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Thermal Performance Analysis and Optimization Design of Building Exterior Wall Insulation Layers

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ABSTRACT

In the wake of increasing global concern over environmental change and energy consumption, building energy conservation has emerged as a pivotal issue worldwide. The primary energy consumption in buildings stems largely from air conditioning and heating systems. The efficiency of these systems is significantly influenced by the thermal performance of the building's exterior wall insulation layers. In-depth research and optimized design of these insulation layers' thermal performance are thus critical topics in the field of building energy conservation. However, current research methods encounter limitations in addressing these issues, notably neglecting the impact of thermal bridges on the insulation layers' thermal performance and focusing solely on single parameters in insulation optimization design. This study addresses these challenges by conducting a comprehensive analysis and optimization design of the thermal performance of building exterior wall insulation layers. It includes an analysis of heat transfer through thermal bridges and the optimization of insulation parameters, aiming to provide a more holistic and systematic approach to optimizing the thermal performance of building exterior wall insulation layers. Specifically, this study uses thermal simulation software to conduct three-dimensional simulation of thermal bridges, analyzing the temperature distribution and heat flow in the thermal bridge area. According to international or domestic standards, the linear heat transfer coefficient of the thermal bridge is determined through calculation. By using optimization algorithms, the thermal performance parameters of the insulation layer are optimized in design. Through experiments, specific linear heat transfer coefficient and equivalent heat transfer coefficient of thermal bridges are obtained, as well as the extent of the impact of thermal bridges on overall thermal performance. Meanwhile, based on optimization algorithms, a set of materials and structural parameters that enable the building's external wall insulation layer to achieve higher thermal efficiency is obtained. After optimization, a lower heat transfer coefficient of the external wall insulation layer is achieved, improving the insulation performance of the wall. This paper provides a technical method for the analysis of heat transfer in thermal bridges and the optimization of insulation parameters. It helps architects more accurately assess and improve the thermal performance of building exteriors, which is significant for reducing energy loss and lowering operational costs of buildings. The research results can provide scientific basis for the formulation of building energy-saving standards, especially in terms of thermal bridge effects and external wall insulation performance. These standards are crucial in driving the industry towards higher energy-saving goals.

1. INTRODUCTION

As global focus intensifies on energy consumption and its environmental impacts, building energy conservation has become a focal point of worldwide attention [1-4]. The majority of energy consumption in buildings originates from internal air conditioning and heating systems, with the thermal performance of the building envelope playing a decisive role in these systems' energy consumption [5,6]. The thermal performance of insulation layers in exterior walls, as a crucial part of the building envelope, exerts a direct influence on the energy consumption of buildings [7-9]. Hence, conducting thorough research and proposing optimization designs for the thermal performance of these insulation layers have become significant topics in the domain of building energy conservation.

In-depth studies of the thermal performance of exterior wall insulation layers aid in better understanding and controlling the thermal environment performance of buildings, thereby reducing energy consumption and minimizing environmental impact [10-14]. Furthermore, optimizing the design of these insulation layers enhances building comfort while reducing operational costs [15]. Thus, the analysis and optimization design of the thermal performance of building exterior wall insulation layers not only carry practical implications but also hold substantial theoretical value.

However, current research methods often overlook the impact of thermal bridges on the thermal performance of insulation layers. The presence of thermal bridges in exterior walls can significantly increase thermal losses, diminishing insulation effectiveness [16-19]. Moreover, existing methods, in optimizing insulation parameters, tend to focus on a single parameter, such as thermal resistance or heat transfer coefficient, neglecting the influence of other factors like heat storage coefficient, thermal inertia, and energy saving rate [20-24].

This article delves into an in-depth analysis of the thermal performance of building exterior wall insulation layers and proposes optimization design schemes. The research encompasses two main parts: firstly, an analysis of heat transfer through thermal bridges in exterior wall insulation layers, including calculations of thermal bridges and equivalent heat transfer coefficients; secondly, the optimization design of insulation parameters for these layers. These parameters include the thermal resistance of single material layers, thermal resistance of multi-layer homogeneous material layers in exterior wall insulation, heat transfer coefficients of insulation layers, heat storage coefficients of materials, thermal inertia indicators of single and multi-layer homogeneous material layers, energy saving rate, and annual operational costs of heating systems during the heating period. These works are instrumental in enhancing understanding of the thermal performance of building exterior wall insulation layers and offer valuable guidance for the development and promotion of building energy conservation technologies.

2. THERMAL BRIDGE HEAT TRANSFER ANALYSIS IN BUILDING EXTERIOR WALL INSULATION LAYERS

The optimization of thermal performance in building exterior wall insulation layers has garnered widespread attention, with the presence of thermal bridges emerging as a significant issue. A thermal bridge refers to areas within a building's structure where, due to differences in structural form or material properties, thermal resistance is low, and heat transfer occurs more readily. Consequently, the existence of thermal bridges significantly diminishes the thermal performance of building exterior wall insulation layers. To better understand and analyze the impact of thermal bridges in these insulation layers, it is crucial to comprehend their heat transfer mechanisms and calculation methods.

Traditional calculation of thermal bridges first requires identifying their locations in a building, typically at component junctions, such as where walls meet windows, at corners, and where floors meet exterior walls. Further, a detailed geometric model of the thermal bridge area is established using professional thermal simulation software. The model should include all relevant material layers and corresponding thermal physical parameters. At the same time, it's necessary to set appropriate external climatic conditions and internal operational conditions, and use numerical simulation software to conduct steady-state or transient analysis to calculate the local heat transfer coefficient at the thermal bridge. For steady-state analysis, the focus is usually on the linear heat transfer coefficient of thermal bridge, which measures the heat flow per unit length and temperature difference. Finally, the impact of the thermal bridge is internalized into the overall heat transfer coefficient in some way. This can be done by adjusting the non-thermal bridge heat transfer coefficient, or by using the concept of equivalent thermal bridge area.

