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Original Research Article

Research on the Climatic Adaptability of Low-Temperature Radiant Heating under Different Building Energy-Saving Scenarios

Zongjiang Liu[1]*, Zhong Li[1], Wei Xu[1], Deyu Sun[1], Xiaoyi Chen[1]
[1]China Academy of Building Research Co., Ltd., 100013

***Corresponding Author:** Zongjiang Liu
China Academy of Building Research Co., Ltd., 100013

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Abstract: The utilisation of low-temperature heating systems has been demonstrated to enhance heat source efficiency and reduce energy consumption, thereby playing a crucial role in the conservation of building energy and the reduction of associated emissions. The present study investigates the application effects of radiator-based low-temperature heating technology across a range of building energy efficiency levels and climatic conditions. The objective of the study is to promote the adoption of low-temperature heat sources in heating systems and to support sustainable building practices. The TRNSYS simulation platform was utilised to develop building models representative of typical climate zones. The feasibility of radiator-based low-temperature heating was evaluated from the perspectives of thermal comfort (PMV index) and temperature stability, utilising scenario analysis methods. This evaluation encompassed various combinations of building envelope performance and radiator supply water temperatures. The findings indicate that enhancing the thermal performance of building envelopes can mitigate the impact of reduced heat dissipation during low-temperature water supply, thereby facilitating low-temperature heating (with water temperatures as low as 40°C) to meet thermal comfort requirements in energy-efficient buildings. In high-performance buildings, high-convection ratio radiators have been shown to maintain minimal temperature fluctuations. The findings of this research provide a theoretical foundation and practical guidance for the optimisation of heating systems in retrofitted buildings, the adaptation of low-temperature heat sources, and the selection of appropriate radiators. This research offers broad engineering application prospects.

Keywords: Radiator, Low-Temperature Heating, PMV Index, Climate Adaptability, TRNSYS Simulation.

1. INTRODUCTION

Low-temperature heating systems, defined by their utilisation of lower water supply temperatures, have witnessed widespread adoption on an international scale. This can be attributed to their capacity to enhance heat source efficiency and curtail energy dissipation. Several European countries have already implemented heating systems using water below 60°C, with ongoing efforts to further lower system temperatures. Since 1982, the recommended heating medium temperature for such systems has not exceeded 55°C, a factor which has significantly promoted the adoption of low-temperature heating solutions in Europe [1]. According to Germany's VDI 6030 standard, a reduction in the temperature difference of the radiator's heating medium to below 35°C has been shown to result in improved indoor temperature distribution, enhanced thermal comfort, and increased satisfaction [2]. Moreover, the standard prescribes a reduction in the heating medium inlet temperature to a range of 45-55°C, with the objective of optimising energy efficiency in the construction of buildings. The Russian Federation's recently unveiled New Energy Efficiency Strategy (Decree No. 1715-R) has set forth strategic objectives for the domain of sanitary hot water and combined heat and power (CHP) systems. A pivotal mandate within this strategy is the implementation of a 40°C low-temperature water supply for winter heating radiators. This approach has been demonstrated to reduce building heating energy consumption whilst optimising indoor temperature distribution during the winter months, thereby improving thermal environments [3].

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A study was conducted by researchers from the University of Technology Helsinki in Finland, including Ala Hasan, in order to ascertain the level of comfort experienced by radiators when operated within low-temperature conditions. The experimental study involved the use of supply and return water temperatures of 45°C/35°C. The findings of the study indicated that a vertical temperature difference of approximately 0.3°C/m resulted in minimal indoor temperature fluctuations [4]. In Sweden, Jonn Are Myhren and colleagues analysed thermal comfort across various heating methods. Utilising CFD simulations, a comparative analysis was conducted on the heating performance of high-temperature radiator heating, floor radiant heating, medium-low temperature radiator heating, and wall radiant heating. The study examined temperature distribution, airflow patterns, and PPD (Peak Performance Distribution) metrics in heated rooms, concluding that medium-low temperature radiator heating provided optimal comfort [5].

Myhren and Holmberg's investigation into thermal comfort in two offices utilised three heating methods: radiator heating, floor radiant heating, and wall radiant heating. The application of computational fluid dynamics (CFD) enabled the simulation of airflow patterns and temperature distribution within the computational domain. The study revealed that the optimal operating parameters for radiators are a supply water temperature of 55°C and a return water temperature ranging from 35°C to 40°C. In comparison with conventional high-temperature systems, the low-temperature heating system has been shown to significantly enhance indoor thermal conditions, achieving reduced air velocities and diminished vertical temperature gradients. Furthermore, the positioning of radiators beneath cold air inlets (e.g. under windows) has been shown to effectively mitigate the impact of cold air on indoor thermal environments [6].

China's current radiator heating systems are designed for 80/60°C operating conditions. In the event of high-temperature hot water radiators overheating, the resultant harmful substances responsible for the production of burnt smells have the potential to degrade indoor air quality and reduce relative humidity. This can cause electrical ionisation between indoor objects and air, increasing static electricity and causing discomforting dry heat sensations [7]. Statistical analysis shows that people spend 80% of their lives indoors. It is vital to reduce radiator water temperatures while meeting heating demands in order to ensure optimal comfort levels. This is of particular importance in the construction sector when it comes to energy conservation and emission reduction [8]. At present, low-temperature floor radiant heating technology is a subject of significant interest in the field of domestic research. This heating method offers a number of key advantages, including uniform temperature distribution, high thermal comfort, low energy consumption, and safety/hygiene benefits. A substantial body of research has been conducted by Chinese scholars on low-temperature hot water floor radiant heating systems. Scholars such as Hu Jun and Liu Xiaoqin have performed theoretical analyses and experimental studies from various perspectives, including heat transfer mechanisms, heating effectiveness, indoor thermal comfort, operational adjustment measures and economic efficiency. These studies have yielded valuable conclusions [9, 10].

A study was conducted by scholars, including Zhang Liao from Tsinghua University, in which four typical heating demonstration households were established in Beijing's suburban rural areas. The households utilised air-source heat pump systems for residential heating. The demonstration encompassed a selection of domestic heating systems, including an air-source heat pump with floor heating, a radiator heating system, and two hot air heating systems. The researchers evaluated operational performance and discussed system suitability and existing issues by means of continuous real-time monitoring. The results demonstrated that all of the examined rooms exhibited average temperatures that met the established standard requirements. The low-temperature radiator heating system was found to maintain indoor temperatures at 17.9°C (with a minimum of 15°C), thereby underscoring its viability for large-scale implementation [11]. In the context of Beijing's "coal-to-electricity" policy, Yang Qian from the Beijing University of Civil Engineering and Architecture conducted a study on the effectiveness of rural heating systems. The study involved the retention of traditional radiator terminals while utilising air-source heat pumps to provide low-temperature hot water. The present study utilised a combination of field monitoring and numerical simulations to analyse the heating performance, thermal comfort, energy efficiency and economic viability of the system in rural Beijing. The findings of this study confirmed the operational feasibility of the system [12]. Wu Xiaozhou and Zhao Jianing conducted research on the topic of office space heating, utilising low-temperature forced convection radiators, otherwise referred to as heating fan coil units. The development of models for heat exchange and human thermal comfort was undertaken, with single-node simulation being employed to calculate indoor operating temperatures, average radiant temperatures, and air temperatures in typical winter offices across different climate zones, while ensuring thermal comfort. The findings indicate that when the thermal comfort requirements of the human body are met, the indoor operating temperature of the heating office room in the cold region, the cold region and the hot summer and cold winter region are all approximately 20°C. However, the average radiant temperature increases in the order of 19.2°C, 19.4°C and 19.5°C, respectively, while the indoor air temperature decreases in the order of 20.8°C, 20.6°C and 20.6°C, respectively [13].

