 6	47	37.1/34.6
Unit 1 Building 6	43	39.1/36.3	Unit 1 Building 7	60	37.2/35.3
Unit 2 Building 6	37	39.1/36.1	Unit 2 Building 7	16	37.4/35.2
Unit 1 Building 7	45	38.3/35.7	Unit 1 Building 9	76	37.4/34.7
Unit 2 Building 7	56	38.5/34.6	Unit 2 Building 9	60	37.9/32.5
Unit 1 Building 8	22	38/32			
Unit 2 Building 8	22	37.3/33.5			
Unit 1 Building 9	32	38.2/31.8			
Unit 2 Building 9	55	38.4/35.5			

After debugging, the return water temperatures at each heat inlet tend to agree and are controlled between 35°C and 36°C. This indicates that the hot water flow of each unit in the community matches with the heat load, that the uneven temperature difference of each unit in the initial state has been regulated to the maximum extent and that good heat and hydraulic equilibrium are achieved. Besides, in the current working condition, the supply and return water temperature difference of heat consumers in each unit is about 0.013 Mpa. The current valve position is shown in Table 4. All of the monitored indoor temperatures of typical heat consumers in the community are higher than the heating standard and no complaint about super-cold is received from any heat consumer.

4.3 Regulation effect

For each unit controller, the controlled object is the branch pipeline flowing into each heat consumer. The building itself has heat-retaining property, and the temperature adjustment between branches is a process with large capacity delay and pure delay. Through changing valve opening during stable operation of heat exchange station, the step response of controlled objects is studied. When the supply water temperature is 41°C, the valve opening is turned down from 85% to 15%. Correspondingly, when the supply water temperature is 40°C, the valve opening is turned up from 15% to 85%. The data of return water temperature changes with time is recorded, and the step response curve of return water temperature in the process of turning up and down valve is drawn. The generated curves are shown in Figure 11.

In Figure 11, during valve adjustment, if the return water temperature change is delayed for about 30 min, it becomes stable. It is feasible to use first-order inertia elements to substitute into the primary and minor controlled processes and compare it to the single-loop control system. Taking the same damping coefficient, the working frequency ratio can be obtained from Eq. (2):

Table 4 Post-regulation valve opening and return water temperature at heat inlet of each unit.

Heat inlet (lower zone)	Valve opening (%)	Return water temp. (°C)	Heat inlet (higher zone)	Valve opening (%)	Return water temp. (°C)
Unit 1 Building 1	62	35.81	Unit 1 Building 1	95	35.82
Unit 2 Building 1	56	36.14	Unit 2 Building 1	86	35.36
Unit 3 Building 1	54	35.74	Unit 3 Building 1	89	36.26
Unit 1 Building 2	31	35.95	Unit 1 Building 2	24.8	35.76
Unit 2 Building 2	22	36.36	Unit 2 Building 2	24	35.65
Unit 1 Building 3	20.6	35.55	Unit 1 Building 3	26	35.67
Unit 2 Building 3	24	35.85	Unit 2 Building 3	28	35.66
Unit 1 Building 4	12.6	36.12	Unit 1 Building 4	20.8	36
Unit 2 Building 4	18	35.62	Unit 2 Building 4	19	35.51
Unit 1 Building 5	24.8	35.73	Unit 1 Building 6	24	35.92
Unit 2 Building 5	26	35.84	Unit 2 Building 6	18	35.44
Unit 1 Building 6	14	36	Unit 1 Building 7	22	35.75
Unit 2 Building 6	14	36.56	Unit 2 Building 7	22	35.6
Unit 1 Building 7	28	36.1	Unit 1 Building 9	12	36.1
Unit 2 Building 7	38	35.86	Unit 2 Building 9	16	36.22
Unit 1 Building 8	33	35.56			
Unit 2 Building 8	22	35.82			
Unit 1 Building 9	16	35.78			
Unit 2 Building 9	26	35.59			

$$\frac{\omega_{\square}}{\omega_{\square}} = \frac{1 + T_{01}/T'_{02}}{1 + T_{01}/T_{02}} = \frac{1 + \square 1 + K_{c2}K_vK_{02}K_{m2}\square T_{01}/T_{02}}{1 + T_{01}/T_{02}} \quad (4)$$

in which, T_{01} and T_{02} are the time constants of the primary and minor controlled processes.