The development and application of international standards such as *Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations (ISO 10211)*, and *Thermal bridges in building construction - Linear thermal transmittance - Simplified methods and default values (ISO 14683)* also help industry professionals better understand and manage thermal bridge issues, improve the thermal performance of building exteriors, and provide clear guidelines for building design and construction. By adopting these methods and following these standards, the energy consumption and operational costs of buildings can be significantly reduced, while creating a more comfortable indoor environment for the people living and working in them.

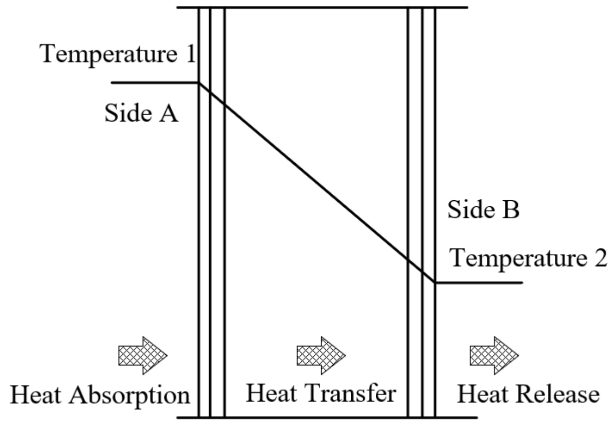

Figure 1. Heat transfer process in building exterior wall insulation layers

The analysis of heat transfer through thermal bridges primarily revolves around two modes of heat transfer: conduction and convection. Figure 1 illustrates the heat transfer process in building exterior wall insulation layers. In these layers, heat transfer at the thermal bridge locations predominantly occurs through conduction, with the rate determined by the thermal conductivity of the bridge material, temperature difference, and material thickness. In contrast, heat transfer with the internal and external environment is mainly through convection, with the rate influenced by the air's convection coefficient, temperature difference, and contact area. In practice, these two modes of heat transfer often occur simultaneously and affect each other. Therefore, accurate prediction and analysis of the heat transfer process in building exterior wall insulation layers composed of multiple homogeneous material layers require considering the combined effects of heat conduction and radiation, along with factors such as thermal conductivity, thickness, and radiative properties of various materials. The analysis of heat transfer through thermal bridges in building exterior wall insulation typically involves calculating the thermal bridge coefficient. This calculation often considers factors such as the shape, size, and material properties of the thermal bridge, and for complex thermal bridge structures, numerical simulation is usually required.

In modern buildings, to enhance thermal performance and meet energy-saving standards, exterior wall insulation layers often adopt multi-layer composite structures comprising various materials. The selection of multiple homogeneous materials involves various factors such as thermal performance, weather resistance, strength, durability, and cost. Expanded perlite, expanded polystyrene foam (EPS), polyurethane foam (PU), asbestos board, mineral wool board, and exterior wall thermal insulation mortar are some commonly used homogeneous insulation materials. In practical applications, these materials are typically selected and combined based on specific design requirements and environmental conditions to achieve optimal insulation effects.

The total heat transfer on the surface of building exterior wall insulation layers primarily comprises two parts: convective heat transfer and radiative heat transfer. Since the mechanisms and influencing factors of these two types of heat transfer are relatively independent, they can be considered separately. Equating the total heat transfer to the sum of convective and radiative heat transfer simplifies the analysis and optimization design of the thermal performance of building exterior wall insulation layers, aligning more closely with practical conditions. This approach also provides a more specific and intuitive direction for optimizing the thermal performance of these insulation layers. For example, altering the properties of insulation materials or adjusting surface treatment methods can independently affect convective and radiative heat transfer, thereby achieving the goal of optimizing the thermal performance of building exterior wall insulation layers.

Let's denote the surface heat transfer quantity as w, the convective heat transfer quantity as w_v, and the radiative heat transfer quantity as w_e. Let the wall surface temperature be represented by ϕ, the indoor (or outdoor) temperature by y, and the surface heat transfer coefficient by β, where $\beta=\beta_v+\beta_e$. The surface heat transfer coefficient of a building's external wall insulation layer refers to the rate of heat exchange between the surface of the building's exterior wall and the surrounding environment. This coefficient is one of the key parameters in quantifying the thermal insulation performance of building exteriors. It consists of two parts: the internal surface heat transfer coefficient (representing the heat transfer capability of the interior surface) and the external surface heat transfer coefficient (representing the heat transfer capability of the exterior surface). These coefficients are used in thermal transfer calculations to determine the amount of heat flow through the wall. These coefficients can be defined using preset empirical values, which are typically derived based on typical climate data, indoor and outdoor conditions, and building characteristics. Alternatively, more accurate local convective heat transfer coefficients can be obtained through computational fluid dynamics simulations that model the actual flow field conditions.

Thus, we have:

$$w = w_v + w_e = \beta_v\left(\varphi - y\right) + \beta_e\left(\varphi - y\right) = \beta\left(\varphi - y\right) \quad (1)$$

There are several methods for calculating thermal bridges, including detailed calculation, equivalent length method, equivalent thermal resistance method, and heat transfer coefficient method. However, the applicability and accuracy of these methods vary. The heat transfer coefficient method is a simple and practical approach for calculating thermal bridges. It is suitable for various complex thermal bridge structures and offers high accuracy. Based on the law of heat conduction, this method calculates the heat transfer coefficient of a thermal bridge by determining the heat flux per unit length and per unit temperature difference. This coefficient intuitively reflects the thermal conductivity performance of the thermal bridge, thus facilitating the assessment and optimization of the thermal performance of building exterior wall insulation layers.

