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Connection Method between Urban Heat-supply Systems
based on Requirement of Limited-heating

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Abstract

In this paper, a mathematical model of connection method between ring-shaped heat-supply systems with multi-heat sources was established based on the requirement of limited-heating in accident conditions. The limited-heating coefficient, pressure bearing capacity of pipeline, heating capacity of heat source, operating parameters of circulating pumps were used as boundary conditions, and the minimum consumption of transmission energy of heat sources was considered to be the objective function. A case was analysed to illustrate the solving process and the calculation method of the model. Using the mathematical model proposed in this paper, the feasibility of the connection method between the heat-supply systems on accident conditions can be analyzed under steady state and system completely be controlled condition. The optimal connecting case was obtained. The results have important significance for urban planning and the reconstruction design of heat-supply system.

Keywords: District heat-supply system; Ring-shaped heat supply network; Accident condition; Connecting method; Limited-heating coefficient

1. Introduction

Urban centralized heat-supply systems are experiencing the development from small-scale to large-scale, from single-heat source to multi-heat sources, from the tree-shaped network to the ring-shaped network. The transmission capacity in accident conditions is more and more important. Therefore, the proper connection method between heat-supply systems could be enhanced on the overall planning, and the reserve capacity of heat-supply network in accident conditions should be improved to ensure the quality and reliability of urban lifeline project.

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Russia is the first country to research the reliability of heat-supply system. As early as in 1986, the reliability theory could be found in the design code of urban heat supply network in the Soviet Union. The heat-supply network failures statistics was obtained, such as fault flow parameters (Stepin and Cukrowiski 1994). The research of heat-supply system reliability in China is established on the basis of Soviet Union. Some key points were put to improve the reliability of ring-shaped heat-supply network from heat sources, pipelines and valves. (Wang and Zou 2008). The principle they put forward is an important guide to the heat-supply network design.

2. Methods

2.1. Scheduling scheme in accident conditions

In accident conditions, different heat-supply system have different scheduling scheme to meet the requirement of the limited-heating and to ensure heating quality.

(1) If a heat-supply system can meet the requirement of the limited-heating coefficient in an accident condition, there is no need to make a hydraulic connection. Each system may operate independently and the failed system must run according to the scheduling scheme. (2) If a heat-supply system cannot meet the requirement of the limited-heating coefficient in an accident condition, a hydraulic connection must be made between different systems and the systems have to operate according to the scheduling scheme. The second situation is mainly analyzed in this paper.

2.2. Mathematical model of connection between heat-supply systems

The location and diameter of interconnecting pipes should be confirmed to achieve the proper connection between heat-supply systems. Based on the requirement of limited-heating in accident conditions, a mathematical model of connection between ring-shaped heat-supply systems with multi-heat sources was established. The limited-heating coefficient, pressure bearing capacity of pipeline, heating capacity of heat source, operating parameters of circulating pumps were used as boundary conditions, and the minimum consumption of transmission energy of heat sources was considered to be the objective function.

2.3. Basic conditions of the model

(1) Heat-supply system is completely under control. The controllability of heat-supply system means that the output parameters can be controlled by adjusting input parameters to operate according the scheduling scheme. Therefore, the limited-heating coefficient of each heat consuming installation is adjustable in this research. (2) Temperature difference between supply water and return water is constant in an accident condition. Calculation and analysis are in steady state and regardless the dynamic temperature change. Meanwhile, the constant temperature difference can insure the change of limited-flux coefficient is in accordance with limit-heating coefficient.

2.4. Objective function

The transmission energy consumption of heat-supply system in an accident means the reasonability of the heat-supply service range and operating parameters of circulating pump. Therefore, the objective function of the model is the minimum transmission energy consumption of heat-supply system.

\[
\min_{\phi \in \chi} W_j (\phi) + W_y (\phi)
\]

Where \(\chi\) is the collection of schemes, \(W_j\) is the circulating pump energy consumption of base-load heat source, kW; \(W_y\) is the circulating pump energy consumption of peak-load heat source, kW; \(\phi\) is one of the alternative cases.