A substantial body of research, both at an international and domestic level, has demonstrated that low-temperature radiator heating technology has the capacity to significantly reduce building energy consumption, optimise indoor temperature distribution during the winter months, and improve thermal environments. A comparative analysis of terminal heating systems reveals that ventilation-type radiators demonstrate comparable performance to radiant floor heating.

Conversely, medium-low temperature radiators exhibit optimal efficacy in environments characterized by inadequate ventilation. Current building energy efficiency standards indicate that low-temperature heating terminals can meet overall thermal comfort requirements. However, extant research has focused primarily on specific operational conditions, such as fixed supply water temperatures, return-heat temperature differentials, and room temperatures. There has been a paucity of systematic evaluations of terminal performance under variable conditions, room temperature fluctuations, and the compatibility between building thermal characteristics and radiator supply temperatures. These discrepancies underscore the necessity for novel methodologies within this domain.

2. RESEARCH TECHNIQUE

In this paper, the TRNSYS simulation software is utilised to establish the building model of a typical climate area in China. The heating load of each climate area is then calculated and analysed following the implementation of the building energy conservation standard. This is done in order to verify the technical feasibility of using radiators in low-temperature working conditions.

In the northern regions of rural China, the predominant architectural form is courtyard-style dwellings, with the three-sided courtyard (sanheyuan) being the most common design. The floor area of these structures is typically in the region of 150 square metres. As a consequence of China's "Energy Efficiency Design Standard for Rural Residential Buildings" (GBT 50824-2013) [14], comprehensive energy-saving renovations of the exterior walls of rural buildings have been undertaken. The calculated layout and dimension diagrams are shown in Figures 1 to 3, while the key parameters of the building envelope are detailed in Table 1.

Figure 1: A typical Beijing courtyard house

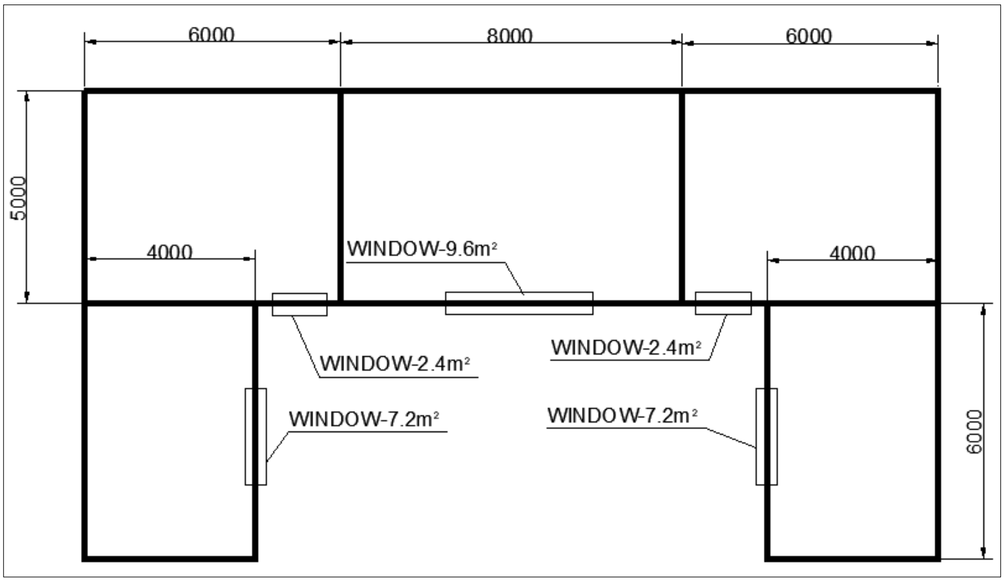

Figure 2: Room dimensions in the computational model

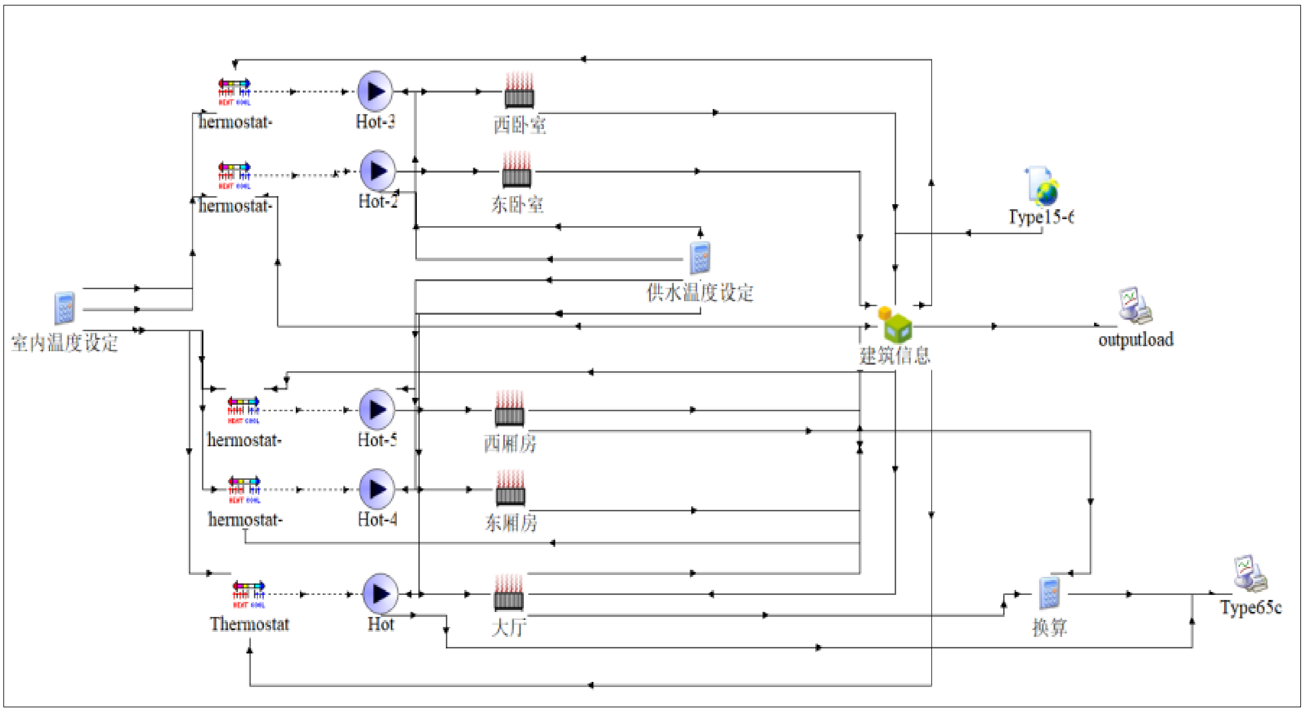

Figure 3: TRNSYS system diagram for radiator operating mode analysis

The model employs radiators for the purpose of heating, with flow control being achieved through thermostatic valves. Each room is equipped with a radiator unit for indoor heating. The following building envelope design is proposed, with the relevant data drawn from meteorological records in Beijing.

