Research on Average Heat Transfer Control Technology of Passive Ultra-low Energy Assembly Building Exterior Wall

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Abstract. This research focuses on passive ultra-low energy prefabricated buildings, aiming to reduce the external wall's heat transfer coefficient and enhance thermal insulation for energy conservation. The study calculates the average heat transfer coefficient of the external wall and surrounding thermal bridges, establishing an objective function for heat transfer control. By solving this function, optimal control parameters are derived. Experimental results demonstrate that this approach effectively improves insulation, maintains comfortable indoor temperatures, and significantly reduces energy consumption of the building's external wall. The experimental results show that the maximum difference between the calculated value and the actual value of the external wall heat transfer coefficient under the proposed method is only 0.02, the limit value of the average heat transfer coefficient is controlled around 2.0, the indoor insulation rate is up to 90.3%, and the energy consumption of the external wall is effectively reduced from 100-145kJ with little fluctuation. Effectively improve the building insulation performance, ensure the indoor temperature stability, reduce energy consumption.

Keywords: Passive; Heat storage efficiency; Average heat transfer; Control technology

1. Introduction

Passive ultra low energy consumption prefabricated buildings use passive technology and advantages of prefabricated buildings to reduce energy demand and improve indoor environmental comfort. This kind of building adopts passive technologies of enclosure structure, high-performance exterior door and window system, good building air tightness system, building node structure without heat bridge and ventilation system with efficient heat recovery, which greatly reduces the energy demand of the building body. By optimizing the energy supply scheme and improving the energy utilization efficiency (Rahman *et al.* 2022), the requirements for indoor thermal comfort and building energy efficiency are met. The characteristics of passive ultra low energy consumption prefabricated buildings include: high-performance thermal insulation and air tightness. The design of this building focuses on thermal insulation and air tightness. Compared with traditional houses, it greatly reduces the effective heat exchange inside and outside the building and saves a lot of energy consumption. Through passive technology and efficient energy management system, make rational use of energy, and greatly reduce the demand for building cooling and heating (Reto *et al.* 2021). At the same time, improve the comfort of indoor environment by means of BIM system modular design, industrial assembly line prefabrication, integrated thermal insulation structure, etc. (Jeong *et al.* 2022). The passive ultra low energy consumption prefabricated building is a low-carbon, environmentally friendly and energy-saving green building, which plays a positive role in promoting sustainable development and building ecological civilization. Controlling the average heat transfer of the external wall of a building is one of the important guarantees for the energy efficiency and comfort of this building (Moore *et al.* 2021). By optimizing the thermal insulation performance of the exterior wall, the energy consumption of the building can be further reduced and its energy efficiency can be improved. This is not only in line with the requirements of green buildings and energy conservation and emission reduction, but also conducive to promoting urban planning and sustainable development (Petras *et al.* 2021). Therefore, in the process of building design, construction and operation, attention should be paid to the control and optimization of the thermal insulation performance of external walls. Efficient measures must be taken to enhance energy efficiency and comfort in buildings by reducing heat transfer through external walls.

At present, many scholars have also studied the average heat transfer control technology of building exterior walls. For example, Elmzughi *et al.* (2021) proposed the thermal insulation control method of building exterior walls in different climatic regions. This method aims at building exterior walls in different climatic regions, and realizes its average heat transfer control by adjusting the material parameters of building exterior walls, so as to improve the thermal insulation capacity of building exterior walls. Only the static factor of different climate regions is considered, but the dynamic climate change of different seasons and different time periods in the same climate region is not fully considered, resulting in poor control effect. Sepehri and Pavlak (2022) proposed an optimization method for active thermal insulation control of residential buildings. This method improves the average heat transfer coefficient by controlling the thickness of the building's exterior wall to achieve the control of this coefficient. Only the influence of external wall thickness on heat transfer coefficient is paid attention to, and other factors such as the thermal performance of external wall materials and the sealing of external wall are not comprehensively considered, resulting in the overall thermal insulation effect is not ideal. Chandhran and Elavenil (2023) proposed a sustainable thermal insulation system for external walls, which reduces the energy consumption of external walls, improves the thermal insulation performance of external walls, and realizes the control of average heat transfer of external walls by designing a sustainable thermal insulation system for external walls. Designing a sustainable insulation system for building exterior walls is relatively complex, involving the integration of multiple links and technologies, and requires a professional design and construction team. This not only increases the construction cost and difficulty of the system, but also causes various problems during the operation and maintenance of the system, affecting the stability and reliability of the system. Dabbagh and Krarti (2021) proposed a switchable transparent heat insulation control method suitable for residential intelligent Windows in the United States. By changing the window size of the exterior wall of the passive ultra-low energy consumption prefabricated building, this method realized the indoor and outdoor heat exchange, reduced the average heat transfer of the exterior wall of the building, and realized the control of its heat transfer. However, the change of window size is limited by many factors such as building lighting, ventilation, safety and so on, and cannot be adjusted without limitation, which may affect the actual control effect of this method. Vivek and Balaji (2023) proposed a method, this method calculates the steady and unsteady heat transfer values of the passive ultra-low energy consumption prefabricated building exterior wall, and realizes the control of its average heat transfer by adjusting the wall thermal resistance. In practical application, it may be due to the difficulty of data acquisition or the inaccuracy of the calculation model, which will lead to a large error in the calculation result and affect the control effect.

The above methods have achieved some results in practical application, but in the process of practical application, some methods are local and affected by the parameters of the building exterior wall, resulting in the poor control effect of the above methods on the average heat transfer of the building exterior wall. In conclusion, the research on average heat transfer control technology for prefabricated building exterior walls is of great significance. By establishing an objective function and solving it, insulation rate can be improved, comfort can be improved, and environmental impact can be reduced. Through experimental analysis, we effectively managed the average heat transfer of prefabricated building exterior walls. This method not only improves the sealing performance of the exterior wall, but also ensures the best indoor comfort. The application of this method has achieved positive results. The positive results obtained from experimental research further highlight the effectiveness of this method in achieving average heat transfer control in prefabricated buildings.

