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Investigating the Thermal Transfer Properties of Green Facades in Urban Buildings

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ABSTRACT

This study focuses on the challenges posed by global environmental issues and the urbanization process, delving into the thermal flux characteristics of green facades. Despite the significant role of green facades in environmental enhancement, energy conservation, and urban microclimate regulation, research on their thermal flux characteristics remains relatively scarce. Current studies mainly examine the impact of green vegetation on buildings' thermal loads, yet descriptions of the heat and mass transfer processes in vegetation layers and mathematical expressions of radiative heat exchange are notably lacking, often overlooking the influence of multiple factors such as solar radiative heat flux, net long-wave radiation heat flux, convective heat transfer flux, and latent heat flux. Through precise analysis and mathematical modeling of the heat and mass transfer processes in the vegetation layers of building facades, this paper aims to provide a scientific basis for green building design, enabling designers to more effectively utilize vegetation layers to regulate buildings' microenvironments, reduce energy consumption, and enhance the comfort of living and working spaces. Optimizing the design of vegetation layers not only enhances the thermal performance of buildings but also improves their aesthetics and ecological value, thereby promoting the development of green buildings. The research outcomes can positively impact policy-making, the updating of building standards, and the perfection of green building certification programs. Specifically, it offers a basis for policymakers, aiding in the establishment of more stringent and detailed green building standards, encouraging the construction industry to adopt green technologies and solutions. Moreover, the research findings serve as an important reference for the assessment and certification of green buildings, helping to establish a more comprehensive evaluation system and further promoting sustainable development in the construction industry.

1. INTRODUCTION

The challenges of global environmental issues and urbanization are intensifying, making the importance of building greening increasingly recognized [1, 2]. It not only improves air quality and reduces urban heat island effects but also enhances the ecological environment and the quality of life for urban residents. Among various building greening methods, greening of building facades has attracted widespread attention for its unique visual impact and energy-saving benefits [3-5]. It primarily reduces the thermal load of buildings by affecting the heat flow transfer characteristics of the exterior walls, thereby reducing energy consumption and effectively resisting the high temperature impact of the outdoor environment. However, the heat flow transfer characteristics of building exterior wall greening, especially the heat and mass transfer processes in the vegetation layer, remain to be studied in depth [6-10].

The study of the heat flow transfer characteristics of building exterior wall greening is of great significance for building energy conservation, environmental improvement, and urban microclimate regulation [11-14]. First, understanding and mastering the heat flow effects of building exterior wall greening helps us design more energy-efficient buildings, reduce building energy consumption, and achieve green and low-carbon urban development [15, 16]. Secondly, by optimizing greening design, the thermal environmental effects of buildings can be improved, enhancing indoor comfort and enriching people's living experience. However, although the importance of this field is increasingly recognized, the corresponding research is still quite limited [17].

Most existing studies focus on the impact of greening vegetation on the thermal load of buildings, but research on the description of heat and mass transfer processes in the vegetation layer and the mathematical expression of radiative heat transfer effects is scarce [18-20], and this limits our understanding and simulation of the specific heat flow transfer process in building exterior wall greening [5]. In addition, when trying to understand and simulate the heat flow transfer characteristics of building exterior wall greening, the influence of various factors such as solar radiation heat flow, net long-wave radiation heat flow, convective heat transfer heat flow, and latent heat flow should not be ignored, but these factors are often not fully considered in existing studies, leading to an inaccurate reflection of the thermal balance process in the vegetation layer [21-26].

In view of these issues, this paper will focus on studying the heat and mass transfer processes in the vegetation layer of building exterior wall greening and the mathematical expression of the radiative heat transfer effects in the vegetation layer, in order to fill the gaps in existing research. Specifically, this paper will conduct in-depth analysis from four aspects: solar radiation heat flow, net long-wave radiation heat flow, convective heat transfer heat flow, and latent heat flow, and construct a thermal balance equation for the vegetation layer to comprehensively analyze the thermal process of building exterior wall greening. Through this research, we hope to gain a deeper understanding of the heat flow transfer characteristics of building exterior wall greening, thereby providing more scientific theoretical guidance for the design and management of building exterior wall greening. We expect the proposed mathematical model to more accurately depict and predict the thermal balance process of the vegetation layer, providing new references and tools for green building design and energy efficiency optimization in practical engineering applications.

2. DESCRIPTION OF HEAT FLOW TRANSFER PROCESS IN THE VEGETATION LAYER OF BUILDING EXTERIOR WALL GREENING

The heat flow transfer process in the vegetation layer of building exterior wall greening refers to the exchange of heat and mass between the vegetation layer and environmental factors, as well as within the vegetation layer itself. This exchange includes the absorption, emission, storage, and transfer of heat, as well as water evaporation through transpiration, thereby affecting the thermal load of the building's exterior walls and the thermal environmental effect indoors. This process encompasses a variety of complex thermophysical processes, such as the absorption and reflection of solar radiation by vegetation, the emission and absorption of long-wave radiation, wind blocking and ventilative heat exchange, and the release of latent heat through transpiration. The characteristics of these processes have a significant impact on the building's energy-saving effects and the benefits of greening. Constructing the thermal equilibrium equation for the vegetation layer is based on the principles of thermodynamics, heat and mass transfer theory, as well as existing research on the regulatory effects of vegetation on the microclimate in environmental science. It comprehensively considers the interaction of four key factors: solar radiation, net long-wave radiation, convective heat transfer, and latent heat, which in previous models were often considered separately or only in part. Unlike other models, this study integrates these factors into a single mathematical framework, providing a more comprehensive and accurate method to assess and predict the impact of green facades on the thermal environment of buildings. Figure 1 shows a schematic diagram of heat flow transfer in the vegetation layer of building exterior wall greening. Figure 2 displays the contact interface between the water storage and drainage layer and the soil layer, and the modes of heat transfer.

The influencing factors of the heat flow transfer behavior in the vegetation layer of building exterior wall greening with the external environment and itself mainly include two aspects: external environmental factors and factors of the vegetation layer itself. External environmental factors include solar radiation, environmental temperature, air humidity, wind speed, etc. Solar radiation directly affects the heat absorption and reflection capacity of the vegetation layer, while environmental temperature and air humidity affect the transpiration and thermal radiation of the vegetation layer, and wind speed affects its convective heat transfer. Factors of the vegetation layer itself include vegetation type, density, leaf area, moisture condition, etc. Different types of vegetation have varying abilities to absorb and reflect solar radiation, vegetation density and leaf area affect the emission and storage of heat, and the moisture condition directly affects the transpiration of vegetation. The relationships among these influencing factors are complex, intertwined, and mutually influencing. For example, the intensity of solar radiation affects the heat absorption and reflection of the vegetation layer, while the type and density of the vegetation layer in turn affect its ability to absorb and reflect solar radiation. At the same time, environmental temperature and air humidity affect the transpiration of vegetation, which in turn is related to the moisture condition of the vegetation. Therefore, these factors form a complex dynamic equilibrium system among themselves, having a significant impact on the heat flow transfer behavior of the vegetation layer.

