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Optimal Regulation of Heating Systems with Metering Based on Dynamic Simulation

Hua Zhao, Associate Prof.
Peng Wang, Postgraduate
Guang Zeng, Postgraduate
Yongzheng Tian, Postgraduate
School of Municipal & Environmental Engineering, Harbin Institute of Technology
Harbin P.R.China, 150090
zh6977@hit.edu.cn

Abstract: The mathematical models of heat networks and heat users are established using the node method. The physical model of a typical room instead of a heat user is used; meanwhile the equation of radiator controlled by thermostat is put forward to compute the radiator's parameters. The primary purpose of these works is the strategy of optimal regulation of heating system with metering. In a ramiform heating system with three heat users, an optimal scheme with certain combination of different object functions is applied, and the optimal supply water temperatures are worked out by the estimate method of linear summation with weights based on dynamic simulation. The simulative results reflect the relationship between energy loss of heating systems and users' comfort.

Key words: heating systems with metering; optimal regulation; supply water temperature

1. INTRODUCTION

In urban heating systems, the purpose of heating regulation is to satisfy users, rationalize production and transportation of heat. Because of heat users' perfect regulation in heating systems with metering, factors affecting heat load are not only outdoor air temperatures, but also users' regulation. Meanwhile, heat transportation in heat networks can delay when it reach users and lose partial energy in the process. Therefore, operational control based on dynamic simulation should be carried out in order to adapt to the variable-flow system and keep balance between supply and demand.

For dynamic regulation of heating system, some key steps are drawn in figure1, including forecast of heat load, simulation of system and theory of optimization.

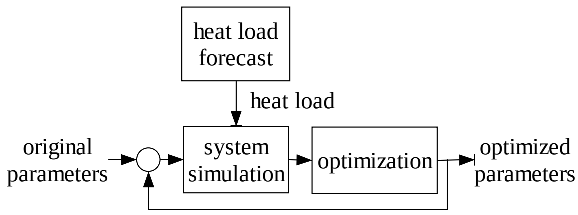

Fig.1 Frame of optimal regulation of heating systems based on dynamic simulation

2. DYNAMIC SIMULATION OF HEATING SYSTEMS

Heating systems consist of heat sources, heat networks and heat users. The complexity and diversity are the key points and difficulties when we simulate a whole system for the purpose of reflecting the hydraulic and thermodynamic properties. Node method is then used to model heat networks and heat users.

2.1 Thermodynamic Model of Rooms Heating by Radiator with Thermostat

The model of rooms is formed by node method mentioned in reference [1]. Specially, in heating systems with metering the flow rate through radiator is lower when radiator remains "duty state" that keeps indoor air temperature 8 . Thus, return water temperatures become low and approach indoor air temperatures. In this condition, we should use logarithmic mean temperature instead of arithmetic mean temperature, because arithmetic mean temperature can be used with accepted error only when the ratio of maximal difference in temperature to minimal difference in temperature is not more than 1.7[2]. The heat load dispersed from radiator is calculated by logarithmic mean temperature as follows.

$$q_{heater} = m\left(T_s - T_r\right) = aF\left(\frac{T_s - T_r}{\ln\frac{T_s - T_{in}}{T_r - T_{in}}}\right)^{1+b} \qquad (1)$$

Where

q_{heater} — heat load of radiator (W)

m — mass flow in heat net (kg/s)

T_s — supply water temperature (℃)

T_r — return water temperature (℃)

T_{in} — indoor air temperature (℃)

F — area of radiator (m^2)

a, b — experimental factors related with heat transfer coefficient of radiator

Thermostat is simplified as a proportion-control component.

$$\bar{m} = \begin{cases} 0 & ,T_e = 0 \\ \frac{m}{m_{\max}} = \frac{1}{R_v} + K_t T_e & ,T_e \neq 0, 0 < m \leq m_{\max} \end{cases} \qquad (2)$$

Where

$\bar{m}$ — relative mass flow in heat net

T_e — input of thermostat, equal to difference between user-set temperature and indoor air temperature (℃)

