

Research on Energy-Saving Structure Optimization and Carbon Reduction Technology of Building Doors and Windows in Cold Regions

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Abstract: The heat loss of the building envelope system, doors and windows, is the component with the weakest thermal insulation performance, and the proportion of heat dissipation is much higher than that of other envelope structures such as walls and roofs. In China's high-latitude cold zone, the extreme low temperature can drop below -40 °C in winter, and there is a huge temperature difference between indoor and outdoor for a long time. The continuous cold and heat exchange behavior of doors and windows continues to aggravate the heating load of buildings and promote the continuous growth of carbon emissions during the operation stage of buildings. Traditional building doors and windows generally have various problems, such as the excellent thermal conductivity of profiles, simple sealing structures, and weak thermal insulation of glass. The joint gap between the window frame matrix, the glass edge, the doors and windows, and the wall will form a continuous thermal bridge channel, which will lead to building diseases such as frosting and mildew on the indoor wall, which will directly affect the building function and living comfort. The long-term high-load operation of heating equipment has caused a lot of inefficient loss of fossil energy, and the pressure of regional carbon emission control has intensified. In this paper, the various channels of heat loss of building doors and windows in cold regions are studied, and the thermal insulation short boards of four structural systems, namely profile structure, sealing system, glass material, and installation nodes, are systematically combed, and targeted structural optimization schemes are formulated for various technical defects. This paper studies the carbon reduction path covering the whole process of building materials production, engineering construction, building operation, and component scrap recycling, and quantitatively analyzes the practical application value of various optimization technologies by combining the measured data of temperature monitoring, energy consumption statistics, and carbon emission accounting at the construction site.

Keywords: Severe cold area; Building doors and windows; Energy-saving structure; Thermal bridge blocking

Online publication: Oct 16, 2026

1. The traditional door and window structures in cold regions have double defects of heat preservation and carbon emission

1.1. Defect of profile thermal bridge structure

The thermal conductivity of ordinary aluminum alloy substrate can reach 237 W/(m k). The traditional aluminum alloy door and window profiles are not provided with closed thermal insulation cavities, and the inner and outer metal structures form a through thermal conduction channel ^[1]. The heat loss in the window frame area accounts for more than 30% of the total heat loss of the whole window, and the heat dissipation problem of the thermal bridge is particularly prominent. In the early stage, the aluminum profile with a broken bridge only adopted a simple single-cavity thermal insulation structure; the width of the thermal insulation strip was less than 24 mm, and the cavity was not filled with thermal insulation foam material ^[2]. The low-temperature environment will accelerate the air convection movement in the cavity, which will cause the overall thermal insulation performance of the profile to be greatly attenuated. Conventional PVC plastic-steel profiles are only provided with two to three cavities, and the wall thickness of the profiles is designed to be thin. At -30 °C low temperature, it is easy to shrink and deform, and the joint gap between the sealing strip and the profile continues to expand, and the cold air permeability shows an obvious growth trend ^[3]. A large number of petroleum-based additives will be mixed in the production process of ordinary wood-plastic composite profiles, and the overall implicit carbon of the components is at a high level. Long-term freeze-thaw cycles will induce surface cracking and peeling of profiles, and the thermal insulation performance will continue to decline with the increase of service life ^[4].

1.2. The short board of sealing system structure

The traditional door and window sealing system is only equipped with a single layer of rubber sealing strip, and the low-temperature resistance of ordinary rubber materials is obviously insufficient. Long-term freeze-thaw cycles will cause problems such as hardening, shrinkage, and aging of rubber strips, and a continuous ventilation gap will be formed between the window sash and the window frame. The airtightness of this kind of doors and windows can only reach the third to fourth standards, which cannot meet the requirements of the design code for energy-saving buildings in cold regions. The conventional sealing structure is not equipped with an isobaric drainage cavity, and outdoor snowmelt water can penetrate into the profile cavity through the gap. In the low-temperature environment, the accumulated water freezes and expands, and the extruded sealing strip is deformed, so the problems of leakage and air leakage are aggravated ^[5]. The gap between the window frame and the hole of the wall is only filled with ordinary foaming agent, and the outside is simply blocked by cement mortar. The thermal conductivity of mortar material is high, and an annular thermal bridge structure is formed around the wall, and the window sill area is in a low-temperature frosting state for a long time. After the wall insulation layer is wetted, the thermal insulation performance is greatly attenuated, and the building heating energy consumption is significantly increased.

