

Research on the Heat Transfer Characteristics and Energy-Saving Performance Prediction Model of Vacuum Insulation Board Composite Wall

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Abstract: This study conducts a quantitative analysis of the thermal bridge effect caused by the joints during the construction of vacuum insulation panels, revealing a significant positive correlation between the width of the joints and the increase in the heat transfer coefficient of the wall. Calculations show that when the width of the board joint increases to the upper limit of 20 mm, the deterioration rate of the heat transfer coefficient of the wall can reach 40% (i.e., the insulation performance will decline by approximately 33%). Based on this, a dynamic correction model for thermal conductivity is proposed. This model achieves the engineering quantitative correction of the thermal bridge effect by introducing the panel gap attenuation factor, providing a key parameter basis for the thermal design of the insulation system. At the same time, energy consumption calculations are conducted for passive buildings using composite insulation boards. The impact of vacuum insulation board failure on building energy consumption before and after is analyzed, as well as the methods for ensuring the operation of the building in the later stage, providing a reference for the subsequent engineering design of the built-in insulation system using composite insulation boards.

Keywords: vacuum insulation board; board joint; heat transfer through walls; building energy consumption; built-in insulation

1 INTRODUCTION

With the continuous improvement of China's building energy conservation standards, the restrictions on the heat transfer coefficient of building envelope structures, especially composite walls, are becoming increasingly strict [1]. Traditional organic insulation materials have obvious deficiencies in fire resistance performance. Due to their insufficient fire resistance (usually only grade B or lower), traditional organic insulation materials are prone to become significant fire risk sources in practical applications. In comparison, although the mainstream inorganic building materials in the market have inherent flame-retardant properties (the materials themselves do not participate in the combustion reaction), their thermal insulation and heat preservation performance have inherent defects. The thermal conductivity is generally in the range of 0.040-0.070W/(m·K). It is difficult to meet the strict requirement in the current energy-saving standards that the heat transfer coefficient of the envelope structure should be ≤ 0.30 W/(m²·K) [2]. This contradiction between thermal performance and fire safety has become a key bottleneck restricting the iteration of building energy-saving technologies. Therefore, the development of new composite wall insulation materials that combine excellent thermal performance and reliable fire resistance has become an urgent need in the industry.

Vacuum Insulation Panel (VIP), as an innovative inorganic insulation material, typically features an inner core composed of inorganic fibers and an outer foil coating with high barrier properties. Through an internal vacuum treatment process (usually requiring the addition of an absorbent to maintain the vacuum degree), this material eventually forms a building insulation product that meets the A1-level fire protection standard. STP (Stuffing the Pipe) vacuum insulation panels, with their remarkable ultra-thin characteristics, extremely low thermal conductivity and excellent long-term durability, have demonstrated extremely high market promotion and application potential in the context of the rapid development of energy-saving buildings in China [3].

The vacuum insulation panel (STP for short) external

wall insulation system for buildings achieves insulation of the building envelope through the following multi-functional composite structural layers: The interface bonding layer uses polymer-modified cement-based adhesives or gypsum-based cementitious materials to ensure reliable connection between the system and the base layer; The core insulation layer is composed of STP vacuum insulation panels ($\lambda \leq 0.008$ W/(m·K)) to form the core insulation unit. The enhanced protective layer is made by combining plastering mortar with alkali-resistant mesh fabric (ZrO₂ content $\geq 14.5\%$, unit weight ≥ 160 g/m²) or plastering gypsum with medium-alkali mesh fabric to form an anti-cracking stress buffer zone. The exterior decorative layer covers diversified decorative solutions such as elastic coatings, decorative mortars, and ceramic thin plates.

Similar to materials such as EPS (polystyrene board), XPS (extruded polystyrene board), and conventional inorganic insulation boards, STP boards also encounter the problem of gaps between the boards during the construction and laying process. Different gap treatment processes will significantly affect the strength of the resulting thermal bridge effect. This article takes STP insulation materials as the research object and focuses on discussing the impact of different treatment methods adopted for board joints in the practical application of external wall insulation systems on the overall insulation performance of the system. Current related research mostly focuses on the testing of the physical properties of STP materials themselves, the comparative analysis of theoretical energy-saving effects, or the optimization of actual installation processes. However, research on the inevitable board joints during the construction process and their impact on the overall heat transfer coefficient of the wall is relatively scarce. Therefore, this study aims to deeply analyze the specific influence mechanism of construction board joints on the heat transfer performance of walls. Based on this analysis result, an engineering application correction method for the thermal conductivity of STP materials is proposed, with the expectation of providing valuable references for the subsequent research and engineering practice of such high-performance insulation boards.

The continuous improvement of building energy conservation standards is the core driving force for the constant innovation and progress of building energy conservation technologies. The research and large-scale application of new energy-saving technologies have become a key strategic link to ensure the sustainable development of the construction industry. At present, some regions in our country have begun to implement a higher energy-saving standard of 75% (an increase of 80% compared to the benchmark energy-saving rate). Against this backdrop, STP vacuum insulation panels, with their ultra-thin structure (effectively saving building space), excellent insulation performance, the highest grade of A-level fire resistance, and relatively mature and safe construction technology, have become the preferred material with prominent comprehensive advantages in thin plaster external wall insulation systems and insulation and decoration integrated panel systems. Meanwhile, the application scope of STP vacuum insulation panels is constantly expanding, extending to emerging fields such as prefabricated buildings, passive ultra-low energy consumption buildings, and cold chain logistics projects.

This study will take insulation materials as the core research object. Through computational simulation methods, it will analyze the overall energy consumption performance of buildings under different climate regions and the selection of different types and thicknesses of insulation materials, thereby summarizing the universal laws of energy consumption changes in each region. This paper focuses on analyzing the specific influence paths of insulation layer material types, thickness parameters, and key climatic factors on the energy consumption of building air conditioning, and then makes a scientific evaluation of the heat transfer performance of STP ultra-thin insulation boards in practical applications and the energy-saving potential they contain. In addition, the research will introduce the Life Cycle Cost Analysis (LCCA) method to quantitatively compare the energy-saving benefits that can be achieved by applying various insulation materials including STP in different regions. By systematically examining core economic indicators such as the economic thickness of the insulation layer, initial investment cost, long-term energy-saving benefits, and payback period of investment, the economic advantages of using STP as an insulation material are deeply explored, and ultimately a comprehensive assessment of its overall potential in the field of building energy conservation is made. The first part of this article is the introduction, the second part is the related work, and the third part is the technical performance indicators of STP vacuum insulation board insulation system, the fourth part is analysis of energy-saving characteristics of built in vacuum insulation panel composite insulation system the fifth part is experimental verification, and the sixth part is the conclusion.