In the analysis of building thermal performance, linear and point thermal bridges are two common types. They represent linear and point-like heat conduction paths in building structures, respectively. Due to their different shapes and scales, their heat transfer performance varies, necessitating the use of linear and point heat transfer coefficients for description. The impact of a linear thermal bridge is primarily along its length, making the linear heat transfer coefficient the most intuitive descriptor. It reflects the heat flux per unit length and per unit temperature difference, vividly describing the heat transfer performance of linear thermal bridges. The impact of point thermal bridges is concentrated at their locations, making the point heat transfer coefficient the most suitable descriptor. It reflects the heat flux per unit area and per unit temperature difference, clearly describing the heat transfer performance of point thermal bridges. This article will describe the heat transfer impact of thermal bridges using linear and point heat transfer coefficients, thus providing a clearer and more intuitive reflection of the thermal bridge's performance, benefiting the analysis and optimization of the thermal performance of building exterior wall insulation layers. Let's denote the two-dimensional thermal coupling coefficient (two-dimensional heat transfer coefficient) as M_{2D}, the one-dimensional heat transfer coefficient of homogeneous material k as I_k, and the thickness of the one-dimensional homogeneous material layer k as m_k. The calculation formula for the linear heat transfer coefficient φ value is given by the following equation:

$$\varphi = M_{2D} - \sum_{k=1}^{B_u} I_k m_k \quad (2)$$

Assuming the three-dimensional thermal coupling coefficient (three-dimensional heat transfer coefficient) is represented by M_{3D}, and the area of the flat wall is denoted as A_u, the calculation formula for the point heat transfer coefficient Υ is given by the following expression:

$$\gamma = M_{3D} - \sum_{u=1}^{B_u} I_u A_u - \sum_{u=1}^{B_u} \phi_k m_k \quad (3)$$

Due to the complexity of the shape and materials of thermal bridges, directly calculating their heat transfer coefficients and integrating them into simulation processes is often challenging. Therefore, a method is needed that can accurately analyze the heat transfer of thermal bridge effects while equivalently representing it in a form that energy consumption simulation software can process. This article utilizes numerical calculation methods to precisely analyze the heat transfer situation of thermal bridge effects. The obtained total heat transfer coefficient of the thermal bridge's homogeneous material layer can be equivalently represented as the heat transfer coefficient of the thermal bridge node in energy consumption simulation software. This approach simplifies the processing in the simulation software, reducing the complexity of the simulation. Let's denote the total heat transfer coefficient (equivalent heat transfer coefficient) of the thermal bridge's single homogeneous material layer as I, the total steady-state heat transfer of the thermal bridge's single homogeneous material layer as W_{TO}, the external (internal) surface area of the thermal bridge as S, and the indoor-outdoor temperature difference as ΔY. The following formula gives the calculation for the equivalent heat transfer coefficient of the thermal bridge in the building exterior wall insulation layer:

$$I = \frac{W_{TO}}{S\Delta Y} \tag{4}$$

ANSYS and *THERM* are two widely used finite element analysis software in the field of thermal engineering science. Both these software employ finite element analysis methods to perform precise numerical simulations and calculations on various complex heat conduction problems, thereby obtaining accurate heat transfer results. Compared to simplified calculation methods, which may overlook some critical influencing factors leading to inaccurate results, ANSYS and THERM provide robust modeling tools. These tools enable the modeling of various complex thermal bridge structures and detailed heat transfer analysis. This flexibility allows these software packages to meet a wide range of research needs.

In addressing the heat conduction problems of building exterior wall insulation layers, *ANSYS* and *THERM* primarily use Fourier's law and the first law of thermodynamics to establish the heat conduction differential equations that describe the heat conduction process in materials. This equation reflects the relationship between the internal heat distribution in the material and the material's thermal properties, geometric shape, boundary conditions, and external environmental conditions. When solving the heat conduction differential equation, appropriate boundary conditions must be provided, such as specifying the temperature or heat flux on the material's surface. Solving the heat conduction differential equation yields the internal temperature distribution of the material, i.e., the temperature field. The characteristics of the temperature field at the thermal bridge are crucial for analyzing the heat transfer performance of the thermal bridge. Let's denote the material density as ϑ, thermal conductivity of the material as η, the intensity of internal heat sources in the material as w_c, spatial coordinate variables as a, b, c, and the time variable as π. The constructed heat conduction differential equation is given by the following formula:

$$\vartheta\frac{\partial y}{\partial \pi} = \frac{\partial}{\partial a}\left(\eta\frac{\partial y}{\partial a}\right) + \frac{\partial}{\partial b}\left(\eta\frac{\partial y}{\partial b}\right) + \frac{\partial}{\partial c}\left(\eta\frac{\partial y}{\partial c}\right) + w_c \tag{5}$$

In this research, considering the practical application scenarios of building exterior wall insulation layers, a steady-state temperature field with constant material properties and without internal heat sources was chosen as the subject of study. Under these conditions, it is assumed that the thermal properties of the material (such as thermal conductivity) are constant, there are no internal heat sources in the material, and the temperature field is in a steady state (i.e., the temperature distribution does not change over time). Based on these assumptions, the heat conduction differential equation can be appropriately simplified. The simplified equation is as follows:

$$\frac{\partial}{\partial z}\left(\eta\frac{\partial y}{\partial z}\right) + \frac{\partial}{\partial t}\left(\eta\frac{\partial y}{\partial t}\right) + \frac{\partial}{\partial x}\left(\eta\frac{\partial y}{\partial x}\right) = 0 \tag{6}$$

