The Environmental Characteristics and Model Design of Low Energy Indoor Buildings Based on Human Thermal Comfort

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Abstract: To thoroughly evaluate both the comfort and energy consumption aspects of thermal environment regulation models, a low-energy building model centered on human comfort was investigated and developed. This model was based in an analysis of indoor building thermal environment characteristics and active-passive thermal environment regulation technologies that prioritized human comfort. The research confirmed the efficacy of the proposed low-energy building model focused on human comfort. The predicted average voting index for this building demonstrated greater stability compared to other models, fluctuating within the range of -0.5 to 0.5. Furthermore, the percentage of dissatisfied individuals in this model stood at 9.7%, which was lower than that observed in other models. In addition, the study engaged 500 participants to conduct a satisfaction survey regarding the thermal environment regulation performance of the model. The satisfaction ratios for temperature, humidity, and wind speed were 87.2%, 79.8%, and 78.5%, respectively, all of which surpassed those of other models. Moreover, the energy consumption of this model was 6.1 kW/h, with an energy efficiency ratio of 6.5, outperforming other models in this regard. In summary, the low-energy building model based on human comfort, developed through this research, excels in meeting human comfort needs by adjusting temperature, humidity, and wind speed. Additionally, its superior energy consumption control performance offers theoretical support for the advancement of green and environmentally friendly building thermal environment regulation technologies in the future.

Keywords: Human comfort; Low energy consumption; Active and passive thermal environment regulation; Green and environmentally friendly; Indoor architecture

1. Introduction

With the continuous intensification of the global energy crisis and the increasing awareness of environmental protection, Low Energy Building (LEB) environmental design has become a hot topic in architecture. Alongside the principles of green environmental protection, the significance of living comfort in buildings must not be overlooked. Human thermal comfort, serving as a crucial measure of indoor environmental quality, bears a direct correlation with individuals' quality of life and overall health [1-2]. However, in traditional architectural design, excessive reliance on mechanical equipment not only increases Energy Consumption (EC), but also leads to a decrease in indoor environmental quality, thereby affecting human comfort [3]. Therefore, how to minimize EC while meeting human body's thermal comfort needs has become an urgent issue in current architectural design. Active and Passive Thermal Environment Regulation (APTER) technology, as a technology used to regulate indoor temperature and humidity, has the advantages of wide applicability, strong flexibility, and energy conservation and environmental protection [4-5]. Therefore, in order to solve the contradiction between thermal comfort and energy consumption control, the study introduces active and passive thermal environment regulation technology, which has low energy dependence and can reduce energy consumption to a certain extent. Combined with human comfort analysis of building thermal environment characteristics, a low-energy building model is ultimately constructed.

The purpose of the research is to break through the technical bottleneck of balancing energy efficiency and comfort in traditional building thermal environment regulation, and achieve precise control of building energy consumption. The innovation of the research mainly lies in the following two aspects. Firstly, a low-energy building model based on human comfort has been designed to achieve real-time prediction and dynamic response to human thermal sensation; The second point is interdisciplinary technology integration innovation, which integrates multidisciplinary methods such as building physics, ergonomics, and energy system engineering to provide systematic solutions for the development of green buildings. The research contribution is to minimize EC through in-depth research on human thermal comfort needs and indoor environmental characteristics, providing scientific basis and technical support for LEB design. The model constructed through research can reduce EC and greenhouse gas emissions, which has a positive impact on alleviating energy crises and improving environmental quality. The research structure is as follows. The first chapter elaborates on the current development status of thermal environment management and low-energy buildings. The second chapter constructs a low-energy building model for human comfort. The third chapter is to conduct performance testing on the selected thermal environment parameters, active and passive environmental regulation models, and low-energy building models based on human comfort. The fourth chapter is the conclusion and prospects for future research directions.

2. Related Works

The continuous progress of social sciences has led to an increasing number of studies on the design and management of thermal environments. To more efficiently manage the cabin thermal environment of electric vehicles, Lajunen et al. proposed analyzing the efficiency management methods of cabin thermal system control to obtain new directions for future efficiency management. These analyses confirmed that improving individual electrical components and vehicle system was no longer sufficient to meet the current needs of thermal environment management. In the future, flexible and comprehensive approaches should be adopted to manage the cabin thermal environment [6]. To enhance the temperature regulation capabilities of high-temperature underground passive thermal management systems, Zhang et al. suggested refining the passive thermal management system utilizing the finite element method and the Nelder Mead algorithm. Following validation of the optimized system's efficacy, it demonstrated a remarkable reduction of 30.1 ℃ in the heat source's maximum temperature, showcasing excellent temperature control performance. This refined system holds potential for practical application in high-temperature underground settings [7]. To directly utilize human body temperature to construct a heat map of the human body, Geng et al. proposed building a lightweight human body localization model based on machine learning. This model located the human body based on the camera distance and the characteristics of human head. After verifying the effectiveness of the positioning model, it could accurately locate the human body and had practical application value [8]. To improve the applicability of remote sensing soil moisture models, Wen et al. proposed a high-precision passive microwave observation method based on a medium resolution imaging spectrometer and geographic weighted regression. After verifying the effectiveness of this method, it not only ensured the accuracy of scaled remote sensing of soil moisture, but also improved the resolution of the traditional model [9]. Jaguemont et al. proposed a thermal management model for battery systems based on phase change materials and active cooling mechanisms to address the issue of overheating in lithium-ion capacitors. The effectiveness verification confirmed that phase change materials had good thermal conductivity, and the thermal management model of the battery system constructed could effectively reduce the heat of the battery system [10].

Scientific progress has led to an increasing focus on building EC in recent years. To further optimize building energy management, Liu et al. proposed multi-objective optimization of building energy from the perspectives of investment cost, thermal comfort, and system elasticity. Meanwhile, they utilized adaptive reference vector-assisted algorithms to achieve the optimization objectives. The effectiveness verification confirmed that this algorithm performed better than other algorithms [11]. To accurately and efficiently implement building control and achieve energy-saving management of building energy, Yu et al. proposed building an intelligent building energy management model based on deep reinforcement learning. However, there was currently a lack of research overview on building intelligent building energy management methods based on different deep learning algorithms. Therefore, Yu et al. conducted a comprehensive review of it from the perspective of system scale, providing new solutions for future research on building control [12]. To achieve the optimal solution for energy management in civil buildings, Ahrinouri et al. proposed building an energy management model based on reinforcement learning for practical scenarios. The effectiveness verification confirmed that this model had better effectiveness and robustness compared to traditional models, and had practical application value [13]. To achieve the construction of near zero energy buildings, Tsioumas et al. proposed building energy management models based on genetic algorithms and cost functions by determining the size of renewable energy and battery storage systems. The effectiveness verification confirmed that the model could minimize the cost function and had certain practicality and effectiveness [14]. Zhang et al. proposed an energy control management model based on reinforcement learning and edge cloud to address the lack of versatile and cost-effective automation systems in buildings. The effectiveness verification confirmed that the model had different application effects and learning efficiency on buildings of different sizes, and could achieve higher reward returns in large-scale buildings [15].

Based on the above content, it can be concluded that significant progress has been made in research on thermal environment management and low-energy buildings. However, existing technologies still face challenges, such as a lack of flexibility in indoor environment regulation, high energy consumption, and a lack of comprehensive evaluation of building energy consumption. The active and passive environmental regulation technology has the advantages of energy conservation and environmental protection. Therefore, the research combines it with the human thermal comfort structure to construct a low-energy indoor building model, in order to meet the dual goals of low energy consumption and high comfort.

3. Construction of A LEB Model for Human Thermal Comfort

To optimize the human comfort and building EC of thermal environment regulation, the characteristics of Building Thermal Environment (BTE) based on human comfort are analyzed and thermal environment regulation parameters are selected. Moreover, based on this, an LEB model based on human comfort is designed by combining human comfort and active passive thermal environment regulation technology to improve the thermal environment regulation and EC control effects of buildings.