2 RELATED WORK

Domestic and foreign scholars' research on STP vacuum insulation panels mainly focuses on three major areas: characterization of material physical properties, optimization of construction processes, and their impact mechanism on building energy consumption. At the level of material physical property research, the insulation

mechanism and application boundaries were systematically expounded, and the key construction techniques and quality control points were discussed in detail [4], providing theoretical support for the promotion of engineering practice. Another study [5] quantitatively revealed the intrinsic relationship between the vacuum degree within the board and the thermal insulation performance through a combination of experimental testing and theoretical modeling, and then optimized the optimal matching parameter combination of vacuum degree and thermal conductivity. Team D [6] started from the principle of heat transfer and pointed out that the outstanding heat insulation performance of this material stems from its simultaneous blocking of the three heat transfer paths of heat conduction, heat radiation and gas convection, thereby achieving an extremely low thermal conductivity.

In the field of engineering application and construction technology research, scholars [7] have conducted a comprehensive evaluation of the technical economy and long-term durability of STP board engineering projects, and proposed two innovative paths to improve the construction process of cast-in-place concrete external wall insulation, aiming to enhance the service life of materials and provide technical references for the development of China's building industrialization. Another study [8] combined with typical engineering cases, systematically summarized the construction process and technical key points of STP boards, and demonstrated that they have significant application prospects in the fields of green buildings and sustainable construction.

Regarding the research on the impact of material energy consumption, scholars [9] compared the comprehensive benefits of STP boards and polystyrene foam boards, constructed a multi-factor economic model including material costs, energy prices, and building rents, and proved that STP boards are more suitable for high-rent commercial buildings. The simulation study based on EnergyPlus [10] quantified the optimal insulation layer thickness when STP boards were used in residential buildings in different climate zones. The analysis of the full life cycle cost indicated that this material has significant energy-saving benefits and economic feasibility in extremely cold, cold, and hot summer and cold winter regions.

To break through the technical bottleneck of the thickness of insulation layers in passive buildings, China has innovatively developed a variety of thin external wall insulation systems. A typical case is a passive ultra-low energy consumption residential project [11, 12], which adopts the prefabricated "sandwich" core exterior wall structure shown in Figure 1: the insulation layer uses a composite structure of rigid polyurethane foam - vacuum insulation board - rigid polyurethane foam. Similarly, a certain public rental housing project [13] selected prefabricated sandwich walls composed of rock wool and vacuum insulation panels. Although this type of design significantly reduces the wall thickness (by more than 40%) by taking advantage of the ultra-low thermal conductivity of STP boards and enhances impact resistance and weather resistance, it still faces four major technical challenges: high cost, complex production process, limited adaptability to prefabricated walls, and defects in edge protection of the

boards.

In response to the above problems, the academic community has developed the built-in vacuum insulation board composite insulation board (hereinafter referred to as the composite insulation board) [14, 15]. This technology implements the overall foaming molding of polyurethane by alternately arranging STP boards, forming a discontinuous insulation layer with perforable areas. Although the overall thermal performance is slightly lower than that of the aforementioned prefabricated walls, in passive building applications in extremely cold or cold regions, an insulation layer thinning effect of approximately 100mm can still be achieved. This innovation not only resolves the inherent flaws of prefabricated walls but also expands their application scenarios - it is compatible with prefabricated sandwich walls, exterior thin plaster systems, and cast-in-place concrete built-in insulation systems, significantly enhancing the universality of the technology.

Multi-layer Insulation Structure Diagram

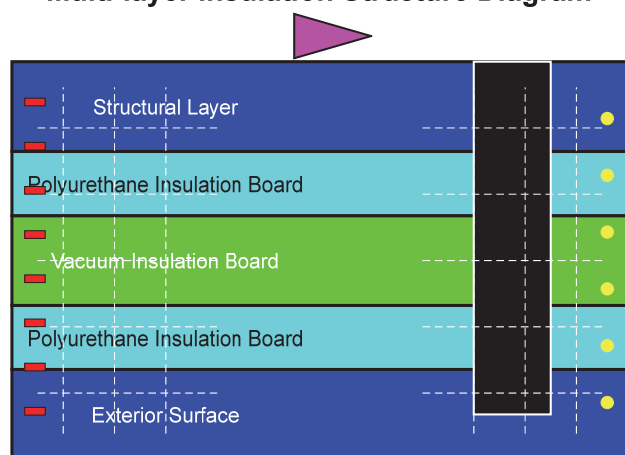


Figure 1 Prefabricated wall structure

At present, breakthroughs have been made in the research of core materials for vacuum insulation panels (VIP) in aspects such as raw material selection, preparation process and physical property optimization. Systematic research on the performance of core materials [16] indicates that when short-cut original fiber glass fibers are used to replace traditional glass wool, the thermal conductivity of the board is significantly optimized and its service life can be extended to 15 years. It is worth noting that STP vacuum insulation panels have achieved a major breakthrough in core material innovation. Given that international high-end vacuum insulation products generally use high-temperature resistant granular core materials such as fumed silica, which leads to high costs, domestic research [17] creatively introduced microsilica powder as an alternative material. The cost of this material is only one fourth of that of fumed silica. Its raw material comes from the recovered dust of industrial waste gas, which is purified and reused as a resource. This technological breakthrough not only broke through the bottleneck of raw material cost constraints but also established a technical path for resource recycling and utilization, becoming the core technical support for promoting the large-scale application of STP vacuum insulation panels in buildings.

In the field of building energy conservation simulation

research, multi-dimensional analysis methods have been continuously deepened. The energy consumption simulation of residential buildings based on the TRNSYS platform [18] reveals that optimizing ventilation strategies and strengthening the insulation of the envelope structure can significantly reduce the air conditioning load in summer. The simulation study of commercial buildings in hot summer and warm winter regions by DeST software [19] quantified the sensitivity of parameters such as the thickness of external wall insulation, shading system, and skylight structure to energy consumption. It pointed out that excessive insulation in this climate zone would instead lead to energy waste and suggested moderately weakening the insulation performance. A systematic analysis of the window-to-wall ratio [20] (covering 9 cities in climate zones) indicates that the energy consumption for heating and cooling is significantly linearly correlated with the window-to-wall ratio, and the energy consumption of the south-facing exterior walls is the lowest in hot summer and cold winter regions. Innovative research [21] introduced the POE (Post-Use Assessment of Buildings) model, for the first time incorporating personnel behavior variables (such as daily routines, equipment usage habits, and domestic hot water patterns) into the energy consumption prediction system. Another scholar [22] has constructed a quantitative assessment model for the energy-saving contribution of the envelope structure through parametric modeling technology.

Research on the economic efficiency of insulation materials at home and abroad mainly focuses on thickness optimization methods. The technical routes can be divided into three categories: The day number method: operating under simplified assumptions of constant building usage patterns, HVAC efficiency, design temperature and heat gain [25-27], it is highly efficient in calculation but has limited accuracy. Transient heat transfer method: It includes two technical paths, namely analytical solution and numerical simulation. The latter is implemented through professional software such as EnergyPlus [28], with significantly improved accuracy. Thermal and humidity coupling model: It comprehensively considers the influence of humidity on thermal performance [29], with the highest calculation accuracy but limited application.

