Experimental Study on Indoor Thermal Environment and Heating System Optimization in Cold Regions During the Heating Season in Universities

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Abstract: As the global energy demand continues to soar, China, being a major energy consumer, is confronted with a severe energy situation. In cold regions, winter heating is a crucial element to ensure the normal living and working conditions of residents. However, traditional heating systems are fraught with problems during operation, such as energy waste and suboptimal heating performance. This paper focuses on the indoor thermal environment of various buildings in a university in Zhangjiakou, a cold region, during the heating season. Field measurements of the indoor thermal environment were conducted, and the supply and return water temperatures of the heating system were investigated. A thorough analysis of the measured data was performed to reveal the operating characteristics and existing issues of the heating system. Targeted optimization strategies were then proposed. The findings of this research are of great significance for improving the efficiency of distributed heating systems and enhancing the indoor thermal environment.

Keywords: Heating System; Optimization Strategies; Supply and Return Water Temperature; Thermal Comfort; Heating Season Analysis

1. Introduction

To accelerate the achievement of "carbon neutrality" and "carbon peak", the "14th Five-Year Plan for the Modern Energy System" sets energy decarbonization targets: reducing carbon dioxide emissions per unit of GDP by 18% and energy consumption per unit of GDP by 13.5% within five years [1]. However, China's overall energy situation remains extremely challenging, with total carbon emissions continuing to rise. Notably, carbon emissions from the building operation phase account for 21.6% of the nation's total emissions [2]. Among these, the heating process constitutes the primary source of carbon emissions from building operations. Therefore, enhancing the energy efficiency of heating systems to achieve energy conservation and emission reduction has become a key research focus in the energy sector.

In recent years, a significant number of researchers both domestically and internationally have conducted extensive studies on the indoor thermal environment across various regions [3]. Qian Jiaqi [4] and colleagues focused their research on four classrooms located on the third floor of a university teaching building in Guilin. Their findings indicated that during the winter season, classrooms in Guilin universities generally experience low temperatures and high relative humidity. Additionally, the limited fresh air intake and the resulting strong stuffiness contribute to a poor indoor thermal environment. Li Runchun carried out on-site investigations and questionnaire surveys in six universities in Lhasa. The results showed that student dormitories in these universities use centralized heating during winter, with relative humidity levels below 30%, indicating a dry condition that necessitates humidification. Zhu Rongxin [5] and others, taking Kunming as an example, analyzed the indoor thermal environment and thermal comfort of office buildings through questionnaire surveys. They concluded that during winter, the indoor temperature is relatively low, and approximately 40% of the occupants reported feeling uncomfortable.

Currently, traditional heating models are transitioning toward smart heating systems. The core of smart heating lies in ensuring that the operational parameters of the heating network align with users' actual thermal demands, thereby reducing overheating and improving thermal utilization efficiency. Consequently, demand-based heating constitutes a crucial component of smart heating within distributed heating systems [6]. Measurement data of supply and return water temperatures, along with indoor temperatures, can provide an intuitive understanding of the performance of heating systems in different buildings and serve as a critical basis for system optimization. In this paper, data on supply and return water temperatures of a university's distributed heating system and indoor temperatures of various buildings were collected. The operating parameter patterns of the heating system, temperature differences among different buildings, and their influencing factors were analyzed to propose optimization strategies. The study covered various types of public buildings, including office buildings, dormitories, and teaching buildings, ensuring the broad applicability of the research findings.

2. Data Collection and Collation of Heating Systems

2.1 Subjects

Located in the northwestern part of Hebei Province, Zhangjiakou is characterized by a temperate continental monsoon climate. According to the Chinese National Standard GB 50178-1993 "Standard for Architectural Climate Zone Division" [7], Zhangjiakou is a typical city in the cold climate zone of the building thermal division. The city experiences four distinct seasons throughout the year, with cold and dry winters that require an extended heating period.

