Research on Load Distribution Algorithm of Central Heating Network

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Abstract. Hydraulic and thermal imbalance is very common in central heating system, resulting in energy loss and poor heating experience of heat users. In order to solve the problem of hydrothermal imbalance, a control method based on Modeling and Simulation of central heating system and PSO particle swarm optimization algorithm is proposed. Firstly, the mathematical modeling and analysis of the hydraulic and thermal conditions of the central heating system are carried out, and the actual operation of the system is simulated by using MATLAB/Simulink to build and simulate the model of the central heating system. Then, the valves of each heat exchanger station are analyzed by using particle swarm optimization (PSO) with the variance of return water temperature as the control objective, and the appropriate valve openings are calculated iteratively, so as to solve the problem of hydro-thermal imbalance in the central heating system. The traditional PID control method is used to carry out comparative experiments. The experiment shows that the particle swarm optimization method performs better than the PID control method. The return water temperature of the heat exchanger station is similar, and it can meet the heating demand better.

1. Introduction

At present, the branch pipe network is the main arrangement of central heating system [1]. The main control method for the central heating pipe network is to control the total water supply flow rate and water supply temperature of the primary network at the heat source. The heat exchange station controls the flow rate through the valve opening, so that the water supply temperature reaches the standard under the conditions of certain outdoor air temperature, and the temperature indoor is guaranteed within the national regulations.

However, in the design of the traditional heating mode, the circulating water pump at the heat source needs to meet the water supply pressure requirement of the most unfavorable loop at the far end of the primary network. Therefore, the near-end heat exchange station close to the heat source tends to pass a large water supply flow, and thus the problem of "high flow rate and low temperature difference" occurs. Secondly, there is a strong coupling problem in the branch pipe network. Because the water supply pipe is long, even if the pipe diameter takes a large value, there is still a non-negligible pipe resistance coefficient. Therefore, when the near-end heat exchange station uses a valve to control the flow rate, it will affect the flow rate of the remote heat exchange station.
The computer is used to analyze and calculate the load of the central heating system, and the strong coupling relationship between the branch pipe networks is removed by the algorithm. The control signal is directly imparted to control the valve opening, so that the return water temperature of each heat exchange station is in the range of standard demand.

The main control methods currently used in central heating systems are manual control and traditional PID control. The main method of manual control is that the heat exchange station monitors the supply and return water temperature of the secondary network, and the control room personnel adjusts the valve according to experience to meet the heat demand of the heat exchange station. The disadvantage of this method is that the control precision of the manual control is not high, and the control personnel cannot reasonably distribute the heat flow resources, resulting in the occurrence of uneven heating between the heat exchange stations.

The traditional PID control means that each heat exchange station controls the flow rate of the heat exchange station according to the return water temperature of the heat exchange station. This control method has high precision and fast response, which can have a faster response speed when the load changes or the water supply temperature is not ideal. However, since the data between the heat exchange stations cannot communicate with each other and there is a coupling phenomenon [2], the near-end heat exchange station close to the heat source has a great influence on the far-end when it is regulated. When there are many heat exchange stations, the near-heat and far-cold conditions are likely to occur.

This paper proposes a method to simulate the hydraulic and thermal operating conditions of a central heating network by modeling the heating system. Using the particle swarm optimization algorithm to find the optimal valve opening degree of each heat exchange station in the central heating system, the temperature between the heat exchange stations can reach the demand or relative balance, and solve the problem of coupling and uneven heating.

2. Research on load distribution algorithm of central heating network
The research on the load distribution of the central heating network is mainly divided into two parts. The first part is the mathematical modeling of the central heating branch pipe network and the Matlab/simulink simulation model [3]. The second part is to analyze and calculate the appropriate control quantity and control the system through the particle swarm optimization algorithm [7].

2.1. Heating system modeling
The main system architecture of the central heating primary network is divided into a heat source, pipe section and heat loads. The heat source heats the circulating water, and the circulating water meets the pressure demand of the centralized heating pipe network through the water pump. Under normal circumstances, the heat source will determine the temperature of the primary network flow according to the external temperature and heat loads [5]. The pipe section provides a heat source to the heat load with a certain resistance coefficient. The primary network and the secondary network exchange heat in the heat exchange station which output heat to the user [6]. Its system architecture is shown in Figure 1.