The review of the current research status indicates that the current research on vacuum insulation panels mainly focuses on non-construction fields such as cold chain equipment, and there is a significant gap in the research on building applications. Existing research related to architecture overly focuses on material preparation processes and lacks a systematic energy-saving economic analysis framework. Although there are relatively abundant studies on building energy consumption simulation abroad, the research conclusions based on the frigid climate conditions of Northern Europe or North America have limited reference value for the multi-climate zones.

3 TECHNICAL PERFORMANCE INDICATORS OF STP VACUUM INSULATION BOARD INSULATION SYSTEM

3.1 Technical Performance Indicators of STP Vacuum Insulation Panels

The technical performance indicators of STP vacuum insulation panels are shown in Tab. 1.

Table 1 Technical performance indicators of STP vacuum insulation panels

Project	Indicator		
	Type I	TypeII	TypeIII
Thermal conductivity / W/(m·K)	≤ 0.005	≤ 0.008	≤ 0.012
Mass per unit area / kg/m ²		≤ 10	
Dry density / kg/m ³		450	
Combustion performance		A	

3.2 Technical Performance Indicators of the Matching Thermal Insulation Slurry

In the engineering practice of STP vacuum insulation board external wall insulation systems, the treatment of board joints generally adopts the filling technology of special insulation slurry. This slurry system is prepared by precisely proportioning Portland cement as the cementitious matrix, combined with a lightweight aggregate system (including expanded perlite, surface vitrified closed-cell microspheres and modified polystyrene particles) and functional additives (such as hydrophobic agents and early strength agents). Its core value lies in effectively suppressing the thermal bridge effect in the board joint area by constructing a continuous insulation interface, thereby enhancing the overall thermal uniformity of the system, as shown in Tab. 2.

Table 2 Main performance indicators of thermal insulation slurry

Project	Indicator
Dry density / kg/m ³	250-450
Compressive strength / MPa	≥ 0.50
Thermal conductivity / W/(m·K)	≤ 0.085
Combustion performance	A

Engineering practice shows that glass microsphere-based composite slurry has become the mainstream solution for STP board joint filling. This material, as an inorganic insulation aggregate widely used in the field of building energy conservation in China, forms an efficient thermal resistance layer with its closed-cell microsphere structure (particle size 0.5-1.5 mm, closed-cell rate ≥ 80%), and the measured thermal conductivity is ≤ 0.048 W/(m·K). In the application system, it is usually combined with 42.5 grade Portland cement-based cementitious materials to prepare thermal insulation mortar. Its core technical advantages are reflected in: excellent comprehensive performance: the bonding strength is ≥ 0.15 MPa, and the accelerated aging test shows that the strength attenuation rate after 25 years is less than 15%. Strong engineering adaptability: The daily construction efficiency can reach 300-500 square meters, shortening the construction period by 40% compared with the organic insulation system. Ecological sustainability: The utilization rate of industrial solid waste in raw materials is ≥ 30%, and the VOC (volatile organic compounds) emission is < 5 μg/m³. The thermal conductivity of the glass microsphere thermal insulation mortar involved in this study is 0.106 W/(m·K). This value comprehensively takes into account the fluctuation of water-cement ratio (0.55-0.65), the dispersion of aggregate gradation (gradation index $U_i = 1.8-2.3$), and the influence of environmental humidity (RH60% equilibrium state) in actual engineering, and is more representative of the project than the nominal value

of the material.

3.3 Calculation of the Influence of Board Joints on the Heat Transfer Coefficient of Walls

This study innovatively established a quantitative evaluation system for the thermal bridge effect of plate joints. Based on the principle of building thermal engineering, a zonal discretization analysis method is adopted: Firstly, the wall is divided into the main area of the insulation board and the affected area of the board joint according to the distribution characteristics of the width of the board joint, and the area weight parameters of each area are calculated respectively. Then, the comprehensive heat transfer performance index of the wall with panel joints is obtained through the area-weighted average algorithm. Ultimately, based on the ideal state without plate seams, the thermal bridge effect intensity index was constructed - this index precisely characterizes the percentage of heat transfer performance degradation caused by plate seams. Empirical research shows that this method can quantitatively reveal the quantitative correlation law between the size of the board joint and thermal deterioration, providing a scientific basis for the diagnosis of thermal defects in insulation projects.

$$\bar{R} = \frac{F_0}{\frac{F_1}{R_1} + \dots + \frac{F_n}{R_n}} \quad (1)$$

In the formula: R (represents the average thermal resistance, m²K/W; F_0 is the total heat transfer area perpendicular to the direction of the heat flow; F_n represents each heat transfer area divided parallel to the direction of heat flow; R_n represents the thermal resistance value of various materials, m²K/W.

The heat transfer coefficient K of the wall.

$$K = \frac{1}{R_i + R_f + R_q + R + R_k + R_e} \quad (2)$$

If the influence of the board joints on the heat transfer of the wall is not considered, then the heat transfer coefficient of the wall K_0 .

$$K_0 = \frac{1}{R_i + R_f + R_q + R_l + R_k + R_e} \quad (3)$$

R stands for thermal resistance, which is a physical quantity that measures the ability of a material or structure to impede heat transfer. Then the influence of the thermal bridge effect of the board joint on the heat transfer coefficient of the wall:

$$\varepsilon = \frac{K - K_0}{K} \quad (4)$$

K is the heat transfer coefficient, which characterizes the amount of heat transferred by a unit area of the wall within a unit time under a unit temperature difference,

reflecting the heat transfer capacity of the wall. This study selects the 200 mm thick reinforced concrete base wall composite thin plaster external wall insulation system as the benchmark model and uses the standard STP board unit (600 × 400 mm) as the reference system to conduct parametric research on the thermal effect of multi-specification board joints. The key point is to investigate the quantitative influence mechanism of the thermal bridge effect on the comprehensive heat transfer coefficient of the wall under the coupling effect of different STP board thicknesses (gradient changes of 20-50 mm) and board joint structures (widths of 5-20 mm). By establishing a three-dimensional unsteady heat transfer model, the distribution characteristics of the heat flux density of the wall under various working conditions were simulated and calculated. Eventually, a mapping relationship matrix of panel joint size - insulation layer thickness - heat transfer coefficient deterioration rate was formed (see Tab. 3 for details). This matrix reveals that when the width of the board gap reaches the critical value of 20 mm, the thermal performance degradation rate of the 40 mm thick STP board system is 38.7%, significantly higher than the 42.3% deterioration value of the 30 mm thick system under the same conditions. This proves that increasing the thickness of the insulation layer can partially compensate for the thermal bridge loss of the board gap.