3.1 Analysis and Design of BTE Characteristics Based on Human Comfort

BTE refers to environmental conditions composed of multiple factors that can affect human body's thermal sensation. Common building environmental factors include temperature, humidity, radiation, wind speed, and airflow, which can interact and collectively form the surrounding environment where human body is located [16]. Amidst the ongoing quest for indoor building comfort and the growing emphasis on environmental sustainability, BTE design has increasingly emerged as an integral component of architectural design. However, it is the subjective perception of the human body that ultimately serves as the benchmark for evaluating thermal environments. The perception and adaptability of individuals to thermal environments differ significantly from one person to another. Therefore, the study uses Predicted Mean Vote (PMV) from Franger, Denmark, as a comfort evaluation indicator to analyze the characteristics of BTE. Equation (1) is the calculation of PMV.

$$S = M - W - C - R - E \tag{1}$$

In equation (1), S refers to the amount of heat required by human. M refers to the metabolic rate. W refers to the external work of human. C refers to convective heat transfer. R refers to the amount of radiation heat dissipation. E refers to the amount of evaporative heat dissipation. Equation (2) is the calculation of metabolic rate.

$$M = 21(0.23RQ + 0.77)V_{O2} / A_D \tag{2}$$

In equation (2), RQ refers to the respiratory entropy of the human body. V_{O2} refers to the inhalation volume of oxygen. A_D refers to the skin area. Equation (3) is the calculation of convective heat transfer.

$$\begin{cases} C = f_{cl} h_c (t_{cl} - t_a) \\ f_{cl} = \begin{cases} 1.00 + 1.29 I_{cl} (I_{cl} \le 0.078) \\ 1.05 + 0.645 I_{cl} (I_{cl} \le 0.078) \end{cases} \end{cases} \tag{3}$$

In equation (3), I_{cl} refers to the thermal resistance of human clothing. h_c refers to the convective heat transfer coefficient. Equation (4) is the calculation of convective heating transfer coefficient.

$$h_c = \begin{cases} 2.38(t_{cl} - t_a), 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{v_{\mathrm{ar}}} \\ 12.1\sqrt{v_{\mathrm{ar}}}, 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{v_{\mathrm{ar}}} \end{cases} \tag{4}$$

In equation (4), v_{ar} refers to the indoor wind speed. t_{cl} refers to the temperature of the outer surface of human clothing. Equation (5) refers to the surface temperature of human clothing.

$$t_{cl} = 35.7 - 0.028(M - W) - Icl\left\{\left(3.96 - 10^{-8}\right) fcl\left[\left(t_{cl} + 273\right)^4 - \left(t_{cl} + 273\right)^4\right] + f_{cl} h_c \left(t_{cl} - t_a\right)\right\} \tag{5}$$

In equation (5), t_a refers to environmental temperature around human body. Equation (6) refers to radiation heat transfer.

$$R = \xi f_{cl} f_{eff} \sigma \left[\left(t_{cl} + 273.15 \right)^4 - \left(t_r + 273.15 \right)^4 \right] \quad (6)$$

In equation (6), ξ refers to radiation surface's emissivity. f_{eff} refers to the effective area correction coefficient. t_r refers to the average radiation temperature of human. Equation (7) refers to the evaporation heat dissipation.

$$\begin{cases} E = C_{res} + E_{res} + E_{dif} + E_{rsw} \\ C_{res} = 0.0014M(34 - P_a) \\ E_{res} = 0.00173M(5.867 - P_a) \\ E_{dif} = 3.04(0.25t_{sk} - 3.335 - P_a) \\ t_{sk} = 35.7 - 0.0275(M - W) \\ E_{rsw} = 0.42(M - W - 58.2) \end{cases} \quad (7)$$

In equation (7), C_{res} refers to respiratory sensible heat. E_{res} refers to respiratory latent heat. E_{dif} refers to the heat loss caused by evaporation on the skin surface. t_{sk} is the average skin temperature. E_{rsw} refers to the heat exchange formed by sweat on the surface of the skin. However, PMV can only represent a measure of comfort for most people, and there are differences in feelings between different people. Therefore, to further represent the comfort level of humans in a certain environment, the study uses Predicted Percentage of Dissatisfied (PDD) to evaluate their comfort level in equation (8).

$$PDD = 100 - 95\exp\left[-\left(0.03353PMV^4 + 0.2179PMV^2 \right) \right] \quad (8)$$

When calculating PMV, the primary factors influencing it encompass both environmental and human-related elements, such as air temperature, mean radiant temperature, metabolic rate of the human body, wind speed, and relative humidity. To develop an efficient and rapid thermal environment regulation model centered on human comfort, key environmental regulation parameters including air temperature, mean radiant temperature, relative humidity, and indoor wind speed have been chosen. In addition, the paper analyzes the impact of various parameters on PMV through effectiveness validation experiments to determine the feasibility of this study. Following the validation of the parameters, the study will proceed to construct a thermal environment regulation model that prioritizes human comfort, utilizing the validated parameters as its foundation. Conventional thermal environment regulation techniques predominantly rely on mechanical equipment, including air conditioning units, heating systems, and ventilation systems, which actively modulate indoor temperature, humidity, and air quality to ensure thermal comfort. However, the operation of these mechanical systems consumes substantial energy and can potentially exert adverse environmental impacts over extended periods of usage. APTER is an emerging technology that focuses on human thermal comfort and combines active and passive building technologies to achieve low EC indoor thermal environment regulation. Compared to traditional mechanical equipment, APTER places more emphasis on utilizing natural resources and has lower dependence on energy. Therefore, the study will combine the selected thermal environment regulation parameters with APTER to construct an APTER model based on human comfort. Figure 1 illustrates the principle underlying passive BTE regulation technology.

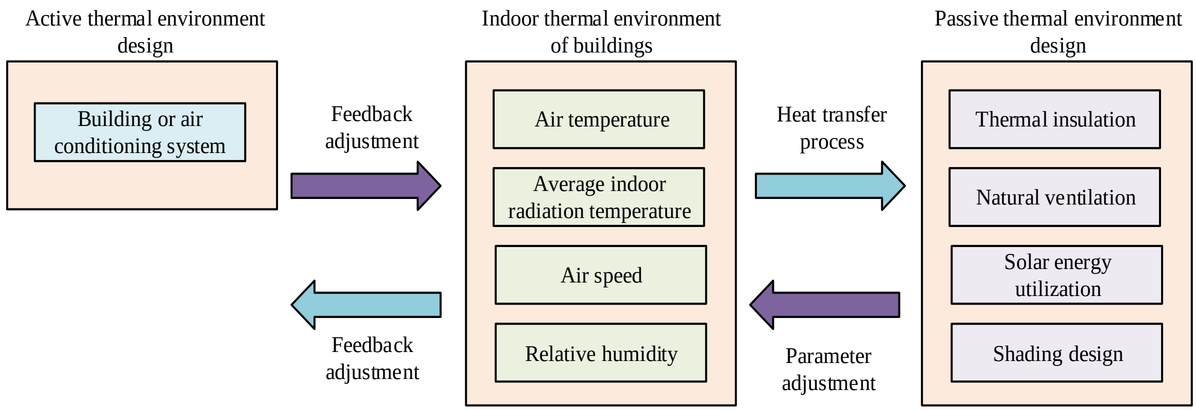


Figure 1. Principle of thermal environment design for active and passive buildings

In Figure 1, the active and passive thermal environment coordination technology can achieve control of indoor temperature, humidity, and air quality by combining building orientation, exterior facade design, selection of insulation materials, natural ventilation, and sunlight utilization. The active and passive BTE regulation technology includes an active regulation module and a passive environmental regulation module. This technology can reduce BTE regulation EC while ensuring human comfort by comprehensively adjusting indoor temperature, radiation temperature, humidity, and indoor air parameters. Passive BTE regulation primarily leverages favorable outdoor and environmental factors, including environmental insulation, natural ventilation, and solar energy utilization, among others, to counteract adverse external influences. This approach ultimately achieves the regulation of the thermal environment. However, when passive regulation cannot meet the requirements of indoor thermal environment parameters, the main passive BTE design can reasonably combine active and passive technologies to provide a comfortable indoor environment. Active technology provides flexibility and precision, which can be adjusted according to different needs. Passive technology utilizes natural resources and reduces dependence on external energy sources. By comprehensively utilizing these two technologies, the goals of energy conservation and environmental protection can be achieved. Figure 2 shows the principle of passive thermal environment regulation.

