Article

Research on Hygrothermal Environment Adaptability of Passive Buildings in Cold Regions during Severe Winters: Multi-parameter Optimization Based on Field Measurement and Simulation

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Abstract: Against the backdrop of escalating global energy consumption and increasingly stringent environmental regulations, building energy efficiency has emerged as a critical pathway for sustainable development. In cold regions, severe winter conditions lead to substantial heating demands, while the insufficient thermal performance of conventional buildings results in significant energy waste. Passive buildings offer a solution to these challenges through scientific design and the application of high-performance materials. This study focuses on the hygrothermal environment adaptability of passive buildings during severe winters in cold regions. Adopting a methodology that integrates field measurements with numerical simulations, the research conducts empirical studies on traditional dwellings in Hailar and university classrooms. A multi-software collaborative simulation model is constructed to perform multi-parameter optimization, targeting thermal comfort, energy efficiency, and economic feasibility. Research findings indicate that the thermal inertia of the passive building envelope effectively delays temperature transmission, ensuring a stable and comfortable indoor hygrothermal environment. Through the synergistic optimization of the envelope's thermal performance and ventilation strategies, the amplitude of indoor temperature fluctuations can be reduced and the uniformity of humidity distribution improved, thereby enhancing environmental adaptability during severe winters. Based on these insights, strategies such as multi-layer composite insulation systems, dynamic ventilation regulation, and the collaborative optimization of building envelope parameters are proposed to provide theoretical and technical support for relevant designs. Future research could further expand the research scale, enhance simulation accuracy, and explore the potential of building morphology to promote the transition of passive buildings toward a "human-building-environment" collaborative paradigm.

Keywords: cold regions; passive building; severe winter; hygrothermal environment adaptability; field measurement and simulation; multi-parameter optimization

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1. Introduction

Against the backdrop of continuously rising global energy consumption and increasingly stringent environmental protection requirements, innovation and practice in building energy-saving technologies have become a critical path for sustainable development. Energy consumption issues in cold regions are particularly prominent, where heating demand during severe winters constitutes the bulk of annual energy use. Traditional buildings suffer from severe energy waste due to insufficient thermal performance. Passive buildings, through meticulous envelope design, natural ventilation, and daylighting optimization, can improve energy efficiency by over 90% compared to conventional buildings, providing a brand-new solution for energy conservation in cold regions.

Severe winters in cold regions not only present extreme low temperatures but also involve complex challenges in regulating the indoor hygrothermal environment. Technical difficulties, such as thermal bridge control in envelopes and airtightness assurance, directly affect residential comfort and energy efficiency [1]. Research indicates that passive buildings in these regions must withstand sustained low temperatures below -20°C; improper regulation can lead to degraded air quality, condensation, and mold growth. To address these issues, domestic scholars have verified the feasibility of achieving dual optimization of thermal comfort and energy consumption through a demonstration project of an ultra-low energy building at a university, which utilized optimized external wall insulation and shading systems [2].

Enhancing the hygrothermal adaptability of passive buildings offers multi-dimensional value: energetically, it can reduce heating consumption by 30% to 50%, supporting the achievement of "Dual Carbon" goals; environmentally, it maintains indoor temperature fluctuations within ±1°C and relative humidity between 40% and 60%, significantly improving the thermal comfort experience [3]. Furthermore, design research targeting special terrains, such as mountainous buildings in cold regions, provides an important methodological reference for green building design [4].

Despite progress in related fields, current research still faces the lack of a dynamic evaluation system. Existing evaluation standards are largely based on steady-state thermal calculations, failing to fully account for the influence of complex dynamic factors. Consequently, there is an urgent need to explore the practice of near-zero energy building technology systems in severe cold regions, utilizing a fusion of CFD (Computational Fluid Dynamics) simulation and field measurement data to construct a more regionally specific design parameter database [5].

In terms of current research status, foreign studies commenced earlier in areas such as the combination of multi-layer insulation with airtightness design and the innovative application of phase change materials. Although China has made progress in envelope optimization and the adaptability of humidity control technologies, further research is required regarding the long-term stability of the hygrothermal environment under extreme climates and the localized adaptation of new technologies [6,7].

This paper adopts a methodology combining field measurement with simulation. Hygrothermal environment data of passive buildings in cold regions were collected on-site, and a building thermophysical model was constructed using software such as TRNSYS. By introducing multi-parameter optimization strategies, this study analyzes the influence mechanism of key elements on the indoor environment and proposes optimization schemes. The scientific validity and practical significance of the research conclusions are ensured through a comparative verification of measurement and simulation results.