Table 1: Main parameters of building envelope

Exterior-protected construction	**Wall**	**Roof**	**Floor**	**Window**
Primary structural layer	Lime mortar: 20mm EPS board: 40mm Clay brick: 240mm Lime mortar: 20mm	Lime mortar: 20mm Waterproof material: 10mm EPS board: 65mm Reinforced concrete: 200mm	Marble tiles: 10mm Cement mortar: 30mm EPS board: 20mm Clay compaction: 30mm	Double glazing (6/12/6), aluminum alloy window
Parameter	0.65W/(m^{2}K)	0.52W/(m^{2}K)	1.5W/(m^{2}K)	2.6W/(m^{2}K)

In the construction of different working conditions, only the thickness of the insulation layer and the properties of the window glass are changed to produce different performance combinations of the enclosure structure (see Table 2). This structure is used to analyse the heating effect of the radiator under different load conditions and low-temperature working conditions.

Table 2: TRNSYS simulation scenarios

Classify	**Roofing**	**Wall**	**Floor**	**Window**	**Supply Water Temperature**
Operating Condition 1 (A)	1.75（10）	1.21（0）	1.48（0）	3.20（0.7）	75
Operating Condition 1 (B)	1.75（10）	1.21（0）	1.48（0）	3.20（0.7）	60
Operating Condition 1 (C)	1.75（10）	1.21（0）	1.48（0）	3.20（0.7）	45
Condition 2	0.95（30）	0.76（20）	1.09（10）	2.99（0.7）	60
Condition 3	0.56（60）	0.44（60）	0.86（20）	2.43（0.7）	55
Condition 4	0.44（80）	0.36（80）	0.61（40）	2.12（0.7）	50
Condition 5	0.36（100）	0.31（100）	0.61（40）	1.66（0.623）	45
Operating Condition 6	0.25（150）	0.31（100）	0.61（40）	1.40（0.61）	40
Note: The numerical format for roof, wall, and floor surfaces is: heat transfer coefficient (K value, W/(m^2·K)) and insulation layer thickness (mm). For windows, the format is: heat transfer coefficient (K value, W/(m^2·K)) and solar heat gain coefficient (SHGC). The unit for water supply temperature is °C.					

3. ANALYSIS OF CALCULATION RESULTS

3.1 Analysis of Thermal Performance Matching Scenarios for Radiator Water Supply Temperature in Different Buildings

Condition 1 describes a brick wall structure lacking insulation, accompanied by standard single-pane PVC windows, thereby characterizing a building that is energy inefficient. The present study employs Beijing as a case study, to calculate the temperature distribution in a typical room (lounge) under different hot water heating conditions. In order to facilitate the analysis, the hourly indoor temperature distribution for January heating in Beijing is presented in Figure 4.

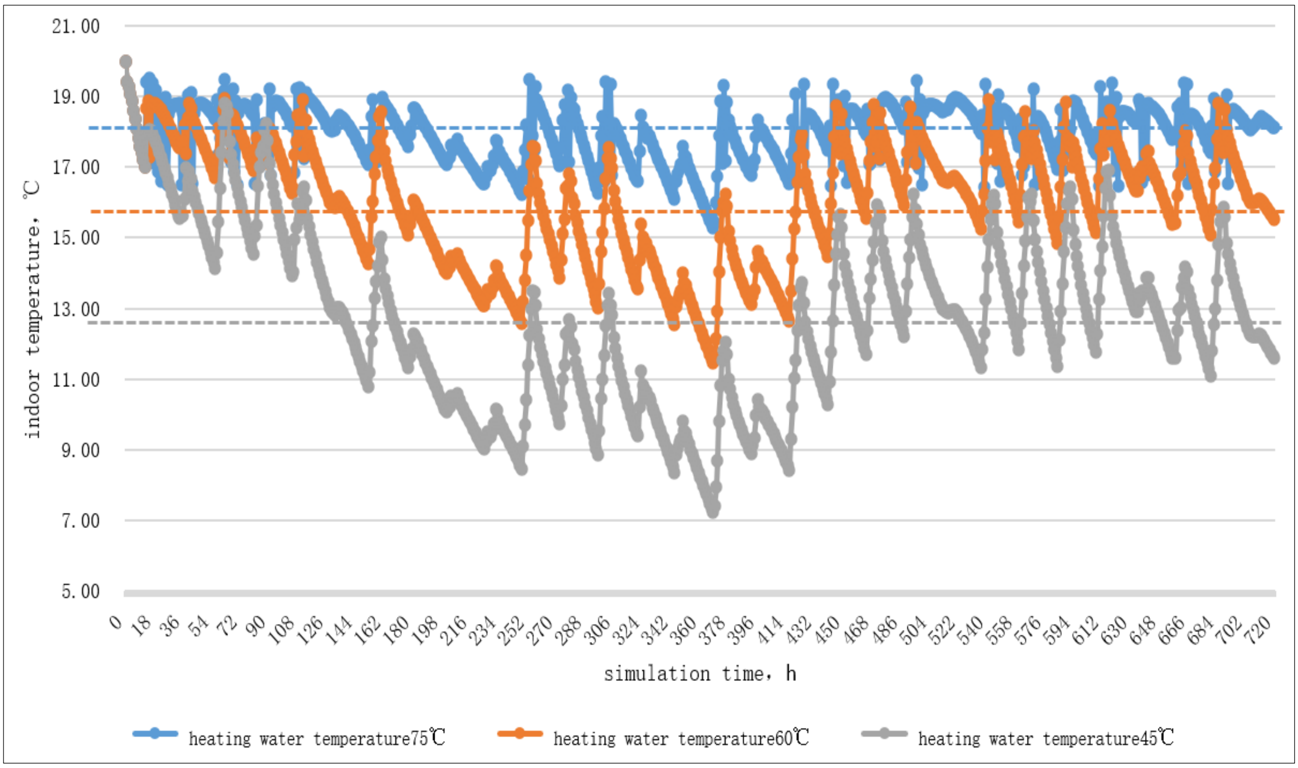

Figure 4: Indoor temperature distribution under different hot water supply temperatures

It is evident that under suboptimal enclosure conditions, characterized by a decline in radiator supply water temperature, there is a precipitous decline in indoor temperature, which in turn results in a reduction in heating efficiency. It is evident that at a supply temperature of 45°C, the indoor temperature falls below 14°C, thus failing to meet the requisite thermal comfort requirements. As this study employs the radiator water supply on/off method for regulation, further analysis of the operating hours of the radiator under the three working conditions is indicated. Condition 1 (A) functions for 577 hours with a heat dissipation of approximately 3.4 kW; Condition 1 (B) functions for 663 hours with a heat dissipation of approximately 2.5 kW; Condition 1 (C) functions for 708 hours with a heat dissipation of approximately 1.8 kW. As indicated by the radiator heat dissipation characteristic formula, the dissipation of heat is directly proportional to the instantaneous indoor air temperature. During periods of low-temperature operation, inadequate heat dissipation can impede effective maintenance of the ambient temperature above the pre-defined threshold. It is evident that, in accordance with the established control logic, there is an augmentation in the duration of the radiator's water supply state.

Subsequent analysis explores the compensation relationship between enhanced thermal performance of building envelopes and diminished radiator supply water temperatures. It has been demonstrated that, under specified operating conditions (Conditions 2-6), the thermal performance of building envelopes exhibits a progressive enhancement that culminates in the fulfilment of current national standards for energy-efficient residential building design. A comparative analysis between Condition 1 (A) and Conditions 2-6 was conducted, revealing that the number of radiators selected under Condition 1 (A) to ensure indoor temperature compliance remains constant. As envelope performance is enhanced, the heat load is reduced, and radiator heat output is diminished when utilising low-temperature hot water for heating purposes. This facilitates the system's capacity to satisfy the heating requirements of more energy-efficient buildings, even when the supply water temperature is lower. The calculation results are displayed in Figure 5.