![Figure 1. Central heating network system architecture.](image-url)
Modeling the heating system is mainly divided into hydraulic working conditions and thermal working conditions. The hydraulic conditions of the system are mainly the flow and pressure distribution of the circulating water. The heating quality of the system is closely related to the hydraulic conditions. The thermal conditions of the system are mainly based on the heat transfer of the hydraulic conditions, including the temperature of the system, the heat supply and dissipation. Hydraulic conditions are a prerequisite for thermal conditions [4].

2.1.1. Modeling of hydraulic conditions in heating pipe network. The pipe section resistance characteristic means that there is a certain pressure loss when the liquid flows in the pipe section, and the value of the pressure loss is related to the pipe resistance characteristic coefficient and the flow rate of the fluid. The basic calculation formula is as follows:

\[ \Delta p = S G^2 \]  

(1)

In the formula \( \Delta p \) is the pressure drop of the pipe section; \( G \) is the volumetric flow of the pipe section, \( m^3 / h \); \( S \) is the resistance characteristic coefficient of the pipe segment, the unit is \( Pa / (m^3 * h^{-1})^2 \).

The coefficient of resistance characteristic of the pipe section mainly depends on the inner diameter of the pipe section and the length of the pipe section. Its calculation formula is as follows:

\[ S = 6.88 \times 10^{-3} \frac{K^2}{d^{4/3}} (l + l_d) \rho \]  

(2)

In the formula \( d \) is the inner diameter of the pipe section, \( m \); \( l \) is the length of the pipe, \( m \); \( l_d \) is the equivalent length of the local resistance of the valve, elbow, etc., \( m \); \( K \) is the absolute roughness of the pipe, under normal circumstances \( K = 0.0005m = 0.5mm \);

It can be concluded from the calculation formula that when the pipe segment parameters are determined, the pressure loss of the pipe segment depends on the heat flow through the pipe segment.

The resistance characteristics of the pipe network are related to the connection mode. When the pipe segments are connected in series, the resistance characteristic coefficient of the heating pipe network is the sum of the resistance characteristic coefficients of the pipe segments.

\[ S = S_1 + S_2 + S_3 + L = \sum_{i=1}^{n} S_i \]  

(3)

In the formula \( i \) is the pipe number; \( n \) is the number of pipe segments in series.

When the pipelines are connected in parallel, the square root reciprocal of the pipe network resistance characteristic coefficient is the sum of the reciprocal of the square root of the resistance characteristic coefficient of the parallel pipe segments.

\[ \frac{1}{\sqrt{S}} = \frac{1}{\sqrt{S_1}} + \frac{1}{\sqrt{S_2}} + \frac{1}{\sqrt{S_3}} + L = \sum_{i=1}^{n} \frac{1}{\sqrt{S_i}} \]  

(4)

2.1.2. Modeling of heating conditions in heating pipe network. For the heat load of the heat exchange station responsible for heating, the original design of the single building is usually calculated using the estimation method. The heating load usually depends on the outdoor temperature, the structure of the house and the heat transfer area. The calculation formula is as follows:
\(Q_w = KF(t_o' - t_i')\)  \hspace{1cm} (5)

\(Q_w\) is total heat load for heating design, \(w\); \(K\) is the heat transfer coefficient of the building envelope; \(F\) is heat transfer area; \(t_o'\) is design outdoor temperature, different values in different regions; \(t_i'\) is design indoor temperature, typically +18°C.

And the heat \(Q_1\) supplied by the heat sink in the heat load is determined under the design outdoor temperature.

\(Q_1 = aF\left(\frac{t_o' + t_i'}{2} - t_i'\right)^{ab}\)  \hspace{1cm} (6)

\(t_o'\) is hot water supply temperature, °C; \(t_i'\) is the return water temperature of the hot user, °C; \(a\), \(b\) is the coefficient associated with the heat sink, determined by the form of the heat sink.