The focus of this paper is on three representative buildings of Hebei Institute of Architecture and Engineering: The Mingde Building (a teaching building), the Energy Building (an office building), and Dormitory No. 3. These buildings feature a frame structure and are oriented in the east - west direction. The architectural layout consists of a central corridor with rooms on both the north and south sides. The Mingde Building has eight above-ground floors and one underground floor. The Energy Building comprises three floors, and the dormitory building has six floors.

2.2 Operating Modes

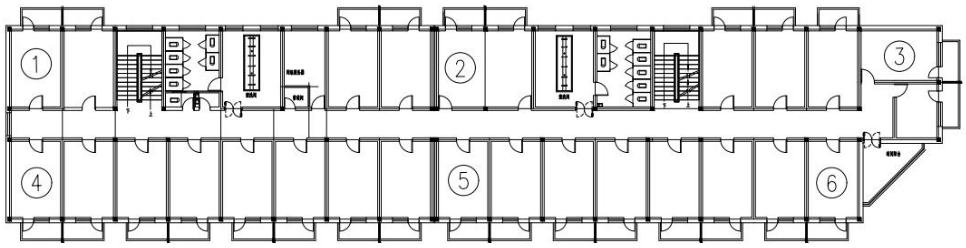
The system operates in three modes: direct heating via electrode boilers, simultaneous storage and heating via electrode boilers, and heating via thermal storage tanks. Currently, campus heating systems predominantly employ a single electrode boiler operating in direct heating mode.

The boiler is manually activated and deactivated at fixed times for heating. Typically, the electrode boiler operates during two periods each day: from 4:00 PM to 9:00 PM and from 12:00 AM to 7:00 AM. It remains deactivated during all other hours.

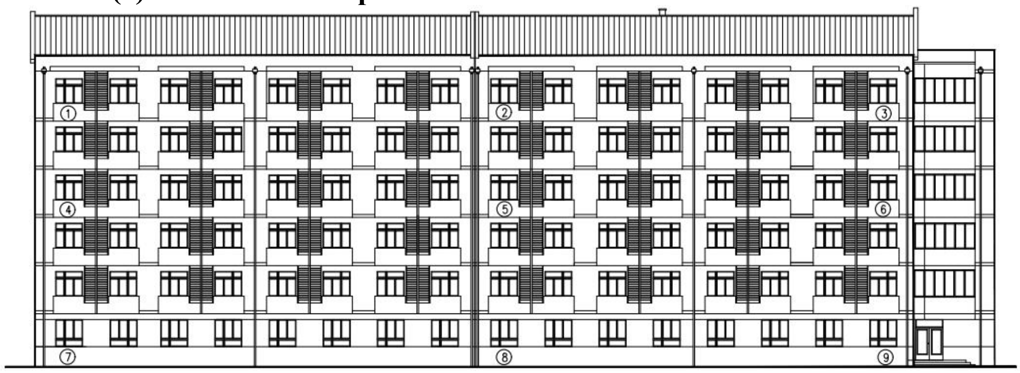
2.3 Data Collection

Temperature sensors are installed at key nodes of the heat-supply network to monitor the supply and return water temperatures, such as at the heat source outlet, the inlet and outlet of heat-supply stations, and the heat entry points of buildings. Within different buildings, indoor temperature measurement points are evenly distributed according to functional areas and spatial layouts, taking into account both frequently occupied zones and special-function areas. For this survey, a sample of 18 rooms with different floor levels, orientations, and usage characteristics was selected within the building. The relative positions of the rooms and the layout of the measurement points are shown in Figure 1. Taking the dormitory building as an example.

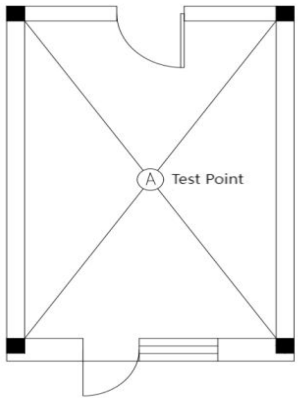
The physical parameters to be tested include indoor air temperature and relative humidity. These parameters are monitored using thermo-hygrographs. In accordance with the requirements of the international standard ISO 7726 – 1998 "Ergonomics of the thermal environment - Instruments for measuring physical quantities" [8], the instruments are positioned at a vertical height of 1.6 m above the floor during testing. The testing period is one week, with measurements recorded every 10 minutes, and the average values are subsequently calculated. The data acquisition system employs high - precision temperature sensors, as depicted in Figure 2. These sensors are equipped with automatic recording and storage capabilities and are configured to collect data at the set interval of 10 minutes. The measurement accuracy of the sensors meets the requirements of the experiment. The sensors have been calibrated and are regularly maintained to ensure the accuracy and reliability of the data.



