Operation Characteristic Analysis and Parameter Optimization of District Heating Network with Double Heat Sources

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Abstract. The heating system is a practical engineering problem with multi-parameter coupling and multi-constraint restrictions. The use of optimization algorithms has guiding significance for its high efficiency and energy saving. This paper takes the district heating pipe network with dual heat sources as an example to analyze the operation characteristics of the heating pipe network and optimize its parameters. The thermodynamic model of the dual-heat source district heating pipe network is established, and the NSGA-II algorithm is applied to analyze the operating characteristics. By comparing the upper and lower limits of the interval and the interval when the pipe length and pipe diameter are the decision variables, it is believed that to reduce the loss during the operation phase of the system, quantity adjustment should be avoided as much as possible. The water supply temperature is greater than 95℃, the greater the system fluctuation. Through the NSGA-II algorithm, the Pareto front is obtained, and the TOPSIS optimization method is used to finally obtain the best operating parameters of the pipe network with the best closeness.

1. Introduction

Due to the process of urbanization, the heating radius of the heat source is rapidly expanding, and the total heating load of the heating network and the demand for peak shaving are also increasing [1]. The central heating system consists of three parts: heat source, heat network and heat user. The heat source is the thermal power plant boiler and its unit, which is the source of heat in the entire heating system. The heat source heats the water in the heating network and sends the water to the heating station through a circulating water pump. The thermal station is equipped with a water-water heat exchanger, which transfers heat to thermal users through heat exchange for heating [2].

As the entire pipeline network involves many parameter variables, to improve the operating efficiency of the system, it is necessary to study the operating characteristics of the heating pipeline network. Gao et al. [3] used primary energy saving rate, exergy efficiency and CO2 emission reduction rate as comprehensive evaluation indicators. By comparing the performance difference of the cogeneration system in the two basic operating modes, the sensitivity effects of energy and environmental parameters on system performance are given. Mancarella [4] constructed a mixed-integer nonlinear programming model of the energy supply system, which realized the multi-objective hierarchical optimization of energy-saving rate and cost-saving rate, and studied the influence of load changes and energy prices on optimization strategies. Some scholars try to use genetic algorithm and Pareto optimal solution to optimize the design of energy system. Li et al. [5] established a micro-
distributed energy system suitable for residential load demand, using the capacity of the constructed system equipment as decision variables, total cost and primary energy consumption as optimization goals, and obtaining the optimal solution through fast elitist non-dominated sorting genetic algorithm II (NSGA-II).

Many studies have shown that the heating system is a practical engineering problem with multiple parameter coupling and multiple constraints [6]. The use of optimization algorithms can provide the heating system with better operating conditions, better-operating parameters, better equipment capacity configuration and user load change operating strategies [7]. This has high theoretical value and important engineering significance for the efficient use of energy.

This paper takes the district heating pipe network with dual heat sources as an example to carry out analysis and design optimization of heating pipe network operation characteristics. On the basis of meeting the energy demand of users, improve the overall thermal efficiency of the system, save energy resources, and reduce environmental pollutant emissions.

2. District heating network with dual heat sources
A community in Luquan District, Shijiazhuang City is equipped with dual heat sources for heating. The pipe network structure is shown in Figure 1.

![Figure 1. Graph theory model of district heating pipe network with dual heat sources.](image)

In Figure 1, I represents circulation and direction. Node 1 to node 3 are connected to user 1 to user 3, and node 4 and node 5 are connected to heat source 1 and heat source 2 respectively. a ~ e represent the water supply pipe section connecting the node with the user and the heat source, $\dot{m}_{a1} \sim \dot{m}_{q5}$ are the corresponding water supply flow. a' ~ e' represent the backwater pipe section connecting the node with the user and the heat source, $\dot{m}'_{a1} \sim \dot{m}'_{q5}$ are the corresponding backwater flow. 1 ~ 5 represent the water supply pipe section in the ring, $\dot{m}_{1} \sim \dot{m}_{5}$ are the flow rate. Similarly, 1' ~ 5' represent the return pipe section in the circulation, and $\dot{m}'_{1} \sim \dot{m}'_{5}$ are the flow rate.

The calculation of the entire pipeline network is an iterative solution. First, the parameters of the K iteration are used for internal iteration, and then the obtained solution is used as the parameters for the K+1 iteration of the external iteration. According to the characteristics of the object, the following equation is established:

1) Flow continuity equation. In the system, all traffic entering the node is equal to the sum of the traffic leaving the node and the traffic consumed at the node.

$$\sum m_{in} - \sum m_{out} = \dot{m}_{q}$$  \hspace{1cm} (1)

Where $\dot{m}$ is the pipe flow (kg/s), $\dot{m}_{q}$ is the heat source input to the node or output to the user through the node (kg/s), leaving the node is a positive value, entering the node is a negative value.
2) Circulation pressure equation. The friction of pipeline will change the pressure and cause head loss. The circulation pressure equation indicates that the sum of head losses of a closed loop must be equal to zero.

\[
\sum h_f = 0
\]  

(2)

Where \(h_f\) is the head loss of the pipe (m).