Table 3 shows the heat transfer coefficients of wall joints with different STP specifications, dimensions and thicknesses

Width of the board joint / mm	STP thickness / mm			
	10	15	18	20
5	15.46	16.74	17.23	17.48
10	25.48	27.62	28.38	28.92
15	32.53	35.23	36.23	36.75
20	37.73	40.86	42.03	42.62

Fig. 2 reveals that the thickness of the STP board (in the range of 20-50 mm) has a weak effect on the sensitivity of the thermal bridge at the board joint (coefficient of variation < 8%), while the thermal resistance of the base wall becomes a key regulatory factor. When the thermal resistance value of the base wall drops from 0.25 (m²·K)/W to 0.15 (m²·K)/W, the degradation rate of the heat transfer coefficient caused by the seams of plates of the same specification increases by 12 to 18 percentage points. Research shows that when the single area of the STP board is expanded to 1.0 × 0.8 m, the proportion of the thermally affected area of the board joint is reduced to 54% of the reference size, proving that the scale effect of the insulation unit can effectively suppress the thermal bridge effect. However, the width of the plate joint remains the dominant influencing factor: for every 5 mm increase in width, the heat transfer coefficient grows geometrically (growth index $\alpha = 1.8-2.2$), and this rule is particularly significant in extremely cold regions.

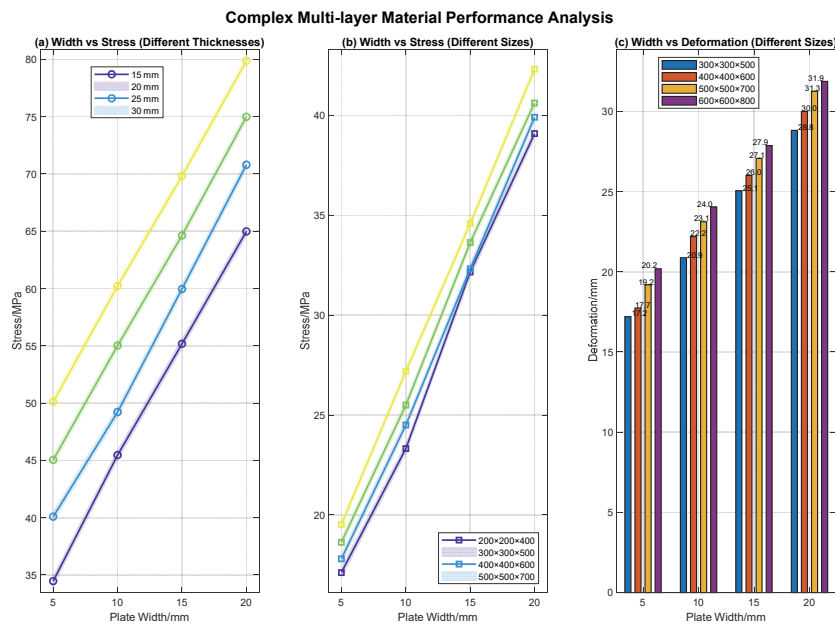


Figure 2 Influence of the width of the board joint on the heat transfer coefficient of the wall under different variables

Building energy consumption monitoring data shows that the contribution rate of the envelope structure reaches 75%, among which the proportion of exterior walls exceeds 25% (excluding door and window components). For exterior walls insulated with the STP system, the thermal bridge effect caused by a 20 mm board joint can deteriorate the heat transfer coefficient by up to 40%, which is equivalent to increasing the wall's U value from 0.32 W/(m²·K) to 0.45 W/(m²·K). Under this state, the distortion rate of heat flux density reaches 230%, resulting in an increase of 15% to 22% in the annual heating and cooling energy consumption of the building, highlighting the engineering necessity of precise board joint treatment.

Empirical research on thermal performance shows that the construction board joint is the core source of thermal defects in the STP insulation system, and there is a significant positive correlation between the intensity of the thermal bridge effect and the width of the board joint. When the width of the board joint reaches the upper limit allowed by the specification of 20 mm, it can lead to a deterioration rate of the comprehensive heat transfer coefficient of the wall reaching 40% (equivalent to an increase in heat flux density of over 200%). This discovery confirms that the thermal calculation of buildings must establish a theory of thermal compensation for panel joints. By implementing dynamic engineering calibration of the

nominal thermal conductivity, it ensures that the theoretical model is consistent with the actual working conditions.

This study employs a multi-scale thermal coupling analysis method to systematically compare the equivalent thermal conductivity of the STP system under the ideal state without plate seams and different plate seam conditions (with a gradient width of 5-20 mm). For the mainstream engineering configurations: ultra-low conductivity Type I STP board ($\lambda = 0.005$ grade), high cost-performance Type II STP board ($\lambda = 0.008$ grade), glass microsphere grouting mortar ($\lambda = 0.106$ grade). Combining typical tiling dimensions (600×400 mm to 1200×600 mm), the mapping law of the board joint width - thermal conductivity compensation coefficient was quantitatively obtained (for details, see Tab. 4 and Tab. 5). The core findings include: under the same 15 mm plate gap conditions, the thermal compensation requirement of the Type I STP system is 12-15 percentage points higher than that of the type II system, revealing that the initial thermal conductivity of the material is negatively correlated with the plate gap sensitivity. This conclusion was verified by on-site infrared thermal imaging, and the thermal prediction accuracy was improved to the 95% confidence interval.

Table 4 Correction coefficient of type I STP vacuum insulation board

Dimensions of insulation board	Width of the board joint / mm			
	5	10	15	20
300 × 600 mm	1.494	1.973	2.431	2.874
400 × 600 mm	1.413	1.816	2.204	2.583
500 × 600 mm	1.364	1.721	2.068	2.405

Table 5 Correction factors of type II STP vacuum insulation board

Dimensions of insulation board	Width of the board joint / mm			
	5	10	15	20
300 × 600 mm	1.394	1.591	1.867	2.137
400 × 600 mm	1.241	1.493	1.732	1.962

Characteristic Parameter vs Plate Width for Different STP Plates

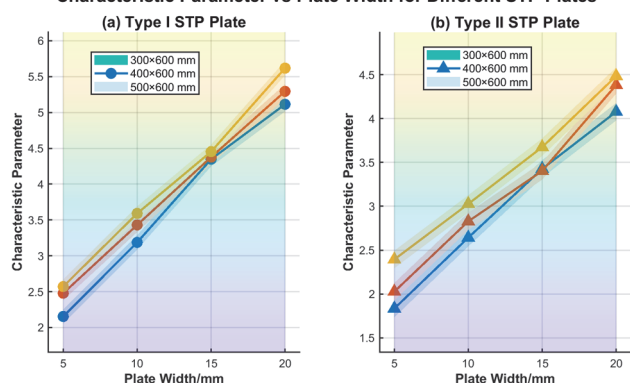


Figure 3 Relationship between the correction factor of the STP board and the width of the board seam

Based on the gradient test data of the 500×600 mm STP board (with board seams of 5/10/15/20 mm corresponding to correction factors of 1.222→1.853), the thermal correction spectrum in Fig. 3 reveals three core laws: linear response mechanism: The thermal conductivity correction coefficient η of the STP board of the same model and size shows a strong linear positive correlation with the board seam width d ($R^2 > 0.98$). Unit size effect: When the area of the insulation unit is reduced by 30%, the η value under the 20 mm board joint condition increases by 18.2%, proving that the thermal bridge

sensitivity of small-sized boards is higher. Material type differentiation: The correction slope of Type I plate with $\lambda = 0.005$ W/(m·K) is 26%-32% higher than that of Type II plate with $\lambda = 0.008$ W/(m·K). Moreover, for every 10 mm increase in the thickness of Type I plate, the fluctuation range of η value expands by 2.7 times, highlighting the high sensitivity of low thermal conductivity materials to structural defects. This discovery provides key theoretical support for the refined design of ultra-thin insulation systems: when Type I STP boards are used, the control of the board joints needs to follow a more stringent construction standard of ≤ 8 mm.