(a) Distribution Map of Measurement Points on the Same Floor



(b) Distribution Map of Measurement Points on the Facade of Dormitory Building



(c) Location Map of Test Points in the Room

Figure 1. Relative Position of the Room and Arrangement of Test Points

Figure 2. Bluetooth Temperature and Humidity Recorder

Data acquisition for each building was conducted over a one-week period to capture the operation data of the heating system under various outdoor temperature conditions, including extreme low temperatures and moderate periods, thereby providing a comprehensive reflection of the system's performance. The Mingde Building was tested from December 25th to December 30th. Dormitory No. 3 was tested from March 12th to March 17th. The Energy Building was tested from March 26th to April 2nd.

2.4 Data Collation and Preprocessing

Abnormal values are handled as follows: supply and return water temperatures exceeding ±10°C from design values, and indoor temperatures exceeding ±5°C from the comfort range, are considered abnormal. Interpolation and mean substitution methods are applied to correct abnormal values, ensuring data continuity and reliability. For minor data gaps, linear interpolation using adjacent time points is employed to fill in missing values. When significant data is missing, the cause is analyzed, and appropriate algorithms are applied to estimate and supplement the missing data based on the operational patterns of the heating system and historical data.

3. Data Analysis of Heating System Operation

For the Mingde Building, the selected date was December 29th, with the outdoor air temperature ranging from a maximum of 1℃ to a minimum of -11℃, averaging -6℃. For the dormitory building, the chosen date was March 14th, with outdoor air temperatures from a maximum of 3℃ to a minimum of -7℃, averaging -2℃. For the Energy Building, the date was March 28th, with outdoor air temperatures from a maximum of 3℃ to a minimum of -5℃, averaging -1℃. On these selected dates, there were no significant temperature drops in the preceding or following two days, indicating relatively stable outdoor temperatures.

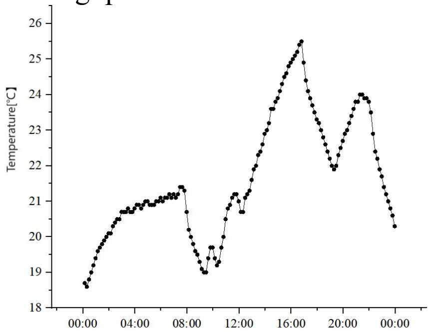
In each building, six representative rooms were selected from the 18 monitored rooms, covering different floor levels (ground floor, middle floor, top floor), orientations (east side, west side), and solar exposure (sunlit side, shaded side). The collected data were organized to reveal the patterns of supply and return water temperature changes as well as the distribution of indoor temperatures.

The indoor temperature data of the Mingde Building, as shown in Figure 3, indicates that the temperature begins to rise rapidly around 10:00 a.m. and reaches a peak at approximately 4:00 p.m., after which it gradually declines. During the 8:00 - 10:00 a.m. period, the temperatures in all six typical rooms were below 19.5℃. This is too low for students attending morning classes and can negatively impact their comfort. The daytime period from 8:00 a.m. to 6:00 p.m. is the core teaching time in the teaching building, when the occupancy is high and the demand for thermal comfort is significant. The typical comfort temperature range for classrooms is 18 - 22℃. Additionally, according to the Chinese National Standard GB 50736 - 2012 "Code for Design of Heating, Ventilation and Air - Conditioning of Civil Buildings" [9], the indoor temperature range in winter should be between 18℃ and 22℃. However, as shown in the figure, Classroom 116 and Classroom 413 had maximum temperatures below 17℃after the daytime temperature increase, which is significantly lower than the comfort range. This can affect the teaching experience and efficiency of both teachers and students.