2. Average heat transfer control technology for building facades

2.1 Measure of the heat transfer coefficient of the building exterior walls

The average heat transfer coefficient (or heat transfer coefficient) of the exterior wall of efficient and energy-saving passive building assembly system refers to the heat transfer of the exterior wall per unit area per unit time under the condition that the temperature difference of the air on both sides of the exterior wall is 1°C, and this coefficient is an important index to measure the thermal insulation performance of the exterior wall of efficient and energy-saving passive building assembly system (Bak and Yoon, 2021). The heat transfer coefficient of the assembly building exterior wall is also affected by a variety of factors, such as the structural form of the efficient and energy-saving passive building assembly system exterior wall, the type and thickness of the thermal insulation material, doors and windows of the airtightness and so on. The main wall and the external thermal bridge parts are the main components of the external wall, and the accurate calculation of their heat transfer coefficients is very important to accurately obtain the average heat transfer coefficient of the external wall, because the two parts have differences in structure and materials, and the influence on heat transfer is different. The heat transfer characteristics of the external wall can be analyzed more carefully by calculating their heat transfer coefficients respectively. This research stage mainly focuses on the basic heat transfer performance of external walls under relatively stable indoor and outdoor temperature differences. Although the solar radiation absorption coefficient and the thermal conductivity of external walls are important factors affecting the heat transfer performance of external walls, the influence of the thermal conductivity of materials has been taken into account when calculating the thermal insulation coefficient of walls. It is clearly pointed out that the calculated thermal conductivity of the structural layer material should obtain the natural equilibrium humidity condition to ensure that the calculated results are more in line with the actual situation. Therefore, in practical application, it is necessary to measure and calculate according to the specific situation.

(1) Calculation of average heat transfer coefficient of external walls

The average heat transfer coefficient K_m of the building's exterior wall is determined by calculating the weighted average of the heat transfer coefficients of the main wall and the surrounding thermal bridge. Its calculation formula is as equation (1).

$$K_m = \left(K_p \cdot M_p + K_{B1} \cdot M_{B1} + K_{B2} \cdot M_{B2} + K_{B3} \cdot M_{B3}\right) / (M_p + M_{B1} + M_{B2} + M_{B3}) \quad (1)$$

In the formula, the K_p denotes the heat transfer coefficient of the main wall of the passive ultra-low-energy assembled building facade; the M_p denotes the area of the main wall part of assembled building exterior wall; the K_{B1}, K_{B2}, K_{B3} denotes the heat transfer coefficient of each perimeter thermal bridge site of assembled building facade; and M_{B1}, M_{B2}, M_{B3} indicates the area of each perimeter thermal bridge site on the exterior wall.

If the main wall of assembly building exterior wall also consists of 2 materials, such as short-limbed shear wall plus infill wall, etc., a weighted average factor can be added to Eq. (1), which will change $K_p \cdot M_p$ into $K_{p1} \cdot M_{p1} + K_{p2} \cdot M_{p2}$. At the same time, according to the attached figure in Appendix A of JGJ 131-2001 Standard for Energy Efficiency Design of Residential Buildings in Hot Summer and Cold Winter Regions and the actual structure of residential buildings in the region, in the calculation, the peripheral thermal bridge of the main wall of the external wall of passive ultra-low energy consumption prefabricated buildings can include the structural (seismic) part in the external wall, the ring beam and the part of the floor extending into the external wall (the end of the external wall), excluding the awning Balcony boards and shelves of outdoor units of split air conditioners also exclude doors and windows.

(2) Calculation of heat transfer coefficient for the main wall and peripheral thermal bridge section

Building facade main wall and perimeter thermal bridge are components of the building facade, but they may be different in construction and materials (Mehrez *et al.* 2022). For example, the main wall can be constructed with concrete hollow blocks, concrete porous bricks, aerated concrete blocks, clay porous bricks, etc., or reinforced concrete cast-in-situ; while the structural columns, ring beams and floor slabs are mostly reinforced concrete structures (a few of them have been constructed with steel). However, K is the same in method, both from the structural thermal insulation coefficient U and the heat transfer thermal insulation coefficient U_0, where U_0 is the sum of the thermal insulation coefficient U and the heat transfer insulation coefficient of the internal and outer surfaces U_i and U_e ; and in general, U_i and U_e can take

0.11m $^2 \cdot$ K/W and 0.04m $^2 \cdot$ K/W (according to winter conditions) respectively. Hence, the formula (2) can be used to express for K of each component of the building exterior wall.

$$K=\frac{1}{U_0}=\frac{1}{U_i+U+U_e} \tag{2}$$

The K for each component of the exterior wall in prefabricated building primarily focuses on determining the thermal insulation coefficient U of the wall structure itself, as described in formula (2). The main factors considered in this calculation include:

The thermal insulation coefficient of the entire passive ultra-low energy prefabricated building wall is expressed as U, which measures the ability of the wall to prevent heat transfer, an important indicator, the smaller the value of U, the better the thermal insulation performance of the wall. U_n represents the thermal insulation coefficient of each structural layer of the wall, where n is the serial number of the structural layer. If the wall is composed of three structural layers of different materials, then n can take 1, 2, 3 in turn, and the corresponding $U_1, U_2, ..., U_n$ represent the thermal insulation coefficient of the first, second and third structural layers respectively. For the solid structure, the thermal insulation coefficient of each structural layer is the ratio of the thickness of the structural layer δ and the calculated thermal conductivity value of the material λ_c, such as formula (3):

$$U=U_1+U_2+\cdots+U_n=\frac{\delta_1}{\lambda_{c1}}+\frac{\delta_2}{\lambda_{c2}}+\cdots+\frac{\delta_n}{\lambda_{cn}} \tag{3}$$

In the calculation of thermal insulation coefficients of walls of assembled buildings (Kalbasi and Afrand, 2022), the calculated value of thermal conductivity of the material of the construction layer λ_c must take the application of the state of natural equilibrium humidity conditions, and can not be taken directly from the dry state of the test value. Specific values can be taken in accordance with the "Thermal Engineering Code", the relevant building energy-saving application of technical regulations (implementation rules), or according to the dry state of the standard value of thermal conductivity multiplied by the corresponding correction factor to determine.