Total electric power of all circulating pumps:
\[
\min \sum_{i=1}^{w} N_i = \sum_{i=1}^{w} 2.78 \times 10^{-4} \frac{G_{pi} H_{pi}}{\rho \eta_i} 
\]  
(2)

Where \(N_i\) is the circulating pump electric power of No.\(i\) heat source, kW; \(G_{pi}\) is the circulating pump flow of No.\(i\) heat source, t/h; \(H_{pi}\) is the circulating pump head of No.\(i\) heat source, Pa; \(\eta_i\) is the circulating pump operation efficiency of No.\(i\) heat source; \(w\) is the number of heat source; \(\rho\) is the density of heat medium, kg/m³.

2.5. Boundary conditions

(1) Limited-heating coefficient

In the design of network reliability, the limited-heating index is formulated according to the minimum indoor temperature and repair time in an accident condition. Limited-heating coefficient should not less than the limited-heating index connected with outdoor design temperature for heating.

\[\beta_i \geq \beta\]

Where \(\beta_i\) is the limited-heating coefficient of No.\(i\) heat source, \(\beta\) is the limited-heating coefficient in design code.

In the Chinese urban heat-supply network design code (CJJ34-2002), the values of \(\beta\) are 0.4, 0.55 and 0.65 according to the different outdoor design temperatures. In the Russian urban heat supply network design code (CHSnIP 41-03-2003), the values of \(\beta\) are set according to the different outdoor design temperatures and pipe diameters.

<table>
<thead>
<tr>
<th>Outdoor design temperature for heating/°C</th>
<th>-10</th>
<th>-10~20</th>
<th>≤-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited-heating coefficient</td>
<td>0.4</td>
<td>0.55</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table1. Minimum value of limited-heating coefficient in Chinese code.

<table>
<thead>
<tr>
<th>D/mm</th>
<th>Outdoor design temperature for heating /°C</th>
<th>-10</th>
<th>-20</th>
<th>-30</th>
<th>-40</th>
<th>-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td></td>
<td>32</td>
<td>50</td>
<td>60</td>
<td>59</td>
<td>64</td>
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<td>400</td>
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<td>41</td>
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<tr>
<td>700</td>
<td></td>
<td>59</td>
<td>70</td>
<td>76</td>
<td>75</td>
<td>78</td>
</tr>
<tr>
<td>800~1000</td>
<td></td>
<td>66</td>
<td>75</td>
<td>80</td>
<td>79</td>
<td>82</td>
</tr>
<tr>
<td>1200~1400</td>
<td></td>
<td>71</td>
<td>79</td>
<td>83</td>
<td>82</td>
<td>85</td>
</tr>
</tbody>
</table>

Table2. Minimum value (%) of limited-heating coefficient in Russian code.

(2) Heating capacity of heat source

The flow of heat source in accidents condition should satisfy the heating capacity as follows.

\[G_{is} \leq G_{in}\]

Where \(G_{is}\) is the distributing flow of heat source in an accident condition, t/h; \(G_{in}\) is the design flow of heat source, t/h.

Distributing flow of heat sources in accident conditions satisfies the proportion as follows:

\[G_{i1} : G_{i2} : \ldots : G_{iw} = a_1 : a_2 : \ldots : a_w\]  
(5)
Where $a_i$ is the flow proportion of heat sources, $a_1+a_2+\ldots+a_n=1$

(3) Operation parameters of circulating pumps

When heat sources operate under the distributing flow, the circulating pump head should not be higher than the maximum head.

$$H_i \leq H_{ip}$$

Where $H_i$ is the circulating pump head of heat sources corresponding to the distributing flow, m; $H_{ip}$ is the maximum circulating pump head of heat sources corresponding to the distributing flow, m.

(4) Pressure-bearing capacity of pipe

Outlet pressure of circulating pumps should be under the pressure-bearing capacity of pipe.

$$H_i \leq H_m$$

Where the $H_m$ is the maximum circulating pump head corresponding to the pipe working pressure, Pa.