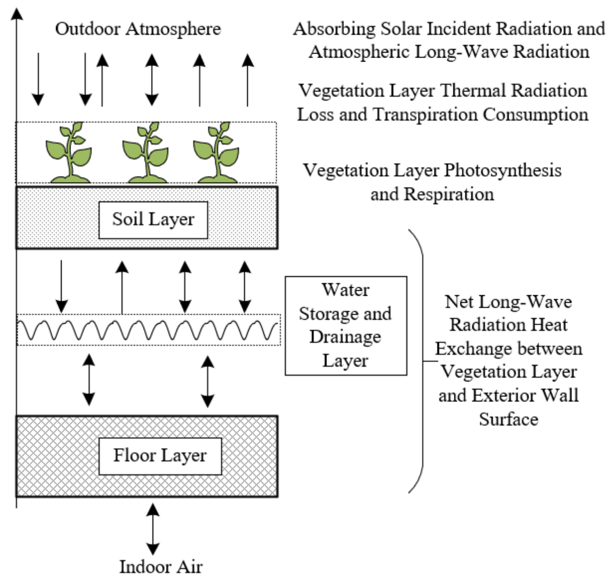

Figure 1. Schematic diagram of heat flow transfer in the vegetation layer of building exterior wall greening

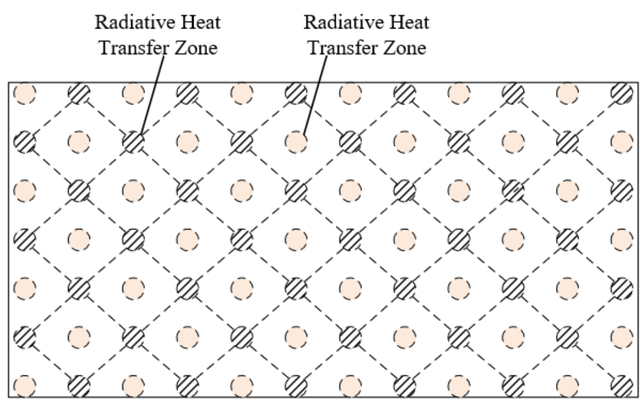

Figure 2. Contact interface and heat transfer modes between water storage and drainage layer and soil layer

Constructing the thermal balance equation for the vegetation layer in the heat process of building exterior wall greening requires considering uncertain factors such as climate change, vegetation growth status, vegetation management measures, and building factors. Based on these uncertainties, the assumptions for constructing the thermal balance equation of the vegetation layer in the heat process of building exterior wall greening are as follows:

(1) Climate Conditions: In reality, climate conditions such as temperature, humidity, wind speed, and solar radiation intensity vary throughout the day or season. To simplify the model and make the equation more accessible for analysis and calculation, it is assumed that the climate conditions are stable during the observation period. However, this assumption may overlook the impact of climate condition changes, and these factors should be considered in practical applications.

(2) Vegetation Growth State: In reality, the growth state of vegetation is influenced by seasons, climate, soil conditions, and other factors, with biological cycles such as growth, leaf fall, and dormancy, affecting its morphological characteristics and physiological functions. To better understand and calculate the thermal balance process of the vegetation layer, it is assumed that the vegetation's growth state remains stable during a certain observation period. However, changes in vegetation growth state should be considered in practical applications.

(3) Vegetation Management Measures: In reality, vegetation management measures such as irrigation and pruning impact the vegetation's moisture condition and morphological characteristics, thereby affecting the heat flow transfer behavior. To simplify the model, it is assumed that vegetation management measures remain consistent during the observation period, and these management measures should be considered in practical applications.

(4) Factors of the Building: The orientation, building materials, building structure, and insulation performance of a building can all affect the heat flow transfer of exterior wall greening. To better understand and calculate the thermal balance process of the vegetation layer, it is assumed that these factors remain constant when constructing the model.

(5) Other Environmental Factors: Environmental factors such as rainfall, snow cover, and air pollution may affect the heat flow transfer behavior of the vegetation layer. To simplify the model, it is assumed that there are no impacts from these sudden environmental factors during the observation period.

The innovative aspects or new insights provided by this paper primarily lie in its comprehensiveness and precision. It not only involves traditional heat conduction issues but also includes detailed analyses of radiation and latent heat transfer, which were often overlooked or simplified in previous studies. Moreover, through in-depth study and mathematical modeling of these processes, this research can reveal the thermal performance of green facades under different environmental conditions, providing more accurate design guidelines for optimization in terms of greening effects and energy saving. The research results will directly contribute to green building practices, offering architects and designers scientific bases and concrete methods to better utilize vegetation layers to improve buildings' energy efficiency and living comfort. At the policy-making and urban planning levels, these achievements can promote the establishment of standards for green buildings and sustainable urban design, encouraging the adoption of greening measures as effective means for urban cooling and environmental improvement. From a broader perspective, the study has significant implications for mitigating urban heat island effects, enhancing urban sustainability, and improving overall environmental quality by increasing building energy efficiency and promoting urban greening. Figure 3 shows the flowchart of heat flow transfer in the vegetation layer before thermal balance analysis.

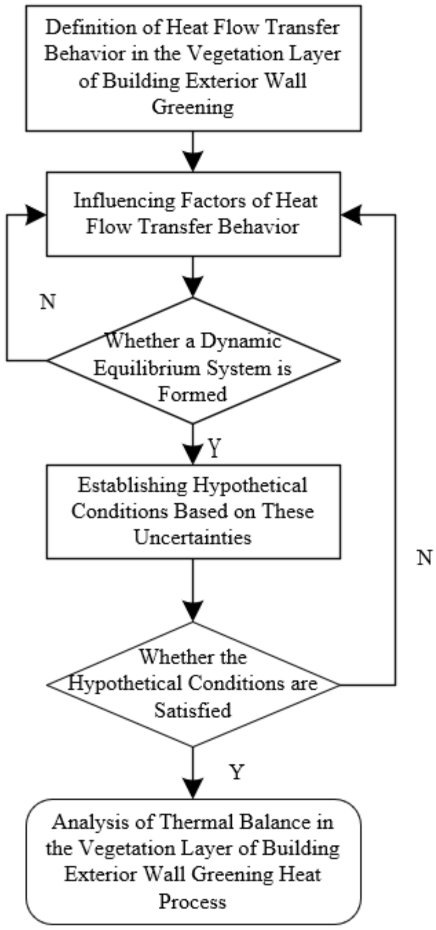

Figure 3. Flowchart of heat flow transfer in the vegetation layer

3. THERMAL BALANCE ANALYSIS OF THE VEGETATION LAYER IN THE HEAT TRANSFER PROCESS OF BUILDING EXTERIOR WALL GREENING

To explore the heat flow transfer characteristics of the building exterior wall greening system, this paper conducts a thermal balance analysis of the vegetation layer in the heat process of building exterior wall greening. By analyzing the thermal balance of the vegetation layer, one can gain a deeper understanding of the effects of factors such as solar radiation, environmental temperature, and air humidity on heat flow transfer, as well as the roles of the vegetation layer's own heat absorption, reflection, and transpiration in the heat transfer process. Further optimization of the design of building exterior wall greening involves choosing appropriate vegetation types, densities, and management measures to achieve optimal thermal comfort and energy efficiency.

