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Application of Nonlinear Programming Algorithms in Dynamic Hydraulic Optimization of District Heat Networks: A Case Study From a Chinese University

Ma Ruijie[1, 2], Yang Junhong [1, 2*] ,Shi Xinyu [1, 2], Cui Xuyang [1, 2], Cui Mianshan [1, 2]
1 Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, Tianjin 300350, China
2 School of Mechanical Engineering, Tianjin University, Tianjin 300350, China
[*] Correspondence author: yangjunhong@tju.edu.cn (Yang Junhong)

ABSTRACT

As one of the important energy systems, heating systems often suffer hydraulic imbalances and high energy consumptions in district heat networks. To further reduce the operational energy consumption of pumps and achieve hydraulic balance, the utilization of nonlinear programming algorithms for hydraulic optimization of district heat networks was proposed. With the actual heating system of a university as a use case, a dynamic hydraulic optimization model was established using the nonlinear programming algorithm to optimize the pump frequency, valve opening and thermal inlet flow rate. The actual data (from 2019 to 2020 and from 2020 to 2021) were selected for the simulation and comparison of the difference between the simulated energy consumption and the actual one by using four different dynamic regulation methods. The results reveal that with the dynamic regulation under day-by-day, day-night, time-by-time, and large temperature difference operation methods, the pump energy consumption could be reduced by 25.0%, 32.7%, 38.2%, and 61.1%, respectively compared with the actual operation. Therefore, the selection of large temperature difference dynamic regulation can further reduce the pump energy consumption of the system, and the work provides a certain reference for the dynamic hydraulic optimization regulation of heat network.

Keywords: heating systems; nonlinear programming; hydraulic optimization; dynamic regulation

1. INTRODUCTION

Centralized heating is the most widely used heating method in China[1-3]. Timely adjustment to improve the hydraulic imbalance of the end pipe network and reduce the energy consumption of the pump is an important means to ensure the efficient operation of the heating system.

In general, to achieve the hydraulic balance at the end of the heating system, and reduce the energy consumption of the pumps during operation, some balancing valves are installed, and the pump operation is optimized for regulation. Shi et al.[4] retrofitted the pipe network by installing dynamic differential pressure balancing valve and static differential pressure balancing valve in an actual heating system. The actual operation shows significant improvement for system hydraulic disorders. Jiang et al.[5] adopted a remote control system for hydraulic balance adjustment, and used a remote control valve and flow meter feedback, which effectively ensures the hydraulic balance of the heating system and energy saving. Zhang et al.[6]regulated the hydraulic balance by installing a secondary pipeline balancing valve in the heat station to change the operating conditions, thereby significantly improving the energy saving effect and economic efficiency in the long run. An optimal pressure control strategy for heating system operation was proposed by Wang et al.[7]based on the variable frequency of pumps, which can reduce the energy consumption of pumps by 14.6% in the entire heating season compared with the traditional constant pressure operation. Elisa et al.[8]proposed a simplified model based on the combination of orthogonal decomposition and radial basis function to optimize the total pump power of a large distributed heating network with multiple heat sources. Wang et al.[9]took a primary pipe network as the research object, and analyzed the theoretically calculated pump power consumption by using the integrated regulation method. Compared with

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the actual operation regulation method, the energy saving rate of the pump was significant. At present, with the completion of the initial adjustment of static hydraulic balance, there are very rare researches on the realization of the optimal adjustment of the starting of pump and opening of the inlet valve in the station under dynamic hydraulic balance. In addition, nonlinear programming can be used to solve the optimization problems with one or several nonlinear functions in the objective function or constraints, which has a wide range of applications in engineering, management, economics, and military use[10-13]. The nonlinear programming algorithm is a powerful tool for optimal design, and of great practical value.

Based on this, this paper takes a university complex with a heating area of about 230,000m^2 as the research object, and proposes to use the nonlinear programming optimization algorithm for the hydraulic optimization of the district heat network. In addition, a dynamic hydraulic optimization model is established to optimize the pump frequency, valve opening and thermal inlet flow, which provides a reference for the dynamic hydraulic optimization regulation of the heat network.