2.2 Establishment of the average heat transfer objective function of the external walls

Establish the average heat transfer objective function of the exterior wall of the assembly building, in the process of controlling the building exterior wall average heat transfer, the introduction of reaction coefficients, assuming that the amount of perturbation every 55min discrete processing, then the process of the exterior wall average heat transfer through the building exterior wall to the interior is expressed as follows.

$$HG(n)=\sum_{i=0}^{\infty}Kt_z(n-t)-\sum_{i=0}^{\infty}\lambda(x)t_r \tag{4}$$

In the formula, the $HG(n)$ denotes the process of transferring the average heat transfer from the exterior wall of a passive ultra-low energy assembly building through the exterior wall to the interior; the t_z is the thermal action of all external factors on the external walls of assembly buildings. t_r is the room temperature. t is the discrete processing time. $\lambda(x)$ indicates the speed of response of different locations of the building façade to changes in outside temperature.

According to the calculation results of Eq. (4), the relationship between the $HG(n)$ and the heat transfer coefficient is constructed, i.e.

$$\frac{HG(n)}{K}=dT(1-T)\cdot\frac{1}{\int_0^z(z-1)dz} \tag{5}$$

Compton scattering, also known as the Compton effect. When high-energy photons such as X-rays or gamma rays collide with electrons in matter, the photons will transfer part of their energy and momentum to the electrons, resulting in longer wavelengths of photons and lower energy, while the electrons gain energy and recoil. In this study, Compton scattering is mainly applied to the analysis of heat transfer coefficient of building exterior wall through Compton backscattering detection technology. Compton backscatter detection technology uses high-energy photons to generate Compton scattering with electrons in exterior wall materials. By measuring the intensity and energy changes of backscattered photons, information such as density and structure inside exterior wall materials can be obtained. This information is closely related to the heat transfer performance of the exterior wall, because the density and structure of the exterior wall material affect its thermal conductivity, which in turn affects the heat transfer coefficient of the exterior wall. In the formula, the z is the heat transfer coefficient, the T is the surface temperature of the exterior wall of a passive ultra-low energy assembly building.

Based on equation (5), the influence of the Compton scattering intensity and the window width ratio on the heat transfer coefficient of the building facade is analyzed.

$$\sum_{h} \frac{I_{DN} A_w}{dz} = \frac{\rho_d}{T \rho_d} - \frac{m_c U_v \rho_d}{K_w (1-T)} \tag{6}$$

In the formula, the I_{DN} is the Compton backscattering intensity, the A_w is the window aspect ratio of the building, and ρ_d is the proportion of windows to walls, and m_c is the thermal bridge area, the U_v is the width of the opening, the K_w is the limit value of the heat transfer coefficient, the $K_w(1-T)$ is the multidimensional heat transfer function.

With the support of Compton's backscatter detection technique, the insulation performance limits for calculating heat transfer coefficients of external walls of passive ultra-low-energy assembled buildings were calculated, i.e.

$$K' = \frac{W}{A(T_i - T_e)} = \frac{q}{T_i - T_e} \tag{7}$$

Where, K' is the insulation performance limit of the heat transfer coefficient of the building exterior wall. W is the amount of heat transferred to the surface of the building envelope. A is the area of heat from the external environment that passes through the building envelope. T_i is building indoor temperatures. T_e is building outdoor temperature, which is q consultations with W corresponding heat flow density.

According to the calculation results of Eq. (7), when the limit value of heat transfer coefficient of building exterior wall insulation is at the maximum, the control objective function K_w of building exterior wall insulation performance is established, which is expressed as:

$$K_w = \frac{K' T_e}{\alpha_e} \cdot \frac{1}{T_i - T_e} \tag{8}$$

In the formula, the α_e indicates the temperature regulation coefficient.

In order to be able to construct a relatively concise and easy to analyze theoretical model, it is necessary to properly simplify the complex practical situation. By reducing the heat transfer mode between soil and exterior wall to heat conduction, the method can focus on the core factors of heat transfer process, establish a basic theoretical framework and calculation formula, and help to understand the heat transfer mechanism between soil and exterior wall from a macro level, and provide a basis for further research. Although factors such as water migration in the soil and air convection do affect heat transfer, heat transfer is usually the main method of heat transfer in the heat transfer process of the basement exterior walls of passive ultra-low energy prefabricated buildings. According to the relevant research and actual monitoring data, in most cases, the proportion of heat transfer between the soil and the external wall is high, while the influence of water migration and air convection is relatively small. By simplifying the heat transfer mode to heat conduction, we can grasp the main aspect of the problem and get relatively accurate calculation results. The basement portion of the exterior wall of assembly building is in direct contact with the soil, and the temperature of the wall surface can be considered to be the same as the calculated average temperature of the soil in engineering (Perras *et al.* 2023). Therefore, the average heat transfer energy exchange between the soil and the inner surface of the façade is carried out only by thermal conductivity. In order to ensure that the basement wall is not subject to indoor water vapor condensation and wall moisture phenomenon, the wall internal surface temperature must be theoretically greater than or equal to the indoor calculated dew point temperature. Therefore, when the two are equal, can be obtained at this time the external wall thermal conductivity calculation formula.

$$W_g = K_g A_d (T_{soil} - T_{iw}) \tag{9}$$

In the formula, the W_g is the thermal conductivity of a basement facade; K_g is the heat transfer coefficient of the exterior wall section. A_d is the calculated area of the basement facade load. T_{soil} is the calculated mean thermodynamic temperature of the soil. T_{iw} is the calculated dew point thermodynamic temperature in the basement.