In thermodynamics, the thermal equilibrium state of any object is the result of multiple heat flows interacting and balancing each other. In the heat process of building exterior wall greening, solar radiation heat flow, net long-wave radiation heat flow, convective heat transfer heat flow, and latent heat flow are the four main heat flow sources. This paper chooses to construct the vegetation layer thermal balance equation based on these four heat flow parameters. Assume the solar radiation heat flow of the vegetation layer is represented by $E_{SUN,vs}$, the net long-wave radiation heat flow by $E_{e,vs}$, the convective heat transfer heat flow by G_{vs}, and the latent heat flow by M_{vs}. The following formula gives the thermal balance equation of the vegetation layer in the building exterior wall greening heat process:

$$E_{SUN,vs} + E_{e,vs} + G_{vs} + M_{vs} = 0 \tag{1}$$

In the heat process of building exterior wall greening, solar radiation heat flow is an important factor as it is the main source of energy received by the vegetation layer. According to the principles of thermodynamics, solar radiation heat flow can be calculated by the solar radiation incident on the plane of the vegetation layer and the short-wave radiation absorptivity of the canopy. The parameter of solar radiation incident on the plane of the vegetation layer can be obtained through measurement of solar radiation intensity or by consulting meteorological data. Factors to consider include geographical location, season, time, etc. The short-wave radiation absorptivity of the canopy can be obtained through experimental measurements or by consulting relevant research materials. Factors to consider include the type, density, and morphology of vegetation. According to the principles of thermodynamics, solar radiation heat flow equals the solar radiation incident on the plane of the vegetation layer multiplied by the short-wave radiation absorptivity of the canopy. Assuming that the solar radiation incident on the plane of the vegetation layer is represented by U_0 and the short-wave radiation absorptivity of the canopy by β_{vs}, the calculation formula is:

$$E_{SUN,vs} = U_0 \beta_{vs} \tag{2}$$

In the heat process of building exterior wall greening, the net long-wave radiation heat flow of the vegetation layer involves thermal exchange between the vegetation layer and the outside environment, as well as with the substrate layer or the exterior surface of the wall. This paper analyzes the net long-wave radiation heat flow of the vegetation layer in three aspects of building exterior wall greening: planted roofs, planted surfaces, and planted walls, based on two aspects of heat exchange: the net long-wave radiation heat exchange between the vegetation layer and the outside, and between the vegetation layer and the exterior surface of the substrate layer or wall. This model can provide significant guidance for architects, engineers, and urban planners in designing more energy-efficient and sustainable buildings. By analyzing in detail the impact of vegetation layers on the thermal processes of building facades, the model can predict the specific effects of different types of vegetation, layouts, and densities on building energy efficiency. This enables designers to consider the optimal configuration of vegetation layers during the design phase, optimizing the thermal performance of buildings, reducing heating and cooling loads, and thus achieving the dual goals of energy saving, emissions reduction, and enhanced living comfort.

The parameter of net long-wave radiation heat exchange between the vegetation layer and the outside mainly considers the heat radiated by the vegetation layer to the outside and the radiative heat received from the outside. This can be calculated using the *Stefan-Boltzmann* constant by measuring the temperature of the vegetation layer and the surrounding environment, and considering weather conditions, among other factors. The parameter of net long-wave radiation heat exchange between the vegetation layer and the substrate layer's exterior surface mainly considers the radiative heat exchange between the vegetation layer and the substrate layer. Similarly, this can be calculated using the *Stefan-Boltzmann* law by measuring the temperature of the vegetation layer and the substrate layer. According to the principles of thermodynamics, the net long-wave radiation heat flow of the vegetation layer equals the net long-wave radiation heat exchange between the vegetation layer and the outside, plus the net long-wave radiation heat exchange with the exterior surface of the substrate layer. Assume the long-wave radiation absorptivity of the vegetation layer is represented by γ_{vs}, the coverage rate of the vegetation layer by δ_{vs}, the sky long-wave radiation incident on the canopy surface by $E_{e,vs}$, the *Stefan-Boltzmann* constant by δ, the long-wave radiation absorptivity of the substrate layer by γ_a, the temperature of the vegetation layer leaves by Y_{vs}, and the exterior surface temperature of the substrate layer by $Y_{a,r}$. The net long-wave radiation heat flow of the vegetation layer in the building exterior wall green roof can be calculated through the following formula:

$$E_{e,vs} = \gamma_{vs}\delta_{vs}\left(E_{e,SKY} - \delta Y_{vs}^4\right) + \delta_{vs}\gamma_a\gamma_{vs}\delta\left(Y_{a,r}^4 - Y_{vs}^4\right) \tag{3}$$

The coverage rate δ_{vs} of the vegetation layer refers to the proportion of the area covered by vegetation relative to the total area. It is an important parameter for measuring the density of the vegetation layer. The size of the coverage rate directly affects the absorption and scattering of solar radiation by the vegetation layer, thereby influencing the net long-wave radiation heat flow of the vegetation layer. A vegetation layer with a high coverage rate can absorb more solar radiation, thereby increasing the thermal load of the vegetation layer. At the same time, a high-coverage vegetation layer can also provide better shading effects, reducing the temperature of the exterior surface of the wall and decreasing the thermal radiation from the wall to the vegetation layer. Assume the coverage rate of the vegetation layer is represented by γ_{vs}, the Leaf Area Index (LAI) of the vegetation layer by *MSU*, and the vertical LAI by MSU_c. The calculation formula is as follows:

$$\delta_{vs} = 0.9 - 0.7\exp\left(-0.75 \cdot MSU\right) \tag{4}$$

The parameter of net long-wave radiation heat exchange between the vegetation layer and the exterior surface of the wall mainly considers the radiative heat exchange between the vegetation layer and the exterior surface of the wall. This can also be calculated using the *Stefan-Boltzmann* law by measuring the temperature of the vegetation layer and the exterior surface of the wall. Assume the long-wave radiation absorptivity of the vegetation layer is represented by γ_{vs}, the coverage rate of the vegetation layer by δ_{vs}, the external long-wave radiation incident on the plane of the vegetation layer by $E_{e,INC}$, the *Stefan-Boltzmann* constant by δ, the long-wave radiation absorptivity of the substrate layer by γ_a, the temperature of the vegetation layer leaves by Y_{vs}, and the exterior surface temperature of the wall by $Y_{WA,r}$. The net long-wave radiation heat flow of the vegetation layer in the building exterior wall planted skin can be calculated through the following formula:

$$E_{e,vs} = \gamma_{vs}\delta_{vs}\left(E_{e,INC} - \delta Y_{vs}^4\right) + \delta_{vs}\gamma_a\gamma_{vs}\delta\left(Y_{WA,r}^4 - Y_{vs}^4\right) \tag{5}$$