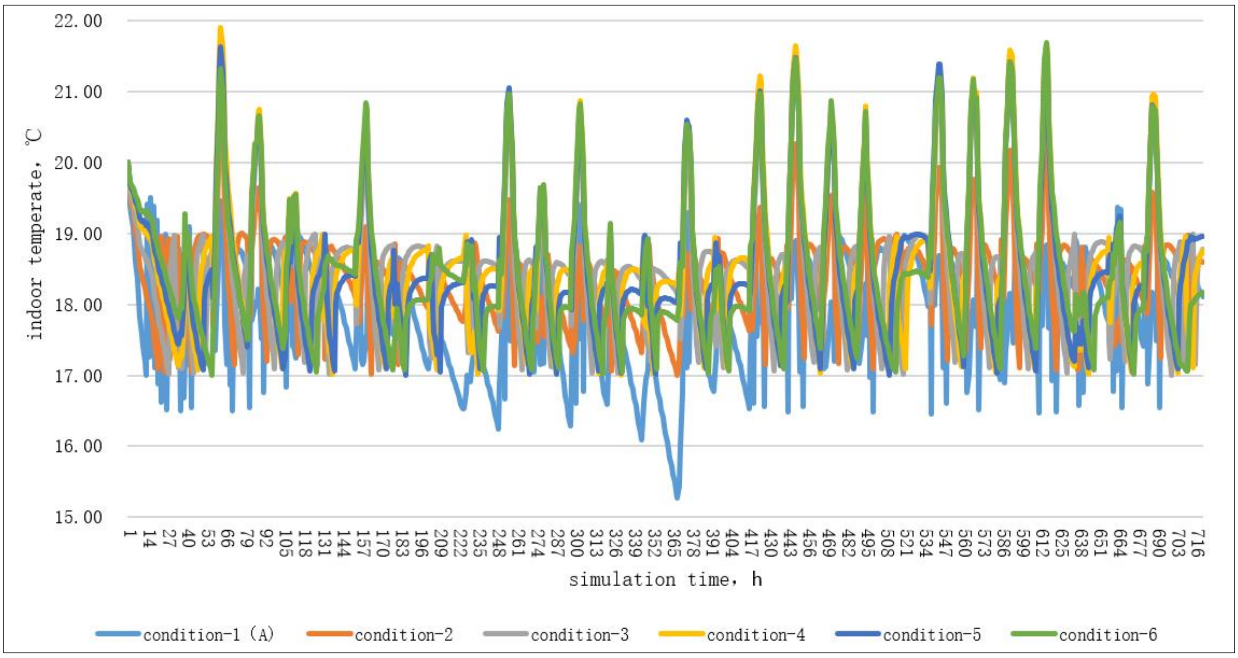

Figure 5: Indoor temperature distribution under six different operating conditions in Beijing

Table 3: Statistical Description of Indoor Temperature Distribution under Six Different Operating Conditions

Classification of Working Condition	**Condition 1 (A)**	**Condition 2**	**Condition 3**	**Condition 4**	**Condition 5**	**Condition 6**
Mean	17.94	18.42	18.59	18.58	18.52	18.49
Standard Error	0.81	0.61	0.89	1	0.97	0.99

The temperature distribution curve shows that the lowest temperature in January is between 297 and 450 hours, corresponding to January 14th to 20th. This chapter summarizes the indoor thermal comfort index for this week, as calculated in Figure 6.

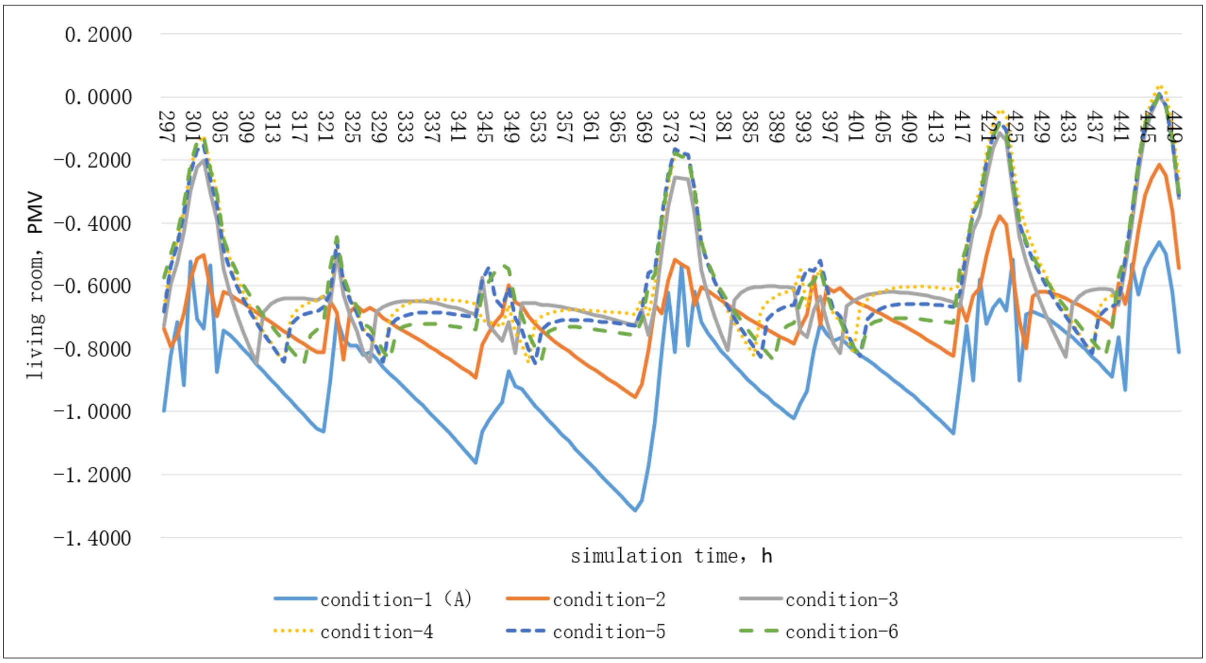

Figure 6: Distribution of PMV Indicators under different operating conditions

In the context of Beijing's meteorological conditions, the thermal performance of building envelopes undergoes a progressive enhancement from Condition 1 (A) to Condition 6, concomitant with a gradual decline in radiator supply water temperatures. The mean indoor temperature in January remains consistently above 18°C, with Conditions 2-6 exhibiting analogous values around 18.5°C. The calculated thermal comfort index (PMV) indicates that buildings with high insulation levels maintain adequate thermal comfort at low supply water temperatures, achieving a PMV value of approximately -0.5 and meeting heating comfort requirements. It is important to note that indoor temperature variations are considerably impacted by external meteorological factors. The graph shows that the peak temperature is reached during the day when the sun is strongest, and that the radiation intensity is directly related to the indoor temperature. It has been demonstrated that during nocturnal periods, edifices equipped with advanced insulation properties exhibit enhanced stability in preserving internal temperatures. A gradual stabilisation of temperature is evident as Condition 1 (A) transitions to Condition 6, with the attainment of near-stable states.

