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A temperature control strategy to achieve low-temperature district heating in North China

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ABSTRACT

Low-temperature district heating (LTDH) systems can improve energy efficiency and better combine with factory waste heat and renewable energies. In this paper, we develop a data-based temperature control method to reduce the supply and return temperature of the heat exchange station. The relationship between distribution temperature and outdoor temperature is used to achieve lower supply temperature. The reduction of supply temperature is used to evaluate the benefit of the control strategy. Moreover, a return temperature prediction model is established to verify the feasibility of different control strategies proposed in our article. The comparison results of different control strategies indicate that the hourly average supply temperature can be reduced by more than 4°C whereas the return temperature keeps above 29°C at all times. To sum up, the supply temperature control strategy proposed in this paper provides a guide for the transformation of existing heat exchanger stations to low-temperature district heating systems in North China.

Keywords:

Low-temperature district heating (LTDH);
Energy efficiency;
Supply temperature control;
Safe heating;

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1. Introduction

The global building sector accounts for more than 30% of the final energy consumption of world and about 30% of global carbon dioxide (CO_2) emissions [1,2]. According to the research of the International Energy Agency (IEA), China is the second-largest building energy user in the world after the United States, representing about 14% of the total final energy consumption in buildings globally in 2014 [3]. Building energy use accounted for 20% of the total primary energy consumption in China in 2016. Building energy conservation work has become one of the biggest challenges for China's energy conservation and emissions-reduction work [4].

District heating (DH) is a cost-effective heating method, especially to areas with high heat density [5]. The existing systems, commonly referred to as the third generation DH systems, have a supply/return temperature of 80/50°C. To further reduce the DH system energy losses, a low-temperature DH (LTDH) network with supply/return temperature at 55/25°C was developed to supply heat for 30 residential houses [6]. Henrik Lund et al defined the concept of 4th generation district heating (4GDH) in 2014 [7]. The 4GDH, also known as LTDH, have a supply temperature as low as 50°C even lower. The ultra-low-temperature district heating (ULTDH) was defined with supply temperature at 35-45°C in [5]. To improve the efficiency of the ULTDH system, the return temperature should be as low as possible [5]. In [8], eighteen Danish single-family houses were supplied by ULTDH with temperature as low as 45°C, and the existing houses can be heated safely. Three alternative concepts for DH temperature level were compared on grid loss, production efficiencies and building requirements in

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[9]. The analysis results on software EnergyPLAN showed that the LTDH (55/25°C) outperformed ULTDH with electric boosting (45/25°C) and ULTDH with heat pump boosting (35/20°C). Moreover, LTDH can contribute to more efficient use of energies and better integration of renewable energies [10].

The long-term development of DH systems depends heavily on the improvement of existing control strategies. The effects of the transition to low distribution temperature in existing DH systems were studied, and corresponding technical solutions and evaluation methods were proposed in [11]. In 2018, based on the current heat demand and temperature scenario, the study of heat demand savings and reduction of pipe network temperature in Northern Denmark was studied. The conclusion is that there is great potential for heating in low temperature [25]. In 2018, the challenges and development potentials of transitioning from existing high-temperature DH systems to LTDH in Norway were analyzed. The results showed that the lower supply temperature can reduce heat loss [24]. In 2018, the operation of the LTDH system of five single-family houses in Denmark was investigated. The results showed that all houses operated well under low-temperature supply [23]. In 2019, the cost and benefits of providing LTDH for existing space heating systems were evaluated. Studies showed that it is economically feasible to reduce return temperatures with improved heating system control strategy [21].

In order to transform from existing heating systems to the LTDH, it is necessary to reasonably control the network distribution temperature, that is, to reduce the supply and return temperature on the premise of ensuring safe heating. In this paper, existing temperature control strategies are divided into two categories: (1) optimization strategies based on pipe network structure and heating device [12,13,20,26,27,28] and (2) control methods based on operational data of heat exchange stations [14–19,22].