The canopy refers to the top part of the vegetation layer, which is the main interface for the direct exchange of energy between the vegetation layer and the external environment. Long-wave radiation incident on the canopy mainly comes from the sun and the atmosphere. This portion of radiation energy is the main way the vegetation layer absorbs and scatters solar radiation, and thus, it has an important impact on the thermal balance and net long-wave radiation heat flow of the vegetation layer. Calculating the long-wave radiation incident on the canopy can more accurately calculate the net long-wave radiation heat flow of the vegetation layer. On the other hand, it can provide a basis for optimizing the design of the vegetation layer of building exterior wall planted walls. Assume the long-wave radiation incident on the canopy is represented by $E_{e,INC}$, the sky long-wave radiation incident on the surface of the vegetation layer by $E_{e,SKY}$, the ground long-wave radiation incident on the vegetation layer by $E_{e,GR}$, and other surface long-wave radiation incident on the vegetation layer by $E_{e,OS}$. The calculation formula is as follows:

$$E_{e,INC} = E_{e,DSKY} + E_{e,GR} + E_{e,OS} \tag{6}$$

Assuming the long-wave radiation absorptivity of the vegetation layer is represented by γ_{vs}, the coverage rate of the vegetation layer by δ_{vs}, the external long-wave radiation incident on the plane of the vegetation layer by $E_{e,INC}$, the *Stefan-Boltzmann* constant by δ, the long-wave radiation absorptivity of the substrate layer by γ_a, the temperature of the vegetation layer leaves by Y_{vs}, and the exterior surface temperature of the substrate layer by $E_{e,vs}$. The net long-wave radiation heat flow of the vegetation layer in the building exterior wall planted walls can be calculated through the following formula:

$$E_{e,vs} = \gamma_{vs}\delta_{vs}\left(E_{e,INC} - \delta Y_{vs}^4\right) + \delta_{vs}\gamma_s\gamma_{vs}\left(Y_{a,r}^4 - Y_{vs}^4\right) \tag{7}$$

Assuming the convective heat transfer coefficient in the absence of wind is represented by r_0, the canopy transmission coefficient by V_{vs}, the air temperature within the canopy by $E_{s,vs}$, the wind speed at the interface between the canopy and air by $Q_{s,vs}$, the specific heat capacity of air at constant pressure by $v_{o,s}$, and the air density of the vegetation layer by $\vartheta_{e,vs}$. The convective heat transfer of the vegetation layer in the heat process of building exterior wall greening can be calculated through the following formula:

$$G_{vs} = \left(r_0 + 1.1 \cdot MSU \cdot \vartheta_{s,vs} v_{o,s} V_{vs} Q_{s,vs}\right)\left(Y_{s,vs} - Y_{vs}\right) \tag{8}$$

In the absence of wind, the heat exchange between the vegetation layer and the surrounding environment mainly relies on natural convection, which is caused by air density differences due to temperature differences. In areas with higher temperatures, the air density is lower and rises, while in cooler areas, the air density is higher and sinks, thus forming convective flow. The convective heat transfer coefficient in the absence of wind represents the intensity of this natural convection. It depends on the temperature difference between the vegetation layer and the surrounding environment, as well as the physical characteristics of the vegetation layer, such as plant type and density. The coefficient can be calculated through field measurements of the temperatures of the vegetation layer and the surrounding environment, combined with relevant empirical formulas or models. The internal air temperature of the canopy is an important factor determining convective heat transfer. Generally, the air temperature inside the canopy is affected by the vegetation layer's transpiration cooling, convective heat transfer, and radiative heat transfer. The parameter can be obtained by measuring the air temperature inside the canopy. It should be noted that since the air temperature inside the canopy may vary with time and environmental conditions, multiple measurements may be needed for more accurate data. By illustrating with examples or reference measurements, such as comparing the energy consumption of a specific building before and after the implementation of greening, thermal environment simulations, and surveys of residents' comfort levels, the impact of vegetation on the energy-saving effects and greening benefits of buildings can be vividly demonstrated. This comparison not only quantifies the energy-saving and emissions reduction effects of greening measures but also shows the additional environmental and social benefits of greening, such as improving the microclimate, increasing biodiversity, etc., providing strong case support for the wider promotion of green building facades.

The specific heat capacity of air at constant pressure and the air density of the vegetation layer are physical properties that determine convective heat transfer. The specific heat capacity of air represents the amount of heat absorbed or released by a unit mass of air when its temperature changes by 1K under constant pressure, while the air density of the vegetation layer represents the mass of air per unit volume. These parameters can be obtained by consulting relevant physical parameter tables. It should be noted that as the specific heat capacity of air and the air density of the vegetation layer vary with temperature and pressure, appropriate values should be selected according to the actual environmental conditions. Assuming the air density in the vegetation layer is represented by $\vartheta_{s,vs}$, the air density in the outdoor environment by ϑ_s, and the air density at the same atmospheric pressure in the outdoor environment when the temperature is equal to the leaf temperature Y_{vs} by ϑ_{vs}. The calculation formula is as follows:

$$\vartheta_{s,vs} = \frac{\vartheta_s + \vartheta_{vs}}{2} \tag{9}$$

The canopy is the top part of the vegetation layer and is the main site for convective exchange in the vegetation layer. The canopy transmission coefficient represents the capacity of the canopy for convective exchange, which is closely related to the structure and physical properties of the vegetation layer. Specifically, factors such as the height of the canopy, plant type, and LAI all influence the canopy transmission coefficient. This coefficient can be calculated by measuring these structural parameters in the field, combined with relevant empirical formulas or models. Assume the canopy transmission coefficient is represented by V_{vs}, the calculation formula is:

$$V_{vs} = 0.01\left(1 + 0.3/Q_{s,vs}\right) \tag{10}$$

Wind speed has a significant impact on convective heat transfer in the canopy. At the interface between the canopy and the air, the magnitude of the wind speed affects the intensity of convective heat transfer in the vegetation layer. High wind speeds increase convective heat transfer, while low wind speeds reduce it. The wind speed at the interface between the canopy and the air can be measured with an anemometer. It should be noted that since changes in wind speed can cause drastic changes in convective heat transfer, representative time periods should be selected for measurement, and multiple measurements should be taken to obtain more accurate data. Assume the wind speed in the canopy is represented by $Q_{s,vs}$, then the calculation formula is:

$$Q_{s,vs} = 0.83Q'\sqrt{V_{gb}^{vs}} + \left(1-\delta_{vs}\right)Q' \tag{11}$$

The transmission coefficient near the leaf interface of the canopy is represented by $V^{vs}{}_{gb}$, and the calculation formula is:

$$V_{gb}^{vs} = \left[j \Big/ \ln\left(\frac{X_s - X_f}{x_0^{vs}} \right) \right]^2 \tag{12}$$