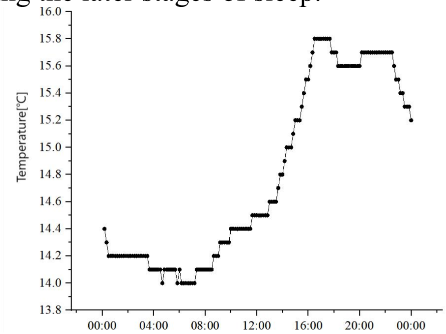
As shown in Figure 4, the supply water temperature of the Mingde Building exhibits significant fluctuations throughout the day, peaking in the morning and afternoon to ensure that the indoor temperature reaches a comfortable level before people start their activities. At night, when the heating demand is lower, the supply water temperature decreases correspondingly. The return water temperature follows a similar trend to that of the supply water temperature. The fact that the supply water temperature does not drop significantly at night may lead to energy waste. During the night, especially in the late hours, the heating demand is typically low. Therefore, measures can be taken to reduce the heat supply to save energy.

The indoor temperature data of the dormitory, as illustrated in Figure 5, shows that the temperature begins to rise gradually in the early morning and reaches a relatively stable level by 8:00 a.m. It then starts to decline gradually until around 11:00 a.m., when it begins to rise again, peaking at around 2:00 p.m. before gradually decreasing. The fluctuations in temperature during the midday period may indicate insufficient stability in the heating system regulation, which leads to discomfort in the indoor environment and can affect rest and daily life in the dormitory. Moreover, based on the activity patterns in the dormitory, the periods from 9:00 a.m. to 12:00 p.m. and from 2:00 p.m. to 6:00 p.m. are times when the indoor temperature can be reduced to avoid overheating and the associated energy waste. During the nighttime rest period, the demand for temperature in student dormitories is for a mild, comfortable, and energy - efficient environment. The recommended comfortable temperature range for dormitories in winter is typically 18 - 22℃. However, as shown in the figure, Dormitory 3601 and Dormitory 3610 have minimum temperatures above 23℃, and the temperature continues to rise to above 26℃ at night. This not only affects students' sleep quality due to excessive dryness but also leads to significant energy waste due to over - heating.

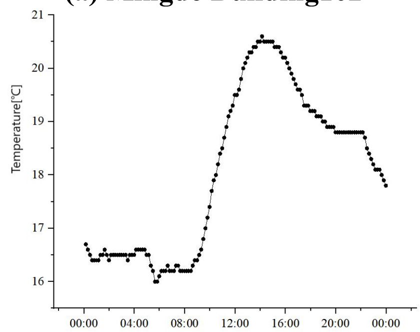
The supply and return water temperature data of the dormitory, as shown in Figure 6, reveals that the period from 8:00 p.m. to 6:00 a.m. is a critical rest period for students, during which a stable and comfortable indoor temperature is highly demanded. However, the data indicates a continuous drop in supply and return water temperatures during the night, with temperatures falling to around 25℃ in the early morning, which is significantly lower than the typical supply and return water parameters required for dormitory heating. This results in insufficient heating capacity, making it difficult to maintain a comfortable indoor temperature. During the early morning period from 4:00 a.m. to 8:00 a.m., when students are still resting, the supply water temperature rises sharply to above 55℃, with the return water temperature also increasing correspondingly. This phenomenon, known as "overheating in non - demand periods", not only leads to energy waste but also causes a sudden increase in indoor temperature due to excessive heat supply. This abrupt temperature rise disrupts the comfort sensation during the later stages of sleep.