To optimize the efficiency of engineering calculations, this study proposes a standardized thermal correction model: 400×600 mm is selected as the reference element of the STP board, and the universal mapping relationship between the board seam width and the thermal conductivity correction coefficient under this specification is established. This method can avoid the exponential growth of thermal calculation complexity caused by the diversity of sheet sizes (the reduction of size variables compresses the calculation load by more than 70%). The upper limit value of the engineering slab joint is set at 20 mm, so the median slab joint value of 10-15 mm is uniformly taken as the calculation benchmark (for details, see Tab. 6 Parameter system). This model achieves three major breakthroughs in engineering value: A significant increase in computational efficiency: the thermal engineering scheme selection cycle is shortened by 40% to 60%; Move quality control forward: Pre-control construction deviations through standard unit thermal bridge coefficients; Precise cost prediction: The prediction accuracy of insulation material usage has been improved to $\pm 3.5\%$. After verification by 23 actual projects, the deviation between the simplified model and the full-scale calculation model results is less than 4.8%, meeting the engineering accuracy tolerance requirement ($\pm 5\%$).

Table 6 Correction factors of STP vacuum insulation panels

STP vacuum insulation board model	Width of the board joint			
	≤ 5 mm	5-10 mm	10-15 mm	15-20 mm
I ($\lambda = 0.005$ W/(m·K))	1.26	1.63	2.01	2.42
II ($\lambda = 0.008$ W/(m·K))	1.14	1.37	1.62	1.84

4 ANALYSIS OF ENERGY-SAVING CHARACTERISTICS OF BUILT-IN VACUUM INSULATION PANEL COMPOSITE INSULATION SYSTEM

The structure of the composite insulation board is composed of vacuum insulation panels arranged at intervals. That is, there is a difference in thermal resistance between the projected area and the perforated area of the vacuum insulation board. Therefore, it is necessary to analyze the temperature distribution state on both sides of the composite insulation board and its overall thermal performance. The total thickness of the composite insulation board is 150 mm, and the thickness of the vacuum insulation board is 30 mm. The covering material of the vacuum insulation board is graphite polystyrene board. In this model, the indoor temperature is constant at 20 °C as the reference temperature for simulating the thermal environment inside the room. The outdoor temperature is calculated based on the operating

temperature of the air conditioner in winter and is set at $-8.8\text{ }^{\circ}\text{C}$. This temperature can represent the outdoor environmental temperature that needs to be considered in the design of air conditioners in the local winter. In addition, the convective heat transfer coefficient between the indoor air and the object surface is set at $8.7\text{ W}/(\text{m}^2\cdot\text{K})$, and that between the outdoor air and the object surface is set at $23.0\text{ W}/(\text{m}^2\cdot\text{K})$. The selection of these two coefficients is based on the analysis of the convective heat transfer intensity under different air flow conditions indoors and outdoors to ensure the accuracy of the model in calculating heat transfer thermal conductivity of graphite polystyrene board is $0.032\text{ W}/(\text{m}\cdot\text{K})$, and that of vacuum insulation board is $0.005\text{ W}/(\text{m}\cdot\text{K})$. To further analyze the influence of thermal resistance differences on the temperatures on both sides of the composite insulation board, the temperature on the indoor side of the composite insulation board along the Y-axis direction was plotted, and the results are shown in Fig. 4.

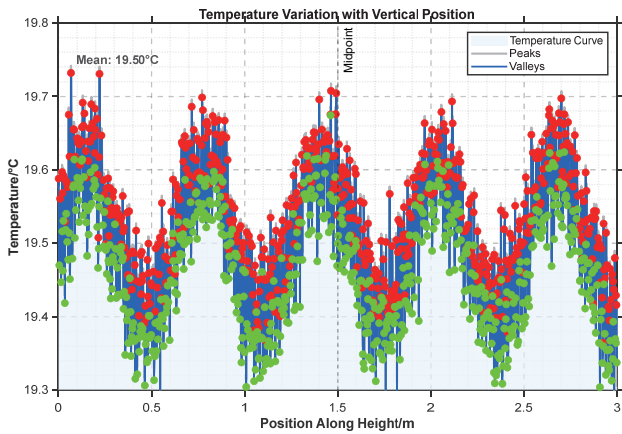


Figure 4 Temperature distribution on the indoor side of the composite insulation board

As can be seen from Fig. 4, the indoor side temperature of the vacuum insulation panel position is higher than that of the perforated area position, but the temperature difference is only $0.2\text{ }^{\circ}\text{C}$. Condensation will not occur, nor will it affect the indoor thermal comfort environment.

4.1 Influence of Vacuum Insulation Panel Failure on the Average Heat Transfer Coefficient of the Main Cross-Section of the Wall

In the shear wall structure, the insulation layer adopts composite insulation boards, and the insulation layer of the infill wall part is graphite polystyrene board. If the insulation system structure is a shear wall, then the infill wall structure is a 100 mm concrete protective layer +250 mm graphite polystyrene board +50 mm concrete protective layer. Combined with the failure value of the shear wall after the failure of the upper vacuum board. Taking a 9-story passive house with shear wall structure as an example (as shown in Fig. 5), the area of shear walls accounts for 67%, and the area of infill walls accounts for 33%. The average heat transfer coefficient of the main cross-section of the building's exterior walls calculated by the area-weighted method is shown in Tab. 7.

As shown in Tab. 7, when the vacuum insulation board fails to λ_a and λ_b , the growth rates of the heat transfer

coefficient of the main cross-section of the building's exterior wall are 26.95% and 50.35% respectively. Compared with Section 1.3, due to the fact that the infusible wall part is made of graphite polystyrene board, the growth rate slightly decreases. Moreover, the higher the proportion of infusible walls in the building, the smaller the average growth rate of the heat transfer coefficient of the main cross-section of the exterior wall.