3. OPTIMIZATION DESIGN OF INSULATION PARAMETERS FOR BUILDING EXTERIOR WALL INSULATION LAYERS

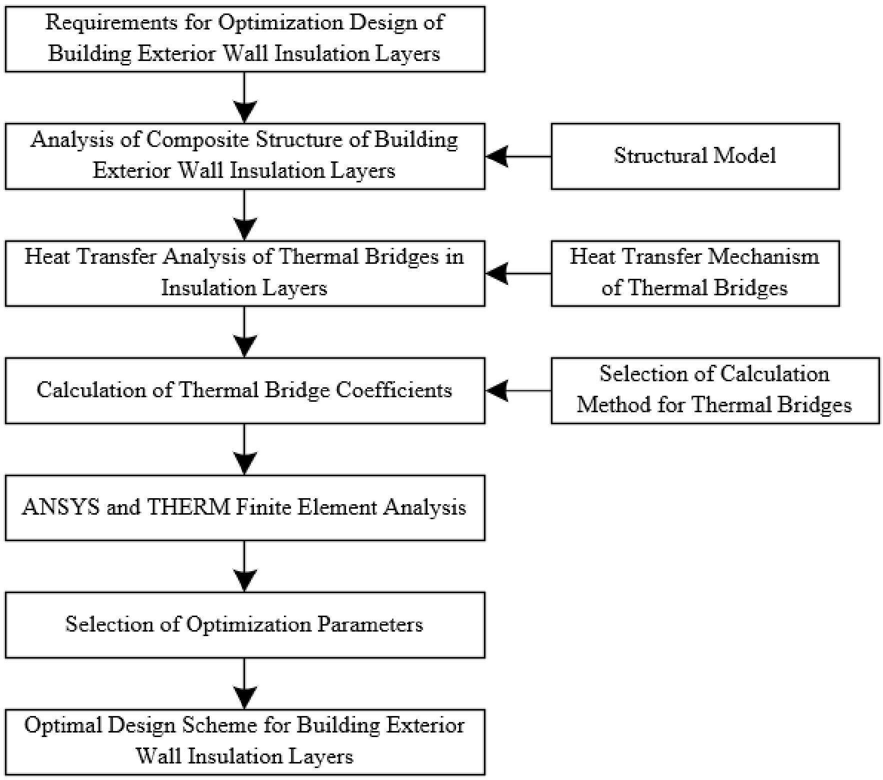

Figure 2. Process flow diagram for the optimization method of insulation parameters in building exterior wall insulation layers

The thermal performance of building exterior wall insulation layers significantly impacts the energy efficiency and comfort of a building. Optimizing these parameters can enhance the building's energy efficiency, reduce energy consumption, lower operational costs, and also improve indoor comfort. This article focuses on the optimization design of eight parameters: thermal resistance of single homogeneous material layers, thermal resistance of flat walls composed of multiple homogeneous material layers, heat transfer coefficient of the insulation layers, heat storage coefficient of the materials, thermal inertia index of single homogeneous material layers, thermal inertia index of flat walls composed of multiple homogeneous material layers, energy saving rate, and annual operational costs of the heating system during the heating period. Figure 2 illustrates the process flow diagram for the optimization method of the insulation parameters of the building exterior wall insulation layers.

Thermal resistance is a parameter that describes a material's ability to impede heat flow. The greater the thermal resistance, the better the insulation effect. Optimizing these parameters can enhance insulation effectiveness and reduce energy consumption. Let's denote the thermal resistance of a material layer as E, the thickness of the material layer as σ, and the thermal conductivity of the material as ε. The calculation formula for the thermal resistance of a single homogeneous material layer is given as follows:

$$E = \frac{\sigma}{\varepsilon} \tag{7}$$

The principle of optimizing the thermal resistance of a single homogeneous material layer involves selecting materials with better insulation properties and arranging the material thickness appropriately. Firstly, thermal resistance can be optimized through material selection. Generally, thermal resistance is inversely proportional to the material's thermal conductivity, so choosing materials with lower thermal conductivity can increase thermal resistance. Additionally, the thickness of the material also affects thermal resistance; the greater the thickness, the higher the thermal resistance. However, choosing materials with low thermal conductivity and increasing material thickness is not always feasible, as it may add to the building's structural complexity and cost. Therefore, a comprehensive optimization is needed, considering the cost, construction difficulty, durability of materials, while ensuring insulation performance. During the optimization process, the impact of different materials and thicknesses on thermal resistance, as well as on building energy efficiency and operational costs, can be predicted through experiments or numerical simulation, leading to the optimal design scheme.

Let's denote the thermal resistance of each layer of material as $E=E_1,E_2,......E_b$. The calculation formula for the thermal resistance of flat walls composed of multiple homogeneous material layers in building exterior wall insulation layers is given by the following equation:

$$E = E_1 + E_2 + \ldots + E_b \tag{8}$$

For building exterior wall insulation layers composed of multiple homogeneous material layers, the flat wall thermal resistance is a key parameter determining its insulation performance. The magnitude of flat wall thermal resistance depends on the thermal resistance and thickness of each layer of material. To optimize the flat wall thermal resistance of such layers, one should consider using materials with high thermal resistance for insulation, effectively enhancing the flat wall thermal resistance. Factors such as the stability, durability, and cost of materials should also be considered. In terms of material layering and structure, adjusting the thickness and order of each material layer, employing thermal break designs, or adding air layers can effectively increase the flat wall thermal resistance.