Similarly, this chapter analyzes radiator heating performance in several typical cities across severely cold regions. First, under Condition 1 (A) envelope conditions, the number of indoor radiator panels is configured until achieving a target indoor temperature of 18±1°C. Then, under Conditions 2 through 6, the supply water temperature is reduced while maintaining the same radiator panel count, to evaluate the heating efficiency of the original configuration under low-temperature water supply and high-performance building conditions.

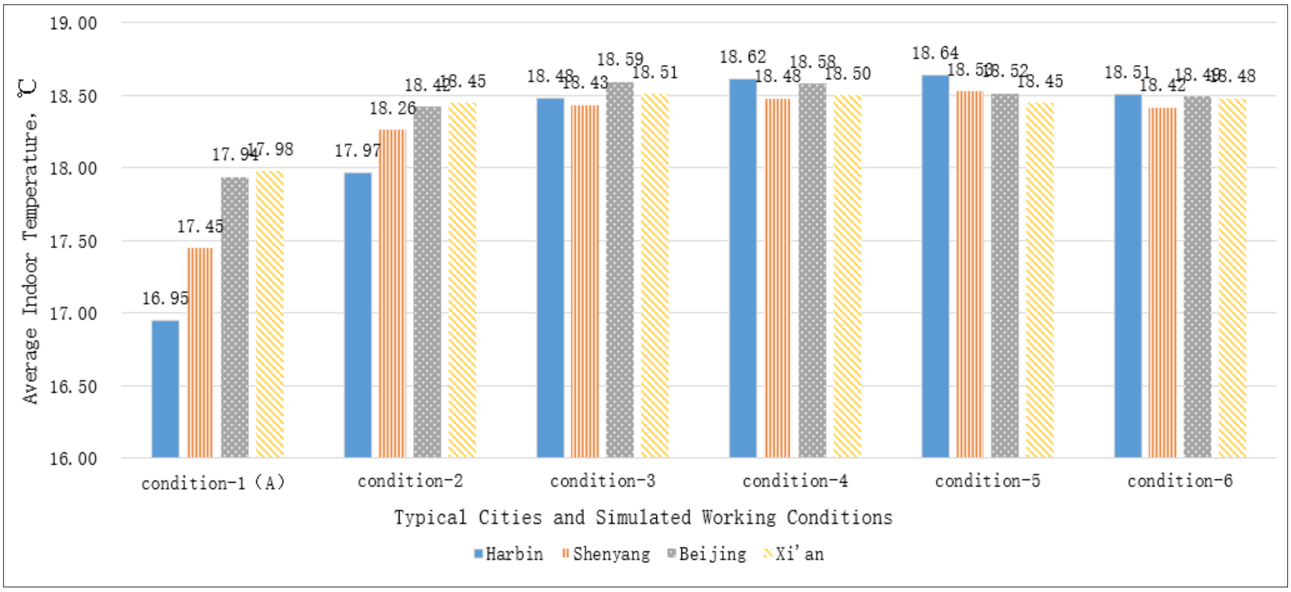

Figure 7: Comparison of indoor temperature in typical cities under different operating conditions

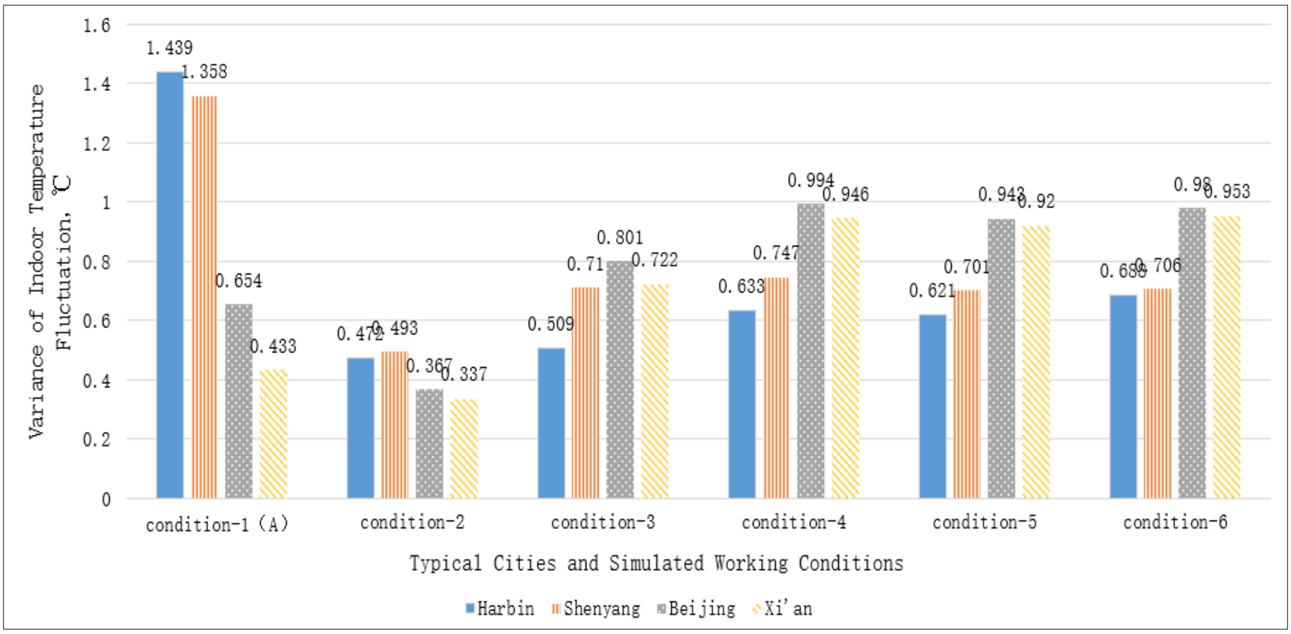

Figure 8: Comparison of indoor temperature distribution variance in typical cities under different operating conditions

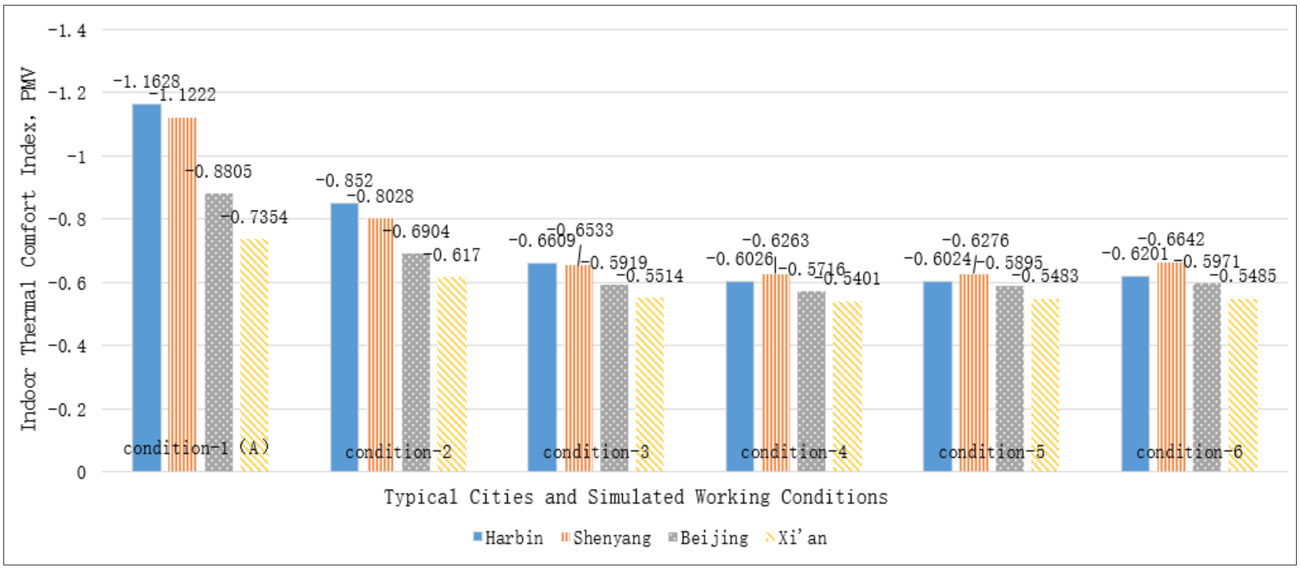

Figure 9: Comparison of PMV values in heating rooms under different operating conditions in typical cities