The former mainly tries to modify the pipe network structure and/or change heating device to optimize the operation on the building level. Three layout (centralized, semi-decentralized and decentralized) of district heating network with combining heat storage was compared and optimized with genetic algorithm in [26]. An innovative LTDH network was developed and the possibility of applying the return water of current district heating system to a LTDH system was explored in [27]. Technical and economic assessment of the LTDH system with thermal energy storage was presented in [28]. In [12], the concept of cascade utilization of residual energy in DH network was proposed, and the return water of high-temperature DH was used as the heat source of LTDH. The author of [13] developed the concept to reduce return temperature by implementing thermal energy cascades between different building types. A technical solution was proposed to achieve lower return temperature in new residential buildings [20].

Data-based control methods mainly explore optimal control strategy through supply temperature and/or flow mass rate. An adaptive control method was developed in [14] to provide the lowest possible return temperature, reducing the average flow by 3.5%. A novel method for temperature difference fault detection using temperature difference signature was presented in [15]. A strategy to improve the distributed heat exchange station system was proposed in [16] to apply LTDH to the traditional domestic hot water circulation system, which reduced the heat loss by 39%. In [17], Magnus Dahl et al. used optimized temperature control method and time-based weather uncertainly to reduce supply temperature and heat losses. In [18], the outdoor temperature forecast and historical operating data were used as inputs of the neural network to predict the future heat demand and return temperature. Moreover, a delay distribution function based on the distances between heat consumers and the suppliers was established to minimize the pumping cost and heat loss, and one-year data from a DH system in Finland was used for demonstrating the optimization. In [19], the author proposed a novel control method based on the relationship between the on-off time of valves and return temperature. And the experiment results showed good prospects for development. In 2018, the problem of hydraulic imbalance in the heating pipe network that transformed the existing boiler houses into LTDH was studied. A novel hydraulic model using real-time weather and boiler operation data was proposed. Based on the model, the hydraulic imbalance of the four different control scenarios is analyzed [22].

However, the return temperature should not be as low as possible. Too low return temperature discomforts the consumers, and few kinds of literatures impose restrictions on the return temperature. Moreover, recent research about LTDH is still mainly aimed at the DH systems in Nordic countries (such as Denmark and Sweden). There is relatively little research focus on DH systems in China, although China has a large proportion of building energy consumption. Actually, the supply temperature of secondary pipe is still primarily adjusted manually by the operator in northern China DH systems. And the secondary supply temperature has to be determined conservatively to ensure a sufficiently high temperature in DH networks at all times, which usually leads to too high secondary supply temperature and unnecessary energy loss.

In this article, we aim to explore the temperature control strategies of the secondary network for converting from existing DH systems to the LTDH in North China. The optimal operation of the distribution network is achieved by minimizing secondary supply temperature under certain restrictions. First, the temperature control method is described in detail in Section 2, and then the benefits and the safety of different control strategies are evaluated and compared in Section 3. Finally Section 4 concludes the entire work and lists our contributions.

2. Temperature control method

In this section, we will introduce our temperature control method in details. Our method aims to achieve minimum supply temperature for existing DH systems while ensuring heating safety. Based on the actual DH operating data and weather forecast data, the return temperature prediction model is established in Section 2.1. The supply temperature control strategies are developed in Section 2.2 and evaluated in Section 2.3. The overall temperature control strategy proposed in this paper is described in Figure 1.

2.1. Return temperature prediction model

This section mainly introduces the establishment process of the return temperature prediction model. We first introduce the data used in the experiment, then present a feature selection method based on the Pearson coefficient, and finally describe the established linear regression model.