The mathematical model was given as follows:

$$\min_{\phi \in \mathcal{X}} W_j (\phi) + W_y (\phi)$$

subject to:

$$\beta_j \geq \beta$$
$$G_{is} \leq G_{iw}$$
$$H_{js} \leq H_{ip}$$
$$H_{is} \leq H_m$$

2.6. Analysis of limited-heating boundary condition

When the flow control devices were set at the end users, the system can run by limited-heating method to decrease the end user flow in proportion to avoid hydraulic disorder and guarantee heating quality. Pressure of interconnection point should be checked to make sure that the heat users can realize limited-heating.

The branch flow of users is known. By adjusting valve, the hydraulic resistance characteristic is to be the unknown. The topology model of heat-supply system is changed. The outflow of water supply interconnection point connected by heat user is the limited-flow of branch and the value is same as the inflow of water return interconnection point (Wang and Zou 2006). The judgment formula is as follows:

$$\Delta H_u \geq S_{u,\min} q^2$$

Where $\Delta H_u$ is the limited-flow available head of user branch, m; $S_{u,\min}$ is the branch limited-flow hydraulic resistance characteristic when the entrance valve of heat user is widely open, m·h$^2$/t$^2$; $q$ is the limited-flow of user branch, t/h.

If all the limited-flow available head of heat user branch satisfy the above formula, it means that the existing system can realize limited-heating. Otherwise, the circulating pumping head should be increase or change the limited-flow of customer branch.

2.7. Calculation method of Mathematical connection model

The topology model of heat-supply system is established by grid analysis method. The process of calculation and analysis method of mathematical connection model was explained based the topology model.

2.8. Topology model by grid analysis method

Topology models of heat-supply system were connected to research the feasibility of connection between heat-supply systems. In order to simply calculations, two same topology models were connected in this paper, and the model was defined as basic topology model. The information of basic topology model of heat-supply system are as follows: 20 heat users, the area of heat-supply service of per user is 200000 square meters, space-heating load data
per unit floor area $q=50W/m^2$, the available pressure head in the consumer is $5mH_2O$, the step length is $500m$, the length of branch pipe is $250m$, the design supply and return temperature of heat source is $130/70^\circ C$, the internal head lose is $15mH_2O$, the heating capacity of $S_1$ is $120MW$, the heating capacity of $S_2$ is $80MW$, the proportion of local resistance and on-way resistance is $3:10$. By the hydraulic analysis of operation regime of hot water heat-supply network, the circulating pump operating parameters of $S_1$ are as follows: the pump flow is $1713.6t/h$, and the pump head is $59.6m$. The circulating pump operating parameters of $S_2$ are as follows: the pump flow is $1142.4t/h$, and the pump head is $56.0m$.

Fig. 1. Distribution of heat sources and substations.

The most unfavourable condition is some heat sources of one system do not work, and only two heat sources supply heat to the overall system. The diameter of interconnecting pipe can be confirmed according to the flow in accident conditions.

Case 1: Two heat-supply systems are connected by one interconnecting pipe and both ends of the pipe connect to the area near the hydraulic confluence.

Case 2: Two heat-supply systems are connected by one interconnecting pipe and both ends of the pipe connect to the area near the heat sources.

Case 3: Two heat-supply systems are connected by two interconnecting pipes and both ends of the pipe connect to the area near the heat sources.
3. Results and discussion

3.1. Boundary condition check

(1) Heating capacity check of heat source
The design flow of heat source are $G_{1n}=1713.6$ t/h and $G_{2n}=1142.4$ t/h. The distributing flow of heat source in an accident condition is $G_{1s,1}=G_{1s,2}=G_{1s,3}=G_{1n}$ and $G_{2s,1}=G_{2s,2}=G_{2s,3}=G_{2n}$; $G_{1s}$: $G_{2s}=a_1:a_2=0.6:0.4$, $a_1+a_2=1$. Therefore, three cases are all meet the heating capacity boundary conditions.

(2) Operating parameters check of Circulating pumps
The maximum circulating pump head of heat sources $S_1$ in the distributing flow of three cases are $H_{1p,1}=H_{1p,2}=H_{1p,3}=54.5$ mH2O. The maximum circulating pump head of heat sources $S_2$ in the distributing flow of three cases are $H_{2p,1}=H_{2p,2}=H_{2p,3}=50.8$ m.