As demonstrated in Figures 7-9, when high-temperature hot water systems are compared with non-energy-efficient buildings, the reduction in heat loss caused by lower water supply temperatures can be effectively compensated by enhanced building envelope performance. This finding indicates that contemporary energy-efficient buildings are well-suited for low-temperature hot water radiator heating systems. In this section, Conditions 5 and 6 correspond to the thermal performance requirements for building envelopes in severely cold and cold regions, respectively. In such circumstances, non-energy-efficient buildings have the potential to attain equivalent heating performance to that of existing energy-efficient buildings following retrofitting of the building envelope. It has been demonstrated that when low-temperature hot water (40-45°C) is utilised within the original radiator system, there is minimal impact on indoor thermal comfort. This finding suggests that, despite the substantial reduction in heat loss experienced by traditional radiator heating systems in the present low-temperature heat source environment, their utilisation remains feasible in accordance with China's prevailing building energy efficiency standards. In comparison with non-energy-efficient buildings, radiator systems require a significantly lower number of units. In practical applications, the combined improvements in building envelope performance and reduced water supply temperatures compensate for each other, thereby ensuring effective heating performance with minimal impact on radiator efficiency.

3.2 Heating Effect Scenario Analysis of Radiators with Different Convection Ratios

It is evident from extant research that forced convection represents a pivotal technical approach with the potential to enhance the thermal performance of radiators. Experimental studies reveal that in natural convection conditions, steel finned radiators primarily rely on convection, achieving 80% heat dissipation through this mechanism. Steel cylindrical and flat tube radiators demonstrate convection ratios of 61% and 47%, respectively, while cast iron radiators typically maintain 45%-55% convection efficiency [101]. This section employs the TRNSYS platform to simulate the effects of heat dissipation across varying convection intensities by adjusting the ratio between radiant and convective heat transfer. The research scope for convection heat transfer ratios in radiators ranges from 30% to 80%.

The present study investigates the distribution of indoor temperature and PMV under three distinct working conditions, with the proportion of convective heat dissipation set at 30%, 50%, and 80% in cases where the enclosure structure is either good or poor. The model employs meteorological data from Harbin and Beijing to facilitate a comparative analysis of the impact of climate factors on regions experiencing cold and severe cold conditions. The working conditions are described in Table 4.

Table 4: Comparison of Study Conditions

Classify	Roofing	Wall	The earth's surface	Window	Supply water temperature
Operating Condition 1 (A)	1.75 (10)	1.21 (0)	1.48 (0)	3.20 (0.7)	75
Operating Condition 6	0.25 (150)	0.31 (100)	0.61 (40)	1.40 (0.61)	40
Note: The numerical format for roof, wall, and floor surfaces is: heat transfer coefficient (K value, W/(m²·K)) and insulation layer thickness (mm). For windows, the format is: heat transfer coefficient (K value, W/(m²·K)) and solar heat gain coefficient (SHGC). The unit for water supply temperature is °C.					

The following analysis is based on meteorological data from Harbin. In condition 1 (A), characterized by substandard enclosure structure and elevated hot water temperatures, the indoor temperature distribution of three convective proportion radiator heating in January is subjected to further detailed analysis across two consecutive cycles:

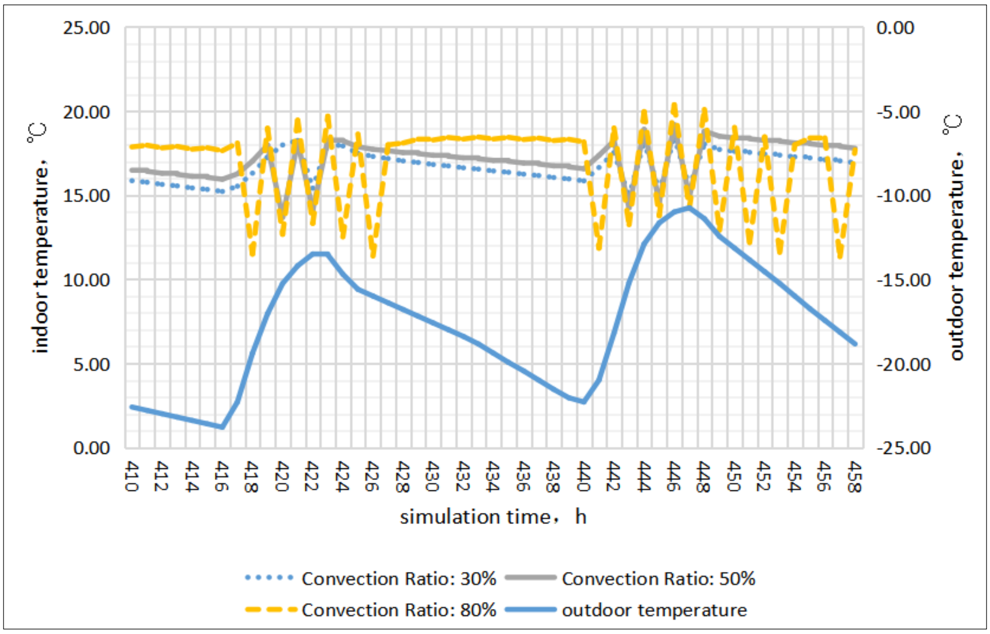

Figure 10: Detailed indoor temperature under condition 1 (A)

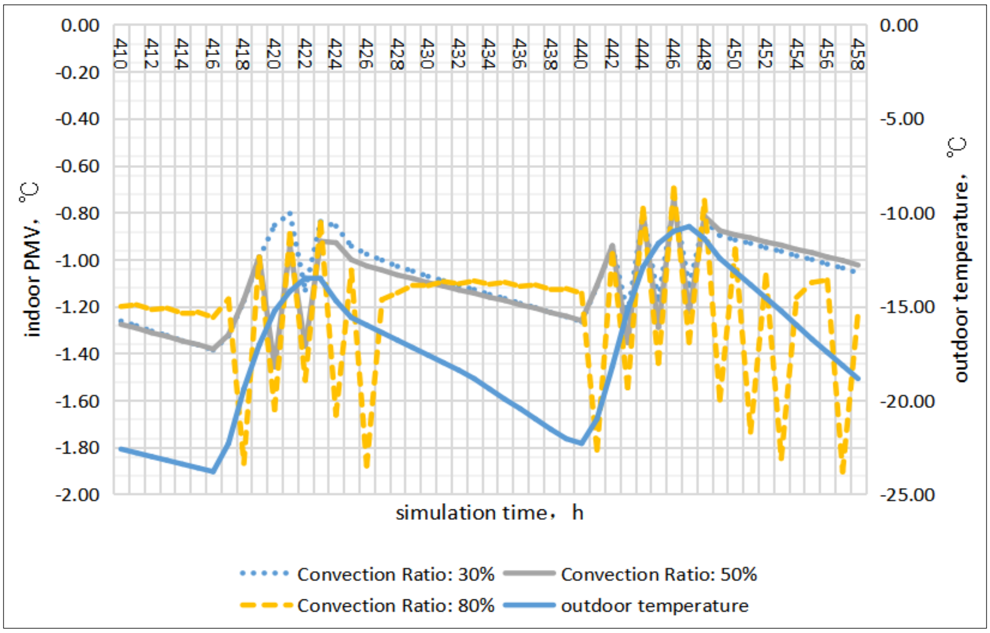

Figure 11: Detailed indoor PMV under condition 1 (A)