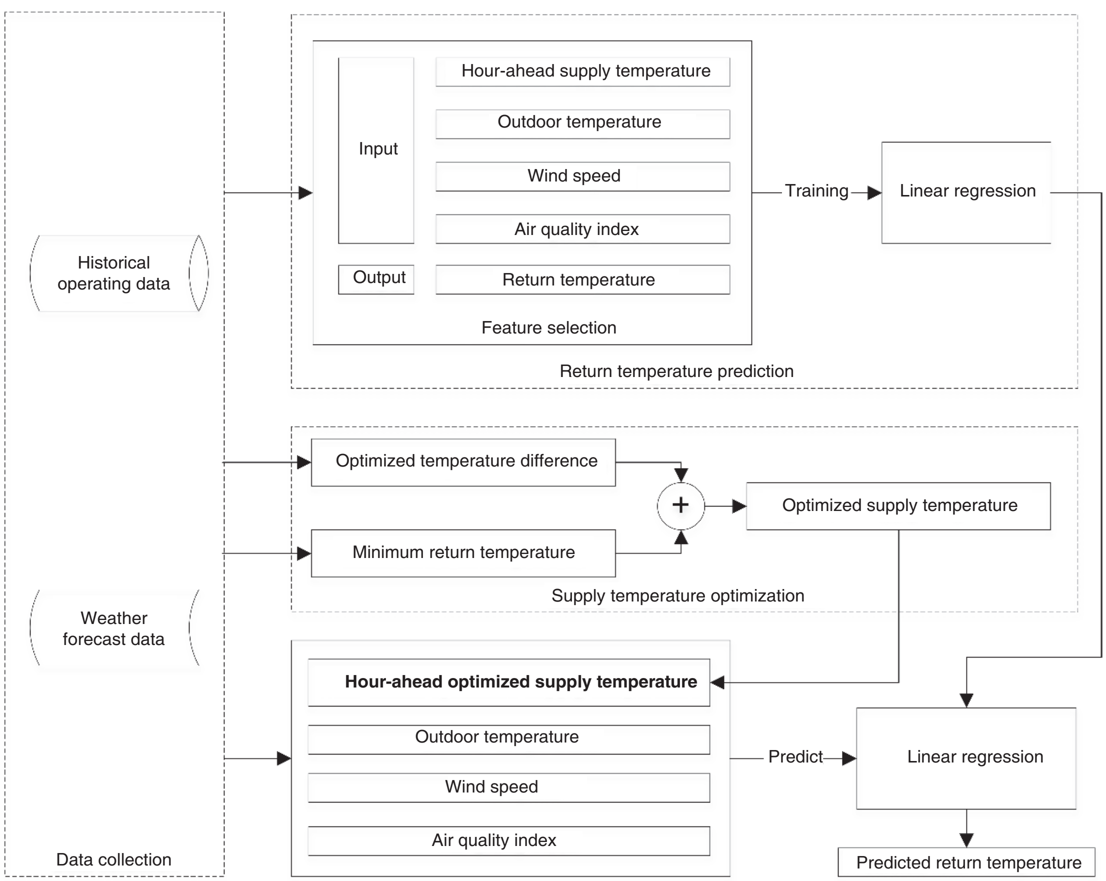

Figure 1: The overall temperature control method proposed in our work, including data collection, return temperature prediction, supply temperature optimization and evaluation

2.1.1. Dataset

The data used in our work include historical actual operating data of a DH system (DHS) and local weather forecast data. The DHS operating data, which includes secondary supply and return temperatures from February 16, 2018, to March 12, 2018, are collected from a heat exchange station in Tianjin, China. The exchange station only supplies space heating for nearly 40 residential buildings in the winter. The operating condition of DHS is always strongly associated with local weather conditions, which is commonly considered as extra information for predicting heat load as well as return temperature. The weather forecast data, which consists of outdoor temperatures, relative humidity, wind speed and air quality index (AQI), is used as inputs of the return temperature predicting model.

2.1.2. Feature selection

The Pearson coefficient, which is a measure of the linear correlation between two variables x and y, is calculated as follows:

$$r(x,y)=\frac{N\sum x_i y_i-\sum x_i\sum y_i}{\sqrt{N\sum x_i^2-\left(\sum x_i\right)^2}\sqrt{N\sum y_i^2-\left(\sum y_i\right)^2}} \quad (1)$$

where N is the number of samples. The $r(x,y)$ ranges from –1 to +1, and the +1/–1 represents total positive/negative linear correlation and 0 denotes no linear correlation. In our work, the Pearson correlation coefficients between potential inputs variables (supply temperature, outdoor temperatures, relative humidity, wind speed, AQI) and target variable (return temperature) are calculated with Eq. (1). And the variable relative humidity is dropped for its weak correlation coefficient with return temperature.