2. SIMULATION MODEL AND METHOD

2.1 Study case: a university from China

The university energy station in Tianjin City (China) has a centralized heating area of about 230,000m^2, and the heating system includes 38 thermal entrances to various types of buildings, such as teaching buildings, dormitories and cafeterias. A total of 28 thermal entrance valves of the system were upgraded in 2019, and 1#—9# entrances and 22# entrance were not renovated due to the environmental restrictions.

2.2 Build the system physical model

This campus piping system is a branch piping network with direct boiler supply, which passes through multi-stage branches between the energy station and the heat inlet. To simplify the model, the branch pipes are classified into two levels. The hot water coming from the station first reaches the primary branch pipe, which can be further connected to the secondary branch pipe or directly to the heat inlet, as indicated by the red line in Figure 1. Most of the secondary branch pipes are directly connected to the heat inlet, with two on the left side of the energy station and three on the right side, as shown in the blue part of Figure 1.

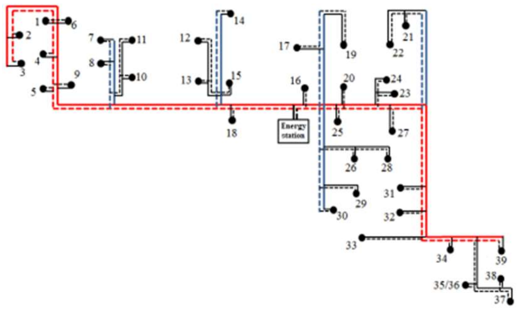

Fig. 1. Distribution of heat inlets of the heating pipe network

Figure 2 shows a simplified calculation model based on the actual pipe network, and since the inlets of 1#-9# are not controlled, they can be regarded as an inlet. The number in the figure refers to the electric valve number of each thermal inlet, and the along-range resistance of the branch pipe corresponding to the previous section of the thermal inlet is indicated by Sn.

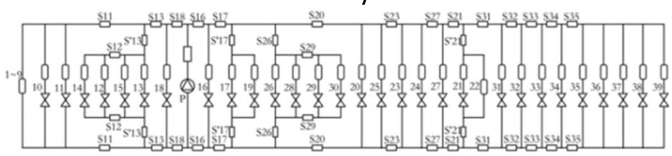

Fig. 2. Simplified model of actual pipe network

2.3 Establish the hydraulic equilibrium equation

1) Flow conservation

In the hydraulic pipe network, the flow rate of each pipe section should meet the requirement that the flow rate of inflow and outflow in each node is equal. In the case that there are m branches and n nodes in the pipeline, based on Kirchhoff's law and graph theory, the flow rate of each branch has the following relationship:

$$AG_0 = 0 \qquad (1)$$

where G_0 refers to the flow column vector of each branch, and A represents an n×m order matrix whose internal elements satisfy the following requirements:

$$a_{i,j} = \begin{cases} 1,\text{The traffic of Branch j flowing from Node i} \\ -1,\text{Flow in Branch j from Node i} \\ 0,\text{Tributary j is not connected to Node i} \end{cases} \qquad (2)$$

the G_0 vector in the equation contains the flow through the branch and the customer.

2) Circuit pressure drop

According to Kirchhoff's voltage law, the algebraic sum of the pressure drop of the closed circuit should be satisfied in the hydraulic pipe network as 0. In the heating pipe network, the pressure drop equation of the pipeline through the total supply and return pipe can be written as:

$$\triangle P - SG^2 - RQ^2 - \triangle Z = 0 \qquad (3)$$

where $\triangle P$ refers to the pump pressure head; SG^2 represents the along-range pressure loss; RQ^2 denotes the user pressure loss, and $\triangle Z$ is the height pressure

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difference, which can be neglected in the closed pipe network. Combined with the system hydraulic pipe network model, the pressure drop equation can be written in the form of a matrix, expressed as follows:

$$P - S(BQ*BQ) - (R + R_v)(Q*Q) = 0 \qquad (4)$$

where P refers to the pressure drop vector of the water supply main; S represents the along-range resistance matrix; R and Rv denote the user and motorized valve resistance matrices at the heat inlet; "*" refers to the Hadamard product of the matrix, and the value is the multiplication of the corresponding elements of the two matrices.