From the calculation method of basement wall load and the principle of thermal conductivity (Meister and Beausoleil-Morrison, 2021), the load of the basement wall W_c of the prefabricated building is equal to the heat conductivity W_g of the basement wall, then Eqs. (10) and (11) can be obtained.

$$W_c = K_t A_d (T_{soil} - T_i) \tag{10}$$

Where, K_t is total heat transfer coefficient of basement façade for passive ultra-low energy assembly building.

$$W_g = W_c \tag{11}$$

In the study, the relevant variables were substituted into equation (11) using equations (9) and (10), and the equation was simplified to obtain equation (12). The purpose of this step is to better understand and analyze the model by reducing the complexity of the equations.

$$K_g (T_{soil} - T_{iw}) = K_t (T_{soil} - T_i) \tag{12}$$

Substituting Eq. (1), (2) into the formula (12), the derivation of transformation to ensure that the passive ultra-low energy assembly building basement wall, not due to indoor water vapor condensation and the occurrence of moisture phenomenon of the minimum thermal resistance of the insulation layer required to calculate the formula.

$$R_{hp\min} = \frac{K_m \cdot R_{ih} T_{iw} - K \cdot T_i - R_{ih} \cdot T_{soil}}{T_i - T_{iw}} \tag{13}$$

In the formula, the R_{ih} is the convective heat resistance between the interior surface of the basement facade and the indoor air of the assembly building. $R_{hp\min}$ is minimum thermal resistance of the insulation required to ensure that the basement façade of assembly building does not experience moisture return due to indoor water vapor condensation.

Considering the symmetrical structure of assembly building exterior wall air and the two sides of the wall (Mikhailenko *et al.* 2021), with the center of the cavity as the boundary, part of the wall is intercepted, and the heated hot air is sent into the hollow inner wall by the fan to the inner wall in the form of convective heat transfer to the inner wall on both sides of the inner surface for heat exchange, the inner surface of the outer wall transfers heat to the heated inner surface through conduction, while the outer surface dissipates heat through convection with the indoor air as well as with other surfaces within the room, there are three kinds of heat transfer methods: thermal conductivity, convection and radiation (Jeong *et al.* 2022), and the radiation heat transfer is negligible due to the same surface condition on both sides of the hollow inner wall, which is regarded as a symmetric condition. Passive ultra-low energy assembly building using fans to provide power, circulation of hot air flow in the cavity, can be treated as a tube forced convection heat transfer. The formula W_f of the heat flow in the external wall of assembled building is:

$$W_f = R_{hp\min} h_f A_n \Delta T \tag{14}$$

Where, h_f denotes the rate of heat transfer by convection of of assembly building. A_n denotes the area of convective heat transfer on the inner surface of the inner wall of a passive ultra-low-energy assembled building. ΔT denotes the convective heat transfer temperature difference.

The formula of the temperature difference of heat exchange ΔT between internal and external wall flow in assembly buildings is as follows:

$$\Delta T = \left[(T_{fi} - T_n) - (T_{fo} - T_n) \right] \cdot \frac{1}{\ln \frac{T_{fi} - T_n}{T_{fo} - T_n}} \tag{15}$$

Where, T_{fi} indicates inlet temperature of the circulating air. T_{fo} indicates the circulating air outlet temperature. T_n indicates the average temperature of the inner wall surface of an interior wall.

The mean Nussel number reflects the relationship between convective heat transfer and pure heat conduction, and is an important parameter in the study of convective heat transfer. The mean Nussel number is defined as the ratio of the resistance of convective heat transfer in the boundary layer of a fluid to the resistance of heat conduction inside the fluid. The larger the value of the mean Nussel number, the stronger the role of convective heat transfer relative to pure heat conduction. Introducing the mean Nussel number, the expression for h_f is as follows:

$$h_f = \psi \frac{\lambda_f}{d_k} \tag{16}$$

Where, ψ denotes the average Nussle number; the λ_f denotes the heat conducting property of the circulating air. d_k indicates cavity equivalent diameter.

The inner and outer surfaces of assembled building walls transfer heat by thermal conductivity, and the differential equation for thermal conductivity is given by:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda (\frac{\partial^2 T}{\partial^2 x^2} + \frac{\partial^2 T}{\partial^2 y^2} + \frac{\partial^2 T}{\partial^2 z^2})}{\rho c} \tag{17}$$

Where, λ denotes the thermal conductivity of assembly building walls; the c denotes the specific heat capacity of wall materials for assembled buildings; the ρ denotes the density of wall materials for assembled buildings. τ represents a time variable to describe the dynamic conduction process of heat over time in a passive ultra-low energy prefabricated building wall. By introducing the time variable, the thermal conductivity differential equation can be used to simulate and predict the temperature distribution of the wall at different times, so as to provide a more accurate basis for the thermal performance analysis and energy saving design of the building.

Due to the assembly building indoor air for the natural flow (Thu and Zakharov, 2021), the heat exchange between the outer wall surface of the inner wall and the interior through the natural convection and radiation form, the characteristic number correlation formula is:

$$Nu_a = 0.14(Gr_a \Pr_a)^{0.33} \tag{18}$$

$$Gr_a = g\alpha_V (l_c^3 t_s - l_c^3 t_a) \cdot \frac{1}{v_a^2} \tag{19}$$

Where, g represents the acceleration of gravity; α_V represents the gas volume expansion coefficient; t_s indicates the external wall temperature of the internal wall of consumption assembled building; t_a indicates the indoor air temperature of consumption assembled building room; l_c represents the feature size; v_a represents the kinematic viscosity of indoor air in assembled building.

Convective heat transfer coefficient h_c is calculated according to the following formula:

$$h_c = \frac{Nu_a \lambda_a}{l_c} \tag{20}$$

The convective heat transfer quantity is:

$$W_c = h_c A_s t_s - h_c A_s t_a \tag{21}$$

Where, A_s represents the area of the outer wall of assembled building wall.