2.1.3. Linear regression model

Overall, the secondary supply temperature, outdoor temperature, the wind speed, and the AQI are normalized and then used to establish a simple linear regression model to predict hour ahead return temperature of secondary network. The normalization process is as follows:

$$x'=\frac{x-\mu}{\sigma} \quad (2)$$

where μ and σ are the mean and standard deviation of variable x. The linear regression model is as follows:

$$T_{ret,t}=a*T_{sup,t-1}+b*\hat{T}_{out}+c*\hat{S}_{wind}+d*\widehat{AQI}+e \quad (3)$$

where a,b,c,d,e are learnable parameters trained with the least square method.

2.2. Supply temperature control method

Based on [17], we propose a novel method to reduce the supply temperature. Firstly, we define the minimum return temperature, which is regarded as one of the restrictions to ensure heating safety. Then, the temperature difference fault detection method introduced in [15] is extended to explore the relationship between temperature difference and outdoor temperature. Finally, the optimized supply temperature is easily obtained by summing the minimum return temperature and optimized temperature difference.

2.2.1. The minimum return temperature

The return temperature plays an extremely significant role in the actual operation of DH systems. The heat supplied by the heat exchanger is usually not enough to meet the heat demand of the consumers when the return temperature is too low, and the operator needs to raise the supply temperature and/or increase the flow rate in time. And too high return temperature is not conducive to efficient energy supply, usually causing unnecessary energy loss. Therefore, the return temperature should be as low as possible but still ensure heating safety.

The return temperature is mainly affected by supply temperature, facilities quality of consumers and weather conditions. The scatter plot of hourly average return temperature and outdoor temperature is shown in Figure 2. It can be seen that the return temperature mostly located in the range of 29–35°C, which can be further reduced. The minimum return temperature , which is also called “safe return temperature” in our article, is defined as 29°C. The safe return temperature is shown in blue in Figure 2 so that only 0.5% of the data is below this line.

We developed a method to calculate the minimum return temperature based on the actual operational data of a heating exchange station. It should be pointed out that the minimum return temperature depends on many factors including region, climate, building type, heating method and so on. The minimum return temperature calculated here indeed does not apply to all situations. However, the method proposed here makes reference to other regions.

2.2.2. The temperature difference optimization

The heat load P per unit time is calculated as follows:

$$P=c_w m_w\Delta t=c_w\rho_w Q\left(T_{sup}-T_{ret}\right) \quad (4)$$

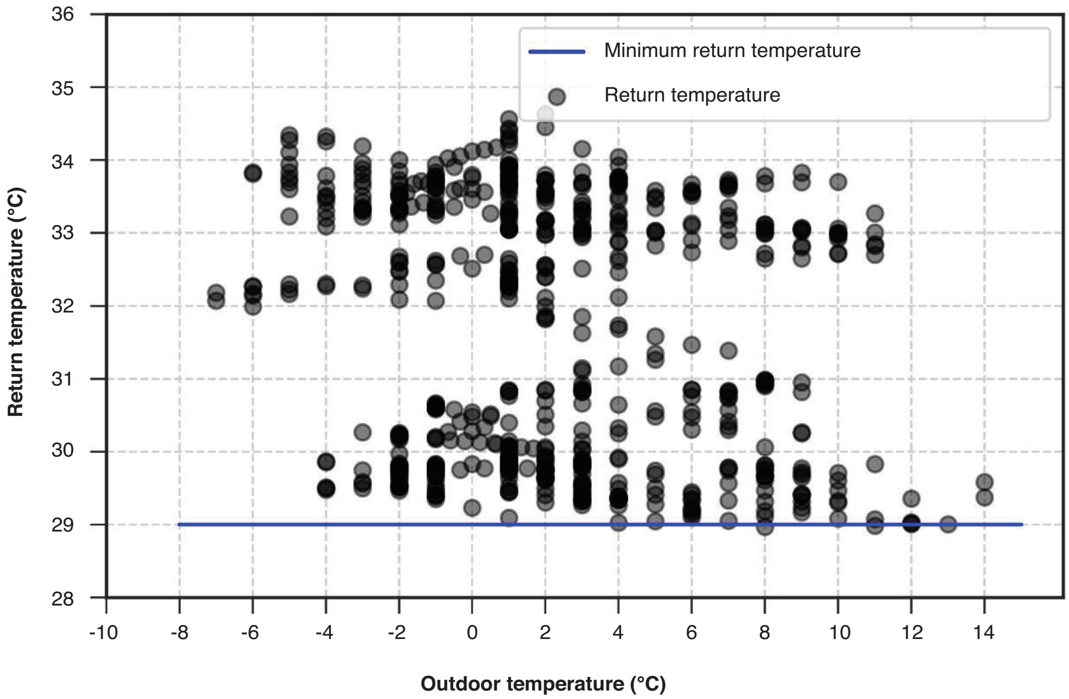

Figure 2: Return temperature versus low-pass filtered outdoor temperature for the district heating station in Tianjin

where c_w and ρ_w are the specific heat capacity and density of water, Q is the flow rate and keep fixed in our study, T_{sup} and T_{ret} represent the supply and return temperature respectively. The temperature difference ΔT is defined as the difference between the supply temperature and the return temperature.

$$\Delta T \overset{\text{def}}{=\!=} T_{sup} - T_{ret} \tag{5}$$

When the water flow is constant, then the heat load P is proportional to the temperature difference ΔT during this period, that is:

$$P \propto \Delta T \tag{6}$$

In many works in the literature, the delivered thermal load of the DH systems is often higher than required, causing significant energy waste. Reducing the temperature difference ΔT can improve this situation according to Eq. (6).

The temperature difference signature is a diagram that plots the average hourly temperature difference as a function of the outdoor temperature. In Figure 3, the temperature difference signature of a DH system in Xiqing district, Tianjin is plotted with an average line and two offset lines. The average line is calculated by the least squares method, and two threshold lines are defined by using 1.5 standard deviations from the average line. There is an offset line above and an offset line below the average line, and the data between the two lines is considered to be normal temperature difference data.

By adding the upper and lower bounds to the temperature difference data, only 3.6% and 2.0% of the data are above the upper boundary and below the lower boundary. In other words, 94.4% of the data is located in the defined interval. The temperature difference fault of the DH systems can be detected based on the defined interval presented here, which is essential for the continuous safe operation of the DH systems. The optimization of the supply temperature needs to be carried out under the normal operation of the heat exchanger station. The relationship between temperature difference and outdoor temperature is:

$$\Delta T_{min} = \begin{cases} k * T_{out} + bias + \gamma * std(\Delta T), T_{out} < 8°C \\ 8k + bias + \gamma * std(\Delta T), T_{out} \geq 8°C \end{cases}, \gamma \in [-1.5, 1.5] \tag{7}$$

Where k and *bias* are the slope and offset of the average line in Figure 3. And *std* (ΔT) represents the standard deviation of the temperature difference.