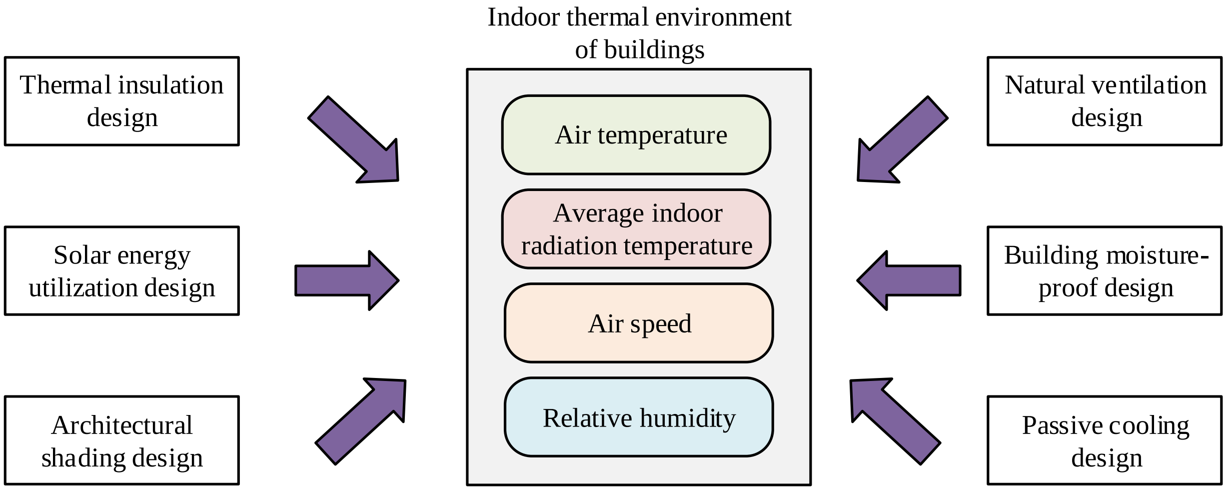


Figure 2. Passive thermal environment regulation principle

In Figure 2, passive environmental regulation is achieved through different functional building designs to regulate the thermal environment, including insulation, solar energy utilization, building shading, and natural ventilation. The design of solar energy utilization can affect indoor temperature and average air radiation temperature, providing a warm indoor environment. Thermal insulation design can reduce the conduction of indoor and outdoor temperatures and improve energy efficiency. Natural ventilation design can utilize the flow of wind to regulate the quality and temperature of indoor air. The most notable feature of passive thermal environment regulation lies in its ability to create a comfortable indoor environment through architectural design and material selection, while simultaneously minimizing EC and enhancing energy efficiency. This approach also boasts a certain level of adaptability and sustainability. Compared to passive thermal environment design, active thermal environment design mainly regulates the indoor thermal environment through mechanical and electrical equipment. Figure 3 shows the principle of active thermal environment regulation.

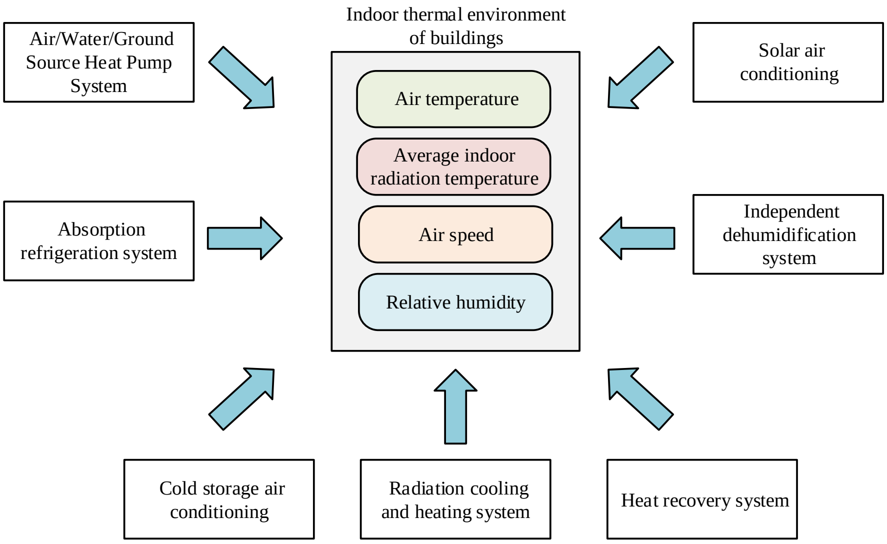


Figure 3. Principle of active thermal environment regulation

In Figure 3, active BTE regulation is generally achieved through mechanical and electrical equipment, such as heat pumps, refrigeration, and heat recovery systems, to achieve precise control of indoor temperature. It can comprehensively adjust the indoor thermal environment parameters of buildings, such as air humidity, relative humidity, air flow rate, and average indoor radiation temperature. Active thermal environment regulation has the advantages of high flexibility and strong adaptability compared to passive thermal environment regulation. It can meet different environments and usage needs. However, active thermal environment design also incurs high EC and operating costs. Therefore, based on this, the study will conduct EC control on the thermal environment regulation model.

3.2 Construction of LEB Model on The Foundation of Human Thermal Comfort

After completing the APTER model on the foundation of human comfort, to minimize the EC of the APTER system, the mechanism modeling and EC simulation software Energyplus is studied to construct a low EC active passive building model. Mechanism modeling, as a modeling technique based on physical and chemical mechanisms of systems, can simulate the dynamic behavior of LEB models by establishing mathematical models and equations [17]. Therefore, it has good applicability in low EC models. Figure 4 shows a low EC active passive building model constructed in this study.

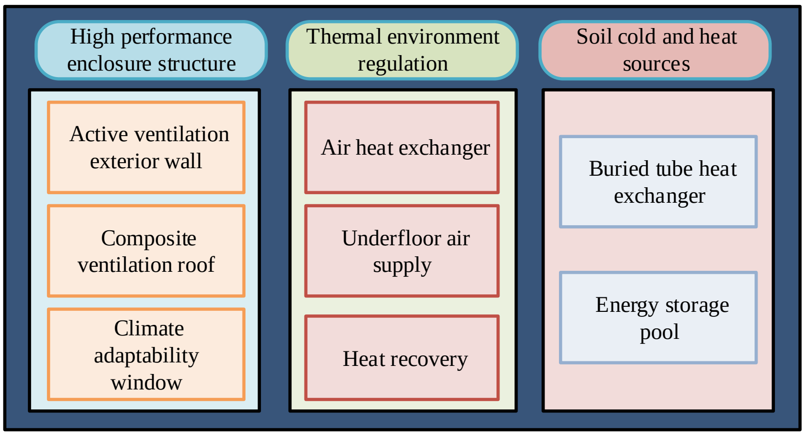


Figure 4. Active and passive building model with low EC

In Figure 4, the low EC active passive building model consists of high-performance enclosure, indoor thermal environment regulation, and soil source thermal environment regulation modules. Among them, the building is located between the outdoor and indoor thermal environments, and spontaneously undergoes a composite heat transfer process of convective heat transfer, radiative heat transfer, and thermal conduction heat transfer. This determines the parameter state of the indoor thermal environment under natural conditions, which fluctuates due to changes in outdoor meteorological parameters. The low-energy active passive building model utilizes active and passive building thermal environment design techniques to comprehensively adjust indoor air temperature, indoor average radiation temperature, relative humidity, and air velocity parameters, so that the combination of indoor thermal environment parameters of the building meets the requirements of human comfort. Specifically, temperature regulation is optimized through passive regulation technology for enclosure structure optimization and thermal inertia utilization, and regulated through active technology for soil source heat pump systems and end systems; Humidity regulation is achieved through a moisture permeable enclosure structure, humidification system, and heat pump dehumidification unit; The wind speed is adjusted through building form guidance, adjustable external windows, and displacement ventilation systems. When the relative humidity is greater than 60%, the temperature setting value automatically increases by 0.5 ℃, and the temperature setting value dynamically adjusts with wind speed. The soil source thermal environment regulation module consists of an indoor thermal environment regulation module, a natural soil cold and heat source, and an energy storage pool. The natural cold and heat sources of soil are achieved through the extraction and utilization of geothermal energy by buried pipe heat exchangers. Figure 5 shows the principle of thermal regulation.