Every circulating pump has one backup in the model. The operating parameters of circulating pumps were got by hydraulic analysis of ring-shaped heat-supply network (Zhou 2006). The distributing flow and circulating pump head corresponding to the distributing flow of every case are in Table 3. The head of parallel pump was calculated by fitting coefficient in practical cases.

Table 3. Operating parameters of circulating pumps in limited-heating.

<table>
<thead>
<tr>
<th>Basic heat source</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{in}$</td>
<td>$Hip$</td>
<td>$G_{is,1}$</td>
<td>$His,1$</td>
</tr>
<tr>
<td>$S1$</td>
<td>1713.6</td>
<td>54.5</td>
<td>1713.6</td>
</tr>
<tr>
<td>$S2$</td>
<td>1142.4</td>
<td>50.8</td>
<td>1142.4</td>
</tr>
</tbody>
</table>
Case 1: \( H_{1s,2} > H_{1p,2}, \ H_{2s,2} > H_{2p,2} \). The circulating pumps of No.1 and 2 heat sources do not meet the operating parameters boundary conditions. There are the situations that high flow through the small diameter pipes, so the circulating pump head of heat sources is high. One interconnecting pipe is set near the hydraulic confluence is not an optimal case.

Case 2: \( H_{1s,2} < H_{1p,2}, \ H_{2s,2} > H_{2p,2} \). The heat sources operate under the distributing flow. The circulating pumps of No.1 heat source meet the operating parameters boundary conditions, but the circulating pumps of No.2 heat source do not. The position of interconnecting pipe is close to No.1 heat source but far away from No.2 heat source. There are the situations that high flow through the small diameter pipes, so the circulating pump head of No.2 heat sources is high. Connecting two different heat-supply systems by one interconnecting pipe is not an optimal case.

Case 3: \( H_{1s,2} < H_{1p,2}, \ H_{2s,2} < H_{2p,2} \). The heat sources operate under the distributing flow. The circulating pumps of No.1 and 2 heat source meet the operating parameters boundary conditions and other boundary conditions should be check.

(3) Limited-heating coefficient check

In order to satisfy users demand of heating, two heat-supply systems were connected to operate in limited-heating when all heat sources of one heat-supply system were in an accident. The flow of heat user is cut by 50%. The limited-heating coefficient of No.1 and 2 heat sources are \( \beta_1=\beta_2=0.5 \). The outlet pipe diameters of No.1 and No.2 heat sources are DN600 and DN500, respectively. According to the limited-heating coefficient in Russian heating network code (CHInП 41-03-2003), the outdoor design temperature for heating calculated by linear interpolation are \( t_{w1}=-8.75^{\circ}C \) and \( t_{w2}=-10.7^{\circ}C \).

The head of case 3 in limited-heating should be check to make sure that the system can operate in limited-heating in an accident. The normal flow of user branch is \( q=142.8t/h \). The limited-flow of user branch is \( q_u=71.4t/h \). \( S_{u\min} \) and \( H_u \) are shown in Table 4.