The heat transfer coefficient is a parameter that describes the material's heat transfer capability. The lower the heat transfer coefficient, the better the insulation effect. Optimizing this parameter can improve insulation effectiveness and reduce energy consumption. Let's denote the heat transfer coefficient of the building exterior wall insulation layer as J, the heat transfer resistance of the insulation layer as E_0, the internal surface heat exchange resistance as E_u, and the thermal resistance of each material layer as E. The heat transfer coefficient J of the building exterior wall insulation layer is calculated according to the following formula:

$$J = 1/E_0 \text{, wherein } E_0 = E_u + \sum E \tag{9}$$

Selecting materials with low thermal conductivity can effectively reduce the heat transfer coefficient. Additionally, factors like material stability, durability, and cost should be considered. In terms of material layout, materials with higher thermal resistance should be placed as close as possible to the heat source.

The heat storage coefficient is a parameter that describes a material's heat storage capacity. The higher the heat storage coefficient, the better the material's heat storage performance. Optimizing this parameter can enhance a building's heat storage performance and reduce energy consumption. Let's denote the heat storage coefficient of the material as A, the thermal conductivity of the material as ε, the specific heat capacity of the material as v, the density of the material as o, and the temperature fluctuation period as Y. The calculation formula for the material's heat storage coefficient is given by the following equation:

$$A = \sqrt{\frac{2\pi\varepsilon vo}{3.6Y}} \tag{10}$$

Selecting materials with a high heat storage coefficient can enhance the heat storage capacity of the insulation layer. In terms of material layout, materials with a high heat storage coefficient should be positioned near the interior side to effectively absorb and store the heat generated indoors.

Thermal inertia is a parameter that describes the response speed of materials to changes in heat flow. The greater the thermal inertia, the slower the material's response to changes in heat flow. Optimizing these parameters can improve the thermal stability of a building and increase comfort. Let's denote the thermal inertia index of a material layer as F, the thermal resistance of the material layer as E, and the heat storage coefficient of the material layer as A. The calculation formula for the thermal inertia index of a single homogeneous material layer in the building exterior wall insulation layer is given as follows:

$$F = E \cdot A \tag{11}$$

Let's denote the thermal inertia index of each material layer as $F_1, F_2, \ldots F_b$. The calculation formula for the thermal inertia index of flat walls composed of multiple homogeneous material layers in building exterior wall insulation layers is given by the following equation:

$$F = F_1 + F_2 + \ldots + F_b \tag{12}$$

Selecting materials with high thermal inertia can enhance the thermal inertia of the insulation layer, thereby stabilizing indoor temperatures and reducing energy consumption. For multi-layer insulation, a reasonable material layout also helps in improving thermal inertia performance. Generally, materials with high thermal inertia should be placed closer to the interior side to more effectively absorb and store heat generated indoors.

The energy saving rate is a parameter that describes the energy efficiency of a building. The higher the energy saving rate, the more energy is saved. Optimizing this parameter can increase the building's energy efficiency and reduce operational costs. The energy saving rate of a building's exterior wall insulation layer refers to the proportion of energy saved in heating and cooling through the use of insulation layers compared to buildings without insulation layers. Let's denote the energy saving rate as γ_1, and let w_{G0} and w_{G1} represent the unit area heat consumption of the building and energy-efficient building, respectively. The calculation formula is as follows:

$$\gamma_1 = \frac{w_{G_0} - w_{G_1}}{w_{G_0}} \times 100\% \tag{13}$$

The annual operating cost of the heating system during the heating period refers to the cost of energy consumed by the heating system to maintain a comfortable indoor temperature throughout the year, along with associated expenses for equipment operation, maintenance, and repairs. Let's denote the annual operating cost of the heating system as V, the unit area annual energy consumption of the heating system as w_v, the market unit price as o, and the building area as B. The calculation formula is as follows:

$$V = w_v \times o \times B \tag{14}$$

Optimizing the above two parameters can be achieved by optimizing the operating parameters of the equipment to enhance energy conversion and utilization efficiency, thereby reducing energy consumption and operational costs. Employing energy-saving technologies, such as improving the building's insulation performance, using efficient heating equipment and systems, or utilizing renewable energy sources like solar and geothermal energy, can lower energy consumption and reduce operational costs. Optimal operational management, such as adjusting heating times and temperatures according to the actual usage of the building to avoid unnecessary energy waste, is also beneficial. Additionally, regular maintenance and inspection of equipment ensure good operational status and reduce the likelihood of failures, which also helps in reducing operational costs. Using high-performance insulation materials in building exterior walls and roofs effectively reduces heat loss and decreases the consumption of heating energy.