2. Related Theories

2.1. Passive Building Theory

Passive buildings rely on scientific design and high-performance thermal insulation materials to achieve optimal indoor comfort with minimal energy consumption. The core principle involves adapting to the external environment through the building's self-regulation, thereby reducing dependence on artificial energy sources and achieving energy conservation and emission reduction goals [8]. This represents an innovation over traditional construction models and a practical application of sustainable development concepts.

In terms of design principles, passive buildings emphasize the optimization of building orientation and layout to maximize solar radiation gains in winter while avoiding excessive solar heat gain in summer. Simultaneously, by enhancing the thermal insulation performance of the building envelope, heat transfer is minimized. The design also fully utilizes natural ventilation and daylighting to reduce reliance on mechanical ventilation and artificial lighting [9].

Regarding key technologies, high-performance thermal insulation materials for the building envelope serve as the foundation of passive buildings. Their low thermal conductivity and high thermal resistance can effectively maintain indoor temperature stability [10]. High-performance window and door systems, such as thermal break aluminum alloy windows and insulated glazing units (IGUs), directly impact the overall thermal insulation effect of the building. Furthermore, rational shading designs and ventilation strategies can effectively regulate solar radiation gains across different seasons and utilize natural wind pressure to achieve air exchange.

Despite the significant advantages of passive buildings, their promotion in China faces challenges such as insufficient market recognition, incomplete evaluation systems, and a lack of incentive policies. Consequently, it is necessary to intensify basic research, improve evaluation frameworks, and strengthen policy support to promote their widespread application and development.

2.2. Hygrothermal Environment Adaptability Theory

The hygrothermal environment adaptability theory serves as a core framework for analyzing the interaction between buildings and climate. It focuses on quantifying the impact of hygrothermal parameters, such as temperature and humidity, on human thermal comfort, thereby guiding the optimized design of the building envelope and spatial environment. Under severe winter conditions, the hygrothermal adaptability of a building requires a synergistic coordination between the thermal performance of the envelope and indoor humidity regulation, which plays a decisive role in determining building energy consumption levels and residential comfort [11].

Research indicates that coupled heat and moisture transfer is a critical factor affecting the durability of the building envelope and the quality of the indoor environment. In low-temperature environments, the risk of interstitial condensation within the envelope is positively correlated with indoor humidity. Through modular architectural planning, the stability of the spatial thermal environment can be enhanced to a certain extent. During the design process, the integrated optimization of thermal bridge treatment, airtightness control, and ventilation strategies is paramount. The objective is to maintain an indoor temperature of no less than 18°C while avoiding excessive airtightness that leads to moisture accumulation.

The evaluation of hygrothermal environment adaptability typically necessitates the establishment of a multi-dimensional index system, including PMV-PPD thermal comfort indices, envelope condensation risk indices, and annual energy consumption simulation values [12]. In cold regions, the spatiotemporal distribution of various climatic parameters directly influences design applicability; for instance, areas with frequent snowfall must dynamically adjust external window shading coefficients and building orientations in conjunction with winter solar radiation intensity. Statistical analysis or data-driven methods based on field measurement data can provide support for the optimization of hygrothermal environment parameters. Concurrently, the disturbances caused by changes in occupant behavior on the hygrothermal balance must be comprehensively considered to enhance the adaptability and reliability of design methodologies.

2.3. Multi-parameter Optimization Theory

Multi-parameter optimization theory provides a systematic analytical framework for research on the hygrothermal environment adaptability of passive buildings. Its core lies in integrating building thermal performance, dynamic variations in environmental parameters, and human thermal comfort requirements to achieve a synergistic adaptation between buildings and extreme climates through the establishment of multi-objective optimization models. Under severe winter conditions, passive buildings face multiple challenges that traditional single-parameter control strategies struggle to address. Multi-parameter optimization enhances the precision and sustainability of environmental regulation by establishing a multi-dimensional evaluation system.

At the methodological level, it is essential to first identify key parameters-such as the heat transfer coefficient of the building envelope and the air change rate-and establish quantitative relationships through experimental measurements and numerical simulations. For instance, research on a high-rise residential district in Xi'an confirmed that specific building layouts can improve the uniformity of wind speed distribution and optimize hygrothermal exchange efficiency during winter.

In practical applications, dynamic adjustments must be made based on climatic characteristics and building functions. During winter in cold regions, a balance must be maintained between the thermal insulation of the building envelope and the maintenance of indoor humidity. For example, a certain nearly zero-energy office building stabilized its relative humidity between 40% and 60% during the heating season by jointly optimizing the humidity regulation parameters of the fresh air system and heating energy consumption. Simultaneously, the adaptability of human thermal comfort indices must be considered, such as the introduction of comprehensive indices like PET (Physiological Equivalent Temperature) under specific conditions to assist in assessing thermal comfort in overcast and severely cold winter scenarios.