Assuming the height at which the external air temperature Y_s is measured is represented by X_s, the thickness of the vegetation layer by X_{vs}, and the von Kármán constant by j, the calculation formulas for X_f and $X^{vs}{}_0$ are as follows:

$$x_f = 0.701X_{vs}^{0.975} \tag{13}$$

$$x_0^{vs} = 0.131X_{vs}^{0.997} \tag{14}$$

Latent heat flow, also known as evaporative cooling, refers to the heat dissipated by the vegetation layer through transpiration. Transpiration is the process by which plants release water into the atmosphere through stomata on their leaves. This process requires the absorption of a significant amount of heat, making it an important pathway for heat dissipation.

The calculation of latent heat flow in the heat transfer process of building exterior wall greening mainly depends on the transpiration rate of the vegetation layer, which in turn is related to the physiological characteristics of the plants and environmental conditions. The calculated value equals the product of the latent heat of water evaporation and the transpiration rate of the vegetation layer. The latent heat of water evaporation is a known physical constant, typically around 2454 kJ/kg at 20 degrees Celsius. The transpiration rate of the vegetation layer can be obtained by measuring the rate of water loss in the vegetation layer. Specific measurement methods include the weight method, water level float method, colorimetric method, etc. It should be noted that since the transpiration rate is influenced by environmental conditions, it is necessary to record the environmental conditions during measurement and make necessary corrections. Figure 4 shows the theoretical and experimental analysis flowchart for the thermal balance of the vegetation layer.

The proposed model can be validated by comparing it with empirical data from actual green facade projects. Specific methods include collecting data such as temperature, humidity, and solar radiation intensity from green facade systems of buildings in specific geographic locations and of different types. These actual measurements are then compared and analyzed against model predictions. By adjusting model parameters to minimize the difference between predicted and measured values, the accuracy and applicability of the model can be verified. This method not only tests the rationality of the model assumptions but also evaluates the model's predictive capability under different environmental conditions. By comprehensively considering multiple factors affecting heat transfer, such as solar radiative heat flux, net long-wave radiation heat flux, convective heat transfer flux, and latent heat flux, as well as their interactions, the model offers a more comprehensive and detailed method of thermal transfer assessment compared to current common methods. Unlike traditional methods that focus on a single heat transfer mechanism or simplify vegetation effects, this model, through precise mathematical expressions and assumptions, can more accurately predict the thermal transfer effects of the vegetation layer, providing a more scientific and refined tool for achieving efficient green building design and urban planning.

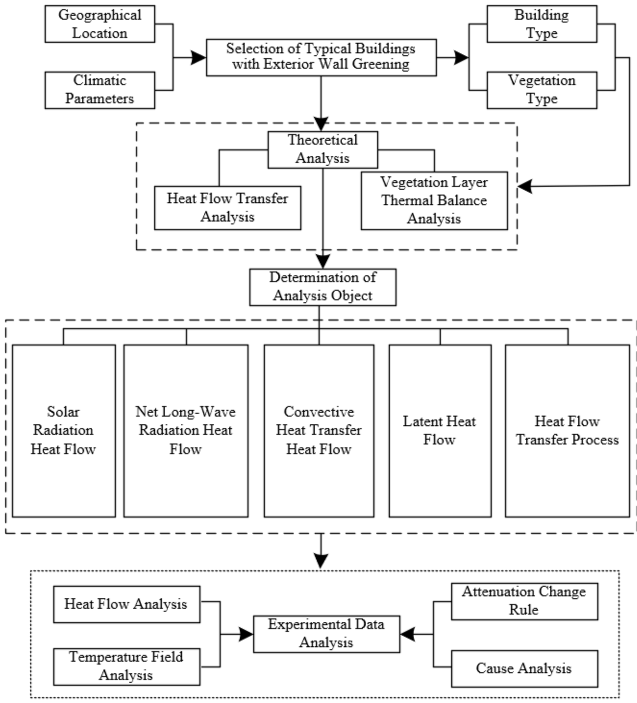

Figure 4. Theoretical and experimental analysis flowchart for the thermal balance of the vegetation layer

4. EXPERIMENTAL RESULTS AND ANALYSIS

The detailed information on parameter measurement techniques in this study involves the use of advanced sensors and instruments to accurately capture real-time data on environmental factors such as solar radiation, ambient temperature, and air humidity. For example, solar radiation can be measured with a pyranometer, while ambient temperature and air humidity can be captured using temperature and humidity sensors installed at various locations and heights. Additionally, for the absorption, reflection, and transpiration actions of the vegetation layer itself, an infrared thermal imager can be used to measure temperature changes on the vegetation surface, and specialized plant physiology measurement tools like porometers can assess the efficiency of the transpiration process. The combined use of these measurement techniques can provide comprehensive and detailed information about thermal flux characteristics.

Regarding the detailed information on latent heat flux calculation and measuring transpiration rate, the study employs methods of climate chamber or in-situ measurements to assess the transpiration rate of vegetation. Specific methods include using moisture sensors to measure changes in moisture within the soil and plant bodies, and employing tools like porometers and chlorophyll fluorometers to directly measure the transpiration rate of plant leaves and the activity of photosynthesis. Through these measurements, it is possible to accurately calculate the amount of water vapor released through transpiration by the vegetation layer under different environmental conditions, i.e., latent heat flux, which is crucial for understanding and optimizing the role of the vegetation layer in regulating the building's microenvironment.

Relative attenuation factor, thermal flux penetration ratio, LAI, and vegetation thickness are key parameters in assessing the thermal performance of green facade systems. The relative attenuation factor involves the vegetation's capacity to absorb and reflect solar radiation, usually calculated by comparing the intensity of radiation with and without vegetation coverage. The thermal flux penetration ratio refers to the ratio of thermal flux reaching the wall surface through the vegetation layer to the thermal flux without vegetation coverage, determined through analysis of actual measurement data. The LAI is the total leaf area per unit area, reflecting the density of vegetation, usually assessed by direct measurement or using specific instruments like leaf area meters. Vegetation thickness directly affects thermal flux transfer and can be determined through physical measurements.