$m_{\max}$ — maximal mass flow (kg/s)

R_v — adjustable ratio of thermostat, $R_v = m_{\max} / m_{\min}$

$m_{\min}$ — minimal mass flow (kg/s)

K_t — magnifying coefficient of thermostat, $K_t = (1\text{-}1/R_v) / X_p$ (1/℃)

X_p — proportional section of thermostat (℃)

2.2 Thermodynamic Model of Heat Networks

We set a pipe with constant diameter and no branch as a node. Given initial temperature, the temperature of downriver nodes can be computed according to energy balance equation. It means that the temperature profile of every time can be acquired when we already know topology of heat networks, outlet temperature of heat source and flow rate of nodes [3].

Increment of internal energy in pipe = Inlet heat from upriver pipe－Heat loss of the pipe (3)

3. OPTIMAL REGULATION OF HEATING PARAMETERS

Central regulation of heating systems is not only to guarantee heating quality, but also to save energy. The balance between the two goals can be determined by practical condition. We use multi-objective optimal method to solve the problem [4]. Here we aim at three objectives as follows.

(1) Reduction of heating load;

(2) Reduction of heat loss in transportation;

(3) Improvement of heat users' thermal comfort.

Regulation of heating parameters is to change supply water temperatures and flow rate designedly. In variable-flow heating systems, flow rate needs to change according to individual regulation of heat users. Because heat users' regulation is very frequent, flow rate of heating systems will be remain at a low level mostly. Accordingly, we optimize only the supply water temperatures; and guarantee to supply the maximal flow rate if necessary. We recommend that the maximum flow rate of system – in other words, the designed flow rate allowance should be increased as much as possible in order to improve heating quality.

3.1 Mathematic Model of Multi-Objective Optimization

The mathematic models of the goals selected are shown below.

$$J_1 = \frac{1}{t_{opt}} \int_{t_{opt}} \frac{m(t)\left[T_s(t) - T_r(t)\right]}{m'\left(T_s' - T_r'\right)} dt \qquad (4)$$

$$J_2 = \frac{1}{t_{opt}} \int_{t_{opt}} \sum_n K_n \frac{\left(T_n - T_{sur}\right)}{\left(T_n' - T_{sur}\right)} dt \qquad (5)$$

$$J_3 = \frac{1}{t_{opt}} \int_{t_{opt}} \max_i \left\{ \frac{T_{in,i}(t) - T_{e,i}(t)}{\Delta T'} \right\} dt \qquad (6)$$

Where

J_1 — objective function of heating load of heat source

J_2 — objective function of heat loss in transportation

J_3 — objective function of users' thermal comfort

t_{opt} — optimal period (s)

m' — designed mass flow of heat net (kg/s)

T'_s — designed supply water temperature (℃)

T'_r — designed return water temperature (℃)

n — number of pipe section

K_n — heat transfer coefficient of pipe section (W/℃)

T_n — water temperature of pipe section (℃)

T_{sur} — temperature of soil surface (℃)

T'_n — designed water temperature of pipe section (℃)

i — number of heat user

$\Delta T'$ — maximal difference in comfort area ASHRAE recommends [5], 4℃

Because variables in the objective functions above are all from simulation, we have to limit only supply water temperature in a certain bound of $\{T_{s\min}, T_{s\max}\}$. Besides, the objective function of heat users' thermal comfort performs as difference between indoor air temperatures and thermostat temperatures set by users. When the user-set temperatures change, the difference will reach maximum because of room thermal inertia. For example, if user set thermostat with a low temperature in order to reduce indoor air temperature, the difference will be large and so as the value of objective function of thermal comfort. Thus, we suppose that the thermal comfort function only be calculated while $T_{in}<T_e$.