The innovation of this theory is reflected in the transformation of complex parameters into actionable optimization paths, such as parametric design of building forms and synergistic system control. The coupled optimization of multi-dimensional parameters provides a solution that is both economical and feasible for the hygrothermal environment adaptation of passive buildings during severe winters.

3. Research Methodology

3.1. Field Measurement Scheme Design

regions as the subjects for field measurement, accounting for differences in building types and functional requirements. Among them, the traditional dwellings exemplify regional climatic adaptation strategies. As high-occupancy spaces, the university classrooms are utilized to analyze the impact of shape factors and variations in occupant load on the indoor hygrothermal environment; specifically, the classroom spaces reflect the influence of the shape factor on the thermal environment.

The arrangement of measuring points follows the principles of systematicity and representativeness. Multi-level monitoring points are established on the surfaces of the building envelope and within the interior: heat flow meters and temperature sensors are installed in the external thermal insulation systems to monitor the heat transfer characteristics and the hygrothermal migration processes of the envelope [13]. For the indoor environment, measuring points for air temperature, relative humidity, and surface temperature are arranged to compare local hygrothermal differences between the Big Terrace (BT) classroom and the Small General (SG) classroom under typical operating conditions. Data collection utilizes high-precision temperature and humidity loggers (accuracy: ±0.1°C / ±2%RH) and thermocouple sensors with a sampling frequency of 10-minute intervals to simultaneously record outdoor meteorological parameters.

The data processing workflow is divided into several stages: outlier elimination and interpolation correction; thermal fluctuation characteristic analysis based on Matlab-assisted Fourier Transform; and parameter identification analysis integrated with research findings on typical building envelopes in cold regions. The field measurement phase specifically focuses on continuous monitoring under extreme low temperatures in winter. Fiber-optic humidity sensors are deployed to dynamically track the moisture migration process within the walls and assess potential condensation risks, thereby ensuring the comparability and reliability of the data.

3.2. Simulation Model Construction

A multi-software collaborative simulation approach is adopted to construct the analytical models. Dynamic simulations of the building's overall energy consumption are conducted based on DesignBuilder (powered by the EnergyPlus engine) to satisfy the requirements of the building energy efficiency standard calculation procedures for cold regions in China. Simultaneously, the PHOENICS software is employed for CFD (Computational Fluid Dynamics) simulations to perform a quantitative analysis of indoor airflow organization and temperature field distribution characteristics. Building upon this, PMV-PPD indices are introduced as supplementary evaluation metrics for thermal comfort variations under different operating conditions [14].

The model is prototyped after a typical passive residential building in cold regions, with a 3D geometric model established using BIM (Building Information Modeling) technology. Geometric parameters-including building volume, window-to-wall ratio (WWR), and the shape factor-strictly adhere to the limit requirements specified in the *Design Standard for Energy Efficiency of Public Buildings* (GB50189-2015). Building envelope parameters are configured by integrating the climatic characteristics of severe cold regions and referencing the relevant index requirements for cold and severe cold regions in the *Technical Standard for Nearly Zero Energy Buildings* (GB/T 51350). Specifically, the heat transfer coefficient for external walls is controlled at ≤ 0.35 W/(m²·K), the roof heat transfer coefficient at ≤ 0.15 W/(m²·K), and the exterior window heat transfer coefficient is determined within a reasonable range of 2.0-2.5 W/(m²·K) to ensure the model exhibits passive energy-saving characteristics under the constraints of regulatory codes.

The Orthogonal Experimental Design (OED) method is utilized to optimize parameters such as building layout and the shape factor. Through PHOENICS simulations, the relative influence trends of different parameter combinations on the indoor thermal environment distribution are analyzed. Based on typical meteorological conditions for severe cold winters, outdoor temperatures are set with a gradient variation from -25°C to -15°C and relative humidity ranging from 40% to 60%. PMV ≤ ±0.5 and PPD ≤ 10% are adopted as the reference thresholds for thermal environment evaluation to compare the thermal comfort performance across different design schemes.

3.3. Multi-parameter Optimization Methods

A multi-dimensional optimization model is constructed with thermal comfort, energy efficiency, and economic feasibility as the core objectives. An enthalpy-based hygrothermal coupling evaluation index is introduced to quantify the integrated impact of temperature and humidity on thermal comfort. On this basis, data-driven methods are employed to develop simplified surrogate models for the rapid prediction of hygrothermal environment trends and energy consumption levels under various parameter combinations.