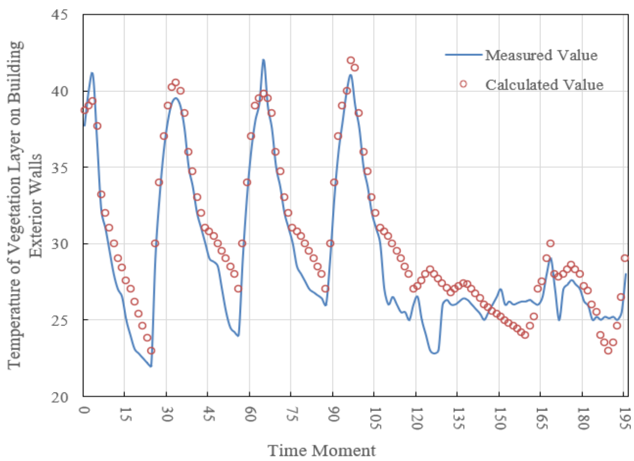

Figure 5. Comparison of measured and calculated temperatures in the vegetation layer of building exterior walls

Figure 5 shows the variation over time of the measured and calculated temperatures in the vegetation layer of building exterior walls. Overall, the trends of fluctuations in the calculated and measured values are basically consistent, exhibiting similar periodic changes. This indicates that the model is effective in capturing the overall trend of temperature changes in the vegetation layer. Although the overall trends are similar, there are certain deviations between the calculated and measured values at specific time points. This is due to the weather data used in the model calculations, such as radiation intensity, air humidity, temperature, etc., not being exactly the same as the actual values in the measured environment, or the model not fully considering some complex factors that affect the temperature of the vegetation layer. In terms of peak temperatures, the calculated values are generally slightly higher than the measured values, especially in the time period from 0 to 60 on the horizontal axis. This suggests that the model underestimates the cooling effect of the vegetation layer under high temperature radiation. During lower temperature phases, the difference between calculated and measured values is smaller, reflecting that the model predicts more accurately under lower temperature conditions or at night when there is less solar radiation.

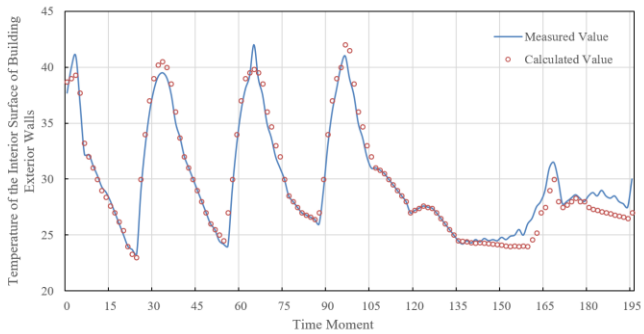

Figure 6. Comparison of measured and calculated temperatures of the interior surface of building exterior walls

Analyzing the comparison between the measured and calculated temperatures of the building exterior wall's interior surface as presented in Figure 6, the following conclusions can be drawn. Looking at the overall trend of the measured values (blue line) and the calculated values (red circles), they match, indicating that the model used can accurately predict the trend of temperature changes on the interior surface of the exterior wall to a certain extent. Both the measured and calculated values exhibit a certain periodicity, and they are relatively close at the peak and valley positions, indicating that the model has the capability to capture the key features of temperature changes on the interior surface of the exterior wall. Although the overall trend is consistent, at certain moments, there are deviations between the calculated and measured values. Particularly in the trough part of the 90-135 interval on the horizontal axis, the calculated values are significantly lower than the measured values, indicating that the model underestimates the actual temperature of the exterior wall under certain conditions. In high-temperature intervals (such as the 0 to 45 and 135 to 180 intervals on the horizontal axis), the calculated values are very close to the measured values, especially when reaching the highest temperature, showing that the model has a strong capability to simulate extreme temperature changes. In summary, it can be concluded that the model used is effective in predicting the temperature of the interior surface of building exterior walls, and it can reflect the trend and periodic characteristics of actual temperature changes well.

The effectiveness of green walls varies under different conditions or climates, mainly depending on the choice of plant species, climatic conditions (such as temperature, humidity, solar radiation), and the design of the greening system. For example, in environments with high temperatures and abundant sunlight, choosing plant species with high reflectivity and high transpiration efficiency can more effectively reduce thermal flux penetration. In contrast, in mild climates, the aesthetics and maintenance costs of the plants might be prioritized. Therefore, the selection of plant species should consider their adaptability to the environment, contribution to thermal comfort, and maintenance needs, to achieve the best energy-saving effects and economic benefits.

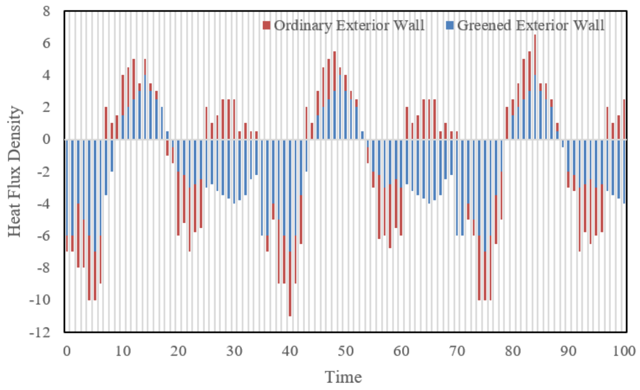

Figure 7. Comparison of instantaneous heat flow transmitted from exterior walls to indoors

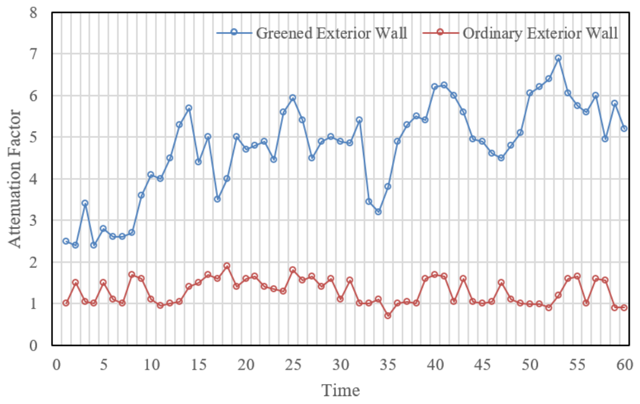

Figure 8. Comparison of attenuation factors of interior surface temperature of building exterior walls

Figure 7 shows a comparison of the instantaneous heat flow transmitted from the exterior walls to the indoors, where the red bar represents ordinary exterior walls and the blue bar represents greened exterior walls. From the figure, it is evident that the heat flux density represented by the red bar is generally higher than that of the blue bar, meaning that greened exterior walls are more effective in reducing heat flow into the interior during the heat transfer process compared to ordinary exterior walls. Positive values represent heat transfer from the exterior wall to the interior, while negative values indicate heat transfer from the interior to the exterior. If the greened exterior walls show more negative value areas, it indicates a more significant cooling effect. By noting the maximum and minimum values of the heat flow transmitted into the interior for both types of walls, the buffering capacity of greened exterior walls can be assessed at the hottest and coldest points. Observing the trend and pattern of heat flow helps understand the characteristics of heat flow changes in different types of exterior walls over a certain period (such as different times of the day, like daytime and nighttime). According to the range of time points on the horizontal axis, it can be understood whether the comparison is based on a specific period of the day or a longer time frame, which is crucial for explaining changes in positive and negative heat flows. From the above analysis, it can be concluded that greened exterior walls perform well in buffering heat flow, reducing thermal load, and improving thermal comfort. This has a substantial impact on building energy conservation, indoor temperature regulation, and sustainable design.