2.4 Planning solution based on nonlinear programming algorithm

This paper aims to achieve the minimum energy consumption of the pump transmission, and the transmission power of the pump can be calculated by the following formula:

$$N = \frac{\rho g Q H}{3.6 \times 10^6} \qquad (5)$$

where Q refers to the flow rate of the pump, m^3/h.H represents the pump head, m. And N denotes the conveying power, kW. The objective function for this optimization problem can be simplified as:

$$f(P,\ Q) = \min(P \cdot \textstyle\sum_{n=1}^{39} Q_n) \qquad (6)$$

Let the minimum valve resistance is R_{v0}, then the valve resistance matrix Rv should meet the following condition:

$$R_v \geq R_{v0} \qquad (7)$$

Combining the above conditions, the constraint equation of this hydraulic optimization problem can be written in the following form:

$$\begin{cases} f(P,\ Q) = \min(P \cdot \sum_{n=1}^{39} Q_n) \\ \mathrm{s.t.} \\ P - S(BQ*BQ) - (R+R_v)(Q*Q) = 0 \\ R_v \geq R_{v0} \\ Q_{1-9},\ Q_{22} > Q_{min} \\ P > 0 \end{cases} \qquad (8)$$

In the above constraint equation, the function of the minimum pump delivery power is the objective function of the solution, of which the constraints include hydraulic balance, minimum valve resistance and minimum pressure drop. The variable parameters include the total pipe pressure drop P, the controlled inlet valve resistance Rv and the uncontrolled inlet flow of $Q_{1\text{-}9}$ and Q_{22}. At fixed total pipe pressure drop, there are corresponding Rv, $Q_{1\text{-}9}$ and Q_{22} in the heating network, and there are infinite combinations of such combinations. Besides, there is a set of feasible solutions available to have the objective function reach the minimum value, which is a typical planning problem, and the optimal solution to the problem can be solved by nonlinear programming.

Before determining the operating frequency of the pump, it is necessary to obtain the P-Q curve of the pump operating at full frequency f_0(generally 50Hz). The actual P-Q curve relationship is more complex, and the engineering is generally fitted to an approximate quadratic curve. The equation of the P-Q curve by fitting is expressed in the following form:

$$P = k_1 Q^2 + k_2 Q + k_3 \qquad (9)$$

where k_1, k_2, and k_3 refer to the quadratic fitting coefficients, respectively.

The rotational speed changes with the change of the pump frequency which is proportional to the rotational speed. In addition, by the law of similarity and then solving for f as:

$$f = \frac{-k_2 Q f_0 + f_0\sqrt{k_2^2 Q^2 - 4k_3(k_1 Q^2 - P)}}{2k_3} \qquad (10)$$

According to the hydraulic balance equation of Equation (4), only the end of the user is taken as the object of study, and for both ends of the differential pressure, including the user and the sum of the differential pressure at the ends of the electric valve, the total differential pressure at the end of the user $\triangle P$ is expressed as follows:

$$\triangle P = (R + R_v)Q^2 \qquad (11)$$

The flow rate through the two ends of the motorized valve can be expressed as:

$$Q = \sqrt{\frac{\triangle P}{R + R_v}} \qquad (12)$$

By using Equation (12), the relative flow rate of the electric valve can be obtained by using the following equation:

$$\overline{Q} = \frac{Q}{Q_0} = \sqrt{\frac{R + R_{v0}}{R + R_v}} \qquad (13)$$

When the relative flow rate and relative opening of the electric valve satisfy the function $\overline{Q} = f(\overline{L})$, the relative opening can be expressed as follows:

$$\overline{L} = f^{1}\left(\sqrt{\frac{R + R_{v0}}{R + R_v}}\right) \qquad (14)$$

If the experimental measurement of different relative opening is $\overline{L}_1, \overline{L}_2, \overline{L}_3, \ldots \overline{L}_n$ with the corresponding relative flow rate of $\overline{Q}_1, \overline{Q}_2, \overline{Q}_3, \ldots \overline{Q}_n$, then by linear interpolation, we can get the valve resistance opening value under Rv.

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Based on the above established hydraulic balance equation, the algorithm flow of dynamic hydraulic regulation is shown in Figure 3.