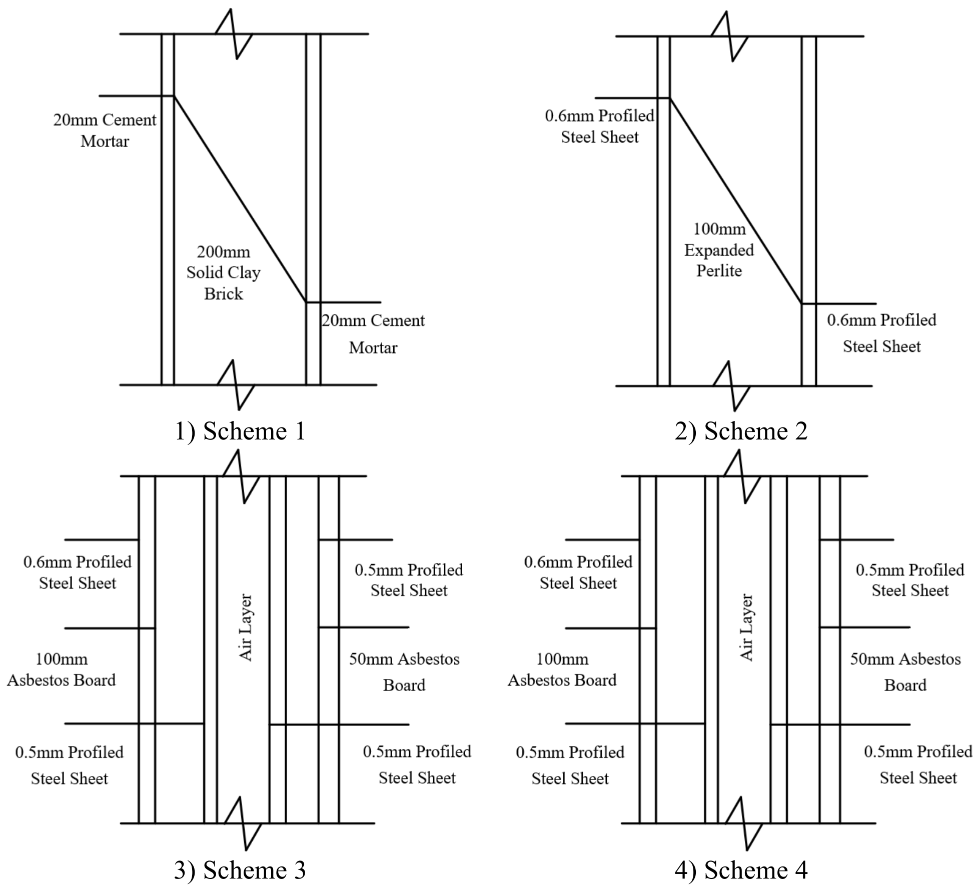

Figure 3. Four optimized design schemes for building exterior wall insulation layers

Following the principles of the previously mentioned parameter optimization design, Figure 3 presents four different optimization design schemes for building exterior wall insulation layers, which are intended for further experimentation.

The research content of this paper, focusing on the thermal performance analysis and optimization design of the external wall insulation layer in buildings, is a universally relevant topic, but it is particularly pertinent for certain types of buildings or those in specific climatic conditions. For high energy-consuming buildings such as hospitals, schools, and commercial centers, optimizing the insulation layer can significantly reduce energy consumption, making this research especially relevant for these buildings. However, the universality of this research implies that it is applicable in many parts of the world, but it may be particularly crucial in the specific types of buildings or climatic conditions mentioned above. In practical application, the research findings and optimization plans need to be appropriately adjusted according to specific situations to meet the local actual needs and regulations.

4. EXPERIMENTAL RESULTS AND ANALYSIS

This article initially conducts a thermal bridge heat transfer analysis of the building exterior wall insulation layers, including the calculation of thermal bridges and their equivalent heat transfer coefficients. It then proceeds with the optimization design of insulation parameters for these layers. Table 1 illustrates the changes in the minimum temperatures and maximum heat flow densities of each homogeneous material layer before and after the optimization design. As evident from the table, the optimization design has led to an increase in the minimum temperatures and a reduction in the maximum heat flow densities of each homogeneous material layer, regardless of whether it's facing light, the roof, or backlight, and whether it's for the overall exterior wall or for individual material layers. This demonstrates the effectiveness of the optimization design.

Before optimization, due to the lack of effective insulation measures, the building exterior wall materials had lower minimum temperatures and higher maximum heat flow densities, meaning that heat passed through the exterior walls quickly, leading to significant indoor heat loss and high energy consumption. After optimization, by selecting insulating materials with low thermal conductivity and high thermal resistance, and by appropriately adjusting the thickness and layout of materials, as well as optimizing the structure design of the insulation layer, the heat transfer coefficient of the exterior walls was effectively reduced, and their thermal resistance was increased, thereby enhancing the insulation performance of the exterior walls.

It can be concluded that the insulation parameter optimization design scheme proposed in this article can effectively improve the insulation performance of building exterior walls, reduce heat loss, lower energy consumption, and achieve energy-saving effects.

Table 1. Minimum temperatures and maximum heat flow densities of each homogeneous material layer

		Overall Exterior Wall			**Analyzed by Single Homogeneous Material Layer**		
		Facing Light	Roof	Backlight	Facing Light	Roof	Backlight
Minimum Temperature (°C)	Before Optimization	11.2	17.5	6.8	11.4	17.8	6.6
	After Optimization	17.8	17.9	14.8	16.9	17.5	13.8
Maximum Heat Flow Density (W/m^2)	Before Optimization	85.23	31.23	102.34	88.27	30.25	101.25
	After Optimization	40.63	23.56	51.23	42.39	23.46	51.23

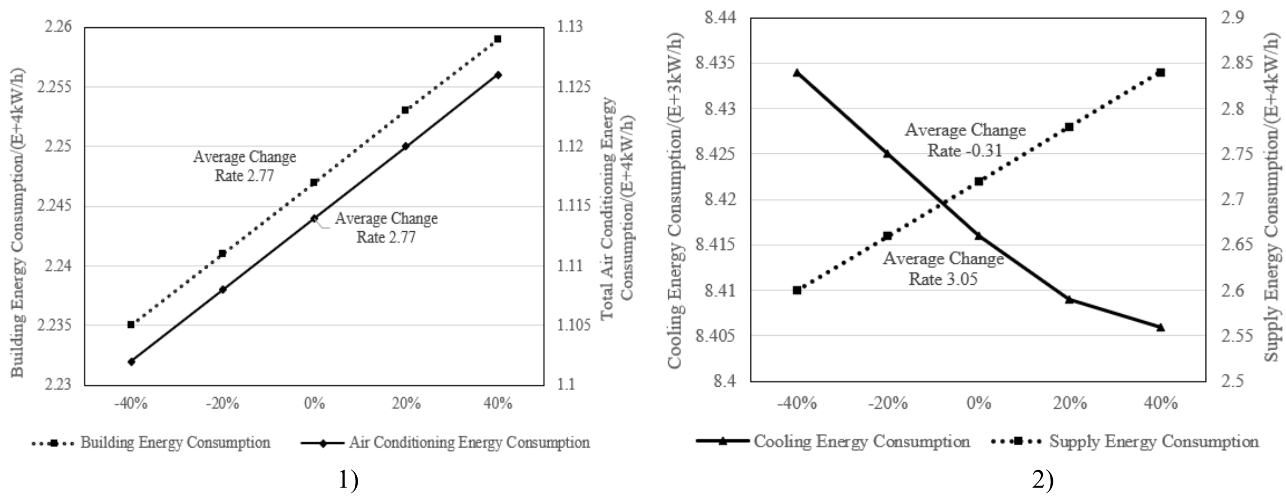

Figure 4. Variation of different energy consumptions with the degree of thermal bridging