Based on the data presented in Figure 8, where the red line represents ordinary exterior walls and the blue line represents greened exterior walls, the analysis and conclusions regarding the comparison of indoor-outdoor temperature difference attenuation factors are as follows. The attenuation factors of greened exterior walls are generally significantly higher than those of ordinary exterior walls, indicating that greened walls are more effective in reducing the impact of external temperature fluctuations on the interior. Greened exterior walls provide better insulation, thereby reducing temperature fluctuations inside the building. The attenuation factors of greened exterior walls are higher than those of ordinary walls at most time points, especially at certain peak moments, where the attenuation effect of greened walls is more pronounced. These peaks correspond to periods of strong sunlight or higher external temperatures, indicating that the vegetation layer can more effectively inhibit heat entry into the interior during these times. The attenuation factors of ordinary exterior walls are relatively stable with smaller fluctuations, due to the lack of a buffering effect against sunlight and external temperature changes in walls without green coverage. The larger fluctuations in the attenuation factors of greened exterior walls reflect the sensitivity of the vegetation layer to external weather changes and the impact of management and maintenance factors on the performance of the greening. Overall, greened exterior walls demonstrate stronger performance in mitigating the ingress of external temperature differences compared to ordinary walls. This can be explained by the natural insulation layer provided by greening, which can absorb and dissipate heat generated by solar radiation, and further cool through transpiration, releasing moisture. Thus, greened exterior walls can be an effective means of improving building energy efficiency and indoor comfort.

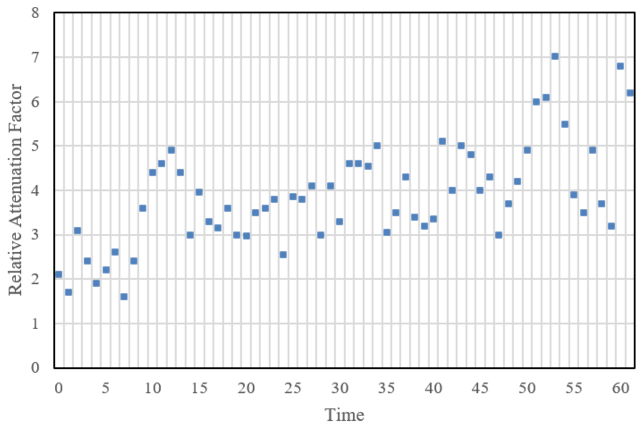

Figure 9. Relative attenuation factors of greened exterior walls

The data presented in Figure 9 shows that the relative attenuation factors of greened exterior walls exhibit certain fluctuations over time. From the figure, it is evident that the relative attenuation factors of greened exterior walls are above 1 at most time points, indicating that the green layer is effective in reducing the impact of outdoor temperature changes on the indoor environment. The values fluctuate between 2 and 7, demonstrating varying degrees of effectiveness of the green walls in attenuating external temperatures. The fluctuations in the relative attenuation factors reflect changes in environmental conditions, such as day-night temperature differences and climatic conditions, as well as the different physiological responses of the vegetation layer, such as variations in the intensity of transpiration. At certain time points, such as 15, 30, 45, and 60 minutes, the relative attenuation factors peak, which may be related to specific environmental conditions, like periods of maximum solar radiation intensity or biological rhythms. These peaks indicate that greened exterior walls are particularly effective in mitigating temperature fluctuations during these periods. The frequency of higher attenuation factors and the duration for which the attenuation factor remains at a higher level both indicate the comprehensive performance of greened exterior walls in resisting the entry of high temperatures indoors. Overall, greened exterior walls significantly weaken the impact of outdoor environmental temperatures on the indoors by providing an additional insulation layer and utilizing the transpirational cooling mechanism of plants. The data of the relative attenuation factors of greened exterior walls demonstrate the effectiveness and variability of this technology at different time points and under various environmental conditions. This analysis can provide valuable information for architectural design, urban planning, and climate regulation strategies, especially in the context of increasing urban heat island effects and extreme climatic events.