As demonstrated in Figures 10 and 11, the implementation of radiator flow control for the regulation of indoor temperature results in the maintenance of constant water supply temperature and radiator number. The adjustment of the convective heat dissipation ratio of indoor radiators follows the same temperature fluctuation pattern as the PMV index. The analysis of outdoor temperature curves indicates that elevated convective ratios preserve stable mean indoor temperatures whilst substantially amplifying temperature variance. This finding suggests intensified fluctuations and wider temperature ranges. The hourly data indicates that elevated convective ratios are associated with a heightened frequency of diurnal temperature adjustments and augmented amplitude of temperature and PMV fluctuations. During nocturnal periods, when ambient outdoor air temperatures undergo uniform linear changes (with the exception of instantaneous solar radiation effects), indoor temperatures stabilise. Radiators with high convective ratios have been shown to exhibit smoother nighttime temperature curves, thereby demonstrating superior control capabilities during periods of outdoor temperature variation. This configuration facilitates proactive adaptation to weather conditions through enhanced flow control cycles.

Statistical analysis indicates that increased convective ratios under identical heat dissipation levels reduce PMV index averages, resulting in diminished heating comfort.

In the context of Harbin's meteorological conditions, the optimisation of the thermal performance of building envelopes has been shown to significantly reduce the frequency of radiator activation and deactivation, thereby minimising indoor temperature fluctuations. A comparative analysis of the two envelope designs (see Figures 12-13) demonstrates that envelope performance exerts a substantial influence on indoor temperature dynamics. Condition 1 (A) stipulates that when the convective heating ratio increases to 80%, the standard deviation of the indoor temperature becomes significantly larger, indicating pronounced thermal fluctuations. This finding suggests that enhanced envelope performance can contribute to the maintenance of stable indoor temperatures, even in conditions of higher convective ratios. The enhanced thermal performance of these systems also confers upon buildings a heightened adaptive capacity to external weather variations, thereby diminishing the necessity for recurrent adjustments by indoor heating systems. Despite the utilisation of high-convection heating methods, minimal temperature fluctuations and variations in thermal comfort index were observed, thereby indicating that increased convective ratios exert a negligible influence on thermal comfort.

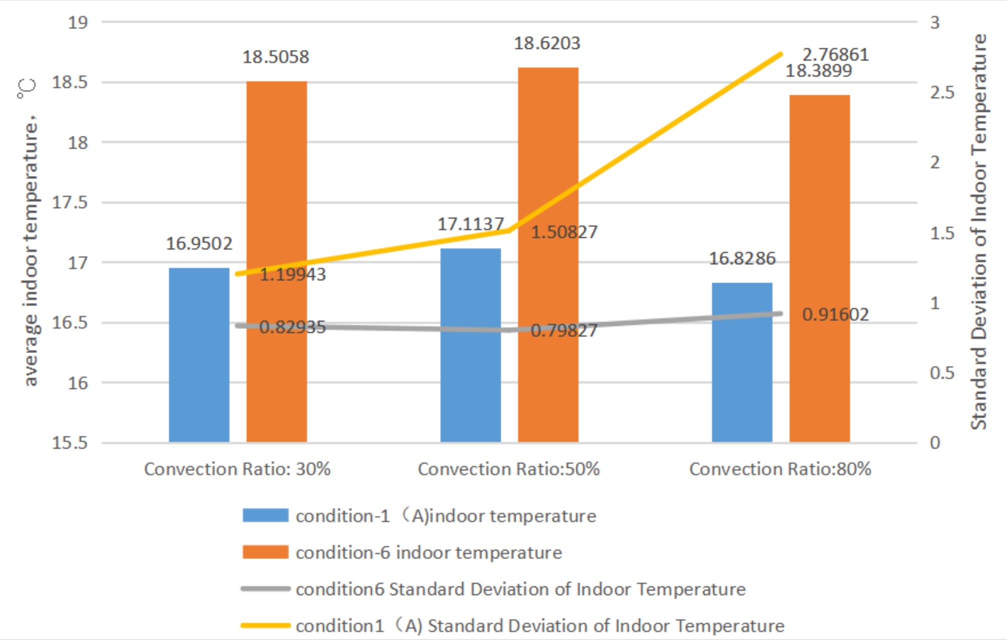

Figure 12: Temperature Comparison in Harbin

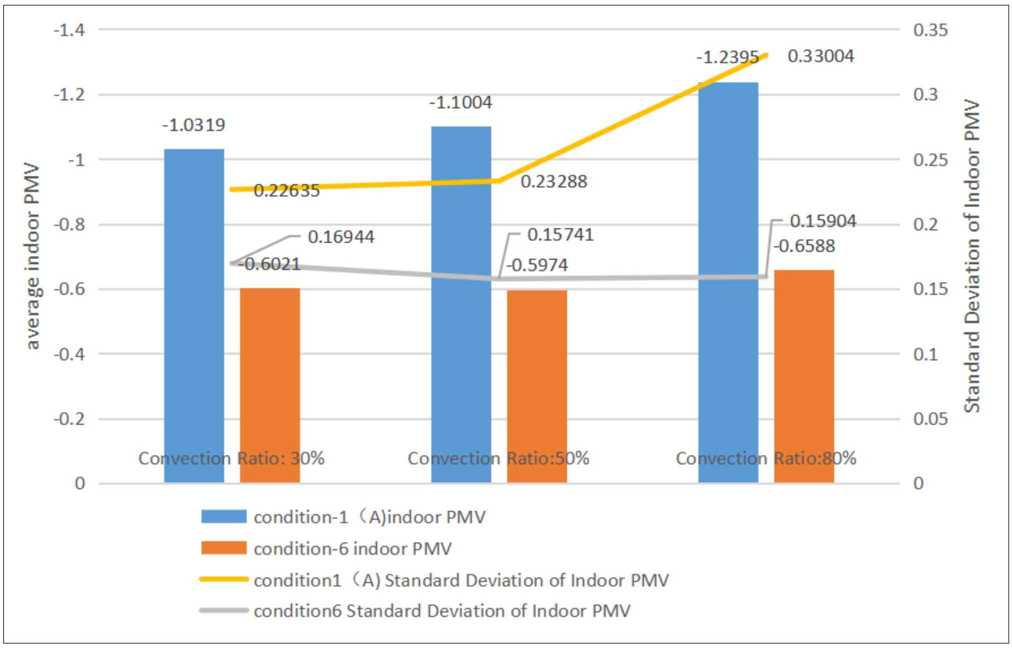

Figure 13: Comparison of PMV Values in Harbin

The calculation results using Beijing meteorological data are shown in Figures 14 to 15 below.