Figure 4 shows the changes in building energy consumption, air conditioning energy consumption, cooling energy consumption, and supply energy consumption with varying thermal bridge area. An increase in the thermal bridge area corresponds to an enhanced thermal bridge effect, indicating a decline in the thermal insulation performance of building exterior walls. It is observed that with the increase in thermal bridge area, there is a rising trend in building energy consumption, air conditioning energy consumption, and supply energy consumption, while cooling energy consumption shows a decreasing trend. This indicates that an increase in the thermal bridge area leads to intensified indoor heat loss, necessitating more energy consumption to maintain indoor temperature and humidity conditions. Meanwhile, the indoor temperature drop caused by the thermal bridge effect results in decreased cooling energy consumption. These data further validate the effectiveness of the optimized design scheme for the insulation parameters of building exterior wall insulation layers proposed in this article. Through optimization design, it is possible to reduce the area of thermal bridges, lessen the thermal bridge effect, enhance the insulation performance of building exterior walls, thereby lowering building energy consumption, air conditioning energy consumption, and supply energy consumption, and improving energy usage efficiency.

Figure 5 displays the air conditioning energy consumption, heating energy consumption, and annual energy consumption for four different schemes. It is evident that Scheme 4 has the lowest heating energy consumption and annual energy consumption, with its air conditioning energy consumption being roughly on par with other schemes. This implies that Scheme 4 requires the least amount of energy to maintain indoor temperature and humidity. Previous discussions mentioned that optimizing the design of building exterior wall insulation layers can effectively reduce the building's heat transfer coefficient, thereby minimizing heat loss and reducing the energy consumption for air conditioning and heating. Considering this, it can be inferred that the outstanding performance of Scheme 4 is due to its optimized design of the building exterior wall insulation layers. Specifically, Scheme 4 utilized materials with low thermal conductivity and high thermal resistance, increased the thickness of the insulation layer, and optimized the layout and structural design of the materials to achieve the purpose of reducing the heat transfer coefficient. These optimization measures effectively controlled the loss of indoor heat, thereby reducing the energy consumption for air conditioning and heating.

Table 2 presents the building energy consumption simulation results, encompassing a range of indicators including annual energy consumption per unit area, total annual heat consumption, total annual coal consumption, energy saving rate, annual operating cost of the heating system during the heating period, increase or decrease in habitable area, and aesthetic degree. From the table, it is evident that Scheme 4 exhibits superior performance across several key indexes: it has the lowest annual energy consumption per unit area, the least total annual heat consumption, the lowest total annual coal consumption, the highest energy saving rate, the lowest annual operating cost for the heating system, and also ranks highest in terms of aesthetic appeal.

Figure 6 shows the balance index for single layer structures and multi-layer composite structures under different schemes. The balance index comprehensively considers the carbon emission coefficient and additional financial expenditure coefficient of the building exterior wall insulation layers. Therefore, a smaller balance index implies better overall performance of the scheme in terms of energy saving and cost. From the figure, it is observed that the multi-layer composite structure has the smallest balance index value under Scheme 4, at -0.9676, indicating that Scheme 4 offers the best overall performance in multi-layer composite structures. This result is due to the optimization in the design of the building exterior wall insulation layers in Scheme 4, which includes using materials with low thermal conductivity and high thermal resistance, increasing the thickness of the insulation layer, and optimizing the layout and structural design of the materials. Moreover, looking at the single layer structure, although the balance index for Scheme 4 is not the smallest, the difference is minimal, indicating that Scheme 4 also performs quite well in single layer structures. This can be attributed to effective control over carbon emissions and financial expenditures in Scheme 4. It can be concluded that Scheme 4 in the optimized design plan for insulation parameters of building exterior wall insulation layers proposed in this article, shows excellent energy-saving and cost-control effects, both in single layer and multi-layer composite structures, making it a very effective design scheme.

Different regions may have different architectural traditions, material availability, and construction techniques, which can affect the design and optimization of insulation layers. Moreover, in areas with high energy costs or strict environmental policies and building energy efficiency requirements, the design of scheme 4 may be more impactful.