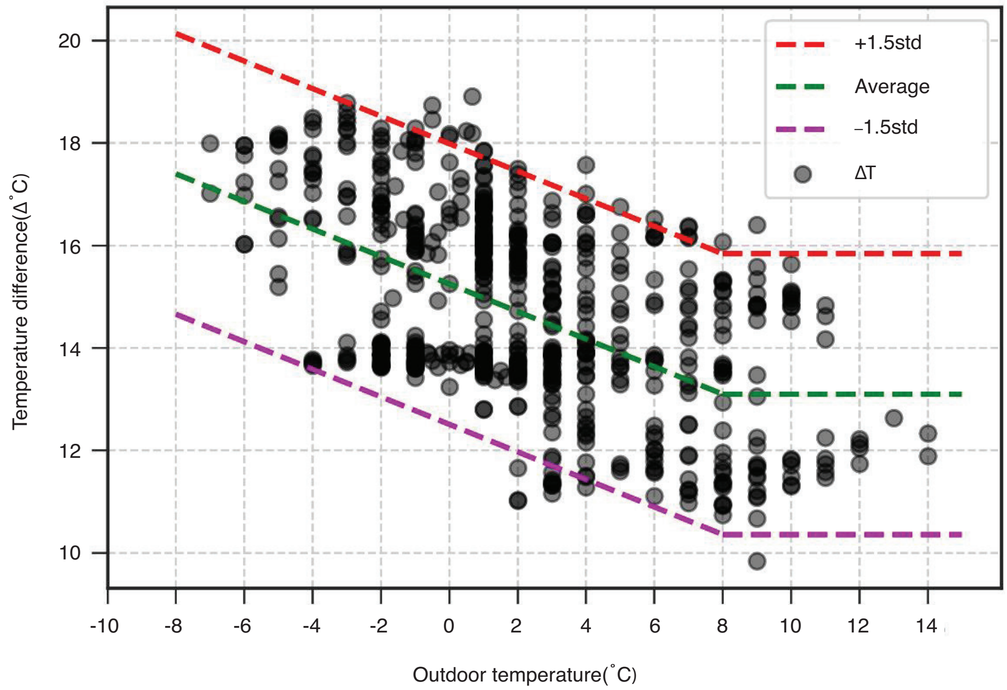

Figure 3: Temperature difference signature in the district heating station

2.2.3. Supply temperature optimization

According to Eq. (5), the minimum supply temperature T_{sup}^{min} can be calculated as the sum of optimized temperature difference and minimum return temperature T_{ret}^{min}.

$$T_{sup}^{min} = \Delta T_{min} + T_{ret}^{min} \tag{8}$$

2.3. Evaluation method

As with [17], we use the sum of the supply temperature reductions for all hours over the entire simulation period to estimate the benefits of our proposed optimization method.

$$\sum_{t=1}^{587} \left(T_{sup,t} - T_{sup,t}^{min} \right) \tag{9}$$

The linear regression model established in Section 2.1 is used to evaluate the safety of our proposed supply temperature control method. Specifically, the actual supply temperature one hour ago $T_{sup,t-1}$ in the model (3) will be replaced with the optimized supply temperature $T_{sup,t-1}^{min}$ calculated with Eq. (8), and the model output will be compared to the minimum return temperature T_{ret}^{min} introduced in Section 2.2.1.

3. Results

The significant changes of the supply temperature are usually the main cause of the "unnormal" operation of the heating system and the temperature difference "fault". By optimizing the supply temperature, it is possible to effectively overcome the problem. Figure 4 compares the optimized and actual supply temperature of the DH systems. The black line is the actual supply temperature from February 16, 2018, to March 12, 2018. The green line is the optimized supply temperature with the average line in Figure 3, and the red and magenta line is the optimized supply temperature with ±1.5 standard deviations in Figure 3. It can be seen that the actual supply temperature varies considerably. For example, the change range of February 26 is about 8°C, and the range of March 7 is nearly 7°C. The optimized supply temperature changes no more than 4°C daily, which greatly improves the operation of the heating system.

The actual and optimized return temperatures are compared in Figure 5. The black line is the actual return temperature from February 16, 2018 to March 12, 2018. The green line is the predicted return temperature with average-based optimized supply temperature (green line in Figure 4), and the red and magenta lines are the predicted return temperature with ±1.5 standard

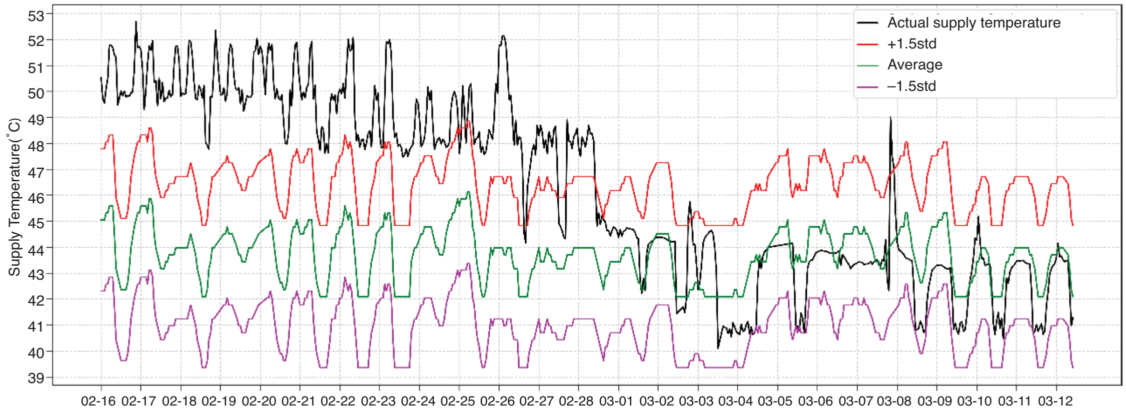

Figure 4: Optimized supply temperature with different optimization strategies versus actual supply temperature