3) Head loss equation. The relationship between pipeline flow and pressure between nodes is as follows:

\[
h = Km|\dot{m}|
\]  

(3)

Where \(K\) is the resistance coefficient of the pipe section usually determined by the pipe diameter.

4) Energy conservation equation. A mixed node represents a pipe where fluid flows into more than one place at a node. According to the law of conservation of energy, the sum of all the energy of the fluid leaving the mixing node is equal to the sum of all the energy of the incoming fluid:

\[
(\sum \dot{m}_{out})C_p T_{out} = \sum (\dot{m}_{in} C_p T_{in})
\]  

(4)

Where \(T_{out}\) is the temperature of the mixing node (°C), \(T_{in}\) is the temperature of the fluid at the end of the input pipe (i.e. at the mixing node, °C), \(\dot{m}_{out}\) represents the flow away from the mixing node (kg/s), \(\dot{m}_{in}\) represents the flow into the node (kg/s).

3. Analysis of operation characteristics of heating pipe network

For the dual heat source district heating pipe network in Figure 1, the parameters describing the system include: user load, heat supply of heat source, flow, water supply temperature, return water temperature, pipe diameter, pipe length, resistance coefficient, resistance loss, pressure drop, flow rate and so on. According to the equations (1) to (4), the flow rate, pipe diameter, pipe length, and water return temperature of the pipe network are variables of operation and design.

Using the Gamultiobj optimization toolbox in MATLAB software, the parameter settings are:

1) The population size is 400, and the stagnation generation number is 1000.

2) Select a feasible solution population in the creation function.

3) Initialize the parent population, and assign values using random values.

4) Mutation rate selects adaptive feasible solution.

5) The migration rate chooses to migrate forward, the ratio is 0.2, and the interval is 20.

6) Pareto elite degree (optimal front individual ratio) is set to 0.35.

7) The specified tolerance value is 1E-100.

| Change of pipe length \(L\) (km) | Interval of individual value | Interval degree | Distribution |
|---------------------------------|-----------------------------|----------------|--------------|
| 10                              | [0.3, 0.6]                  | 0.3            | Even         |
| 20                              | [0.3, 0.7]                  | 0.4            | Even         |
| 30                              | [0.3, 0.9]                  | 0.6            | Relatively even |
| 40                              | [0.3, 1.0]                  | 0.7            | Relatively even |
| 50                              | [0.4, 1.1]                  | 0.7            | Uneven       |
| 60                              | [0.3, 1.1]                  | 0.8            | Uneven       |
| 70                              | [0.4, 1.5]                  | 1.1            | Uneven       |
| 80                              | [0.4, 1.6]                  | 1.2            | Uneven       |

The influence of pipe length on the heating pipe network of the dual heat source area is shown in Table 1. The larger the interval in the table, the wider the distribution range of optimization points, and the more discrete the population iteration process. At the same time, the smaller the upper limit and
the lower limit of the interval, the more concentrated the population iteration process, the better the optimization effect, and vice versa.

Table 1 illustrates that the distribution of tube lengths of 10 km and 20 km is uniform, the distribution of tube lengths of 30 km and 40 km is relatively uniform, and the distribution of tube lengths above 40 km is uneven. And as the tube length increases, the interval increases. Description

Generally speaking, the length of the heating pipe network is appropriate within 20 km, and the longest can be 40 km. However, more than 40 km, technical means need to be used to optimize the pipe network.

Table 2. Analysis table of different pipe diameters.

| Pipe diameter change $D$ (mm) | Interval of individual value | Interval degree size | Distribution |
|-------------------------------|-----------------------------|---------------------|--------------|
| 800                           | [0.32, 0.83]                | 0.51                | Relatively even |
| 900                           | [0.4, 1.0]                  | 0.6                 | Even         |
| 1000                          | [0.53, 1.4]                 | 0.87                | Relatively even |
| 1100                          | [0.4, 1.0]                  | 0.6                 | Even         |
| 1200                          | [0.47, 1.2]                 | 0.73                | Even         |
| 1300                          | [0.55, 1.26]                | 0.71                | Even         |
| 1400                          | [0.32, 0.83]                | 0.51                | Relatively even |
| 1500                          | [0.4, 1.0]                  | 0.6                 | Even         |

The influence of different pipe diameter changes is shown in Table 2. The distribution of each body under different pipe diameters is above a relatively uniform level, and the interval of individual values and the degree of interval change are consistent.

Table 3. Analysis table of different flows.

| Flow change $\dot{m}$ (kg/s) | Interval of individual value | Interval degree size | Distribution |
|-------------------------------|-----------------------------|---------------------|--------------|
| 1E5                           | [0.1, 3.7]                  | 3.6                 | Relatively even |
| 2E5                           | [0.25, 2.5]                 | 2.25                | Relatively even |
| 3E5                           | [0.3, 5.4]                  | 5.1                 | Uneven       |
| 4E5                           | [0.4, 5.1]                  | 4.7                 | Uneven       |
| 5E5                           | [0.1, 3.7]                  | 3.6                 | Uneven       |
| 6E5                           | [0.48, 5.65]                | 5.17                | Uneven       |
| 7E5                           | [0.9, 5.0]                  | 4.1                 | Uneven       |
| 8E5                           | [1.1, 5.7]                  | 4.6                 | Uneven       |

The influence of flow is shown in Table 3. Compared with the upper and lower limits and the interval when the pipe length and pipe diameter are decision variables, the value when the flow rate is a decision variable increases significantly. This shows that in order to reduce the loss during the operation phase of the system, volume adjustment should be avoided as much as possible.