Angular the rate of heat transfer through thermal radiation between the outer wall of consumption assembled building interior wall and other indoor walls F_{s-i}, radiation coefficient $F_{\varepsilon s-i}$ can be calculated according to formulas (22) and (23):

$$F_{s-i}=\frac{\int_{A_i}\int_{A}\frac{\cos\theta}{\pi r^2}dAdA_i}{A_s} \tag{22}$$

$$F_{\varepsilon s-i}=\frac{1}{\left[\frac{1-\varepsilon_s}{\varepsilon_s}\right]+\frac{1}{F_{s-i}}+\frac{A_s}{A_i}\left[\frac{1-\varepsilon_i}{\varepsilon_i}\right]} \tag{23}$$

Where, θ represents the Angle between the outer wall of the passive ultra-low energy consumption prefabricated building and other indoor walls; ε_s indicates the surface emissivity of the inner wall and outer wall of consumption assembled building; A_i represents the area of other indoor walls; ε_i indicates the emissivity of other indoor surfaces, and the outer envelope and roof are colored steel plates, which is 0.66, and the ground is concrete surface, which is 0.94.

Radiation heat exchange of assembled building interior wall W_r is:

$$W_r=\sigma A_s\sum_{i=1}^{5}(F_{\varepsilon s-i}T_s^4-F_{\varepsilon s-i}T_i^4) \tag{24}$$

Where, σ represents the blackbody radiation constant; T_i indicates the indoor surface temperature.

Equivalent radiation thermal conductivity of assembled building interior wall h_r is:

$$h_r=\frac{W_r}{A_s(t_s-AUST)} \tag{25}$$

In order to analyze the total heat transfer characteristics of assembled building inner wall and outer wall to the room (Mcelroy and Guj, 2022), the operating temperature is proposed t_{op} , t_{op} is the weighted average of AUST and ambient temperature t_a, can be calculated as follows:

$$t_{op}=\left(h_c t_a+h_r AUST\right)\cdot\frac{1}{h_c+h_r} \tag{26}$$

The heat sent into the cavity by circulating hot air is not only introduced into the room, but also accumulated in the wall. For a period of time, the heat sent into the cavity is:

$$W_1=A_k\int_{\tau_1}^{\tau_2}(c_{fp}u_f\rho_f t_{fi}-t_{fo}c_{fp}u_f\rho_f)d\tau \tag{27}$$

In the formula, the A_k represents the cavity area.

Heat transfer from interior wall of assembled building to indoor W_3 is:

$$W_3=A_s\int_{\tau_1}^{\tau_2}(Kt_s-Kt_{op})d\tau \tag{28}$$

Therefore, when the assembly building thermoregulation system carries out non-steady state operation, the thermal energy storage capability of the wall W_s is:

$$W_s=W_1-2W_3 \tag{29}$$

In addition to the use of the unit area of surface of the wall to the room time by time heat release W_p to analyzing the exothermic properties throughout the day, the wall heat transfer can also be analyzed from the air supply time period and non-air supply time period (Li and Zhu, 2021). For the former, it is proposed that the time-by-time heat storage capacity W_s and thermal storage efficiency η two indicators, the larger the thermal storage efficiency η is, the more heat is stored in the wall, and the heat storage performance is good. Calculation formula for heat storage efficiency is:

$$\eta=\frac{W_s}{W_1} \tag{30}$$

In the non-air supply time period, the cumulative heat release of the outer wall surfaces during this time period is presented. W_z and exothermic ratio θ two indicators, exothermic ratio θ is the ratio of the cumulative heat W release during non-air supply hours as a percentage of the cumulative heat release for the whole day. The larger the exothermic ratio is, the better the internal wall will accumulate heat and release it in the required time period. The specific expression is:

$$\theta = \frac{W_z}{W} \tag{31}$$

By solving the objective function, the limit value of heat transfer coefficient of the building exterior wall insulation, the minimum thermal resistance of the required insulation layer,and the exothermic ratio of heat transfer are obtained for the control of the average heat transfer of the exterior wall of the assembly building. The control parameters are used to realize the average heat transfer control of consumption assembly building exterior wall.

3. Experimental analysis

In this study, a real-life residential area was chosen as the experimental subject. This residential area encompasses a total construction area of more than 70,000 square meters and consists of 16 12-storey high-rise residential buildings. All of these buildings are constructed using passive and ultra-low energy-consumption assembly techniques.

To ensure optimum thermal insulation performance, the exterior walls of these buildings are built using high-grade anti-freezing bricks. Its freeze resistance grade is F500, can withstand more than 500 freeze-thaw cycles without quality problems, can adapt to harsh cold climate environment; The thickness of the wall tile is 60mm, and the thermal conductivity is 0.35W /(m·K), which can effectively reduce heat conduction and enhance thermal insulation performance while ensuring a certain strength. The external wall is also made of extruded panel high standard external wall insulation, the thermal conductivity of the insulation material is as low as 0.028W /(m·K), the insulation thickness is up to 100mm, which can significantly reduce the heat transfer of the external wall, improve the building insulation capacity, and the compressive strength reaches 300kPa, ensuring the stability of the construction and long-term use process. The window adopts 57, 60 series of thermal insulation cold bridge casement Windows, of which 57 series is 5+12A+5 double tempered insulating glass, the thermal conductivity of the glass is 1.1W /(m·K), which can effectively prevent heat conduction and loss, and has good sound insulation effect. The window frame adopts aluminum alloy broken bridge profiles, the thermal conductivity is 1.8W /(m·K). The bridge design blocks the heat conduction path and improves the thermal insulation performance. The 60 series adopts 5+15A+5 double tempered insulating glass, the thermal conductivity of the glass is 1.05W /(m·K), which further improves the thermal insulation and sound insulation performance. The thermal conductivity of the aluminum alloy broken bridge profile window frame is 1.7W /(m·K), the broken bridge design is optimized, and the insulation effect is better. In this paper, the proposed method is used to control the average heat transfer of the exterior wall of the passive ultra-low energy prefabricated building in this community, so as to improve its thermal insulation capacity, and the practical application of the method is analyzed. The external wall parameters of the consumption assembled buildings in this community are outlined in Table 1. This comprehensive data serves as a basis for further analysis and evaluation of the average heat transfer control technology employed in these buildings, with the ultimate goal of achieving energy conservation and emission reduction.