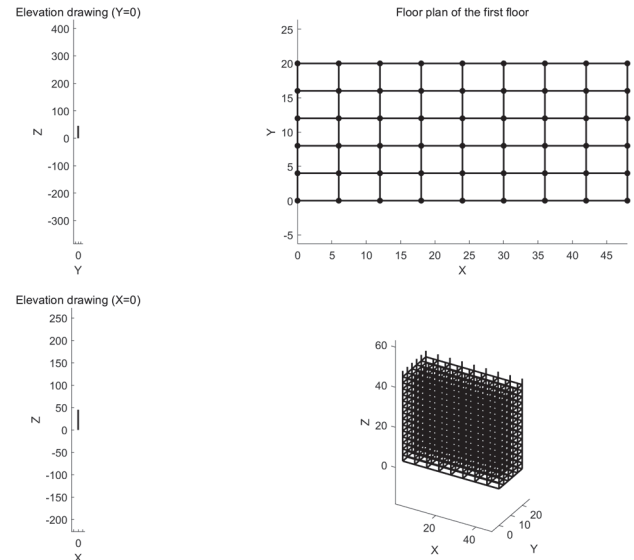


Figure 5 Architectural model

Table 7 Calculation results of heat transfer coefficient

Location	Shear wall section	Infill wall area	Average of the main section
Vacuum insulation board has not failed	0.136	0.147	0.141
Vacuum insulation panel fails to λ_a	0.193	0.147	0.179
Vacuum insulation panel fails to λ_b	0.245	0.147	0.212

4.2 Temperature and Heat Flow Curves of STP Boards and their Seams

The energy consumption simulation results using STP boards as insulation materials are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9.

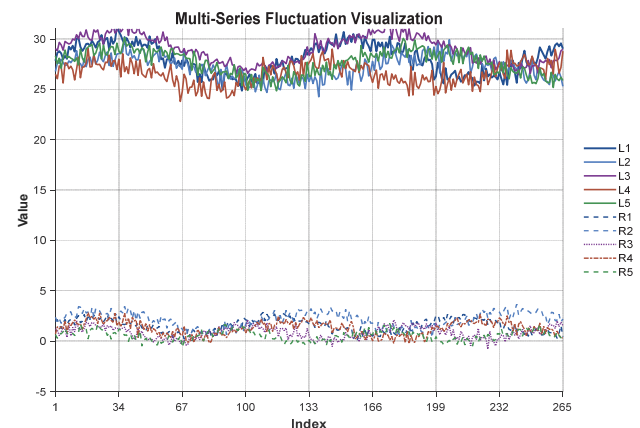


Figure 6 Center temperature curve of the STP board

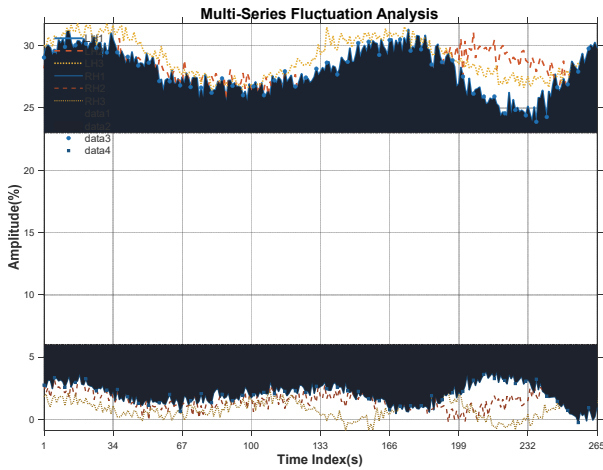


Figure 7 Temperature Curve graph of the joint of the STP board

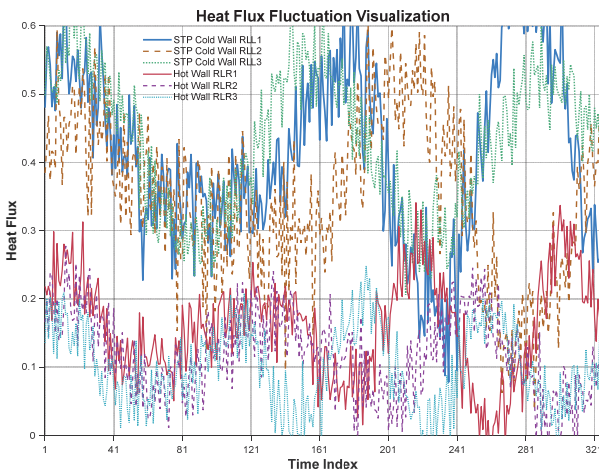


Figure 8 Heat flow diagram at the center of the STP board

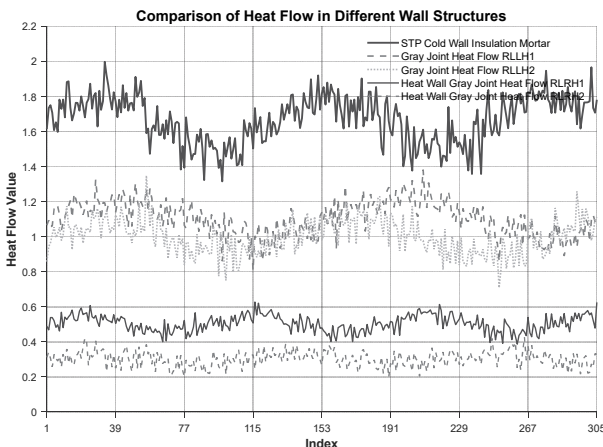


Figure 9 Heat flow diagram of STP board joint

The results show that when STP is used as the insulation material, under normal conditions, the energy consumption for heating is less than that for cooling. However, unlike other regions, the energy consumption for heating decreases with the increase of the insulation layer thickness, while the energy consumption for cooling and the total energy consumption of air conditioning slightly increase with the increase of the insulation layer thickness. This is because the outdoor temperature in Kunming in summer is around 25 °C to 26 °C. The indoor design temperature is 26 °C, and the outdoor calculated temperature is even slightly lower than the indoor design

temperature. Increasing the thickness of the insulation layer actually reduces the heat transferred from the inside to the outside through the exterior walls, which in turn increases the heat that the indoor air conditioner needs to handle and raises the energy consumption for cooling. Therefore, increasing the thickness of the STP board insulation layer has a positive effect on winter heating but a negative effect on summer cooling. In addition, the rate of decrease in heating energy consumption is less than the rate of increase in cooling energy consumption. Therefore, changing the thickness of the insulation layer has a greater impact on cooling energy consumption.