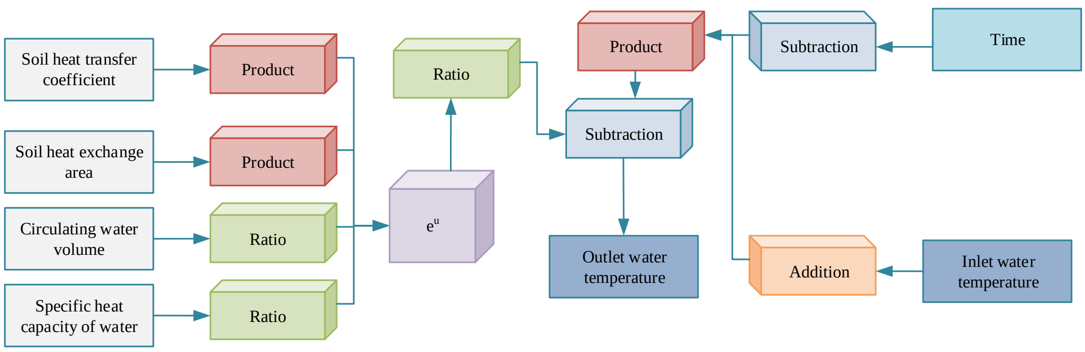


Figure 5. Heat regulation principle of soil natural cold and heat source

In Figure 5, when the indoor environment requires heating, the natural cold and heat sources of the soil use the geothermal energy extracted from the buried pipe heat exchanger to achieve indoor temperature regulation. When the internal environment requires cooling, the soil cold and heat sources use the ground cooling extracted from the buried pipe heat exchanger to achieve indoor temperature regulation. Therefore, the utilization of soil cold and heat sources can greatly reduce the EC of building models. The study uses a constant heat flux model to calculate its heat flux, as presented in equation (9).

$$\Delta t_g = t_g - t_b = \frac{q}{K_s L} G(F_0, P) \tag{9}$$

In equation (9), t_g is the ambient temperature at the apogee. t_b stands for the hole wall temperature. q means the heat flow rate. K_s represents to the soil thermal conductivity. $G(F_0, P)$ stands for the Green's function. F_0 refers to the Fourier number. P refers to the ratio of the distances from the calculation point to the center of the buried pipe and the radius to the buried pipe well. Equation (10) refers to the temperature difference heat transfer process between the circulating water in the buried pipe and the soil.

$$G_c C_{p,w} \left(t_{wc2} - t_{wc1}\right) = K_d F_d \frac{\left(t_{wc2} - t_{wc1}\right)}{\ln \frac{t_{wc2} - t_b}{t_{wc1} - t_b}} \tag{10}$$

In equation (10), G_c refers to the water circulation flow rate of the buried pipe. $C_{p,w}$ refers to the specific heat capacity of water. t_{wc2} stands for the inlet temperature of the buried pipe. t_{wc1} means buried pipe's outlet temperature. K_d refers to the soil heat transfer coefficient. F_d refers to the soil heat exchange area. The advantage of the soil natural cold and heat source module lies in its stable geothermal energy and high energy utilization efficiency. Compared to traditional air conditioning and heating systems, it can significantly reduce EC and carbon emissions, saving energy costs. In addition, this module can also achieve indoor air purification and humidity regulation through the operation of buried pipe water circulation and building end water circulation. The energy storage pool achieves an adjustable connection between buried pipe water and the water circulation at the end of the building, including energy storage and functions. Figure 6 shows the thermal regulation principle of the energy storage pool.

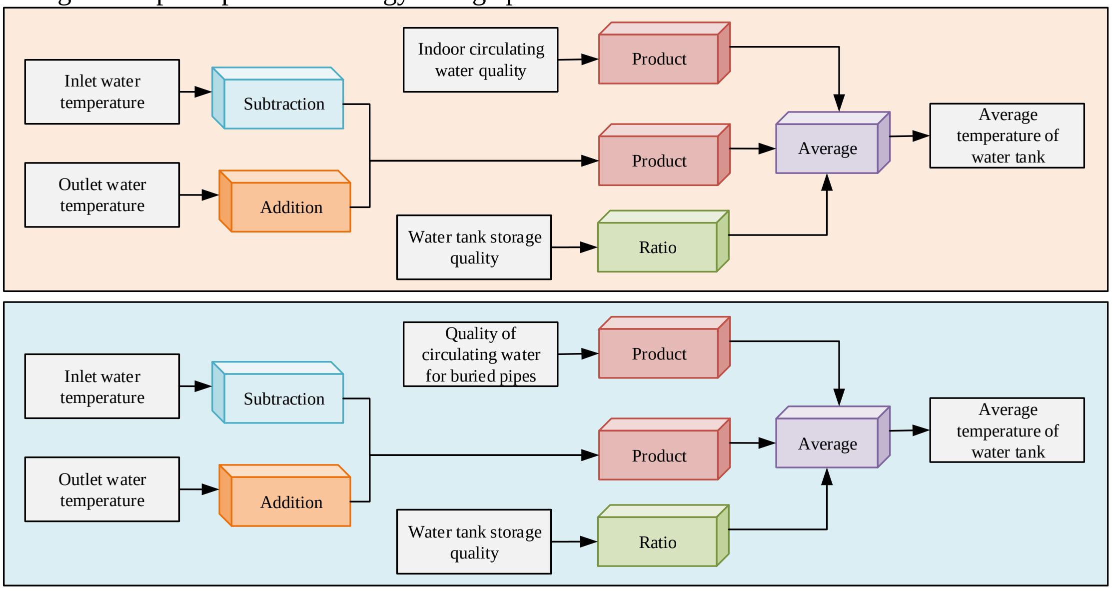


Figure 6. Thermal regulation principle of energy storage pool

In Figure 6, the energy storage pool can activate the underground pipe heat exchange cycle to store energy. By initiating the heat exchange cycle at the building's terminus, it is possible to furnish heating or cooling within the indoor environment, thereby sustaining a consistent indoor temperature. The expression for the energy storage tank in both supply and storage modes is shown in equation (11).

$$\begin{cases} C_{w,p} m_{\tan k} \dfrac{d_{t_{\tan k}}}{d_{\tau}} = C_{w,p} m_{t} (t_{w2} - t_{w1}) \\ C_{w,p} m_{\tan k} \dfrac{d_{t_{\tan k}}}{d_{\tau}} = G_c C_{w,p} m_{t} (t_{w2} - t_{w1}) \end{cases} \tag{11}$$

In equation (11), $m_{\tan k}$ refers to the water storage quality of water tank. $t_{\tan k}$ refers to the average temperature of water tank. m_t refers to the mass flow rate of indoor water circulation. G_c refers to the underground water circulation flow rate. The indoor thermal environment regulation module is responsible for monitoring and controlling indoor temperature. It can adjust the operation of the system by adjusting the indoor temperature through the end fan panel, maintaining a comfortable indoor temperature. In addition, the indoor thermal environment regulation module can also collaborate with other thermal environment regulation modules to achieve comprehensive thermal environment regulation. The heat transfer equation between the fan disk and the building interior, as well as the calculation formula for indoor heat balance, are shown in equation (13).

$$\begin{cases} Q_{w,p} m_t (t_{w2} - t_{w1}) = K_p F_p \dfrac{(t_{w2} - t_{w1})}{\ln \dfrac{t_{w2} - t_n}{t_{w1} - t_n}} \\ c_{air} m_{air} \dfrac{d_{tn}}{d_\tau} = Q - c_{w,p} m_t (t_{w2} - t_{w1}) \end{cases} \tag{12}$$

In equation (12), K_p stands for the heat transfer coefficient. F_p means the heat transfer area. c_{air} refers to the constant volume specific heat of indoor air. m_{air} refers to indoor air quality. d refers to the drilling diameter. Q refers to the building load. Within the high-performance enclosure module, research is conducted on a ventilation enclosure structural design that channels indoor exhaust into the air interlayer, aiming to enhance indoor air quality and thermal comfort. Figure 7 shows the heat conduction principle of the ventilation enclosure structure.