3.2 Solution to the Multi-Objective Problem

There are mainly two methods to solve multi-objective problems that are direct method and indirect method. We choose a direct method which is called estimate method of linear summation with weights [6]. The method can change multi-objective problems to single-objective problems that will be easily solved.

$$J = \alpha_1 J_1 + \alpha_2 J_2 + \alpha_3 J_3 \qquad (7)$$

Where

J — objective function

α_1 — weight of heating load of heat source

α_2 — weight of heat loss in transportation

α_3 — weight of users' thermal comfort

In the formula above weights each reflect directly importance of each objective—the more important the objective is, the larger its weight is. And a principle should be as follows.

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \qquad (8)$$

4. APPLICATION

In a ramiform heating system with three heat users, optimal regulation is applied using method above and with hypotheses that properties of typical room are representative and hydraulic condition of system changes instantaneously compared to thermal condition. Taking Harbin as example, designed supply water temperature of the heating system is 95 , designed return water temperature is 70 , designed indoor air temperature is 20 , and designed outdoor air temperature is -26 . Hydraulic calculation results of the heat networks are shown in Tab.1.

Tab.1 Hydraulic calculation of heat networks

Pipe number	Mass flow (kg/s)	Length of pipe (m)	Equivalent length (m)	Nominal diameter (mm)	Velocity of flow (m/s)	Specific resistance (Pa/m)	Loss of pressure (Pa)
Primary line							
a-b	86.01	500	650	300	1.2	49	12740
b-c	57.34	500	650	250	1.15	57.3	14898
c-3	28.67	500	650	200	0.89	44.6	11596
Branches							
b-1	28.67	100	130	150	1.69	241.9	31450
c-2	28.67	100	130	200	0.89	44.6	5798

In the heating system with metering, maximal flow rate of system is 1.3 times larger than designed value considering unexpected increase of users' indoor air temperatures. According to regulating formula of supply water temperatures and considering that supply water temperatures should not exceed the designed value, its lower limit is 45 .

In order to distinguish each user’s heat load properties, we suppose three users with different heat load properties that are shown in pictures from Fig.2 to Fig.4.

4.1 Period of Regulation

Heating system is so huge and complicated that its time constant almost exceed 1 hour or even more than 10 hours. In this example the time constant of the supply water system is 20.6 min. Then we set regulating period as 1 hour.