While designing the outdoor temperature \(t_o'\) determine the heat \(Q_2\) that the heating pipe network delivers to the load for:

\[Q_2 = \frac{G'(t_o' - t_i')}{3600} = 1.163G'(t_o' - t_i')\)  \hspace{1cm} (7)

In the formula \(G'\) is the heat flux of the heat exchange station. \(c\) is the specific heat capacity of water, \(c = 4.187(kJ / kg°C)\).

Without considering heat loss, \(Q_w = Q_1 = Q_2\). Based on this, thermodynamic conditions are established.

2.1.3. Centralized heating system simulation modeling Taking the heating pipe network of the south line of a thermal power plant as the simulation object, the total heating area is 479704.9m², and the total flow rate is 244.3m³/h. The thermal power plant controls the water supply temperature of the primary network according to the adjustment mode according to the quality adjustment. The design criteria for the supply and return water temperature under certain outside air temperature conditions are shown in Figure 2:

![Primary network supply and return water temperature design standard](image)

**Figure 2.** Primary network supply and return water temperature design standards.
The distribution of the branch pipe network of the south line heating system is shown in Figure 3. The raw data of the heat exchange station is shown in Table 1.

According to the actual data and the distribution map of the branch pipe network, the simulation model of the central heating system was established by Matlab/Simulink. The thermal power plant output was the hot water with the constant temperature and flow, which were transported through the pipe network. A valve model is established in each heat exchange station to control the flow rate of the heat exchange station. The overall simulation model is shown in Figure 4.
2.2. Central heating network control method

The traditional central heating system uses the PID control method. Each heat exchange station is controlled separately. By measuring the temperature of the return water, the return water temperature obtained according to the actual measurement is compared with the return water temperature according to the standard, and the obtained error value is calculated and a suitable valve opening. The steady state error of the heating system is eliminated by continuously adjusting the valve opening. The traditional PID control schematic is shown in Figure 5.

\[
\begin{align*}
    u(t) &= K_p e(t) + \frac{1}{T_i} \int e(\tau) d\tau + T_d \frac{de(t)}{dt} \\
    e(t) &= r(t) - c(t)
\end{align*}
\]

In the formula: \( e(t) = r(t) - c(t) \) to control deviations; \( K_p \) is the proportionality factor; \( T_i \) is the integral time constant; \( T_d \) to differentiate the time constant.

The central heating pipe network is a strong coupling system, and the nearest heat exchange station closest to the heat source has strong ability to control the flow. When the heat supply capacity of the
heat source is insufficient, the near heat exchange station can meet the demand of the heat load through the control valve, while the heat flow rate of the remote heat exchange station is also insufficient when it is opened to the maximum. Therefore, in the centralized heating pipe network system, the traditional PID control method usually has the phenomenon of “near heat and far cold”. In order to solve this imbalance problem, this paper proposes to use particle swarm optimization to analyze the system and calculate the optimal valve opening. Particle swarm optimization is a computational method that mimics biomes searching for food. Each elementary particle adjusts its position and path through its own experience and information interaction between all particles to calculate the optimal position.

The variance of the return water temperature of each heat exchange station in the central heating pipe network system is selected as the control target, and the minimum variance is taken as the optimal control state. The valve opening degree of each heat exchange station is used as the control quantity, which is the self variable in the function space. Variance calculation method:

$$s^2 = \frac{1}{n} \sum_{i=1}^{n} (T_{i} - \bar{T})^2$$

(9)

$T_i$ is the return water temperature of number i heat exchange station, $\bar{T}$ is the average value of the return water temperature for each heat exchange station.

Using the particle swarm optimization algorithm to randomly generate n multiply m-dimensional numbers as the valve opening degree of m heat exchange stations, calculate the variance of n return water temperatures through the simulation program, and find the valve opening degree of the heat exchange station with the smallest variance, use which is the most advantage point to update the position and velocity of n particles and perform the next iteration until n particles converge to a point, as shown in Figure 6:

![Figure 6. Particle Swarm Algorithm Flowchart.](image-url)
The core of the particle swarm optimization algorithm is to continuously calculate and iterate the velocity position of the particle. The calculation method is as follows:

\[
\begin{align*}
\mathbf{v}_{id}^{t+1} &= \mathbf{w} \mathbf{v}_{id}^{t} + c_1 \mathbf{r}_1 (\mathbf{p}_{id}^g - \mathbf{x}_{id}^{t}) + c_2 \mathbf{r}_2 (\mathbf{p}_{id} - \mathbf{x}_{id}^{t}) \\
\mathbf{x}_{id}^{t+1} &= \mathbf{x}_{id}^{t} + \mathbf{v}_{id}^{t+1}
\end{align*}
\]  

(10)

In the formula \( \mathbf{v}_{id}^{t} \) is particle speed; \( \mathbf{x}_{id}^{t} \) is particle position; \( \mathbf{w} \) is inertia weight; \( c_1 \) is self-learning factor; \( c_2 \) is group learning factor; \( \mathbf{r}_1, \mathbf{r}_2 \) is random number; \( \mathbf{p}_{id}^g \) is the best position in individual history; \( \mathbf{p}_{id} \) is the best position in group history.

The inertia vector, superposition of the self-impact vector and population influence vector superposition is the velocity of the particle in the next calculation period, and the sum of the velocity and the current position is the position of the particle in the next calculation period, that is, the opening degree of the valve of the heat exchange station. The calculation method is shown in Figure 7:

3. Analysis of experimental results

Emulation hardware device:

(1) CPU: INTEL core i5 8400 2.8 GHz
(2) RAM: 16 G ddr4 2400 MHz
(3) Hard drive: 256g nvme ssd
(4) Software platform: Matlab 2018b

The simulation uses the PID algorithm and the PSO particle swarm algorithm to control the central heating system separately, and collects and calculates the variance of the return water temperature data of each heat exchange station for the heat supply temperature of different outdoor temperature conditions. According to the standard of one net design, when the outside temperature is 5°C, 0°C, -5°C, the supply and return water temperature standards are 62.1/37.6°C, 68.0/39.6°C, and 73.9/41.7°C, respectively. The PID control method takes the standard return water temperature as the control target, and the particle swarm method takes the minimum backwater temperature variance as the control standard. The experimental results are shown in Table 2:
Table 2. Experimental results data sheet.

| Heat exchange station       | Outside temperature 5°C | Outside temperature 0°C | Outside temperature -5°C | PSO | PID | PSO | PID |
|-----------------------------|-------------------------|-------------------------|--------------------------|-----|-----|-----|-----|
| Green Ivy                   | 36.89                   | 37.65                   | 38.62                    | 39.5| 40.47| 41.88|
| Green Spring                | 36.9                    | 37.48                   | 38.25                    | 39.94| 40.29| 41.36|
| One stop of the artillery    | 36.59                   | 36.61                   | 38.19                    | 39.2| 39.61| 39.34|
| Riverside garden            | 36.48                   | 36.06                   | 38.12                    | 37.61| 39.36| 38.49|
| Hongqiao Homeland           | 36.23                   | 35.92                   | 38.09                    | 36.82| 39.29| 37.78|
| variance                    | 0.08097                 | 0.63183                 | 0.04573                  | 1.77828| 0.29468| 3.1909|

It can be concluded from the simulation experimental data that the particle swarm control method has a smaller variance than the PID control method. The simulation results show that the particle swarm optimization algorithm is feasible and effective in the overall optimization control of the central heating network.

4. Conclusion

Through the research and mathematical modeling of the heating and hydraulic conditions of the heating system, and then using Matlab/Simulink to establish the simulation model of the central heating system, the actual engineering problem of the central heating system is solved by computer simulation. The transformation can make the central heating system more concise and clear, and create favorable conditions for the optimization of the heating system. At the same time, using the particle swarm optimization algorithm to iteratively calculate the central heating system can make the hydrothermal power of the central heating system more balanced, thus avoiding the occurrence of “near heat and far cold”, which is an energy saving problem for the central heating system. Significant improvements are also made, while improving the heating experience for hot users. Compared with the traditional PID control method, the particle swarm algorithm is more scientific and efficient, but it is more dependent on the accuracy of the simulation model. The method of using particle swarm optimization to optimize the central heating network provides a theoretical basis for the future optimization of central heating system.

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