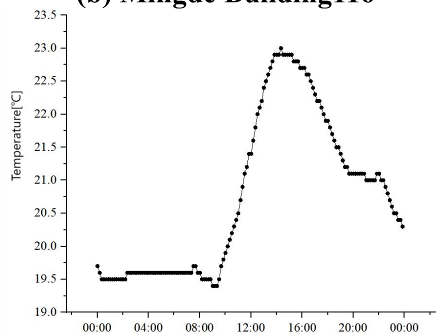
(a) Mingde Building102



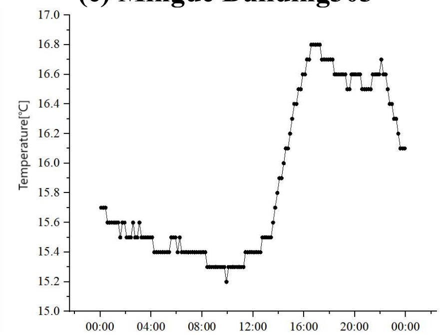
(b) Mingde Building116



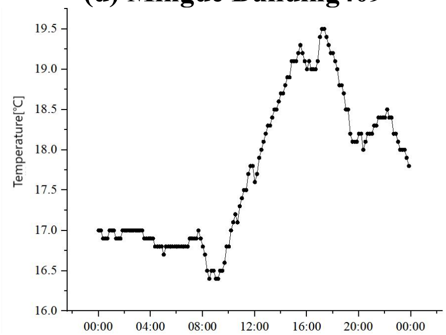
(c) Mingde Building303



(d) Mingde Building409



(e) Mingde Building413



(f) Mingde Building813

Figure 3. Indoor Temperature of Mingde Building

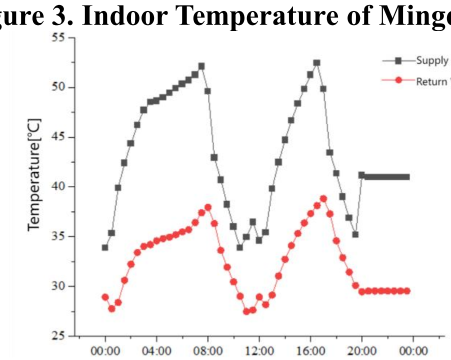
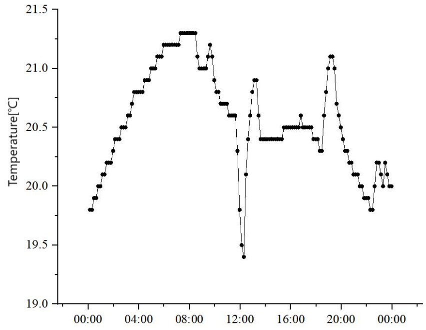
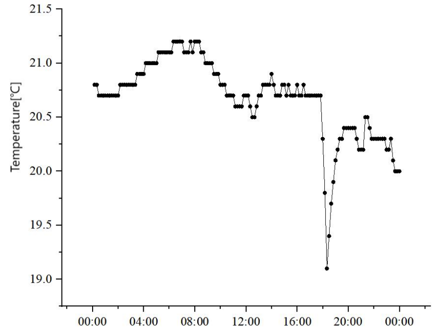


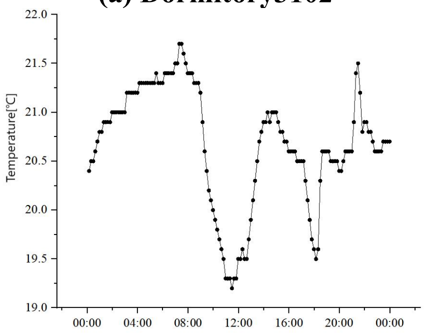
Figure 4. Supply and Return Water Temperature of Mingde Teaching Building