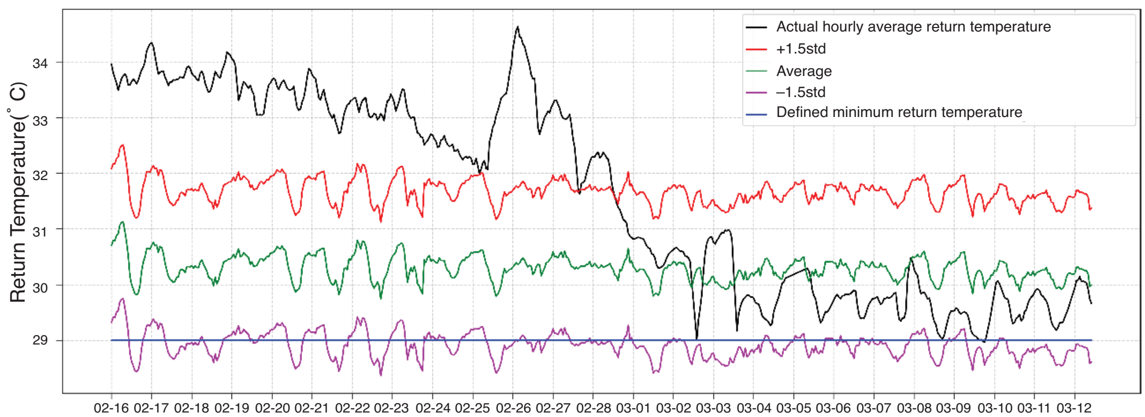

Figure 5: The return temperature predicted by linear regression model (3) with different optimized supply temperature in Figure 4

deviations-based optimized supply temperature (red and magenta line in Figure 4). The blue line represents the defined minimum return temperature, which is defined as 29°C in Section 2.2.1 and also plotted in Figure 2 with blue. The optimized return temperature is predicted with the optimized supply temperature obtained above. It can be seen that the actual return temperature varies greatly, especially during the period of February 25-March 3. Moreover, the change in the optimized return temperature is relatively slight, and the daily variation does not exceed 1.5°C at any time. However, the return temperature optimized with strategy −1.5 standard deviations deviates on both sides of the minimum return temperature, which will not ensure heating safety at all times.

The hourly supply temperature reduction in simulation period and the percentage of predicted return temperature above the minimum return temperature (29°C) with different optimization strategies are plotted in Figure 6. The overall supply temperature reduction on the simulation period, which is calculated by Eq. (9), is used to estimate the benefits of temperature control strategies whereas the distribution of return temperature is regarded as a metric to ensure heating safety. The different optimization strategies are determined by the parameter γ in Eq. (6). The $\gamma = \pm 1.5$ and $\gamma = 0$ give the optimization strategy of ±1.5 standard deviations and the average line in Figure 3. With γ increase from –1.5 to +1.5, the supply temperature reduction decrease nearly linearly, from 3136°C ($\gamma = -1.5$) to –80°C ($\gamma = +1.5$). The hourly supply temperature reduction is from 5.34°C ($\gamma = -1.5$) to –0.14°C ($\gamma = +1.5$). The smaller the value of γ, the larger the supply temperature reduction. However, the premise of lowering the supply