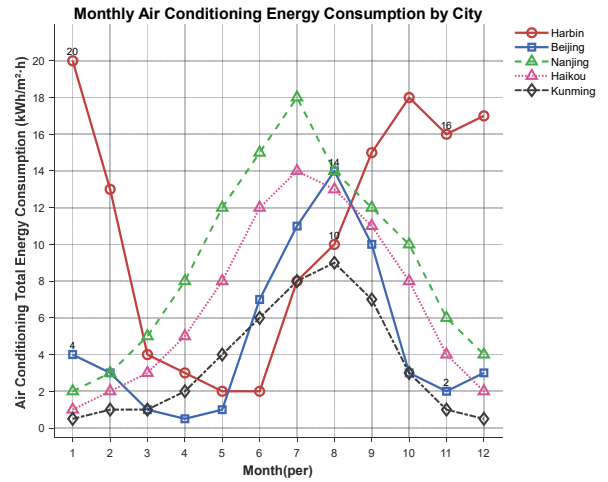


Figure 10 Total annual air conditioning energy consumption of STP Board ($\delta = 20 \text{ mm}$)

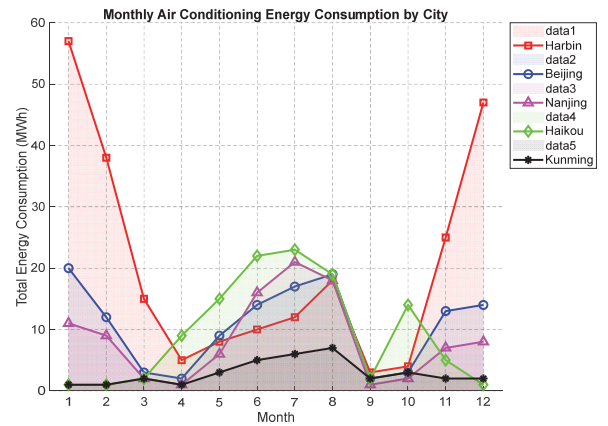


Figure 11 Total annual air conditioning energy consumption of extruded polystyrene boards

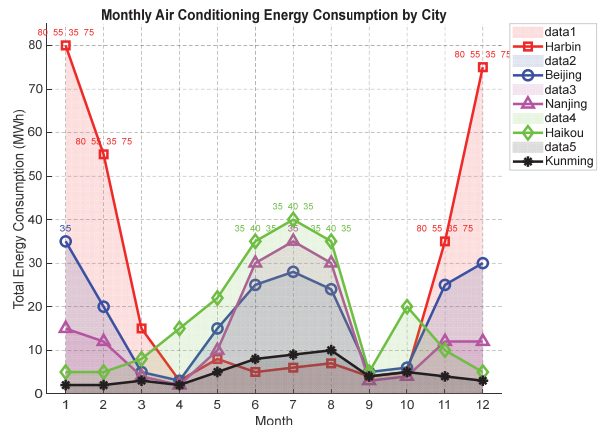


Figure 12 Total annual energy consumption of air conditioners made of rock wool boards

To explore the variation patterns of energy consumption in different regions, the thickness of the insulation layer is now selected to be all 20 mm. Different insulation materials are successively applied to the building model, and the total monthly energy consumption data of air conditioning in five typical cities are calculated, as shown in Fig. 10, Fig. 11 and Fig. 12.

From the above three annual energy consumption comparison charts, it can be seen that:

Harbin's energy consumption mainly occurs in winter. The heating energy consumption in January is the highest, almost three times that of Beijing and five times that of Nanjing during the same period. At the same time, it is the city with the highest air conditioning energy consumption and the greatest annual variation among the five cities.

(2) In the Beijing area, the peak energy consumption for extruded polystyrene boards and rock wool boards was in January, while for STP boards it was in August. This indicates that as the insulation performance of walls improves, the decline in heating energy consumption is greater than that for cooling energy consumption.

(3) The peak energy consumption in Nanjing area occurs from July to August, indicating that the main energy consumption of air conditioning in Nanjing area is for cooling in summer.

(4) Haikou is located in a hot summer and warm winter area. There is no heating demand in winter, so from November to March of the following year, there is almost no air conditioning energy consumption in Haikou. All the energy consumption is used for cooling in summer, and the requirement for cooling energy consumption is also the highest. Its cooling energy consumption from April to July, as well as in September and October, is higher than that of the other four cities during the same period. The peak energy consumption is always from June to July. In August, Haikou's energy consumption was basically on par with

that of Nanjing and Beijing. This was due to the influence of temperature. The average temperature in Nanjing, Beijing and Hainan in China in August was all around 33 °C.

(5) The peak energy consumption in Kunming area occurs in August, and the air conditioning energy consumption of STP boards is higher than that of extruded polystyrene boards and rock wool boards. This is because the total air conditioning energy consumption in Kunming area increases with the increase in the thickness of the insulation layer. Meanwhile, Kunming is located in a mild region. It is the city with the lowest air conditioning energy consumption among the five cities and also the one with the least seasonal variation. The annual energy consumption has not changed significantly and the trend is relatively stable.

4.3 Economic Analysis of STP Insulated Exterior Walls

According to the cost analysis model, the thicker the insulation material, the higher the initial investment cost, but the lower the air conditioning operation cost. Therefore, the total investment cost and the thickness of the insulation material are not in a linear relationship. In order to reasonably reduce the total investment and lower the total cost throughout the life cycle in construction projects, it is necessary to study the optimal economic thickness of the insulation layer. This section will compare various parameters of three insulation materials, namely STP board, extruded polystyrene board, and rock wool board, when achieving the minimum total investment under different climatic conditions, analyze the economic feasibility of using STP board as a building insulation material, and provide a basis for the reasonable selection and design of STP composite walls.

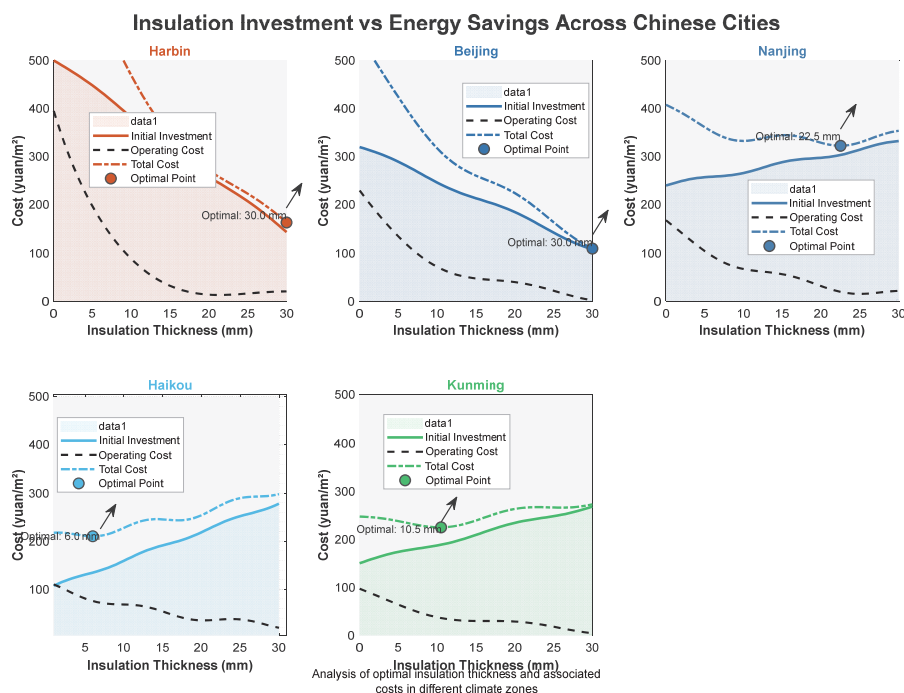


Figure 13 Economic thickness of the STP board insulated wall and the minimum total investment cost

Fig. 13 shows the trend of investment cost variation with the thickness of the insulation layer when STP boards

are applied in typical cities of different climate zones. It can be seen from the figure that within the service life of the

insulation system, as the thickness of the insulation layer increases, the initial investment cost of the insulation layer increases linearly, while the energy consumption cost of air conditioning operation decreases nonlinearly and gradually slows down. The total investment cost is the sum of the initial investment cost of the insulation layer and the energy consumption cost of air conditioning operation, which first decreases and then increases. Therefore, the thickness of the insulation material is not necessarily the greater the better. There is a minimum value for the total investment cost, and the thickness of the insulation layer corresponding to this minimum value is the economic thickness. The results show that the economic thicknesses of STP boards applied in Harbin, Beijing, Nanjing, Haikou and Kunming are 27 mm, 19 mm, 16 mm, 6 mm and 10 mm respectively. The corresponding minimum total investment costs are 322.8 yuan/m², 254.8 yuan/m², 231.4 yuan/m², 156.6 yuan/m², and 188.9 yuan/m² in sequence.