Table 1 External Wall Parameters of Passive Ultra Low Energy Consumption Prefabricated Buildings

Materials used		thickness	density	Specific heat capacity	thermal conductivity
Special decorative mortar and coating		20	1900	1100	0.94
Load-bearing structure	Brick masonry	240/370/480	1800	1100	0.78

reinforced concrete	200	2400	910	1.76
cement mortar	20	1700	1100	0.88
unit	mm	kg/m3	kg·K	m·K

To regulate the average heat transfer of the external wall in assembled buildings, it is necessary to implement measures for controlling the thermal exchange. It is crucial to accurately calculate the external wall heat transfer coefficient. For the purpose of this study, a specific 12-story building within the aforementioned residential area was selected as the experimental object.

Using the proposed method, the external wall heat transfer coefficient of this 12-story building was calculated. The calculation took into consideration various factors such as the materials used in the construction of the exterior wall, insulation techniques employed, and window specifications. The results of these calculations are presented in Table 2. These calculated values provide important data for evaluating and analyzing the thermal performance of the external wall in the assembled building. With these results, further improvements and optimizations can be made to enhance the energy efficiency and overall performance of the building.

Table 2 Calculation results of heat transfer coefficient for exterior walls of prefabricated buildings

Number of floors	Calculated value	Actual measured value	deviation
1	2.644	2.624	0.02
2	2.017	2.007	0.01
3	1.895	1.895	0
4	2.151	2.141	0.01
5	2.309	2.289	0.02
6	2.511	2.511	0
7	2.332	2.332	0
8	2.158	2.158	0
9	2.169	2.159	0.01
10	2.247	2.237	0.01
11	1.966	1.946	0.02
12	2.039	2.039	0

From the analysis of Table 2, it can be seen that the heat transfer coefficient of consumption assembled building external wall calculated by the proposed method is in good agreement with the actual value, and the maximum difference is 0.02, showing good accuracy. This result reflects the good ability of the proposed method in controlling the average heat transfer of assembled building external wall. The advantage of the proposed method in controlling the average heat transfer of passive assembled building exterior wall lies in the comprehensive consideration of many factors, such as heat preservation, air tightness, waterproof and so on. By optimizing material selection, structural design and intelligent control, the efficiency, energy saving and comfort are improved. In addition, the proposed method has good expansibility and flexibility, and can be combined with other green building technologies to realize diversified utilization and sustainable development of energy. However, although the proposed method shows good performance in the control of average heat transfer on the external wall of assembled buildings, it still needs continuous research and improvement to adapt to different building types and use environments. In the future, we can further explore the development of new materials, the optimization of structural design and the upgrading of intelligent control, so as to make greater contributions to promoting green buildings and sustainable development.

To experimentally validate the effectiveness of controlling the average heat transfer of the external wall in prefabricated buildings, 10 such buildings within the residential area were chosen as the experimental objects. Taking the limit value of heat transfer coefficient as a measurement index, the heat transfer coefficient represents the heat transferred by unit area in unit time when the temperature difference between the two sides of the envelope is 1K under steady state conditions. The heat transfer coefficient is the key index to measure the insulation performance of the enclosure structure, which intuitively reflects the ability of the external wall to transfer heat under the unit temperature difference. The lower the heat transfer coefficient, the better the thermal insulation performance of the external wall, which can effectively reduce the exchange of indoor and outdoor heat and reduce the energy consumption of the building. The formula is as follows:

$$K = \frac{1}{\sum_{i=1}^{n} d_i + R_{hp\min} + R_{ih}} \tag{32}$$

Where, n represents the number of layers of the flat wall; d_i Thickness of the i layer material.

After implementing the proposed method, the limit value of the heat transfer coefficient of the external wall in the passive ultra-low energy-consumption prefabricated buildings was determined. The results of these measurements are visually displayed in Figure 1. The data in Figure 1 provides a clear illustration of the achieved limit values for the heat transfer coefficient. This information is crucial for evaluating the thermal performance of the external wall in prefabricated buildings. By adhering to these limit values, it is possible to optimize energy efficiency and ensure the desired heat transfer control in such buildings.

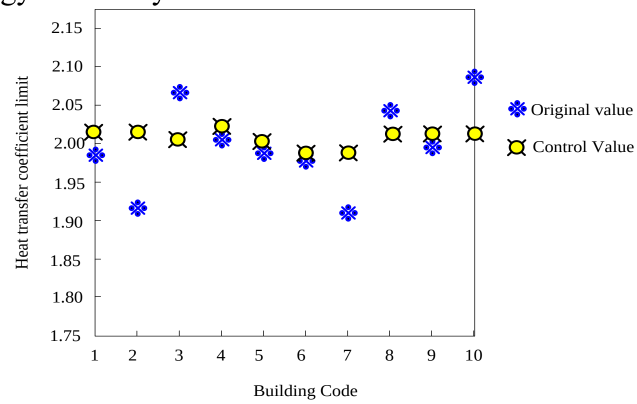

Fig. 1 Average heat transfer control results of consumption prefabricated building exterior walls

It can be found from the analysis of Figure 1 that the heat transfer coefficient limit of consumption prefabricated building exterior wall fluctuates greatly, indicating that there are differences in its thermal insulation performance. After the proposed method is applied to control the average heat transfer of the external wall of the 10 passive ultra-low energy consumption prefabricated buildings, the average heat transfer coefficient limit of the external wall is controlled at about 2.0, and the fluctuation range of the heat transfer coefficient limit is relatively small. This shows that the proposed method can effectively control the average heat transfer of fabricated building exterior wall, and significantly improve its thermal insulation performance. The application effect of the proposed method is remarkable, which can provide effective guidance for the design and construction of passive ultra-low energy consumption prefabricated building exterior walls. At the same time, the proposed method also has good universality and scalability, and can be applied to different types of prefabricated building exterior walls, providing more comprehensive and effective technical support for its design and construction.