Table 4. Analysis table for different supply and return water temperatures.

| Change of supply and return water temperature (°C) | Interval of individual value | Interval degree size | Distribution |
|---------------------------------------------------|-----------------------------|---------------------|--------------|
| 95/70                                             | [1.5, 3.2]                  | 1.7                 | Even         |
| 100/70                                            | [1.4, 8.6]                  | 7.2                 | Uneven       |
| 110/70                                            | [1.6, 8.7]                  | 7.1                 | Uneven       |
| 120/70                                            | [1.4, 12.7]                 | 11.3                | Uneven       |
| 130/70                                            | [1.7, 15.7]                 | 14.0                | Uneven       |
| 140/70                                            | [1.5, 16.7]                 | 15.2                | Uneven       |
The influence of temperature combination is shown in Table 4. As the temperature of the water supply gradually exceeds 95°C, the distribution of optimal points for the individual iteration of the population changes drastically, and the population continues to diverge. As the water supply temperature increases from 95°C to 140°C, the lower limit of the interval does not change significantly, basically around 1.5, the upper limit and interval continue to increase, and the degree of unevenness is getting higher and higher.

4. Pareto optimization of heating pipe network

For the dual heat source district heating pipe network in Figure 1, the Pareto front after iterative 1000 generations optimization is shown in Figure 2.

![Figure 2. Pareto front for heat loss and resistance loss of the heating pipe network.](image)

Point A in Figure 2 is the best point of single-objective optimization with the minimum resistance loss $f_1(x)$ as the goal. The parameters are: $f_1(x)=7.95$ kPa, $f_2(x)=157.96$ kW; Point B is the best point of single-objective optimization to minimizing heat loss. The parameters are: $f_1(x)=88.6$ kPa, $f_2(x)=5.77$ kW. It can be seen that point A has the smallest resistance loss and the largest heat loss, while point B is the opposite. At this time, the heat loss is the smallest but the resistance loss is the largest.

According to the order of closeness, the result of the TOPSIS optimization method is point P in Figure 2. The resistance loss at point P is 79.8 kPa, the heat loss is 15.63 kW, and the closeness is 0.85, which is the optimal solution of the multi-objective optimization method in this paper.

5. Conclusion

In this paper, the NSGA-II algorithm is used to study the operation characteristics and parameter optimization of the dual heat source district heating network, and the following conclusions are obtained:

1) In order to reduce the loss during the operation phase of the system, volume adjustment should be avoided as much as possible. By analyzing the upper and lower limits and the interval when the pipe length and pipe diameter are decision variables, the value when the flow rate is the decision variable increases significantly. This shows that in order to reduce the loss during the operation phase of the system, volume adjustment should be avoided as much as possible.

2) The water supply temperature is greater than 95°C, the greater the system fluctuation. As the temperature of the water supply gradually exceeds 95°C, the distribution of the optimal points of the individual population iterations changes sharply and the population continues to diverge. As the water supply temperature increases from 95°C to 140°C, the degree of unevenness becomes higher and higher.
3) This paper obtains the best operating parameters considering heat loss and resistance loss. Through the NSGA-II algorithm, the Pareto front is obtained, and the TOPSIS optimization method is used to obtain the best operating parameters with the best closeness.

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References
[1] Wang J J, Jing Y Y, Zhang C F, Performance comparison of combined cooling heating and power system in different operation modes, Applied Energy, 88 (2011) 12 4621-4631.
[2] Wu J Y, Wang J L, Li S, Multi-objective optimal operation strategy study of micro-CCHP system, Energy, 48 (2012) 1 472-483.
[3] Gao X, Akashi Y, Sumiyoshi D, Installed capacity optimization of distributed energy resource systems for residential buildings, Energy & Buildings, 69 (2014) 2 307-317.
[4] Mancarella P, MES (multi-energy systems): An overview of concepts and evaluation models, Energy, 65 (2014) 2 1-17.
[5] Li Y, Liao S, Liu G, Thermo-economic multi-objective optimization for a solar-dish Brayton system using NSGA-II and decision making, International Journal of Electrical Power & Energy Systems, 64 (2015) 64 167-175.
[6] Wei D, Chen A, Sun B, Multi-objective optimal operation and energy coupling analysis of combined cooling and heating system, Energy, 98 (2016) 1 296-307.
[7] Ju L, Tan Z, Li H, Multi-objective operation optimization and evaluation model for CCHP and renewable energy based hybrid energy system driven by distributed energy resources in China, Energy, 111 (2016) 322-340.