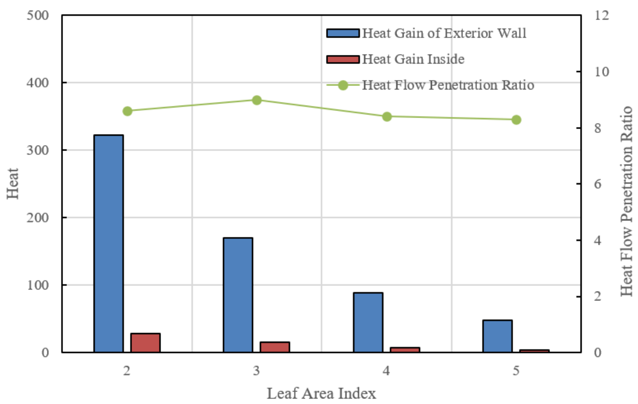

Figure 10. Influence of LAI on heat flow penetration ratio

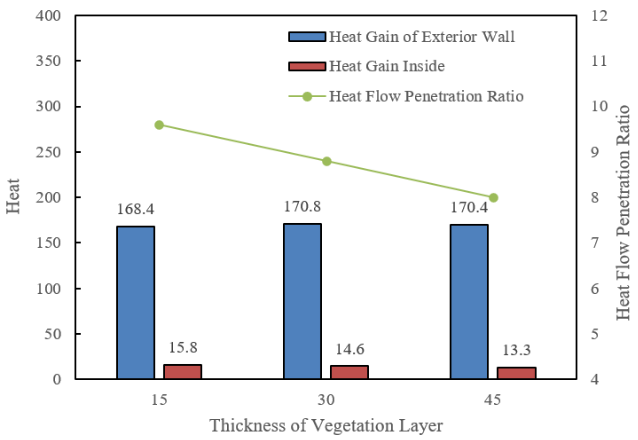

Figure 11. Impact of vegetation layer thickness on heat flow penetration ratio

The data provided in Figure 10 allows us to observe the impact of the LAI on the heat flow penetration ratio. According to the data in the graph, the heat gain of the exterior wall, represented by the blue bars, significantly decreases with an increase in the LAI. When the LAI is at 2, the heat gain of the exterior wall is the highest. As the LAI increases to 5, the heat gain gradually decreases, indicating that as the number of leaves increases, the buffering effect of the vegetation layer on heat transfer to the exterior wall improves. The red bars, representing the heat gain inside, also show a decrease in heat entering indoors with an increase in the LAI, indicating that greened exterior walls have a noticeable effect in inhibiting the transfer of external heat into the interior. The heat flow penetration ratio, represented by the green line, remains relatively stable despite the increase in LAI. This means that although the absolute heat gain of both the exterior wall and the interior decreases with an increasing LAI, the proportion of heat flow entering indoors does not change significantly. Overall, with the increase of the LAI, greened exterior walls effectively reduce the heat gain of both the exterior wall and the interior, diminishing indoor temperature fluctuations caused by external environmental changes, thus aiding in maintaining thermal comfort indoors. It can be concluded that the LAI is an important factor in controlling the thermal conductivity efficiency of greened exterior walls. Increasing the LAI significantly enhances the insulation performance of greened exterior walls, reducing heat flow into the building, and plays a positive role in achieving building energy efficiency and indoor comfort.

Based on the data shown in Figure 11, we can analyze the impact of vegetation layer thickness on the heat flow penetration ratio. In the graph, the blue bars represent the heat gain of the exterior wall, which slightly decreases as the vegetation layer thickness increases from 15 cm to 45 cm. This indicates that a thicker vegetation layer can improve insulation to some extent and reduce the entry of external heat. The red bars represent the heat gain inside, which gradually decreases from a vegetation layer thickness of 15 cm to 45 cm, suggesting that as the vegetation layer thickness increases, the interior's shielding ability against external heat improves. The heat flow penetration ratio, represented by the green line, gradually decreases with the increase in vegetation layer thickness, showing that a thicker vegetation layer significantly reduces the heat flow permeating indoors. The significant drop in the heat flow penetration ratio as the vegetation layer thickness increases from 15 cm to 30 cm demonstrates that a small increase in thickness can achieve significant insulation effects. The additional effect from increasing the thickness from 30 cm to 45 cm is relatively minor, implying that there may be an optimal range of vegetation layer thickness in certain situations. In summary, increasing the thickness of the vegetation layer positively impacts enhancing the insulation performance of exterior walls and reducing heat energy transfer indoors. However, as the thickness increases, the additional insulation effect diminishes, so a balance between cost and benefit should be considered in practical applications to find the most economically efficient vegetation layer thickness.

The study of the durability of green walls and the comparison of different types of vegetation layers involves the growth habits of vegetation, maintenance requirements, adaptability to environmental changes, and long-term impact on the thermal performance of buildings. Durability depends not only on the biological characteristics of the plants themselves but also on the technology used to install and maintain the greenery systems. For instance, naturally grown green walls may require lower maintenance, but their impact on the building structure and long-term stability may not be as good as carefully designed modular or bagged green wall systems. By comparing the initial construction costs, maintenance expenses, lifespan, and the effects on improving building thermal performance of different systems, the overall economic benefits and environmental sustainability of various green wall systems can be evaluated. Such comparative studies are significant for promoting the application of green walls in different regions and buildings.

The results of the study have a direct practical impact on the design and optimization of building facade planting walls. By understanding the effects of different types of vegetation, densities, and management measures on thermal flux transmission, architects and designers can select the greening solution that best suits the specific environmental conditions and architectural needs. This can not only improve the thermal comfort of buildings and reduce energy consumption but also beautify the urban environment and enhance biodiversity. Specifically, choosing vegetation types that can effectively reflect solar radiation and enhance transpiration cooling effects can significantly reduce the cooling load of buildings, thereby improving energy efficiency.

5. CONCLUSION

This paper studied the heat flow transfer characteristics of the vegetation layer in building exterior wall greening systems, aiming to propose a mathematical expression model to deeply analyze and predict the thermal balance state of the greening vegetation layer. By considering solar radiation heat flow, net long-wave radiation heat flow, convective heat transfer heat flow, and latent heat flow as the core research parameters, this paper constructs a thermal balance equation for the vegetation layer to quantify the impact of these heat flows on the thermal process of building exterior wall greening. Experimental analysis of the heat flow transfer characteristics of the vegetation layer demonstrates the significant effect of greened exterior walls in reducing the impact of outdoor environmental heat on the interior. With the increase in the thickness of the vegetation layer and the LAI, both the heat gain of the exterior wall and the interior is reduced, and the proportion of external heat flow penetrating indoors correspondingly decreases. Solar radiation heat flow and net long-wave radiation heat flow have a significant impact on the temperature of the greening vegetation layer of building exterior walls. The comparison of model results with actual measured data indicates that the vegetation layer can effectively absorb and scatter solar radiation, as well as reduce the temperature of the exterior wall. In terms of convective heat transfer and latent heat flow, the greened exterior wall can effectively improve thermal environmental effects with changes in the physical properties of the vegetation layer, such as LAI and thickness of the vegetation layer. This is achieved by adjusting the transpiration and convective exchange capabilities of the vegetation layer. The insulating effect of the vegetation layer is further validated by actual measurement data, particularly manifested in heat flow analysis. Increases in thickness and LAI not only reduce the heat influx to the exterior wall but also decrease the heat transfer from the exterior wall to the interior. The establishment and application of the thermal balance equation demonstrate the effectiveness of the model in predicting the performance of greened exterior walls, but also reveal limitations under specific conditions. After analyzing the differences between calculated and measured values, directions for model optimization are proposed.

The practical application of the results of this study is significantly reflected in enhancing building energy efficiency and living comfort. Through an accurate vegetation layer thermal balance model, architects and engineers can design more efficient green facade systems. By optimizing the thickness of the vegetation layer and the LAI, these systems can effectively reduce the absorption of external thermal flux by buildings, lower the load on air conditioning systems, thus reducing energy consumption and enhancing indoor thermal comfort. Additionally, this research provides a powerful tool to help assess and predict the impact of different vegetation configurations on the thermal performance of buildings, offering a scientific basis for achieving more energy-efficient and environmentally friendly architectural designs.

Regarding the policy implications of the research findings, this study underscores the importance of incorporating green facade systems into urban planning and architectural design. Governments and relevant agencies could establish corresponding policies and incentive measures to encourage developers and owners to adopt green facades, such as offering tax reductions, financial grants, or facilitation of building permits. Moreover, the research results also reveal the economic benefits to consider in the design of green facade systems under different climatic conditions, including the balance between initial investment, maintenance costs, and long-term energy-saving gains. Therefore, policymakers should consider these economic factors and establish reasonable standards and guidelines to promote the widespread application and sustainable development of green facade systems. Through the implementation of these policies and economic incentives, the development of green facade technology can be effectively promoted, achieving urban sustainability goals while raising public awareness of environmental protection and energy conservation.

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