It is known from equation analysis that $\omega_{\text{primary}}/\omega_{\text{minor}}$ increases with T_{01}/T_{02} . It can be observed from the literature [19, 20] that when $\omega_{\text{primary}}/\omega_{\text{minor}} > 3$, the system resonance can be eliminated; then, we can carry out a comprehensive consideration of the dynamic relationship between primary and minor channels of network system and determine the ratio of T_{01}/T_{02} within a range of $\sim 3\text{--}10$, according to the step response curve of controlled object [21, 22]. T_{02} is affected by the valve regulating process, stage and time, and is allowed to fluctuate in a smaller scope. Eventually, the sampling cycles of primary and minor loops are determined:

$$T_{01} = 360 \text{ s} \square T_{02} = 60 \text{ s} \quad (5)$$

During the network branch regulation, it is required that the return water temperature parameters of unit branches should inter-coordinate to meet systemic dynamic hydraulic equilibrium. The return water temperatures of each branch are allowed to fluctuate in a smaller range and change slowly in balance. The opening of electric regulating valves in each branch of the network system is optimised dynamically, while the measured supply and return water temperatures as minor parameters also fluctuate in a smaller range according to the practical working condition of the heating network. To sum up, the primary regulator shall adopt PI regulation and the minor regulator shall adopt P regulation. Observing Eq. (5), the ratio of the sampling cycles of primary and minor loops is rather big; so, the two-step setting method is used to perform parameter setting of primary and minor regulators. In automatic working conditions, a further setting can be made in the SCADA system interface under the averaging idea. In the following, various parameters of the unit control system at the near-end, middle-section and tail end of the building are used for explanation. Detailed controller parameters are shown in Table 5.

Fig. 10 Pre-regulation and post-regulation data curves.

Fig. 11 Return water temperature change curve.

Table 5 Controller parameters.

Unit No.	Controller	Parameters
Higher zone, Unit 2, Building 1	Primary loop	$\delta = 19.2, I = 22.65 \text{ min}$
	Minor loop	$\delta = 29$
Lower zone, Unit 1, Building 6	Primary loop	$\delta = 19.8, I = 21.64 \text{ min}$
	Minor loop	$\delta = 29.8$
Lower zone, Unit 2, Building 9	Primary loop	$\delta = 20.4, I = 19.8 \text{ min}$
	Minor loop	$\delta = 30.1$

Comparing the cascade control system of this system to the single-loop return water temperature control system [23], we observe the effect of controlling the same controlled object by network unit branch. In view of that, the optimised unit inlet device can monitor and run these two control systems, and some experiments has been conducted on the above-mentioned three typical units. We obtain the unit return water temperature response curve under the effect of the unit return water temperature – branch pressure difference cascade (averaging) and the single-loop negative-feedback return water temperature regulation system, as shown in Figure 12.

In the same working condition, when the control centre issues the set value T_0 of return water temperature, the control effect of cascade (averaging) controller and single-loop PID controller on network unit branch is analysed. See detailed comparison results of dynamic performance indexes in Table 6.

Table 6 Comparison of performance indexes of control system.

Working condition	Unit No.	t_r . Controller	(sing time)/s	δ . (ershoot)/%	t. (mp. fluctuation range)/°C
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gh the return water temperature response curve of typical units, an analysis is made on the control performance indexes of network unit branch of the same controlled object by the return water temperature-branch pressure difference cascade (averaging) and the single-loop negative-feedback return water temperature regulation system in the same working condition in Table the proposed return water temperature-branch pressure difference cascade control system, relative control parameters are further regulated using the averaging control idea. Though there is a long rising time in the response curve of lower zone, unit 2, building 9, by observing the curves in Figure 8, certain dynamic disturbance exists in return water temperatures of each unit branch. This is detrimental to the stability of the minor network system and the service life of valves. By observing the response curve designed in this system, the influence of disturbance can be eliminated and the self-adaptive capability of the network system can be enhanced. Through comprehensive analysis, it is identified that compared to single-loop PID controller, the cascade (averaging) controller has a better control effect, smaller overshoot, stronger anti-disturbance capability and good dynamic behaviour. So it can quickly respond to disturbance factors in the minor network system, keep the return water temperature in a smaller range, promote network equilibrium and stability and satisfy the practical systemic need of static and dynamic hydraulic equilibrium.

5 Conclusions

Through optimising unit inlet device and applying new control theory, this system establishes a levelling system of minor heating network and designs a cascade control system of return water temperature T_H – supply and return water pressure difference ΔP_L for network unit branch, to realise the control strategy of stable pressure and temperature regulation. On this basis, the averaging control idea is adopted to set the parameters of the regulation system between each unit. When this system is applied in the heating network system of a community with a total construction area of 118,435 m² and heating area of 43,188.62 m², it greatly improves

(a) Comparison of return water temperatures in the higher zone of unit 2 of building 1

(b) Comparison of return water temperatures in the lower zone of unit 1 of building 6

(c) Comparison of return water temperatures in the lower zone of unit 2 of building 9

Fig. 12 Comparison of return water temperature control effect in typical units.

the non-equilibrium of indoor temperature at the heat consumer side. When the self-designed SCADA system is used to monitor the on-site application effect, the return water temperature response time curve of each unit branch and various performance indexes are obtained. The results show that compared to traditional single-loop negative-feedback return water temperature control system, the cascade (averaging) controller has a better control effect, smaller overshoot and stronger anti-disturbance capacity than single-loop PID controller, which adapts to the minor network system with large time delay and inertia dynamic characteristic. Cascade controller is able to quickly cope with systemic disturbance factors and enables return water temperature between units to inter-coordinate and thus be maintained within a smaller range. It effectively eliminates the influence of static and dynamic hydraulic disorder on entire system stability, and plays a good role in project demonstration and guiding.

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