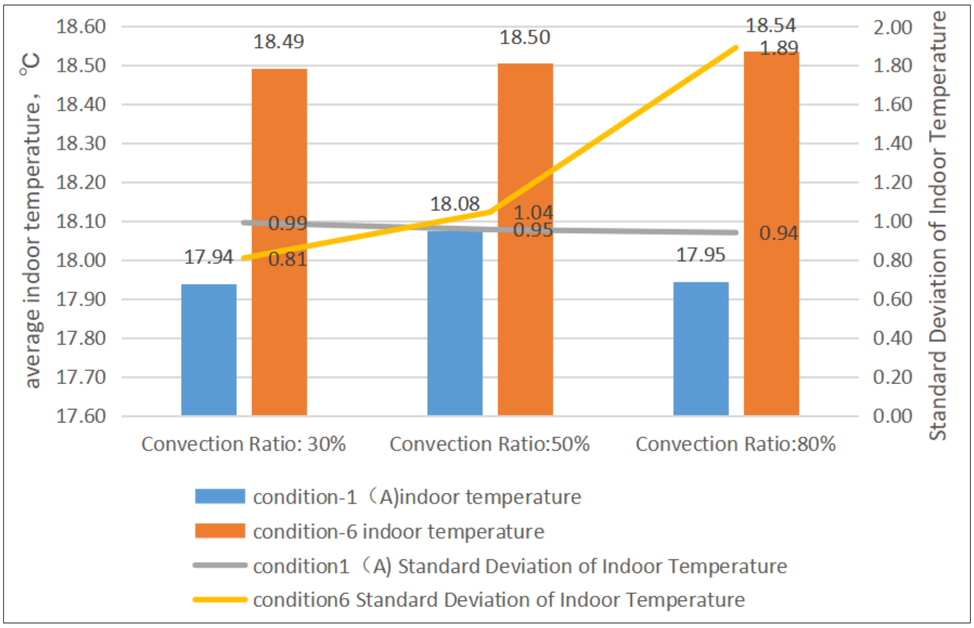

Figure 14: Temperature comparison in Beijing

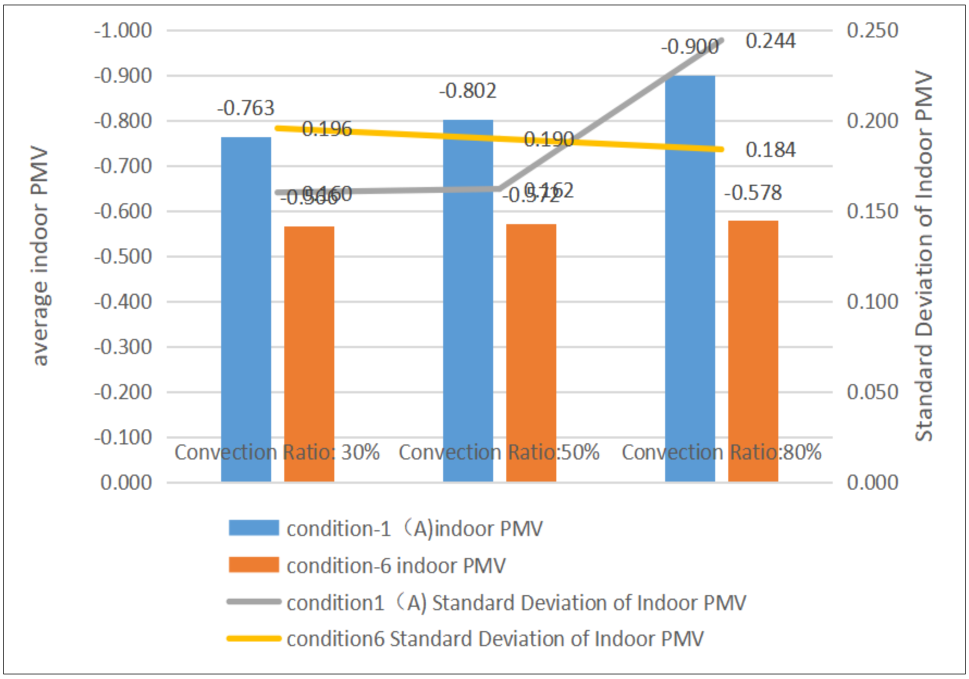

Figure 15: Comparison of PMV values f in Beijing

The computational analysis of Beijing demonstrates that, as illustrated in Figures 14 and 15, the fluctuation patterns of indoor temperature and PMV (Peak Mean Value) in cold regions remain largely consistent with those in severe cold zones when employing different convective heating ratios. As the convective ratio increases, the average indoor temperature and PMV values remain relatively stable, while the standard deviation rises, resulting in more pronounced temperature and PMV fluctuations. It is evident that enhancing the performance of the building envelope has a substantial impact on the enhancement of indoor temperature stability. Notwithstanding an increase in the convective ratio of heating equipment from 30% to 80%, high-performance buildings demonstrate minimal fluctuations in indoor temperature. This finding suggests that variations in outdoor meteorological parameters are the primary drivers of indoor temperature fluctuations. When such envelopes are well-designed, convective heating systems can still deliver relatively stable heating performance.

4. RESEARCH CONCLUSION

The present study employs the TRNSYS software platform to comprehensively evaluate the low-temperature heating performance of radiators under various conditions, taking into account both indoor temperature and PMV (Performance, Maintenance, and Value) metrics. The analysis encompasses a range of enclosure structures and water temperature combinations, while also investigating radiator heating efficiency across varying convection ratios. The research demonstrates the reliability of the technical approach of enhancing radiator heating performance through forced convection measures. The following key findings are presented:

1) The present study conducts scenario analysis by combining different performance building envelopes with varying radiator supply water temperatures. When the performance of the building envelope is enhanced, low-temperature hot water radiators can effectively meet indoor thermal comfort requirements. Despite the fact that traditional radiators exhibit significantly reduced heat dissipation under low-temperature heat source conditions, China's current building energy efficiency standards have substantially reduced building loads, thus allowing radiators to remain viable for heating applications. Utilising high-temperature hot water systems and non-energy-efficient buildings as benchmarks, the study demonstrates that the heating effectiveness reduction caused by lower radiator supply temperatures can be largely compensated by enhanced building envelope performance. The research indicates that current building energy efficiency measures are well compatible with low-temperature hot water radiator heating systems.
2) The present study investigates the heating performance of radiators with varying convection ratios. When the thermal performance of building envelopes is enhanced and the building's self-regulating capacity is improved, the use of a higher convection ratio in heating systems results in minimal fluctuations in indoor temperature and thermal comfort metrics. The research demonstrates that convection-type radiators can maintain stable indoor temperatures with negligible fluctuations in energy-efficient buildings.
3) The study provides two key insights for low-temperature radiator heating applications: Firstly, in the case of buildings with upgraded building envelope insulation, when energy efficiency standards comply with China's current building codes, it has been demonstrated that maintaining the original radiator count (without heating system modifications) while reducing water supply temperature (within the research scope of temperatures above 40°C) can still meet heating demands (Smith *et al*., 2023). Secondly, in buildings with superior envelope performance, even with increased convective heat dissipation, indoor temperature fluctuations remain relatively small compared to non-energy-efficient buildings. This finding indicates that convective radiators demonstrate superior thermal stability in energy-efficient buildings.

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