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THERMAL INSULATION OF RURAL RESIDENTIAL BUILDINGS IN HIGH-TEMPERATURE-DIFFERENCE REGIONS OF NORTHWEST CHINA

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Abstract

In the high-temperature-difference regions of Northwest China, existing rural buildings suffer severe heat loss due to inadequate thermal insulation measures, while the increasing carbon emissions exert tremendous pressure on environmental pollution. Implementing thermal insulation measures for both existing and newly built rural residences is one of the effective approaches to address energy consumption and environmental pollution. This study takes a typical rural residence in Jiuquan City as the research object, conducts comparative analyses of different thermal insulation measures, proposes an optimal solution, and identifies effective pathways for reducing energy consumption. The findings provide valuable references for the renovation of existing buildings and the design and construction of new buildings in Northwest China.

Keywords: High-temperature-difference regions, Rural residential buildings, Thermal insulation, Energy consumption analysis

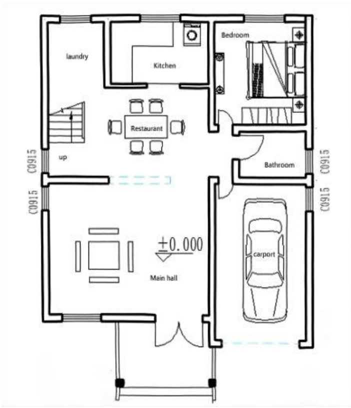
Introduction

With the continuous advancement of China's rural revitalisation policies, rural economic income has steadily increased, and the living standards of farmers have improved significantly. Rural self-built residences have gradually evolved from earth-wood structures to multi-story buildings with brick-concrete or frame structures. However, rural houses, typically standalone structures exposed to the environment, exhibit poor thermal insulation performance in their building envelopes, outdated heating facilities, and extremely low thermal efficiency. Therefore, optimizing the materials and structural forms of building envelopes in rural residences in high-temperature-difference regions is critical for enhancing living comfort and reducing energy consumption. Currently, Western developed countries, particularly in Europe, have conducted extensive research and practices on rural residential energy efficiency. Scholars such as Hanna from the Polish Academy of Sciences [1], Üllar Alev [2], and Arslan [3] have proposed energy-efficient building designs and retrofitting solutions for rural residences, emphasizing pathways to reduce energy consumption, conserve resources, and lower carbon emissions. In China, scholars including Li Ji [4], Dong Xinlu [5], and Yang Panpan [6] have analyzed typical rural house layouts in severe cold regions and proposed effective energy-saving retrofitting solutions. This paper investigates the thermal insulation performance of a rural residence in Jiuquan City, a high-temperature-difference region, and proposes optimized thermal insulation solutions tailored to local conditions.

Energy Simulation Model

Climate Conditions: The study object is located in a village in Jiuquan City (98°20'–99°18' E, 39°10'–39°59' N), situated in the western Hexi Corridor of northwestern Gansu Province. Influenced by a continental arid climate, Jiuquan experiences long and severe winters with a frost-free period of 127–158 days. The historical minimum temperature reaches -24.4°C, while summers are characterized by intense solar radiation, aridity, and extreme heat, with a historical maximum temperature of 43.1°C. The annual temperature differential peaks at 67.5°C, and the average annual sunshine duration is 3,056.4 hours.

Project Overview: The study object is a two-story self-built rural residence with a brick-concrete structure and a north-south orientation. The first floor (124.75 m²) includes a living room, bedrooms, a kitchen, and a tool room (see Figure 1). The second floor (90.54 m²) comprises a lounge, bedrooms, and a terrace (see Figure 2). The roof adopts a hipped design. The building utilizes a coal- and wood-fired steam boiler for winter heating and natural ventilation via open windows in summer. The exterior walls are constructed with 370 mm ordinary clay bricks, interior walls with 240 mm clay bricks, windows with 3 mm single-layer clear glass in aluminum alloy sliding frames, and floors with ordinary ceramic tiles. The roof consists of concrete glazed tiles without effective insulation.