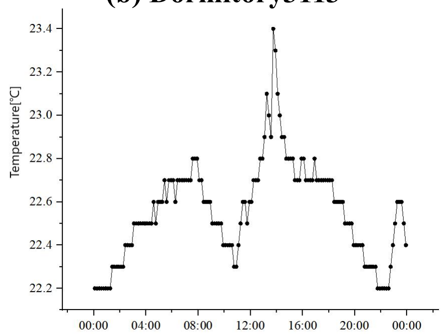
(a) Dormitory3102



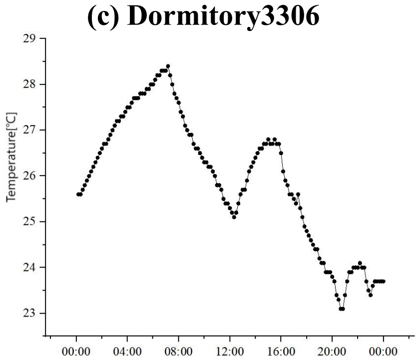
(b) Dormitory3113



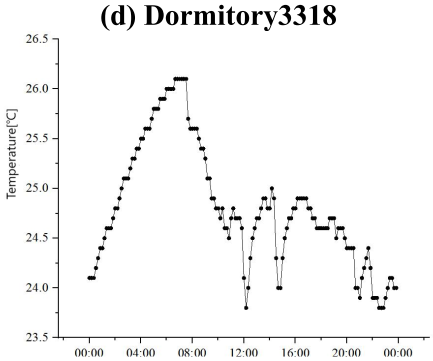
(c) Dormitory3306



(d) Dormitory3318



(e) Dormitory3601



(f) Dormitory3610

Figure 5. Room Temperature in the Dormitory

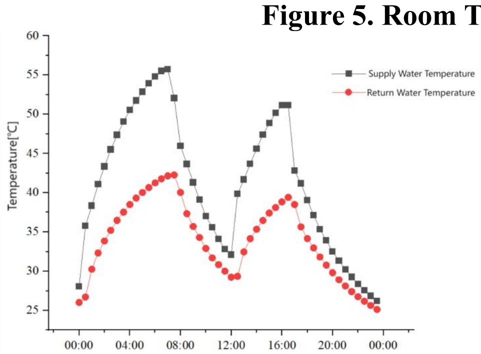
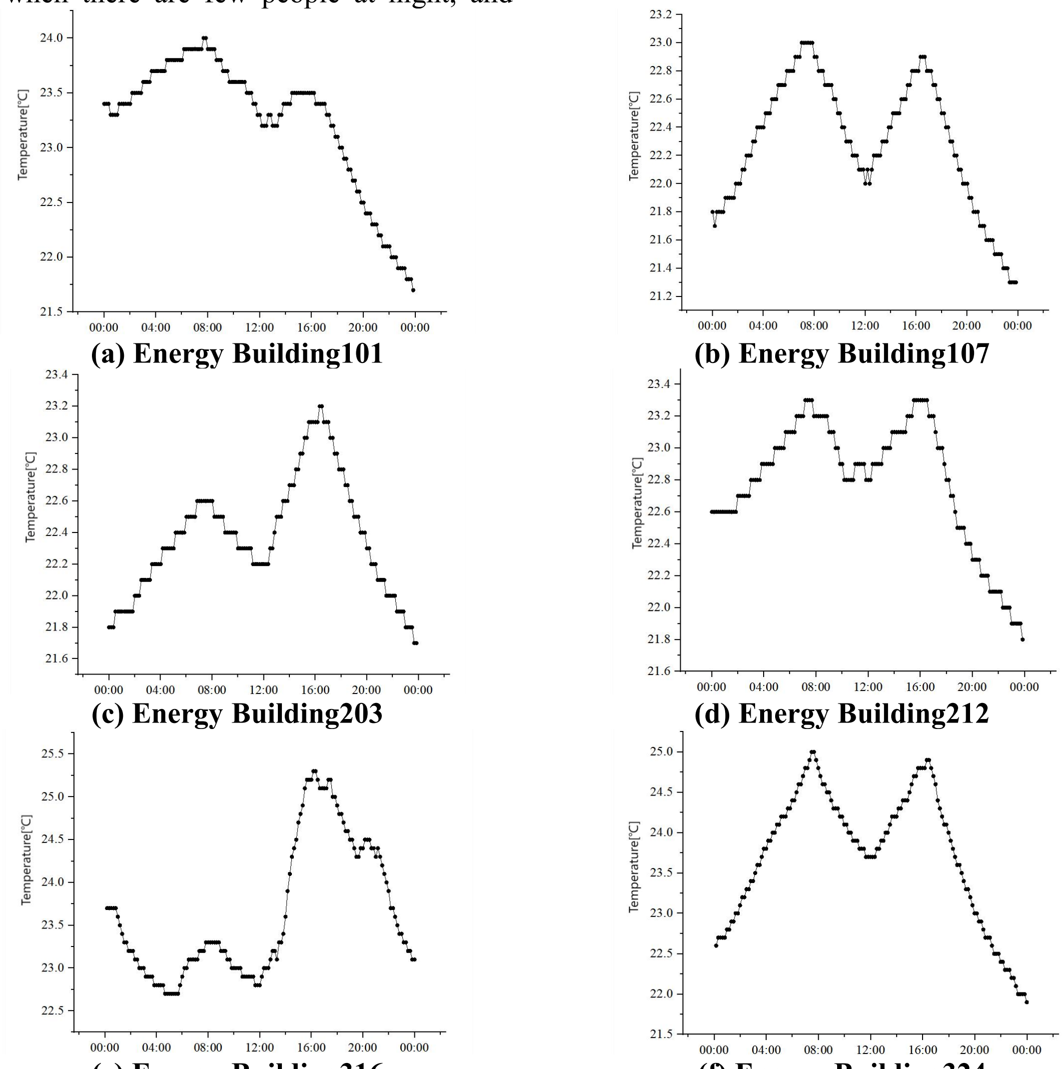