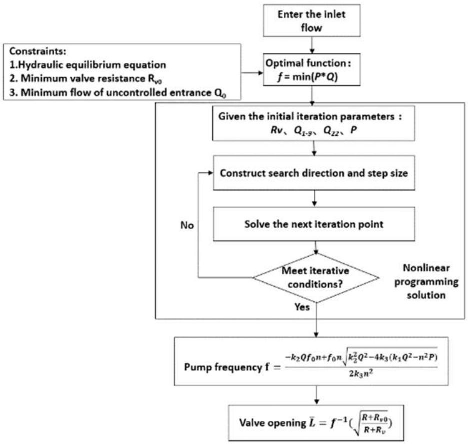

Fig. 3. Flow chart of dynamic hydraulic regulation algorithm

After the establishment of the dynamic hydraulic model, the program code for solving the model is written in Python. The nonlinear programming module in the scipy library is used to solve the problem of nonlinear programming in the model.

The model parameters have to be calibrated before the hydraulic calculations performed through the model. The data of each inlet flow rate and valve opening for a total of 7 days at different stages of the heating season were randomly selected and brought into the model for calculation.

The simulated and actual average opening of each thermal inlet, and the ratio of simulated opening to the actual one are shown in Figure 4. The model is corrected so that the deviation of each inlet does not exceed 10%. As shown in Figure 5, the total simulated flow rate is compared with the actual one, and the simulated and actual values are in good agreement with the total flow rate error not exceeding 5% (confidence level 98.2%). It can be seen that the model is available to characterize the actual pipe network operation more reasonably, and can be used for dynamic hydraulic calculation through the model.

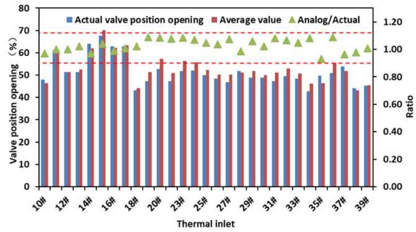

Fig. 4. Comparison of simulated opening and actual opening of each inlet

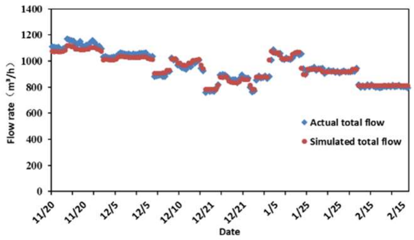

Fig. 5. Simulated total flow value and actual total flow

2.5 *Different dynamic adjustment cases*

As shown in Table 1, the arithmetic cases were optimized for the campus in two heating seasons, i.e., 2019-2020 and 2020-2021, under different operating conditions.

Table. 1 Calculation examples under different working conditions

Cases	Heating season	Calculation basis	Optimization Solutions
Case 1	2019-2020	Actual flow	Time-by-time variable frequency regulation of water pumps
Case 2	2019-2020	Actual flow	Water pump for day and night frequency regulation
Case 3	2019-2020	Actual flow	Day-by-day variable frequency adjustment of water pumps
Case 4	2020-2021	Flow rate under large temperature difference operation	Optimization of the number of pumps under maximum temperature difference operation
Case 5	2020-2021	Flow rate under large temperature difference operation	Optimization of pump frequency under maximum temperature difference operation

Based on the actual operating data of the 2019-2020 heating season, several pump operation regulation schemes are proposed.

(1) Time-by-time variable frequency regulation: achieve the optimal operation of pumps and systems based on the time-zone control strategies of different types of households for dynamic hydraulic regulation.

(2) Day-night variable frequency adjustment: the heat consumption at the end of the day and night shows a large difference, therefore, the manual variable frequency adjustment of the pump can be carried out during the day and night, respectively.

(3) Day-by-day variable frequency adjustment: the whole heating season is divided into 27 variable frequency periods to optimize the variable frequency adjustment of the pump through the model in different temperature periods.

According to the ideal small flow rate and large temperature-difference operation mode, if the operation is made during the whole heating season

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based on the current maximum temperature difference (7.3 ℃), the operating flow rate can be further reduced, and the pump power consumption can be thus reduced.