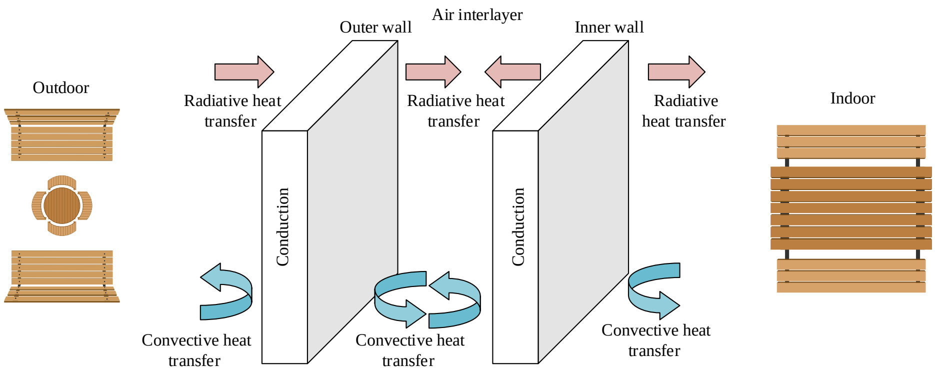


Figure 7. Principle of heat transfer to the envelope structure

In Figure 7, the ventilation enclosure structure mainly involves three heat transfer modes: convection, radiation, and heat conduction. By incorporating vents or ventilation holes on the building's facade or roof, the ventilation maintenance structure facilitates the influx of fresh air while simultaneously expelling indoor pollutants and moisture. This not only enhances indoor air quality but also mitigates the heat island effect. Moreover, this structure effectively utilizes the thermal energy of indoor exhaust by introducing it into the air interlayer, improving indoor thermal comfort, and reducing EC. A low EC active passive building model based on human comfort is constructed, which utilizes soil source thermal environment regulation and LEB enclosure modules to minimize EC during use. Following the completion of constructing a low EC active-passive building model centered around human comfort, an EC verification process is carried out on the newly built model. Equation (13) is the calculation of building EC.

$$\varepsilon = \frac{Q_0}{Q_{sys}} \tag{13}$$

In equation (13), Q_0 refers to the EC of indoor heating or cooling in the building. Q_{sys} refers to the operating EC of the building system. Equation (14) refers to the total EC during system operation.

$$\begin{cases} Q_{sys} = Q_{in} + Q_{ghe} + Q_{fan} \\ Q_{in} = \dfrac{H_{in} \times g \times G_{in}}{\eta_{in}} \\ Q_{fan} = \dfrac{P \times V_{fan}}{\eta_{fan}} \\ Q_{ghe} = \dfrac{H_{ghe} \times g \times G_{ghe}}{\eta_{ghe}} \end{cases} \tag{14}$$

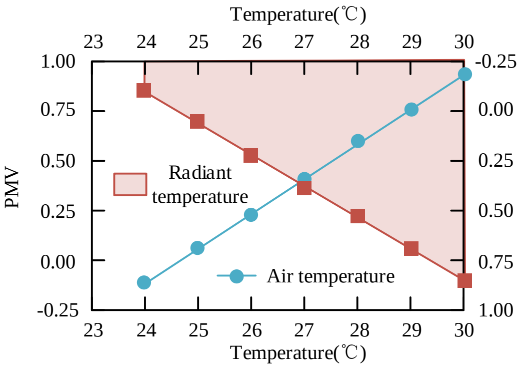
In equation (14), Q_{in} refers to the EC of the indoor circulating water pump. Q_{ghe} refers to the EC of the underground circulating water pump. Q_{fan} refers to the EC of the air heat exchanger fan. H_{in}, G_{in}, and η_{in} respectively represent the head, flow rate, and efficiency of indoor circulating water pumps. P refers to wind pressure. V_{fan} and η_{fan} represent the air volume and efficiency of the air heat exchanger, respectively. H_{ghe}, G_{ghe}, and η_{ghe} respectively represent the head, flow rate, and efficiency of the underground circulating water pump.

4. Empirical Experiments on the LEB Model Based on Human Comfort

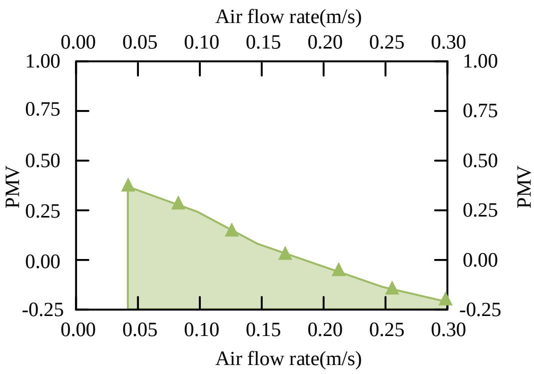
To verify the effectiveness of the indoor thermal environment parameters, APTER, and LEB models based on human comfort selected for the study, performance comparison experiments and empirical analysis were conducted.

4.1 Validation of Indoor Thermal Environment Parameters

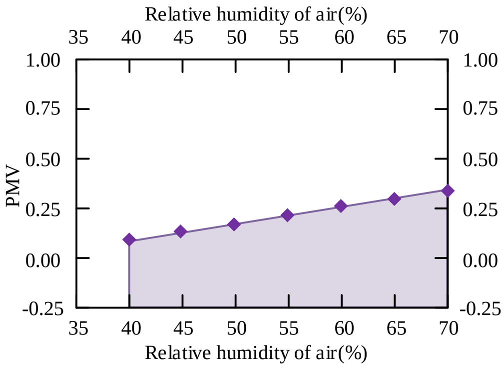
To verify the effectiveness of the indoor thermal environment parameters selected for the study, the study analyzed how each indoor thermal environment parameter affected PMV indicators from winter and summer seasons. The experimental environment for testing includes a classroom and a laboratory, which are used to test the thermal environment regulation performance in summer and winter, respectively. The corresponding experimental building is composed of foam concrete inner wall, middle air layer and outer polyurethane insulation layer Multiple sensors are installed in the experimental area for real-time monitoring of indoor temperature, humidity, wind speed, radiation temperature, and carbon dioxide concentration. At the same time, energy consumption monitoring equipment has been installed to record energy consumption data of air conditioning, ventilation systems, and ground source heat pumps. According to the "International Standard Technology ISO7730 Standard for Building Thermal and Humidity Environment", the thermal resistance of human clothing in summer was set at 1.0 clo and the metabolic rate was 1.1 met. In winter, the thermal resistance of human clothing was 0.5 clo, and the metabolic rate was 1.1 met. In addition, the thermal environment regulation parameters are set as follows: the indoor target temperature in summer is 24 ℃ to 26 ℃, and the indoor target temperature in winter is 20 ℃ to 22 ℃; The target humidity for summer is 40% to 60%, and for winter it is 30% to 50%; The target wind speed ranges from 0.1 m/s to 0.2 m/s; By adjusting curtains and shading facilities, the average indoor radiation temperature is controlled within the target temperature range. The experimental environment was Windows 10 and CPU was Intel i-6-6400. Figure 8 showed the impact of indoor thermal environment parameters on PMV in summer.