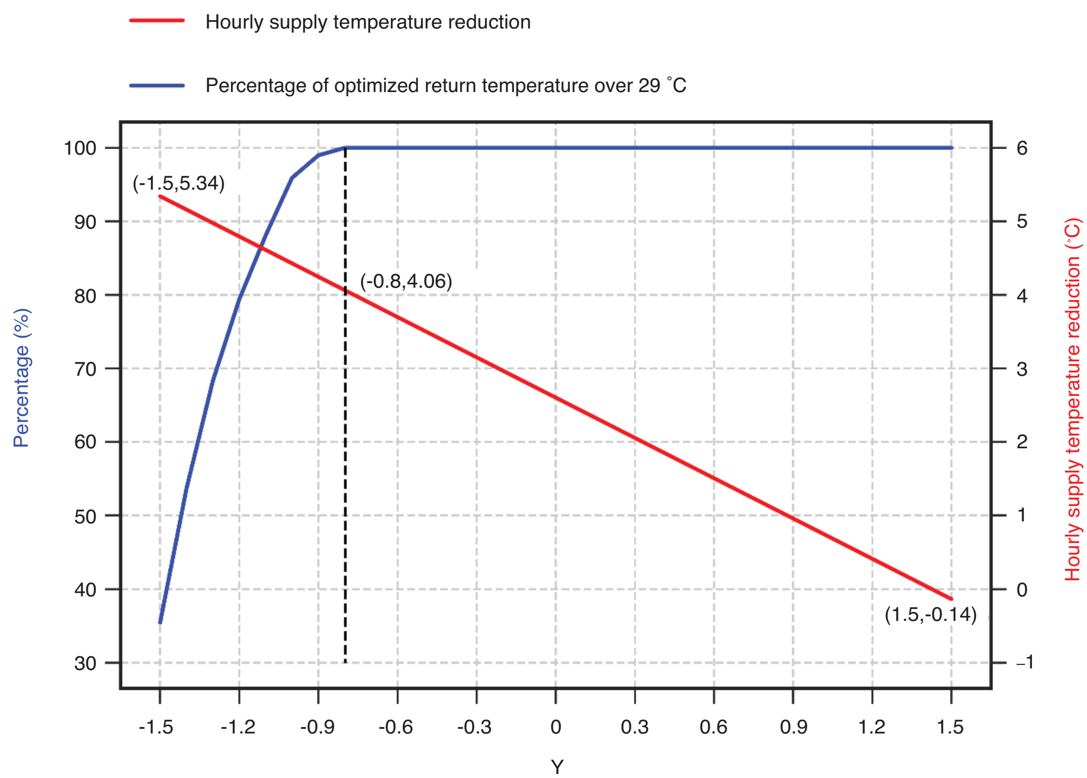

Figure 6: The hourly supply temperature reduction on simulation period and the percentage of predicted return temperature above the defined minimum return temperature (29°C) with different optimization strategies

temperature is heating safety, which means that the return temperature must be above the minimum return temperature at all times. It can be seen that the percentage gradually increases with γ increases. And all data is larger than the minimum return temperature when γ reaches –0.8. Consequently, $\gamma = -0.8$ is the optimal control strategy, the corresponding total supply temperature reduction is 2386°C, and the average hourly reduction is 4.06°C.

4. Conclusion

This paper proposed a supply temperature control method for district heating systems in northern China. Specifically, we developed a novel optimization strategy to reduce the supply temperature based on the actual operating data and weather forecast data, and evaluated the feasibility of the strategy by establishing a simple linear regression return temperature prediction model. The experiment results show that the average hourly supply temperature is reduced by more than 4°C with return temperature kept above 29°C at all times. There are mainly the following three contributions of our work:

(1) The temperature control strategy proposed in this article can effectively reduce the supply temperature and improve heating efficiency while keeping heating safety, which is consistent with the 4GDH system.

(2) The optimized operating interval of the temperature difference of the heat exchanger station is defined, which can be used for eliminating temperature difference fault.

(3) Surprisingly, the proposed optimization strategy can reduce the daily temperature change, which is conducive to the stable operation of the heating system. Specifically, the daily variation of the supply temperature is reduced from the highest over 8°C to 4°C, and the return temperature is reduced from 2°C to not exceed 1.5°C.

In general, we provide a possibility to transform the existing DH systems in northern China to the LTDH. However, the temperature control method is not suitable for all heating systems due to limitations in geographic location, system capacity, climate changes, etc. To apply the temperature control strategies presented here to the respective heating systems, corresponding changes and necessary adjustments are required of the systems.

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