3. RESULTS AND DISCUSSION

3.1 Analysis of the results of the 2019-2020 heating season

The range of pump regulation for the 2019-2020 heating season is 38-45 Hz, and the pump frequency is between 18-45 Hz if time-by-time variable frequency regulation is performed. The diurnal frequency and day-by-day frequency are based on the time-by-time frequency variation. As shown in Figure 6, the optimized pump frequency varies based on the three scenarios. It can be seen from the figure that the frequency variation range is small in the early stage of the heating season, which is because that the stage is in the initial commissioning, and the flow rate of each inlet changes little. On the contrary, the frequency variation range is larger in the middle of the heating season, which is because that the flow rate at each inlet changes a lot at different times in this stage. Basically, the pump frequency variation tends to be smooth in the winter vacation due to the absence of regulation all day in this stage.

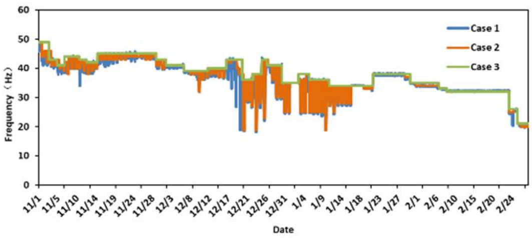

Fig. 6. Variation of pump frequency under different working conditions

The change in pump energy consumption for the three regulation schemes is shown in Figure 7 (the actual flow rate in the station is missing at the end of November and December), and the comparison of the total flow rate change is shown in Figure 8. It can be seen from the pump energy consumption curves that the pump energy consumption is significantly lower than the actual energy consumption with variable frequency regulation. In addition, after the installation of additional pumps from December 30 to January 21, the actual energy consumption of pumps increases sharply, while the energy consumption remains stable at a low level after the adoption of frequency regulation. Therefore, the energy consumption sharply increased with the increase of the number of pumps, which can be reduced by the adoption of frequency regulation. The total energy consumption of the pumps under time-by-time frequency conversion is 51.2 MW·h, which is lower than the actual operation by 38.2%.

The energy consumption of the pump under diurnal frequency conversion is 55.7 MW·h, which is lower than the actual operation by 32.8%. In the early stage of heating, the adjustment range of the pump during day and night is small because the actual flow rate changes little during day and night. While in the middle of the heating period, the adjustment range of the pump in the diurnal period increases due to the large variation of the actual flow rate.

The energy consumption of the pump under day-by-day frequency conversion is 62.1 MW·h, which is lower than the actual operation by 25.0%. Compared with the first two schemes, although the energy saving of day-by-day frequency conversion is less, it usually needs only to be adjusted once every 3-5 days, which is highly operable.

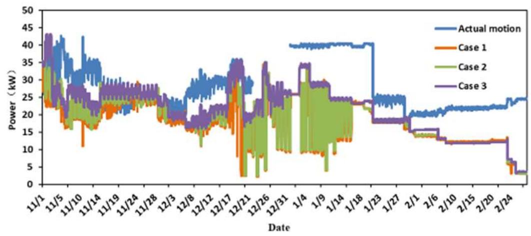

Fig. 7. Comparison of pump power under different working conditions

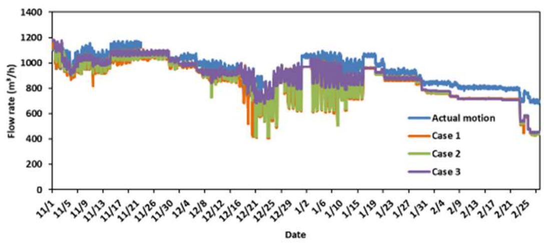

Fig. 8. Comparison of total flow rate under different working conditions

Based on the above simulation analysis of the pump frequency conversion, appropriate regulation mode can be chosen for the heating system according to the actual operating conditions. For example, though the time-by-time frequency conversion is the most ideal dynamic hydraulic regulation scheme with the highest energy-saving rate, it requires the remote transmission and remote-control transformation of the pump frequency converter. The day and night frequency conversion is less adopted than the time-by-time frequency conversion, but because the pump only needs to be adjusted day and

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night every day, the station watchman can carry out manual frequency conversion operation. The day-by-day frequency conversion is based on the optimal calculation of the phased frequency adjustment of the pump, which usually only needs to be adjusted once every 3-5 days, and is more operable, but the energy saving rate is reduced. In that case, the station operators can choose a reasonable operation plan based on the actual situation and demand reference.