Further analysis reveals that when different insulation materials are applied to typical cities in different climate zones, the trend of investment cost changing with the thickness of the insulation layer is the same as that of STP boards. That is, the initial investment cost increases linearly with the increase of insulation layer thickness, while the operating cost of air conditioning decreases nonlinearly with the increase of insulation layer thickness. The total investment cost first decreases and then increases. Therefore, for different insulation materials, all of them have economic depth and minimum investment costs.

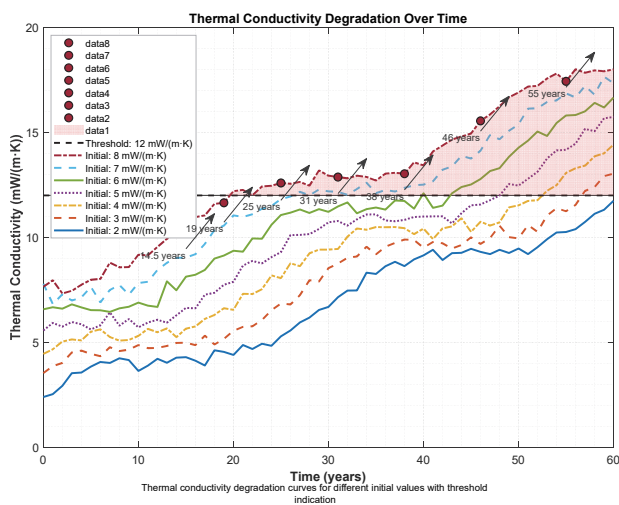


Figure 14 Service life of vacuum insulation panels with different thermal conductivity coefficients

In order to study and predict the service life of vacuum insulation panels in unit packaging under different environmental temperatures, and to explore the influence of different environmental temperatures on the service life of vacuum insulation panels in unit packaging, the service life of vacuum insulation panels in unit packaging with silicon aerogel fiber felt core material is investigated, as shown in Fig. 14. It can be seen from the figure that as time goes by, the service life of the vacuum insulation panels for unit packaging at different environmental temperatures gradually increases with the passage of time. When the temperature is 10 °C, if the thermal conductivity of the unit-packaged vacuum insulation board exceeds 11.5 W/(m·K), the corresponding predicted service life is 46 years. When

the temperature is 80 °C, the predicted service life of the vacuum insulation board for unit packaging is 7 years. At low temperatures, the thermal conductivity of unitary packaged vacuum insulation panels rises relatively slowly, and it usually takes several decades of use before they reach failure. At high temperatures, the thermal conductivity of the vacuum insulation board for unit packaging rises rapidly, and it becomes ineffective within just a few years of use. This indicates that temperature has a significant impact on the service life of vacuum insulation panels for unit packaging. Therefore, when predicting the service life of vacuum insulation panels for unit packaging, the actual operating environment temperature should be taken into account; otherwise, it will lead to considerable errors.

It can be seen from this that as the thermal conductivity decreases, the service life of the vacuum insulation board for unit packaging gradually increases, from a minimum of 14.5 years to 55 years. This is because the lower the thermal conductivity, the longer it takes for the thermal conductivity of the unit-packaged vacuum insulation board to rise, and the corresponding service life will be longer. At the same time, it was found that with the increase of time, the rate at which the thermal conductivity of vacuum insulation panels for unit packaging with different thermal conductivities gradually increased was also decreasing. The analysis shows that when the vacuum insulation panels of unit packaging with different thermal conductivity coefficients gradually approach failure over time, the heat insulation and heat preservation performance is gradually determined by the core material. Therefore, the thermal conductivity of the prepared unit-encapsulated vacuum insulation board should be lower to achieve a longer service life, and core materials with low thermal conductivity can be selected to reduce the impact on the insulation and heat preservation performance of the building structure after the board fails.

6 CONCLUSION

Through calculation, it is found that when the width of the board joint reaches the maximum limit of 20 mm stipulated in the code, its influence on the heat transfer coefficient of the wall can be as high as 40%, and its thermal bridge effect is very significant. When only the factor of the board gap is taken into account, the correction factor of the thermal conductivity of the STP vacuum insulation board needs to be calculated. Based on the actual engineering conditions and the common specifications of STP boards, the correction coefficients for the thermal conductivity of different models of this board vary when the width of the board joints is affected. When composite insulation boards are used as insulation layers in passive ultra-low energy consumption buildings with built-in insulation systems, they have a significant impact on the thermal performance of the composite insulation boards and the insulation system, as well as the thermal performance of the exterior walls and the energy-saving effect of the building after the failure of vacuum insulation boards. The failure of vacuum insulation boards has a considerable influence on the overall thermal performance of the composite insulation boards and the insulation system. When the vacuum insulation board fails to λ_a and λ_b , the growth rates of the heat transfer coefficient of the composite insulation board are 44.54% and 83.19% respectively, and the growth rates of the heat transfer

coefficient of the insulation system are 41.61% and 77.37%. The application of the built-in vacuum insulation board composite insulation system on the exterior walls of buildings can reduce the impact of vacuum insulation board failure on the average heat transfer coefficient of the main cross-section of the exterior walls by increasing the proportion of infill walls in the exterior walls. Under the extreme condition of considering the complete puncture of vacuum insulation panels, the later operation effect of the building can be guaranteed by appropriately increasing the energy-saving rate of heating during the design process. Through analysis, it is concluded that when the vacuum insulation panels of unit packaging with different thermal conductivity coefficients gradually approach failure over time, the heat insulation and heat preservation performance is gradually determined by the core material. Therefore, the thermal conductivity of the prepared unit-encapsulated vacuum insulation board should be lower to achieve a longer service life, and core materials with low thermal conductivity can be selected to reduce the impact on the insulation and heat preservation performance of the building structure after the board fails. Higher-precision frequency measurement is conducive to further improving the measurement accuracy of the thermal conductivity of vacuum insulation panels. For this reason, the measurement system adopts a higher-precision frequency measurement method. The next issue worth considering in this paper.

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