(a) The influence of air temperature and average radiation temperature on PMV



(b) The influence of air flow rate on PMV

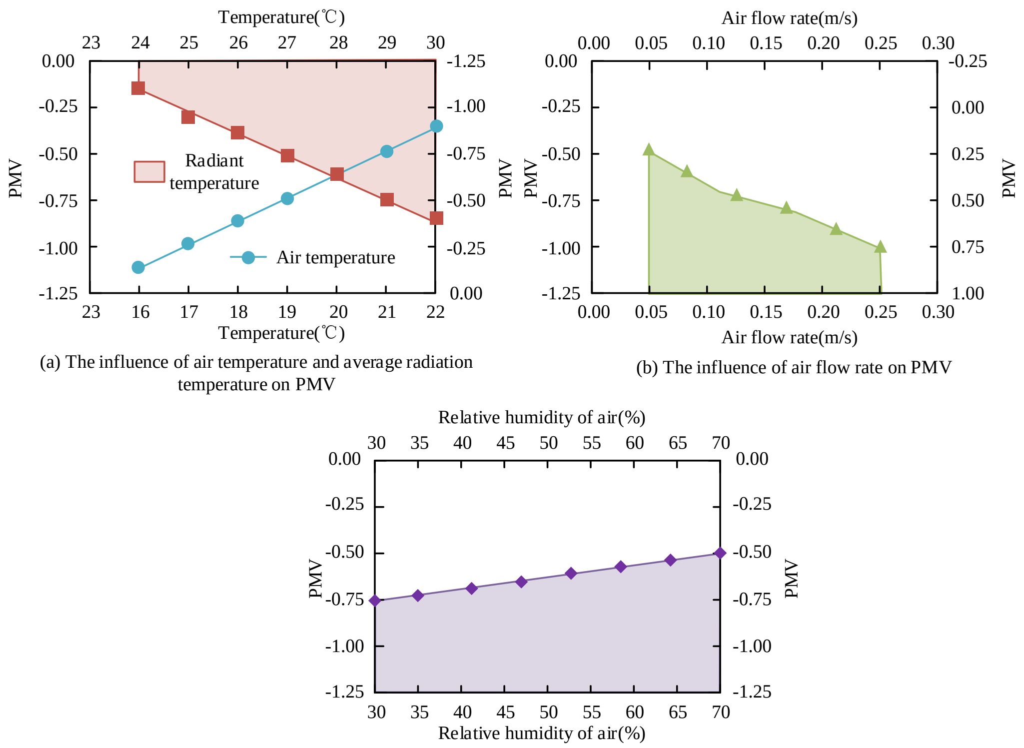


(c) The relative humidity of air on PMV

Figure 8. Effect of indoor thermal environment parameters on PMV in summer

Figure 8 (a) shows the effects of indoor air temperature and average indoor radiation temperature on indoor PMV. As the indoor temperature increased from 24 °C to 30 °C, the indoor PMV value also increased from -0.13 to 0.90. When the average indoor radiation temperature increased from 24 °C to 30 °C, the indoor PMV value increased from -0.12 to 0.86. Therefore, the indoor air temperature had a greater impact on PMV than the average indoor radiation temperature. Figures 8 (b) and 8 (c) show the effects of air flow rate and relative humidity on indoor PMV, respectively. In Figure 8 (b), as the air flow rate increased from 0.05m/s to 0.30m/s, the indoor PMV value also decreased from the original 0.3 to-0.23. In Figure 8 (c), as the relative humidity of the air increased from 40% to 70%, the indoor PMV value also increased from 0.10 to 0.31. In summary, in summer climate, indoor air temperature, average indoor radiation temperature, air flow rate, and relative humidity all had an impact on indoor PMV. The most influential factor was indoor air temperature, followed by radiation temperature, air flow rate, and relative humidity. Figure 9 showed the impact of indoor thermal environment parameters on PMV in winter.

Figure 9 (a) shows the effects of indoor air temperature and average indoor radiation temperature on indoor PMV. As the indoor temperature increased from 16 °C to 22 °C, the indoor PMV value increased from -1.12 to -0.35. When the average indoor radiation temperature increased from 16 °C to 22 °C, the indoor PMV value increased from -1.10 to -0.35. Figures 9 (b) and 9 (c) shows the effects of air flow rate and relative humidity on indoor PMV, respectively. In Figure 9 (b), as the air flow rate increased from 0.05m/s to 0.20m/s, the indoor PMV value also decreased from -0.50 to -0.83. In Figure 9 (c), as the relative humidity increased from 30% to 70%, the indoor PMV value also increased from -0.75 to -0.50. In summary, the impact of indoor thermal environment parameters on PMV in winter climate was smaller than that in summer. In the summer and winter seasons, the indoor temperature and average indoor radiation temperature had the most significant impact on PMV values. In the design of passive thermal environment buildings, it was feasible to use indoor air temperature, average indoor radiation temperature, relative humidity, and air flow rate as thermal environment adjustment parameters.



(a) The influence of air temperature and average radiation temperature on PMV
(b) The influence of air flow rate on PMV
(c) The relative humidity of air on PMV

Figure 9. Effect of indoor thermal environment parameters on PMV in winter

4.2 APTER Performance Verification

To verify the effectiveness of the passive thermal environment regulation model and the active thermal environment regulation model, the study validated the EC effects of these two models in summer and winter, respectively. The study verified the effectiveness of active thermal environment regulation models under different energy efficiency ratio conditions, with an energy efficiency ratio range of [2.4-3.2] in summer and [1.8-2.6] in winter. A performance analysis was conducted on the impact of different parameters on EC for a passive thermal environment regulation model. The study divided the thermal parameters of the passive thermal environment enclosure structure into four levels: A, B, C, and D based on "Energy Efficiency Design Standards for Public Buildings". Table 1 shows the parameters for passive thermal environment design at different levels.

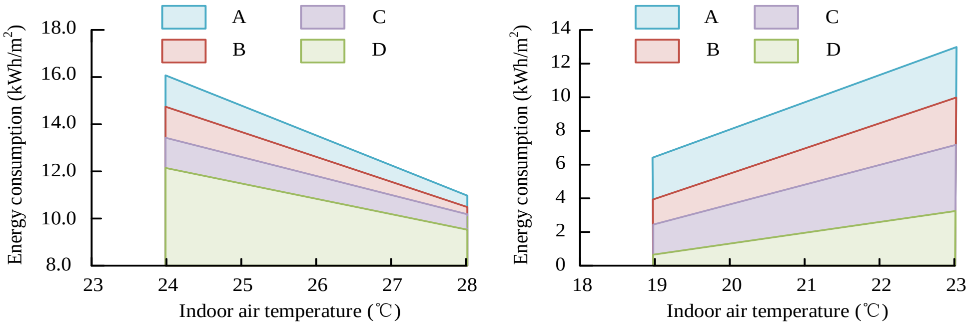
Table 1. Parameters of the passive thermal environment design at all levels

Rank	Non-transparent maintenance structure		Transparent maintenance structure	
	External wall thermal transmission coefficient(W/m^2*K)	Roofing thermal transmission coefficient(W/m^2*K)	Coefficient of heat transfer(W/m^2*K)	Sun heat coefficient
A	0.8	0.5	3.00	0.45
B	0.65	0.35	2.65	0.30
C	0.50	0.25	2.32	0.25
D	0.35	0.21	1.51	0.4-0.15
E	0.20	0.20	1.00	0.4-0.15

Figure 10 shows the EC ratio effects of different passive thermal environment regulation models in summer and winter.

In Figure 10, during summer, with the indoor temperature increasing, the passive thermal environment regulation model's EC decreased. The EC of level D was the lowest, decreasing from 12.4kWh/m2 to

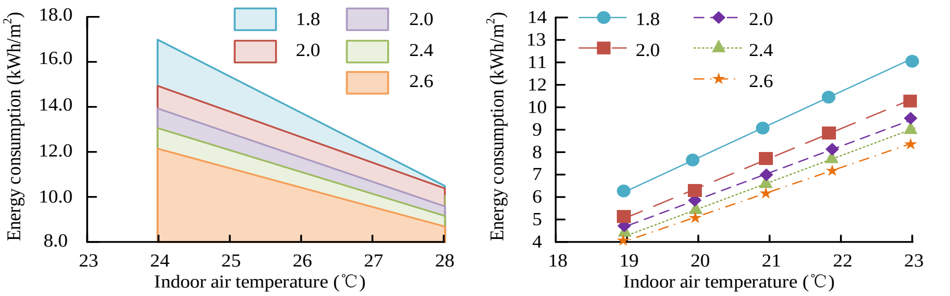
10.4kWh/m2. In winter, as the indoor temperature increased, the EC of the passive thermal environment regulation model increased. The EC of level D was the lowest, increasing from 1.4kWh/m2 to 3.7kWh/m2. In summary, the parameters of the enclosure structure could reduce the EC of the building, and the passive thermal environment regulation model constructed was feasible. Figure 11 shows the EC impact of the active thermal environment regulation model.



(a) Energy consumption impact of passive thermal environment design in summer

(b) Energy consumption impact of passive thermal environment design in winter season

Figure 10. The EC ratio impact of different passive thermal environment design in two seasons



(a) Equipment system energy efficiency ratio in summer

(b) Equipment system energy efficiency ratio in winter

Figure 11. Impact of EC of active thermal environment design

In Figure 11, during summer, as the indoor temperature increased, the EC of the active thermal environment regulation model decreased. The EC with an energy efficiency ratio of 2.6 was the lowest, decreasing from 12.4kWh/m^2 to 8.4kWh/m^2. In winter, as the indoor temperature increased, the EC of the passive thermal environment regulation model increased. The EC with an energy efficiency ratio of 2.6 was the lowest, increasing from 4.0kWh/m^2 to 8.2kWh/m^2. In summary, improving the energy efficiency ratio of active thermal environment design could reduce the EC of buildings, and the passive thermal environment regulation model constructed was feasible.