3.2 Analysis of the results of the heating season 2020-2021

Based on the flow rate assigned at the maximum temperature difference, each inlet flow rate and the actual number of pumps were input into the dynamic hydraulic model for calculation. According to the calculation results, the pump frequency required in the early and middle stages of heating under the ideal flow rate is low, which is generally below 20 Hz. As the long-term low frequency operation will cause the pump to heat up and reduce the efficiency, the operating efficiency of the pumps can be improved by reducing the number of pumps if the requirement of ideal flow rate is satisfied in the early and middle stages. As shown in Table 2, the number of activated units before and after pump optimization is compared. Compared with the actual working condition, the normal operation regulation can still be ensured after the reduction of the number of pumps in the early and middle stages except that the number of pumps remains unchanged during the winter vacation. The comparison of pump frequency before and after optimization is shown in Figure 9.

Table. 2 Comparison of the number of pumps before and after optimization

Date	Actual number of pumps in operation		Number of operating pumps after optimization	
	Large pumps	Small pumps	Large pumps	Small pumps
11.1-11.20	2	1	1	0
11.21-12.8	2	1	2	0
12.8-12.12	3	0	2	0
12.12-1.13	3	0	2	1
1.14-1.18	3	0	2	0
1.18-2.28	2	0	2	0

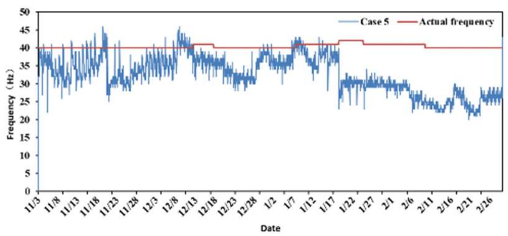

Fig. 9.Comparison of pump frequency under large temperature difference operation in the heating season 2020-2021

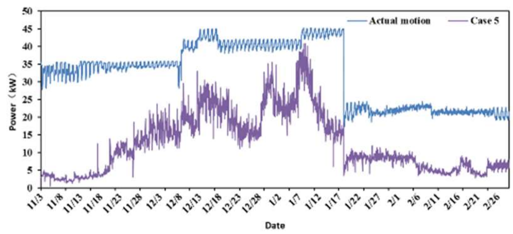

Fig. 10. Comparison of pump power under large temperature difference operation in the heating season 2020-2021

Based on the optimized operation mode, the energy consumption of pumps in the station is significantly reduced. The change of pump energy consumption before and after optimization is shown in Figure 10. Compared with the actual operation, the total energy consumption of pumps after optimization is 35.7 MW·h, which is lower than the actual operation of pumps by 61.1%.

Through the analysis of the above results, the higher frequency of pump adjustments can better control the frequency and flow rate accurately according to the load demand, and the better energy saving effect of the heating system can be achieved.

In this paper, we proposed the dynamic optimization of pump operation regulation on the day-by-day, day-night and time-by-time basis, which is different from the scheme of Liu et al.[14]who changed the pump hydraulic coupling speed regulation to frequency regulation, and that of Li et al.[15]who proposed the optimization of pump operation under the concept of dynamic hydraulic balance control based on energy distribution balance; though all these schemes can reduce the power consumption of the pump, the power saving effect in this paper is more significant. In addition, this paper proposed the dynamic optimization under large temperature difference operation conditions, and the energy saving rate of the pump reaches 61.1%, which is about twice as that of the pump optimized by using genetic algorithm under the idea of variable pressure

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difference regulation[16-17]. The four regulation schemes in this paper are beneficial to the pump operation, which can be easily adjusted in the actual system, and the operators can choose a reasonable operation scheme according to the actual situation and demand reference in the station.

4. CONCLUSION

Based on the campus dynamic hydraulic optimization model, the pump frequency, valve opening and thermal inlet flow were optimized by using a nonlinear programming algorithm. By analyzing the operation conditions of two heating seasons with arithmetic examples, different dynamic hydraulic optimization regulation schemes were proposed. It is found that in the case that the dynamic optimal regulation under day-by-day, day-night, time-by-time and large temperature difference operation is used, the energy consumption of the pumps will be reduced by 25.0%, 32.7%, 38.2% and 61.1%, respectively compared with the actual operation, thereby greatly reducing the energy consumption of the pumps and providing the guidance and reference for the actual operation optimization regulation, which is of great significance to the energy saving and emission reduction of the district heating network.

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