Taking indoor human comfort temperature as a measurement index, the effect of the proposed method on controlling the average heat transfer of passive ultra-low energy assembled building exterior wall is verified, and the test results are shown in Figure 2.

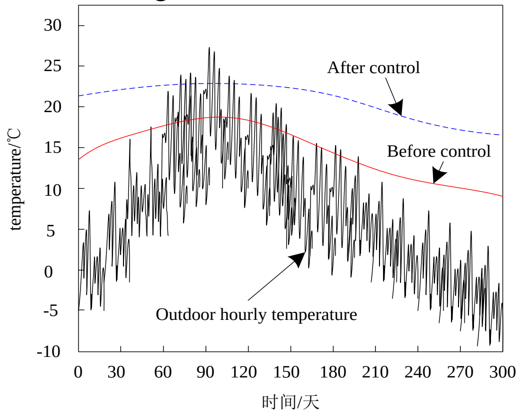

Fig. 2 The average heat transfer control effect of passive ultra-low energy consumption prefabricated building exterior walls

By analyzing Figure 2, it can be found that the hourly outdoor temperature presents an obvious peak distribution, and the maximum temperature is quite different from the minimum temperature. However, before the average heat transfer control of assembled building exterior wall, the comfortable temperature of human body in the building room was low, only about 14-18℃, and its distribution trend was the same as that of outdoor hourly temperature. This means that the indoor temperature of the building will also drop. However, after applying the proposed method to control the average heat transfer of the assembled building exterior wall, the human comfort temperature in the building room is controlled at about 18-22℃, which is more suitable for human habitation and makes people feel more comfortable. Therefore, the proposed method shows a good effect in improving the thermal insulation performance of prefabricated buildings. In addition, this method achieves energy conservation and environmental protection by effectively controlling average heat transfer. The internal temperature of the external wall of assembled building will decrease with the decrease of outdoor temperature. After the average heat transfer of the external wall is controlled by the proposed method, the attenuation change of the internal temperature of the wall is analyzed. In order to make the experimental results more sufficient, the methods of literature (Elmzughi *et al.* 2021), literature (Sepehri and Pavlak, 2022), literature (Chandhran and Elavenil, 2023), literature (Dabbagh and Krarti, 2021) and literature (Vivek and Balaji, 2023) are used at the same time for testing, and the test results are shown in Figure 3.

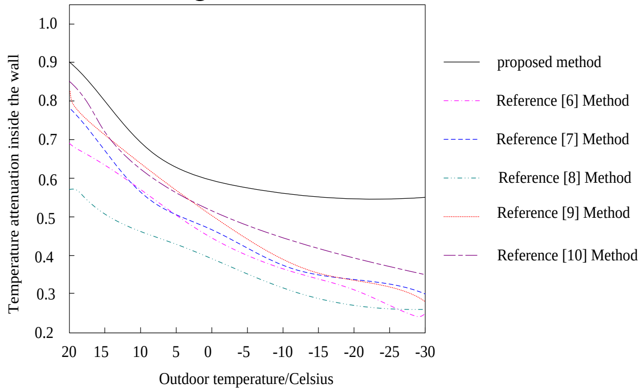

Fig. 3 Temperature attenuation inside the wall

By analyzing the data in Figure 3, we can observe the correlation between the attenuation of internal temperature and outdoor temperature in prefabricated building exterior walls. Particularly, when the outdoor temperature decreases, the proposed method demonstrates more effective control over the average heat transfer of the exterior wall compared to other comparison methods. This control effect is evident in two significant aspects. Firstly, the proposed method significantly reduces the rate at which the internal temperature of the exterior wall decreases in response to changes in outdoor temperature. This signifies that the indoor temperature is less impacted by external environmental conditions and can remain relatively stable. Such stability is of great significance in enhancing occupants' comfort and minimizing energy consumption. Secondly, the proposed method showcases the advantages of improving the air tightness and thermal insulation capabilities of buildings. By regulating the heat transfer of the exterior wall, this method helps mitigate indoor-outdoor heat exchange, consequently reducing energy loss and enhancing the building's thermal insulation performance. In summary, the proposed method demonstrates commendable performance in the design and optimization of prefabricated building exterior walls. It effectively enhances the building's air tightness and thermal insulation capabilities while ensuring the stability of indoor temperatures, thus creating a more comfortable living environment for residents.

To further verify the application effect of the proposed method, the thermal insulation rate of the external wall of prefabricated buildings is taken as the measurement index, and 10 prefabricated buildings are taken as the experimental objects to test the thermal insulation rate of the external wall of the building after the average heat transfer of the external wall is controlled by the proposed method and the comparison method. The test results are shown in Table 3.

By analyzing the data in Table 3, we can see that among the 10 passive ultra-low energy consumption prefabricated buildings, the external wall insulation rate of each building shows a certain fluctuation trend by controlling the average heat transfer of the external wall. However, after using the proposed method for control, the thermal insulation rate of these buildings exceeded 80%, and the highest value reached 90.3%. Compared with other methods, the proposed method performs more significantly in improving the thermal insulation rate of external walls. This shows that through the application of the proposed method, the external wall thermal insulation performance of prefabricated buildings has been effectively improved. This can not only reduce energy consumption and carbon emissions. In conclusion, the proposed method plays an important role in the design and optimization of consumption prefabricated buildings. By controlling the average heat transfer of the external wall, this method significantly improves the insulation rate of the external wall of the building, and provides strong support for promoting the development of green buildings. This is because the method by establishing an objective function and solving it, insulation rate can be improved, comfort can be improved, and environmental impact can be reduced.