4.3 Empirical Experiment on LEB Model Based on Human Thermal Comfort

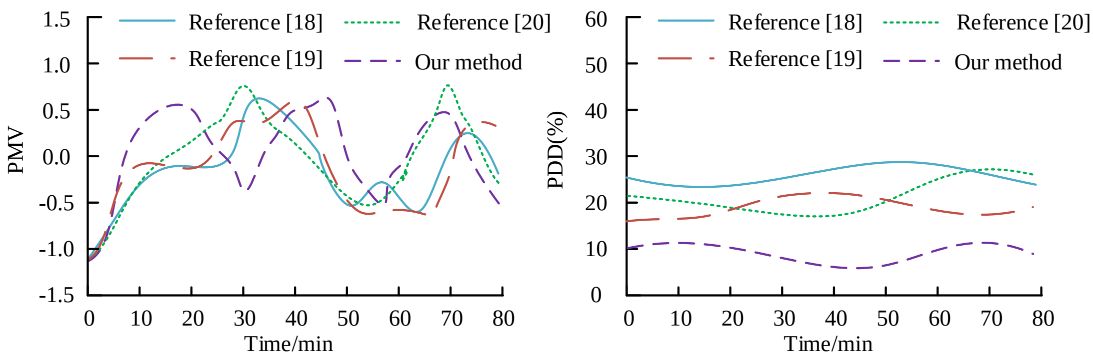
After verifying the effectiveness of the thermal environment parameters and APTER model, the study applied the LEB model based on human thermal comfort to practical applications and analyzed its practical application effectiveness. The study applied this model to a university in Sichuan, with 500 students as research subjects. To ensure the diversity and reliability of participants, the study randomly selected college students from liberal arts majors, science and engineering majors, and arts and sports majors, with male and female students accounting for 50% each. In addition, the experimental control measures are as follows: enter the testing environment 30 minutes in advance and wear standardized clothing; Set up 3 repeated questions to check answer consistency. The application performance indicators included PMV, PDD, EC, energy efficiency, as well as the satisfaction vote and dissatisfaction coefficient of research subjects on the regulated temperature, humidity, wind speed, and air quality. The comparative models were the thermal environment regulation models in references [18], [19], and [20]. The experimental tools were Excel and SPSS. Figure 12 shows the comparison results of PMV and PDD for each model.

Figure 12 (a) shows the PMV values of each model. The LEB model based on human comfort constructed through research could control PMV between 0.5 and -0.5, which had better heating speed and stability compared to other models. When the model was not started, the PMV was -1.2. After the model was opened, the PMV increased to 0.5 and then stopped operating. When PMV dropped to -0.5, the system underwent another temperature rise. Figure 12 (b) showed the PDD values of each model. The LEB model constructed through research provided the lowest PDD of 9.7% for human comfort, which better met the residents' requirements for temperature comfort. In summary, the constructed LEB model based on human comfort could meet the thermal comfort needs of residents. Figure 13 shows the satisfaction voting results of participants towards the temperature and humidity of each model.

In Figure 13, in the temperature satisfaction voting results, the constructed LEB model based on human comfort could meet the residents' satisfaction with temperature. The proportion of residents who believed that the temperature was suitable was 87.2%, which was higher than other models. In the humidity satisfaction vote, the constructed LEB model based on human comfort could meet the residents' demand for humidity.

Ultra LEBs minimize building heat loss and reduce building cooling and heating EC while ensuring indoor comfort [21-22]. The EC indicators were based on the characteristics of domestic climate zones, building forms, lifestyle habits, and EC methods, while the comfort indicators were formulated to meet comfort requirements [23], [24], and [25]. The proportion of residents who believed that the humidity was appropriate was 79.8%, which was higher than other models, this was consistent with the research findings of other scholars [26], [27], and [28]. In summary, the constructed LEB model based on human comfort could meet the needs of residents for temperature and humidity. Figure 14 showed the participants' wind speed and air quality scores for each model.

Figure 14 (a) shows the comparison results of wind speed satisfaction among different comparison models. The constructed LEB model based on human comfort could meet the needs of residents for wind speed, with 78.5% of residents considering the wind speed to be suitable, which was higher than other models. Figure 14 (b) shows the air quality scoring results of each comparative model. The constructed LEB model based on human comfort could meet the residents' demand for air quality, with a satisfaction score of 8.4, which was better than other models. In summary, the constructed LEB model based on human comfort could meet the needs of residents for wind speed and air quality, this was consistent with the research findings of other scholars [29-31]. Figure 15 shows the comparison results of EC and energy efficiency ratio for each model.



(a) Comparison results of PMV among different models (b) Comparison results of PDD among different models

Figure 12. The PMV and PDD comparison results of each model

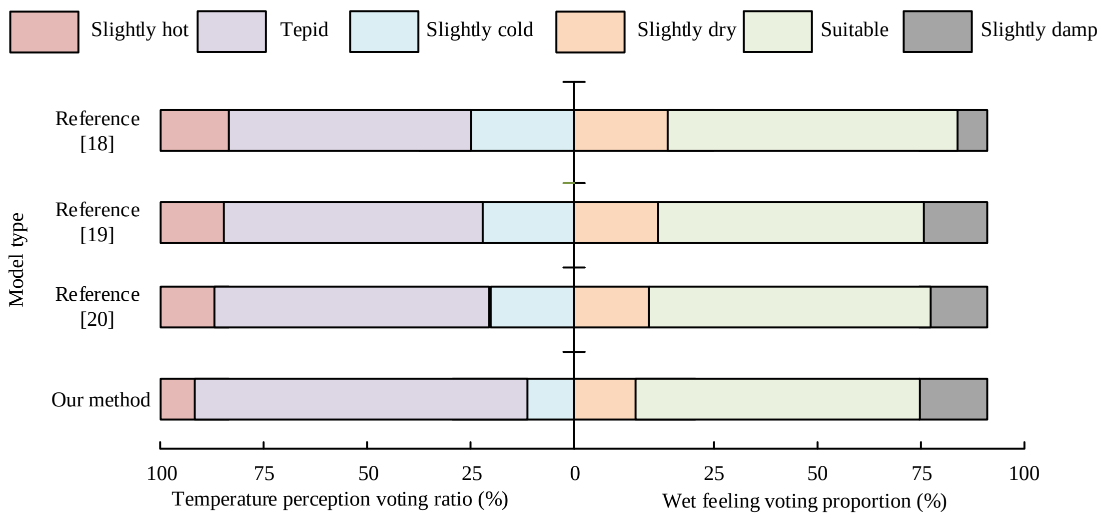
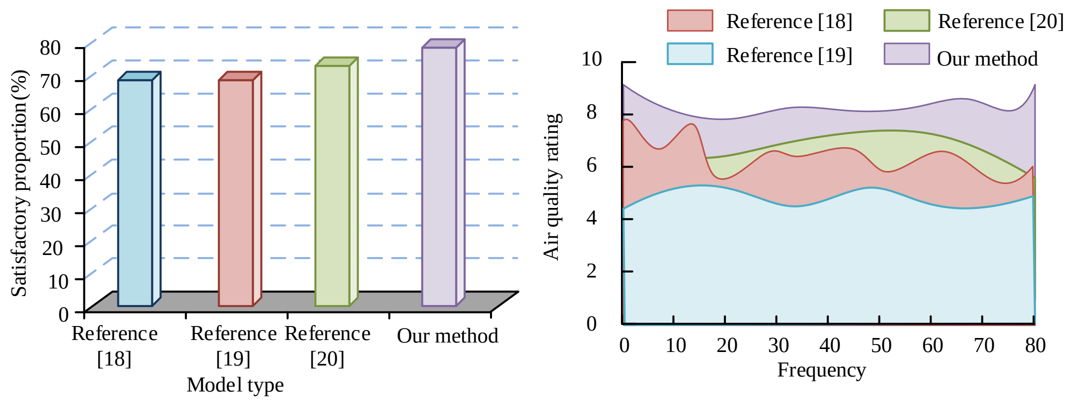