<table>
<thead>
<tr>
<th>Heat user</th>
<th>( S_{u\min} )</th>
<th>( H_u )</th>
<th>( S_{u\min} q_u^2 )</th>
<th>Heat consumer</th>
<th>( S_{u\min} )</th>
<th>( H_u )</th>
<th>( S_{u\min} q_u^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>0.00166</td>
<td>23.85</td>
<td>8.48</td>
<td>U21</td>
<td>0.00166</td>
<td>8.66</td>
<td>8.48</td>
</tr>
<tr>
<td>U2</td>
<td>0.00166</td>
<td>23.85</td>
<td>8.48</td>
<td>U22</td>
<td>0.00166</td>
<td>8.66</td>
<td>8.48</td>
</tr>
<tr>
<td>U3</td>
<td>0.00102</td>
<td>16.49</td>
<td>5.19</td>
<td>U23</td>
<td>0.00102</td>
<td>11.76</td>
<td>5.19</td>
</tr>
<tr>
<td>U4</td>
<td>0.00102</td>
<td>16.49</td>
<td>5.19</td>
<td>U24</td>
<td>0.00102</td>
<td>11.76</td>
<td>5.19</td>
</tr>
<tr>
<td>U5</td>
<td>0.00073</td>
<td>24.54</td>
<td>3.73</td>
<td>U25</td>
<td>0.00073</td>
<td>15.78</td>
<td>3.73</td>
</tr>
<tr>
<td>U6</td>
<td>0.00073</td>
<td>24.54</td>
<td>3.73</td>
<td>U26</td>
<td>0.00073</td>
<td>15.78</td>
<td>3.73</td>
</tr>
<tr>
<td>U7</td>
<td>0.00054</td>
<td>21.43</td>
<td>2.73</td>
<td>U27</td>
<td>0.00054</td>
<td>15.38</td>
<td>2.73</td>
</tr>
<tr>
<td>U8</td>
<td>0.00054</td>
<td>21.43</td>
<td>2.73</td>
<td>U28</td>
<td>0.00054</td>
<td>15.38</td>
<td>2.73</td>
</tr>
<tr>
<td>U9</td>
<td>0.00103</td>
<td>21.47</td>
<td>5.28</td>
<td>U29</td>
<td>0.00103</td>
<td>15.38</td>
<td>5.28</td>
</tr>
<tr>
<td>U10</td>
<td>0.00103</td>
<td>21.47</td>
<td>5.28</td>
<td>U30</td>
<td>0.00103</td>
<td>15.38</td>
<td>5.28</td>
</tr>
<tr>
<td>U11</td>
<td>0.00145</td>
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<td>U31</td>
<td>0.00145</td>
<td>10.06</td>
<td>7.37</td>
</tr>
<tr>
<td>U12</td>
<td>0.00145</td>
<td>26.34</td>
<td>7.37</td>
<td>U32</td>
<td>0.00145</td>
<td>10.06</td>
<td>7.37</td>
</tr>
<tr>
<td>U13</td>
<td>0.00126</td>
<td>17.44</td>
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<td>U33</td>
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<td>U14</td>
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<td>16.95</td>
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<td>2.77</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.00104</td>
<td>21.58</td>
<td>5.31</td>
<td>U38</td>
<td>0.00104</td>
<td>6.58</td>
<td>5.31</td>
</tr>
<tr>
<td>U19</td>
<td>0.00130</td>
<td>14.67</td>
<td>6.64</td>
<td>U39</td>
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<td>7.32</td>
<td>6.64</td>
</tr>
<tr>
<td>U20</td>
<td>0.00130</td>
<td>14.67</td>
<td>6.64</td>
<td>U40</td>
<td>0.00130</td>
<td>7.32</td>
<td>6.64</td>
</tr>
</tbody>
</table>
Table 4 shows that in case 3, the available heads of customer branches in limited-flow are all satisfy the requirement of $H_a \geq S_{u,\min} q_0^2$. Therefore, the limited-heating can be realized with the existing conditions.

3.2. Calculate of operation cost

According to the formula (2) to calculate the total circulating pump power of the case which meets the boundary conditions.

For No.1 heat source, the circulating pump flow is $G_{p1}=1713.6t/h$, the circulating pump head is $H_{p1}=4.17 \times 10^5Pa$, and the circulating pump operation efficiency is $\eta_1=0.8$. The density of heat medium is $\rho=958.4kg/m^3$. Therefore, the circulating pump electric power is $N_1=259.1kW$.

For No.2 heat source, the circulating pump flow is $G_{p2}=1142.4t/h$, the circulating pump head is $H_{p2}=4.48 \times 10^5Pa$, the circulating pump operation efficiency is $\eta_1=0.8$. The density of heat medium is $\rho=958.4kg/m^3$. Therefor the circulating pump electric power is $N_1=185.6kW$.

The total electric power of case 3 is 445kW and the operation cost can be calculated according to the operation time in an accident condition.

4. Conclusions

In this paper, the reasonable connections between heat-supply systems were studied based on the requirement of limited-heating. A mathematical model of connection between ring-shaped heat-supply systems with multi-heat sources was established. Cases were analysed to illustrate the solving process and the calculation method of the model. In practical engineering, several connection cases could be proposed. Using the mathematical model proposed in this paper, the feasibility of the connection between heat-supply systems can be analysed. The result can be widely used in the design and reconstruction of heat-supply system and urban overall planning.

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References