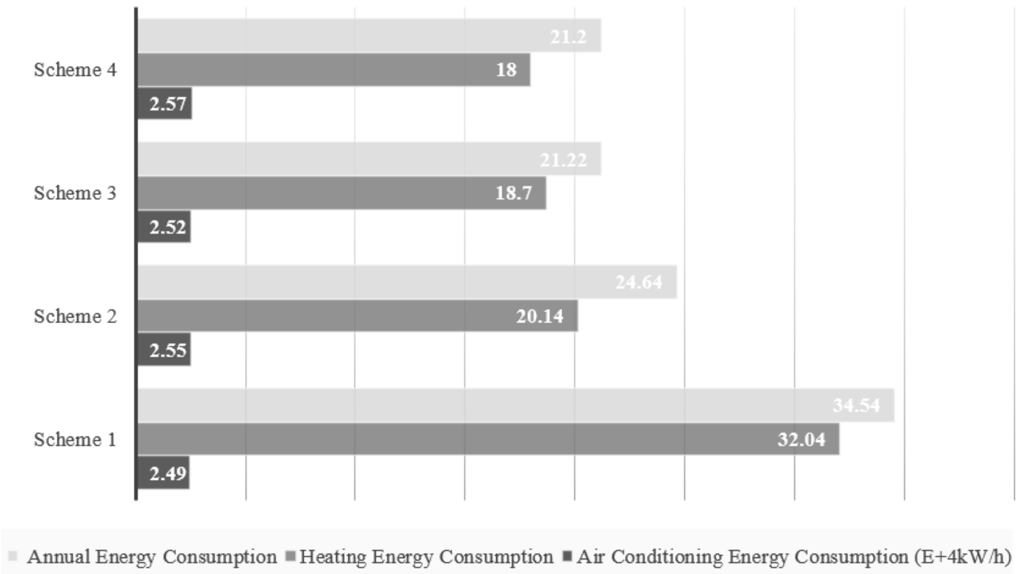

Figure 5. Energy consumption of four schemes

Table 2. Building energy consumption simulation results

Index	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Annual Energy Consumption per Unit Area (kwh/m^2)	181.5	87.56	81.23	81.07
Total Annual Heat Consumption (kw/h)	15966234.2	8123457.25	7432561.8	7389512.4
Total Annual Coal Consumption (*kgce*)	3012542.68	1895242.6	1895634.7	1812453.6
Energy Saving Rate (%)	/	51.23	53.12	55.48
Annual Heating System Operating Cost (yuan)	37854215.8	2134562.85	2123248.21	2122547.3
Increase/Decrease in Habitable Area (m^2)	/	0	-71.23	-5.9562
Aesthetic Degree	Poor	Average	Good	Excellent

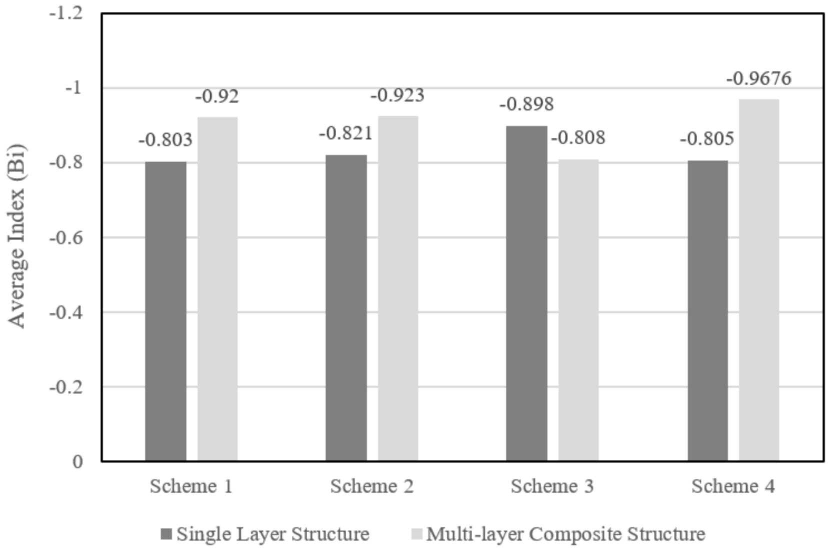

Figure 6. Balance index for different insulation layer structures under various schemes

5. CONCLUSION

This article primarily focuses on the optimization design of insulation parameters for building exterior wall insulation layers, proposing four different design schemes. These schemes were compared and analyzed through simulation experiments. The experimental results show that Scheme 4 exhibits excellent performance across multiple key indicators. For example, in terms of air conditioning energy consumption, heating energy consumption, and annual energy consumption, Scheme 4 achieved the lowest values. It also yielded optimal results in annual energy consumption per unit area, total annual heat consumption, total annual coal consumption, energy saving rate, and annual operating cost of the heating system during the heating period. Furthermore, Scheme 4 demonstrated high practical value in aesthetic degree and usable floor area. It can be inferred from the previous discussions that the success of Scheme 4 is mainly due to the optimization in the design of the building exterior wall insulation layers. This includes the use of materials with low thermal conductivity and high thermal resistance, increasing the thickness of the insulation layer, and optimizing the layout and structural design of the materials. These optimization measures effectively reduced the heat transfer coefficient, minimized heat loss, and thereby lowered energy consumption.

In summary, Scheme 4 of the optimized design plan for insulation parameters of building exterior wall insulation layers proposed in this article exhibits high practical value, not only in terms of energy saving but also in aesthetic appeal and usable floor area, making it a very effective design scheme. This research provides valuable insights for the development of building energy conservation technologies.

The computational models used in the research are based on a series of assumptions, such as steady-state conditions, uniform material properties, or simplified boundary conditions, which may deviate from real-life scenarios. The thermal performance data of materials, such as thermal conductivity, specific heat capacity, and thermal resistance, might be based on experimental values under standard test conditions. In actual applications, these performances may vary with changes in environmental conditions and over time. To overcome these limitations, future research needs to constantly improve the study through experimental validation, long-term performance monitoring, testing in multiple climatic zones, and simulation analysis in multiple scenarios. Also, the implementation of research results should consider a comprehensive cost-benefit analysis, environmental impact assessment, and consistency with existing regulations and building standards.

Future work will investigate the adaptability of insulation layer performance under different climatic conditions, building types, and design standards. It will explore how to adjust and optimize designs to meet diverse environments and needs. Additionally, the development of simulation tools that comprehensively consider thermal bridge effects, thermal mass, building physics, and energy consumption is planned. These tools can assist architects and engineers in making more informed decisions during the design phase.

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