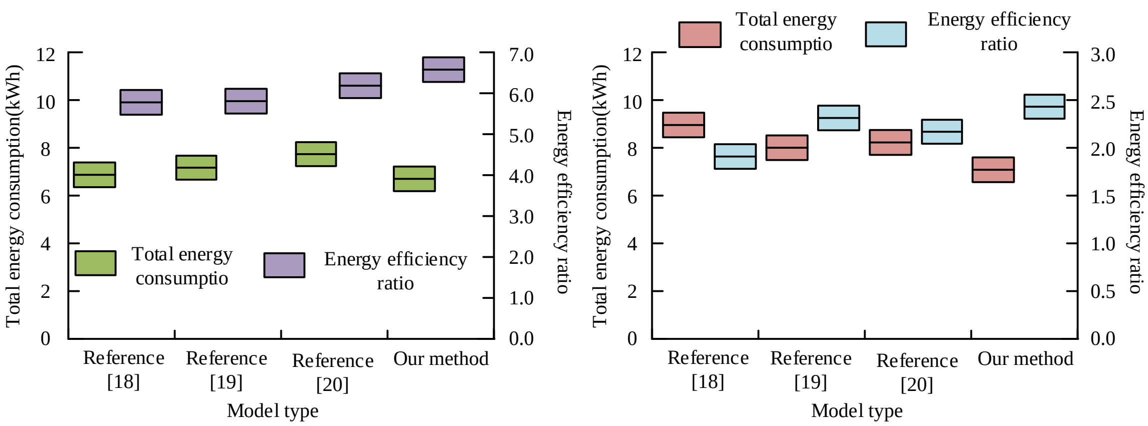
Figure 13. Satisfaction voting results of the temperature and humidity of each model



(a) Satisfactory proportion of air flow rate for each model

(b) Satisfactory proportion of air quality for each model

Figure 14. Results of the wind speed and air quality scores for each model



(a) Heating capacity and energy efficiency ratio of each model in summer

(b) Heating capacity and energy efficiency ratio of each model in winter

Figure 15. Comparison results of EC and EC ratio of each model

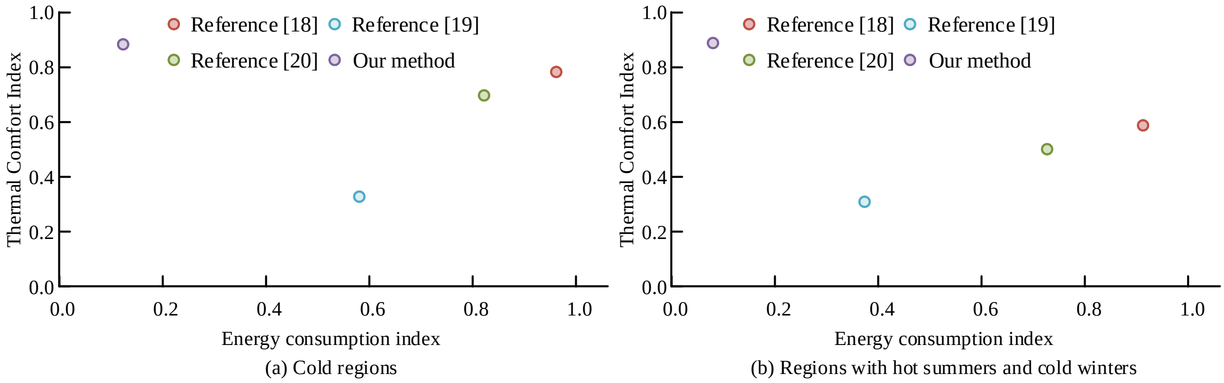


Figure 16. Application effects of various methods in different regions

Figure 15 (a) shows the comparison results of EC and energy efficiency ratio of each comparison model in summer cooling. The constructed LEB model based on human comfort consumed 6.1 kW/h of energy, which was lower than other comparative models. In addition, the energy efficiency ratio of this model was 6.5, which was better than other models. Therefore, in summer, the low energy indoor building model based on human comfort was more energy-efficient. Figure 15 (b) shows the comparison results of EC and energy efficiency ratio of each comparison model in winter heating. The constructed LEB model based on human comfort consumed 1.8 kW/h of energy, which was lower than other comparative models. In addition, the energy efficiency ratio of this model was 2.4, which was better than other models. The above results may be due to the use of a ground source heat pump system in the LEB model, which provides stable cold and heat sources through the constant temperature characteristics of underground soil. Compared with traditional air source heat pumps, ground source heat pump systems are not affected by external temperature changes and can maintain high operating efficiency. During summer cooling, ground source heat pump systems can efficiently transfer indoor heat to the ground, thereby reducing indoor temperature. The LEB model can not only efficiently extract geothermal energy, but also recover and reuse excess heat. In addition, the model also adopts high-performance enclosure structure design; And by precisely controlling key thermal environment parameters such as indoor temperature, humidity, wind speed, and radiation temperature, it ensures human thermal comfort while minimizing energy consumption, thus having a lower energy efficiency ratio. To further demonstrate the effectiveness of the research method in different regions, experiments were conducted in cold regions and hot summer and warm winter regions, and the current mainstream methods were compared. The results are shown in Figure 16.

Figures 16 (a) and 16 (b) show the application effects of each method in cold regions and hot summer and warm winter regions, respectively. From this, it can be seen that the research method has excellent performance in terms of thermal comfort and energy consumption in different regions. It can reduce energy consumption while maintaining stable indoor comfort in Wenchi. The above results may be due to the low surface temperature in cold regions during winter, but the relatively stable underground soil temperature. The LEB model efficiently extracts geothermal energy through buried tube heat exchangers, avoiding the problem of decreased efficiency of traditional air source heat pumps at low temperatures. And the multi-layer insulation design reduces heat loss and lowers heating load. When the humidity is below 30%, the model automatically activates the humidification system to avoid the discomfort caused by dryness. Combining humidity sensors and wind speed regulation to dynamically adjust refrigeration parameters under high temperature and humidity conditions; In summer, indoor heat is transferred to the underground soil, utilizing the cooling effect of the soil to improve refrigeration efficiency, with significantly lower energy consumption than traditional air conditioning. However, the mainstream method lacks insulation performance for the enclosure structure, resulting in excessive heat loss or gain. And it lacks a dynamic feedback mechanism, making it difficult to balance energy consumption and comfort. In summary, the constructed LEB model based on human comfort had the highest energy utilization efficiency.

5. Conclusion

To improve the comfort and EC performance of traditional thermal environment regulation models, a comprehensive analysis of indoor BTE characteristics based on human comfort was studied. The study selected indoor temperature, average indoor radiation temperature, relative humidity, and wind speed as indoor thermal environment regulation parameters. Subsequently, based on parameters, the APTER model was designed and used to construct an LEB model based on human comfort. The study verified the effectiveness of these selected parameters, APTER, and LEB model based on human comfort. The selected thermal environment adjustment parameters could all affect PMV. The indoor air temperature and average indoor radiation temperature had the most significant impact on PMV values. Performance testing of APTER revealed that its EC was 12.4kWh/m^2 in summer and 3.7kWh/m^2 in winter, and its EC was influenced by the parameters of the enclosure structure and energy efficiency ratio. Finally, the study validated the effectiveness of constructing an LEB model based on human comfort, which could control PMV between 0.5 and -0.5, resulting in better startup speed and stability performance. In addition, the PDD of this model was 9.7%, with temperature satisfaction voting accounting for 87.2%, humidity satisfaction voting for 79.8%, and wind speed satisfaction voting for 78.5%. The EC of this model in summer was 6.1kW/h, with an energy efficiency ratio of 6.5, and the EC in winter was 1.8kW/h, with an energy efficiency ratio of 2.4, which was better than other models. In summary, the constructed LEB mold based on human comfort had good thermal environment regulation and EC control performance. It could comprehensively consider human thermal comfort and EC, achieving a comfortable and sustainable indoor building environment construction. However, there are still certain limitations in the research, which mainly focuses on static thermal comfort parameters and does not fully consider the impact of dynamic factors such as personnel behavior patterns and real-time environmental changes on the actual performance of the model. Therefore, in future research, the integration of artificial intelligence, the Internet of Things, and real-time data analysis technology can be explored and applied in intelligent buildings to further enhance the energy optimization of research methods.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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