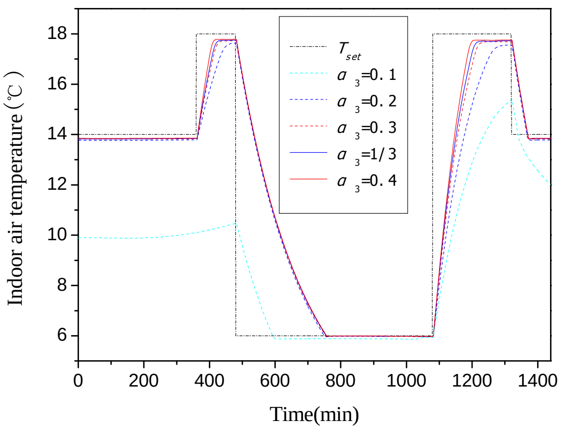

Fig.2 Indoor air temperatures of user1 with different weights of thermal comfort

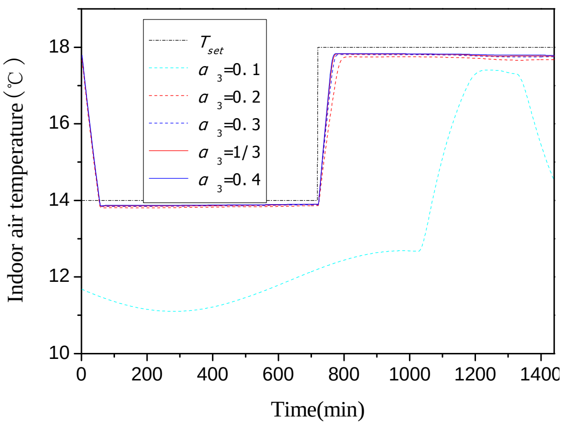

Fig.3 Indoor air temperatures of user2 with different weights of thermal comfort

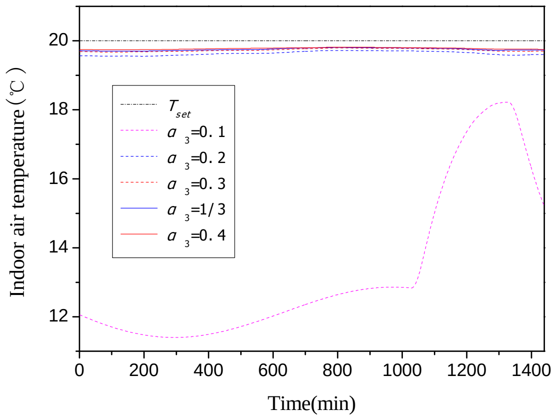

Fig.4 Indoor air temperatures of user3 with different weights of thermal comfort

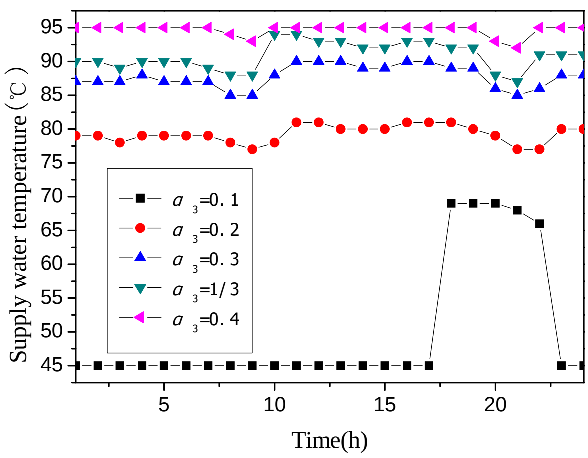

Fig.5 Optimal supply water temperatures with different weights of thermal comfort

4.2 Optimal Solution

The optimal supply water temperatures are shown in Fig.5 considering different weights of thermal comfort while optimal period is 2 hours. Fig.2 to Fig.4 show each user's indoor air temperatures simulated.

From the simulative results, we conclude that the weight of thermal comfort greatly influence indoor air temperatures. It should draw attention that supply water temperatures optimized will become constant 95 when the weight of thermal comfort exceeds 0.4, thus the method loses the ability to estimate objective of energy consumption. Generally the smaller weight of thermal comfort, the lower supply water temperatures are, and the differences between indoor air temperatures and user-set temperatures become much greater – that mainly is represented by calefactive time when user turn up thermostat and difference between indoor air temperatures and user-set temperatures when the system becomes steady again.

(1) In steady condition, most of user3's indoor air temperatures approach closely to user-set temperatures – average values are all less than 0.5 , where weights of thermal comfort are set from 0.2~0.4. When the weight is 0.1, indoor air temperatures are far away from user3's demand.

(2) When user-set temperatures abruptly change from low level to high level, calefactive time of user2 is relatively short when weights of thermal comfort are set from 0.2~0.4, thus user2 can be satisfied. But for user1, there is a high jump of user-set temperature -- 12 , calefactive time will be long where weight of thermal comfort is 0.2.

5. CONCLUSIONS

The traditional method that depends on outdoor air temperatures to regulate heating parameters has not yet adapted to heating systems with random fluctuation of users' heat load; and it loses its base as a static method in variable-flow systems. The optimal regulation method proposed in this paper is based on dynamic simulation of heating systems, and all the variables in objective functions are calculated from simulation and applied in the way that some parameters are directly from the results of the former period. Thus, the regulation method can satisfy heat users with their demands of thermal comfort to a certain degree decided by weight of thermal comfort; it can also adapt to abrupt change of heat load, save energy and reduce heat loss in transportation.

The optimal regulation scheme exemplified is a combination of several objectives. Its goal is to make the most of minimal energy consumption to improve users' thermal comfort. Distinctly, the weight of thermal comfort directly influences optimal results. We can regulate heating parameters according to other objectives, such as operational expense if necessary.

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