Figure 6. Supply and Return Water Temperature of Dormitory

The indoor temperature data of the Energy Building, as depicted in Figure 7, shows that the lowest temperature occurs around 12:00 p.m., after which it begins to rise and reaches its peak at approximately 4:00 p.m., followed by a gradual decline. During the midday to afternoon period, the temperature peaks, generally exceeding 23℃, which is above the comfortable indoor temperature range. This high temperature can cause office workers to feel overheated and uncomfortable. At night, when there are fewer people in the office building, the temperature remains at a relatively high level.

As shown in Figure 8, the supply water temperature of the Energy Building reaches above 45℃ during the peak periods at 8:00 a.m. and 4:00 p.m. This indicates an excess of heat supply during these times, which leads to excessively high indoor temperatures in the offices and negatively impacts the comfort of office workers.

Analysis of the indoor temperature and supply/return water temperature data from the Mingde Building, the dormitory, and the Energy Building reveals that all areas experience unreasonable temperature regulation, which affects the teaching, living, and working experiences of teachers and students. The Mingde Building has low temperatures in the morning, with some classrooms falling below the comfort range during the day, and significant fluctuations in supply/return water temperatures at night. The dormitory sees temperatures rise in the early morning, then gradually decrease, with large fluctuations at noon and excessively high temperatures in some rooms at night. The supply/return water temperature regulation during the nighttime rest period is also unreasonable, leading to either insufficient or excessive heating. The Energy Building experiences excessively high temperatures from midday to afternoon, with high temperatures even when there are few people at night, and peak period supply/return water temperatures that are too high, resulting in overheating. To address these issues, the heating system regulation strategy should be optimized. Based on the characteristics of human activities and temperature demands in different time periods of each area, appropriate regulation modes should be selected to ensure that temperatures remain within the comfort range. This will not only enhance the teaching, living, and working experiences of teachers and students but also avoid energy waste.



(a) Energy Building101 **(b) Energy Building107**

(c) Energy Building203 **(d) Energy Building212**

(e) Energy Building316 **(f) Energy Building324**

Figure 7. Indoor Temperature of Energy Building

4. Optimization Strategy of Heating System

Based on the analysis above, buildings engaged in teaching and research activities, such as teaching buildings and office buildings, have a high demand for heat during the daytime working hours. In contrast, residential buildings like student dormitories see an increase in heat demand during the evening. If the original scheme of direct heating by electrode boiler is still adopted, it will lead to a significant waste of thermal energy. Therefore, considering the type of building, the timing of heat usage, and the heat - storage performance of the building envelope, the existing method of time - and area - based heating can be optimized to provide heat to buildings more efficiently.