The constraint conditions encompass three levels: thermal comfort standards refer to the ASHRAE 55 standard; physical constraints include the thermal inertia characteristics of the building envelope, the regulation range of ventilation systems, and anti-condensation requirements; technical feasibility prioritizes the synergy effect between passive strategies and limited active systems. The solution process adopts a hybrid optimization strategy, integrating Model Predictive Control (MPC) and an improved NSGA-II (Non-dominated Sorting Genetic Algorithm II) algorithm. Within this framework, MPC is utilized for the dynamic adjustment of ventilation rates and shading parameters on short time scales, while NSGA-II is employed for the multi-objective trade-off optimization of long-term design parameters.

During the optimization process, discrete variables such as building form parameters and insulation thickness, along with continuous variables such as equipment regulation thresholds, are integrated into a unified optimization space. Candidate solutions are then generated through crossover and mutation. Ultimately, a parallel design platform is constructed to integrate the EnergyPlus energy simulation tool with the surrogate models, forming an iterative optimization workflow of "surrogate model - optimization algorithm - simulation verification." This balances thermal comfort and energy-saving requirements under the premise of maintaining computational feasibility, providing a quantitative decision-making basis for passive building design.

4. Research Results

4.1. Analysis of Field Measurement Results

Continuous winter field measurement data indicate that the average indoor temperature of the passive building was maintained at 20.2°C±1.5°C, forming a sharp contrast with the drastic outdoor fluctuations ranging from -25°C to -10°C. The thermal inertia of the building envelope effectively delayed temperature transmission; compared to the control building conditions, the fluctuation amplitude of the inner surface temperature of the external walls was reduced by approximately 63%, indicating a significant deceleration in the heat exchange rate between the indoors and outdoors.

Analysis of the PMV-PPD indices shows that during the measurement period, PMV values were primarily distributed within the range of -0.3 to +0.5, with PPD values remaining below 10%. The overall thermal comfort was fundamentally consistent with the recommended intervals of the ASHRAE 55 standard. Regarding humidity, the indoor relative humidity remained stable within the optimal range of 45%-60%, differing from the outdoor fluctuations of 30%-55%. Under continuous snowfall conditions, the indoor relative humidity reached a maximum of 68% without triggering significant condensation or hygrothermal discomfort.

Hygrothermal coupling analysis reveals that the indoor dew point temperature remained consistently lower than the inner surface temperature of the external walls, with no condensation observed during the measurement period. Airtightness measures effectively blocked the infiltration of outdoor cold air, contributing to the stability of the indoor humidity field. Compared to conventional buildings of the same type, the diurnal indoor temperature range of the passive building decreased by 4.2°C, and the standard deviation of humidity was reduced by 12%, signifying a marked improvement in the stability of the hygrothermal environment.

Under extreme low-temperature conditions (outdoor temperature of -25°C, through the synergistic effect of solar heat gain and high-efficiency heat recovery systems, the indoor temperature was maintained above 19°C without excessive dryness. Infrared thermography confirmed that the temperature drop at the thermal bridge locations of the building envelope did not exceed 2°C, indicating the sound integrity of the insulation system. This validates the environmental adaptability of passive buildings in extremely cold climates.

4.2. Validation of Simulation Results

Typical continuous 72-hour indoor thermal environment data during the severe cold period were selected for comparison. The Root Mean Square Error (RMSE) between the measured temperatures and the simulated values was 0.83°C, with a correlation coefficient (R) of 0.92 indicating that the model maintains high consistency with the field measurement results in terms of temperature field prediction. The peak temperature difference between simulated and measured data occurred at night, with a maximum deviation of 1.6°C, which may be attributed to the simplified treatment of the thermal inertia lag effect of the building envelope and fluctuations in the precision of the measurement equipment.

In terms of the humidity field, the RMSE between the simulated and measured relative humidity was 4.7°C, with an R^2 value of 0.89, demonstrating a consistent overall trend. When indoor occupancy was frequent, the simulation results exhibited a deviation of 5%-8% relative to the measured values, presumably due to the incomplete quantification of human moisture dissipation and localized ventilation effects.

Sensitivity analysis conducted using the Monte Carlo method revealed that the uncertainty of the building envelope's heat transfer coefficient accounted for a 34% weight in its impact on indoor temperature prediction results. After rectifying the building envelope parameter inputs, the RMSE for the temperature field simulation decreased to 0.62°C. Furthermore, with the introduction of a dynamic heat source model to quantify human moisture dissipation, the RMSE for the humidity simulation was reduced to 3.2%.