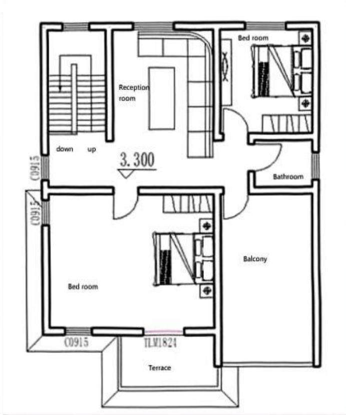


Fig.1 First-floor Plan Fig.2 Second-floor Plan

Proposed Thermal Insulation Measures: The total exterior wall area is 257.4 m², with windows accounting for 21.6 m² (8.4% of the wall area). Due to the poor thermal performance of clay brick walls, single-layer sliding windows with weak sealing, and uninsulated concrete roofs, significant heat loss occurs. Proposed measures include enhancing roof and wall insulation, installing double-glazed casement windows, and applying reflective stone-like coatings on exterior walls. Based on local climatic conditions and engineering characteristics, insulation materials with varying thermal conductivities and glazing configurations were analyzed to determine the optimal retrofitting solution. The thermal performance parameters of the insulation materials and glazing types are listed in Tables 1 and 2.

Table 1: Thermal Performance Parameters of Different Insulation Materials

Roof & Exterior Walls	**Thermal Conductivity (W/(m²·K))**
370 mm clay brick wall	0.114
100 mm EPS insulation board	0.037
100 mm XPS insulation board	0.024
100 mm polyurethane foam board	0.033

Table 2: Thermal Performance Parameters of Different Glazing Types

Glazing Type	**Thermal Conductivity (W/(m²·K))**
3 mm single-layer glazed window	6.4
3+6A+3 double-glazed window	3.4
6+12A+6 double-glazed window	3.3
6 (Low-E) +12+6 outer low-emissivity double-glazed window	1.7

Energy Consumption Analysis During Winter Heating Period

The dynamic building energy simulation software DesignBuilder was employed to model the residence (Figure 3). Computational Fluid Dynamics (CFD) modules were used to analyze velocity, temperature, and pressure distributions inside and outside the building. The simulation evaluated overheating risks, energy consumption, and CO_2 emissions under different insulation scenarios.

Fig.3 DesignBuilder Energy Simulation Model

Four wall configurations were systematically analyzed: 370 mm clay brick (baseline), 100 mm expanded polystyrene (EPS), 100 mm extruded polystyrene (XPS), and 100 mm polyurethane foam (PUR). With a controlled indoor temperature of 18°C, Figure 4 demonstrates that during the coldest month (January), EPS insulation achieved a 23.8% reduction in energy consumption compared to baseline, followed by XPS (25.7%) and PUR (24.6%).

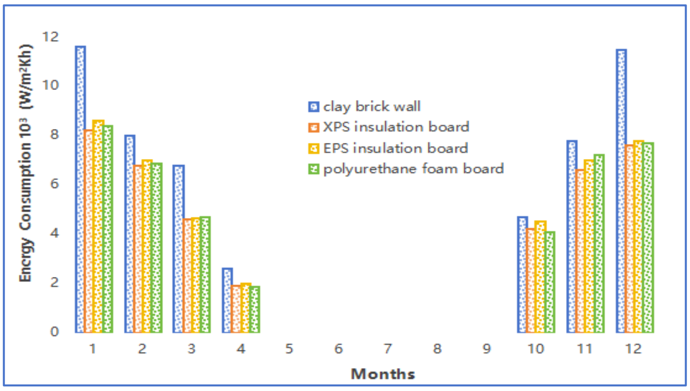


Fig.4: Monthly energy consumption of walls with different Insulation materials

Four roof assemblies were evaluated: 120 mm non-insulated concrete (baseline), 100 mm EPS, 100 mm XPS, and 100 mm PUR. As illustrated in Figure 5, January energy consumption reductions reached 29.8% for EPS, 32.2% for XPS, and 30.3% for PUR relative to baseline performance.