Table 3 Passive ultra-low energy consumption prefabricated building exterior wall insulation rate (%)

Building Code	proposed method	Reference (Elmzughi *et al.* 2021) Method	Reference (Sepehri and Pavlak, 2022) Method	Reference (Chandhran and Elavenil, 2023) Method	Reference (Dabbagh and Krarti, 2021) Method	Reference (Vivek and Balaji, 2023) Method
1	85.5	76.4	81.2	75.4	80.2	77.4
2	89.1	73.2	78.5	74.1	80.1	69.8
3	83.4	71.2	78.6	72.1	72.4	65.9
4	86.1	69.8	78.8	70.6	75.6	68.7
5	82.5	80.1	75.4	66.9	73.1	70.3
6	83.7	79.5	73.1	70.6	71.5	71.5
7	85.4	77.4	70.6	70.9	71.9	75.4
8	90.3	76.7	69.8	78.5	75.4	68.7
9	80.6	66.4	66.7	71.3	72.8	71.9
10	81.4	70.9	73.5	73.2	79.1	70.7

In order to assess the effectiveness of the proposed method in reducing the energy consumption of passive ultra-low energy-consumption prefabricated buildings, the external wall energy consumption was chosen as the measurement index. A total of 10 prefabricated buildings were selected as experimental objects for analysis. The energy consumption of these 10 buildings was evaluated before and after the implementation of the proposed method. By comparing the energy consumption values, the impact of the method on reducing energy consumption could be determined. The test results of this analysis are presented in Figure 4. Figure 4 visually depicts the energy consumption changes in the 10 buildings. The data provides a comprehensive understanding of the energy-saving benefits achieved through the application of the proposed method. These results highlight the potential for significant energy savings in prefabricated buildings, thereby reinforcing the importance of implementing energy-efficient measures in construction practices.

After analysing Figure 4, it is evident that the external wall energy consumption of the 10 prefabricated buildings varies between 100-145 kJ. This variation indicates differences in the average heat transfer and insulation effectiveness of the buildings' external walls. Upon implementing the proposed method to control the average heat transfer of the external walls, a noticeable reduction in energy consumption was achieved, resulting in a smaller fluctuation range. This outcome demonstrates the effectiveness of the proposed method in improving the thermal insulation performance of prefabricated building external walls. By controlling heat transfer through the external walls, the loss of energy is minimized, leading to stable indoor temperatures and reduced overall energy consumption. These findings hold significant importance for promoting the development of green buildings and achieving energy conservation and emission reduction goals. Furthermore, considering that each building has different external wall structures and insulation materials, their thermal insulation effects also differ. Therefore, by tailoring the application of the proposed methods to optimize and control specific building characteristics, the thermal insulation performance can be improved more effectively. The strengths of the proposed method lie in its ability to reduce energy consumption, stabilize indoor temperatures, and promote sustainability in the construction industry. By implementing these methods, Prefabricated buildings can contribute to the broader goal of achieving resource-efficient and environmentally friendly building practices.

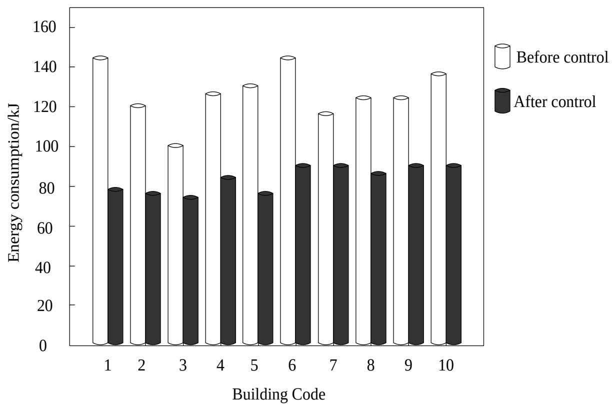

Fig. 4 Energy consumption of passive ultra-low energy consumption prefabricated building exterior walls

4. Conclusion

The main purpose of this study is to explore the average heat transfer control technology of passive ultra-low energy prefabricated building exterior wall, and precisely calculate the average heat transfer coefficient of passive ultra-low energy prefabricated building exterior wall and the heat transfer coefficient of the main wall and the surrounding thermal bridge, considering various factors affecting the heat transfer of the exterior wall, and improve the energy efficiency and comfort of the building by adjusting the average heat transfer. Considering the various factors affecting the heat transfer of exterior walls, by establishing the objective function and solving it, the limitations of traditional methods are broken through, and the accurate control of the average heat transfer of exterior walls is realized. Through experimental analysis, we effectively managed the average heat transfer of prefabricated building exterior walls. This method not only improves the sealing performance of the exterior wall, but also ensures the best indoor comfort. The application of this method has shown positive results. In summary, as a high-performance green building technology, the average heat transfer control technology of prefabricated building exterior walls is the key to achieving high energy efficiency and comfort. The research on average heat transfer control technology for prefabricated building exterior walls is of great significance.

Although this research method has achieved certain results, there are still some limitations. In the process of calculating the heat transfer coefficient and establishing the objective function, the consideration of the actual operating environment of the building is relatively simplified. In the actual use of buildings, environmental factors (such as climate change, solar radiation, etc.) and human factors (such as indoor personnel activities, equipment use, etc.) are complex and changeable, and this study fails to fully incorporate these dynamic change factors into the model, which may lead to a decrease in the adaptability of control parameters in practical applications. Based on the above limitations, the future will be committed to further improving the model, taking more dynamic factors into account, such as the establishment of a dynamic heat transfer model, real-time simulation of different environmental conditions and human factors under the building external wall heat transfer changes, in order to improve the accuracy and adaptability of control parameters, the formation of a more comprehensive and efficient building energy saving solutions.

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