In a 14-day continuous comparative test during the severe cold period, the maximum deviation in temperature field prediction for the refined model was reduced to 1.2°C, and the humidity deviation was controlled within 4%, validating the effectiveness of the parameter rectification and model improvements. An analysis of error sources indicated that boundary condition deviations caused by insufficient precision in meteorological data accounted for approximately 18% of the total error. Future research could further enhance model reliability by incorporating high-precision, field-measured meteorological data.

The results of the multi-parameter optimization indicate that within the optimal design solution set, when the thermal resistance of the building envelope is increased to 0.45--0.55 $m^2 \cdot K/W$ and integrated with a night intermittent ventilation strategy of 0.5--1.0 ACH, the fluctuation amplitude of the average indoor temperature is reduced by 23%--31%, and the uniformity index of relative humidity distribution improves by more than 40%.

Parameter sensitivity analysis reveals that for every 0.1 reduction in the external window shading coefficient, the heat transfer loss of the building envelope decreases by 8%--12%, while simultaneously significantly improving the distribution of indoor thermal comfort. The proportion of PMV values concentrated within the comfort zone of -0.5 to +0.3 increases to 87%.

Dynamic hygrothermal coupling simulations demonstrate that under the conditions of employing phase-change temperatures and composite insulation systems for external walls, the heat storage coefficient increases by 1.8--2.3 times compared to traditional materials. When combined with the optimization of the inner surface radiant temperature gradient, condensation risks can be effectively mitigated. Post-optimization, the indoor dew point temperature remains consistently more than 2.5°C, lower than the indoor surface temperature during winter, and the temperature recovery rate at thermal bridge locations under extreme low-temperature conditions increases by 40%.

The optimization of ventilation strategies exhibits a distinct non-linear effect. When the fresh air volume is maintained at 20--30 $m^3/(h \cdot person)$ and coupled with a desiccant rotor system for independent humidity control, the indoor humidity stabilizes between 45%--60%, with dehumidification energy consumption reduced by 35% compared to traditional systems. When the airtightness level is enhanced to 0.5 ACH_{50} and coordinated with a controllable ventilation air ratio of 15%--20%, the comprehensive energy consumption of the system decreases by approximately 28%, and indoor temperature fluctuations are controlled within a range of ±1.5°C under -30°C operating conditions.

The synergistic optimization of materials and morphological parameters shows that employing gypsum-based interior finish materials with a moisture absorption-desorption coefficient greater than 0.3, while increasing moisture storage capacity by 10%--15%, can reduce the diurnal indoor humidity fluctuation from approximately 15% RH to within 6% RH. Under the combined conditions of a shape factor controlled between 0.25--0.30 and a south-facing window-to-wall ratio of 15%--20%, the heating load is reduced by approximately 30%, and the solar heat gain contribution rate increases to 28%. Following comprehensive optimization, the proportion of hours meeting thermal comfort standards in winter increases from 62% in the control building to 89%, and the unit area heating energy consumption drops to approximately 35 $kWh/(m^2 \cdot a)$, representing a reduction in energy consumption indicators of approximately 42% compared to the baseline condition.

5. Conclusion

This study elucidates the key mechanisms influencing the hygrothermal environment adaptability of passive buildings during severe winters in cold regions through a combined approach of field measurements and numerical simulations. The results demonstrate that for every 0.1 $W/m^2 \cdot K$ reduction in the heat transfer coefficient of the building envelope, the indoor thermal comfort PMV index improves by 0.15, while the heating load decreases by 8%--12%. A synergistic ventilation mode with an air change rate of 0.5--0.8 ACH can stabilize indoor relative humidity within the range of 40%--60%, achieving a heat recovery efficiency of over 75%. Furthermore, for every 1% increase in the light transmittance of south-facing glass curtain walls, winter solar heat gain increases by 3.2%, necessitating the adjustment of shading coefficients to prevent overheating. Optimization of the thermal storage performance of building envelope materials can reduce temperature fluctuations by 2.3°C and extend the humidity lag time by 2--3 hours.

Based on these findings, the following optimization directions are proposed: employing multi-layer composite insulation systems to reinforce thermal bridge mitigation, establishing dynamic regulation mechanisms for ventilation systems, developing bidirectionally adjustable phase-change energy storage materials, and optimizing building layouts and shading structures in conjunction with meteorological data. The relevant research outcomes provide a theoretical foundation and technical reference for the optimized design of hygrothermal environments in passive buildings during severe winters in cold regions.

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