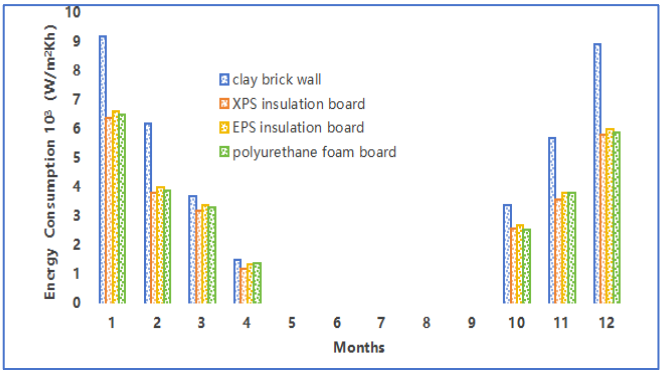


Fig.5: Monthly energy consumption of roofs with different Insulation materials

Four glazing systems were investigated: 3 mm single-pane, 3+6A+3 double-glazed, 6+12A+6 double-glazed, and 6(Low-E)+12+6 low-emissivity double-glazed. Figure 6 reveals January energy savings of 16.04% for 3+6A+3, 24.92% for 6+12A+6, and 22.89% for 6(Low-E)+12+6 configurations compared to single-pane glazing.

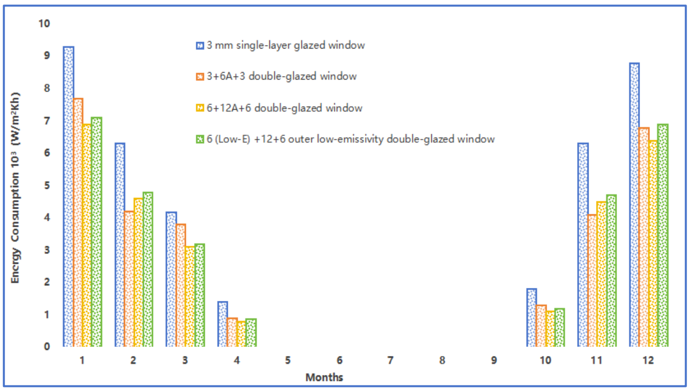


Fig.6:Monthly energy consumption of different glazing types

Summer Thermal Insulation Analysis

In Northwest China's summer climate (July-August peak), characterized by extended solar exposure and intense UV radiation, thermal transfer mechanisms through building envelopes were examined. Reflective stone-finish wall coatings combined with low-emissivity glazing demonstrated significant cooling potential. Simulation of three glazing types – 3+6A+6 (shading coefficient SC=0.90), 6+12A+6 (SC=0.83), and 6(Low-E)+12+6 (SC=0.64) – revealed that the 6(Low-E)+12+6 configuration reduced peak summer cooling loads by 13% through optimized solar heat gain mitigation.

Conclusions

This study addresses the critical need for thermal retrofitting in Northwest China's rural architecture, where extreme annual temperature fluctuations and unregulated insulation practices prevail. Key findings indicate:

(1) XPS insulation boards (100 mm) provide optimal winter energy conservation for walls and roofs

(2) 6+12A+6 double-glazed windows maximize winter thermal performance

(3) 6(Low-E)+12+6 low-emissivity glazing delivers superior summer cooling efficiency

Considering the region's prolonged winters, the synergistic implementation of 100 mm XPS insulation with 6+12A+6 double-glazing achieves 75% annual heating energy conservation. Supplemental reflective coatings and low-emissivity fenestration further reduce cooling demands, presenting comprehensive solutions for enhancing both energy efficiency and occupant comfort in rural Northwest China.

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