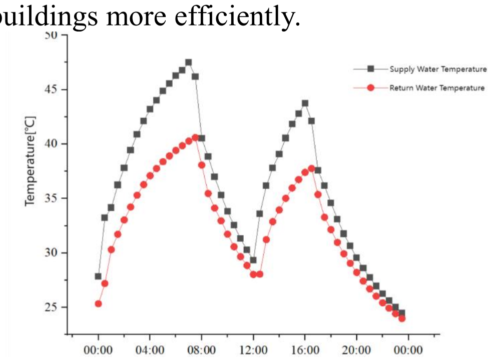


Figure 8. Supply and Return Water Temperature of Energy Building

To address the issue of low morning temperatures and sub - comfort temperatures in some classrooms during the day in the Mingde Building, as well as significant fluctuations in supply and return water temperatures at night, the heating system should be activated earlier in the morning (from 7:00 to 8:00 a.m.) to ensure that classrooms reach a comfortable temperature before students arrive. During the midday period (from 12:00 to 2:00 p.m.), the supply water temperature should be appropriately reduced to prevent overheating. For the dormitory, which experiences a gradual temperature drop after an early - morning rise, significant fluctuations at noon, and excessively high temperatures in some rooms at night, the supply water temperature should be lowered during the late - night period (from 10:00 p.m. to 6:00 a.m.) to enter an energy - saving mode. During peak student activity times (from 9:00 to 12:00 a.m. and from 2:00 to 6:00 p.m.), the supply water temperature should be adjusted to maintain indoor comfort. In the case of the Energy Building, which has excessively high temperatures from midday to afternoon, high temperatures even when there are few people at night, and excessively high supply and return water temperatures during peak periods, the heating system should be activated earlier before office workers arrive (from 7:00 to 8:00 a.m.) to ensure that the office building reaches a comfortable temperature before employees arrive. During the midday to afternoon period (from 12:00 to 4:00 p.m.), the supply water temperature should be appropriately reduced to prevent overheating. At night, when there are fewer people in the office building, the supply water temperature should be lowered. Additionally, a smart temperature control system could be introduced to automatically adjust indoor temperatures based on indoor and outdoor temperatures, human activity patterns, and preferences, thereby achieving smoother temperature control.

As illustrated by the supply and return water temperature charts in Figures 4, 6, and 8, the return water temperatures of different buildings are relatively low. To enhance energy utilization efficiency, it is suggested to incorporate return water temperature boosting technology into the heating system. Specifically, the water with lower return temperatures can be heated using heat pumps. This approach can effectively improve the overall energy efficiency of the heating system by optimizing the use of thermal energy in the return water.

By implementing these optimization strategies, the energy utilization efficiency of the heating system can be enhanced, operational costs can be reduced, and thermal comfort within different buildings can be ensured, thereby meeting the needs of the users.

5. Conclusions and Outlook

This study analyzes supply-return water temperatures and temperature measurement data from various buildings to reveal operational patterns and existing issues in heating systems. The supply-return water temperatures are closely correlated with outdoor temperatures, while indoor temperature distribution varies significantly across different buildings. Campus heating is zoned according to building functions (e.g., teaching buildings, dormitories, office buildings), with distinct heating demands for each functional area. Heating parameters can be adjusted to meet specific requirements, while implementing time-of-day zoning based on user behavior patterns—for instance, reducing heating intensity during nighttime and weekends to conserve energy. The proposed optimization strategies aim to enhance system efficiency, improve indoor thermal comfort, and reduce energy consumption.

Future research should expand data collection to incorporate more operational parameters of heating systems (such as flow rate and pressure) along with user feedback on thermal comfort, thereby building a more comprehensive operational model for heating systems. By conducting in-depth studies on the characteristics of heating systems across different climate zones and building types, we can refine optimization strategies to drive intelligent and precision-driven development of heating systems, ultimately achieving sustainable development goals for the heating industry.

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