1.3. The lack of carbon emission control in the whole cycle

Traditional door and window manufacturing links use a large amount of primary electrolytic aluminum materials, and the electrolytic process is highly dependent on thermal energy; the raw material mining and smelting processes will release a lot of greenhouse gases. The equipment in the processing workshop is not equipped with an energy-saving frequency conversion control system, and the surface spraying process adopts high-VOC organic solvent coatings, so the power consumption and total carbon emissions in the

production process remain high for a long time^[6]. In the service stage of doors and windows, only heating equipment is used to make up for the heat loss, and the abundant solar radiation resources in winter have not been effectively developed and utilized, and the carbon emissions of buildings in long-term operation continue to expand. After the doors and windows reach the designed service life, they are mostly disposed of directly, and the utilization rate of recyclable materials such as aluminum and glass is low. The application of recycled materials in secondary processing accounts for less than 10%, and the problem of resource waste is prominent. The new raw material mining and smelting operation will produce an additional increase in carbon emissions.

2. Systematic optimization technology of energy-saving structure of doors and windows in severe cold area

2.1. Structural upgrade of profile thermal insulation cavity

(1) Structural optimization of multi-cavity widened broken bridge aluminum profile.

The optimized broken-bridge aluminum profile adopts the special base material of 6063-T5 and the PA66GF25 glass fiber nylon thermal insulation strip with a width of 35 mm or more. The thermal conductivity of the thermal insulation base material is as low as $0.3\text{W}/(\text{m}\cdot\text{K})$, which can effectively block heat conduction through the metal. Five to six groups of independent closed cavities are set on the section of the profile, and the cavities are filled with low-density polyurethane thermal insulation foam materials, thus eliminating the heat exchange problem caused by air convection in the cavities. The internal and external structures of the profile are separated by staggered heat insulation strips, which effectively prolong the heat conduction path, and the heat transfer coefficient of the whole frame can be controlled within $1.8\text{W}/(\text{m}^2\cdot\text{K})$ at low temperature. In view of the special working conditions of strong wind and frost heaving in cold areas, the wall thickness of the profile is thickened to 2.0mm, and the overall deformation resistance of the structure is significantly improved, effectively avoiding the sealing failure caused by low-temperature deformation.

(2) Improvement of special multi-cavity PVC composite profile for low temperature.

Improved PVC profiles are prepared based on low temperature-resistant modified substrates, and special antifreeze polymer additives are added, which can keep the structure stable in the extremely low-temperature environment of $-40\text{ }^{\circ}\text{C}$ without brittle cracking and shrinkage deformation. The profile is designed with six or more layered closed structures. The inner and outer cavities are isolated from each other, completely blocking the internal air convection heat exchange channel. Glass fiber-reinforced ribs are embedded in the profile to improve the overall structural stiffness. Exclusive thermal insulation layers are added in the splicing area of window frames and window sashes to prevent local thermal bridge defects caused by splicing gaps. Compared with the traditional single-cavity plastic-steel profile, the heat transfer coefficient of the improved profile is reduced by 40%, and the carbon emissions in the production stage are much lower than those of the original aluminum alloy material, which is suitable for the low-cost energy-saving renovation project of affordable housing in severe cold areas.

2.2. Structural optimization of multilayer isobaric sealing system

(1) Three-way EPDM weatherproof sealing structure

The traditional single-layer rubber sealing structure was abandoned, and three independent EPDM sealing systems were used to upgrade the structure. The outer rubber strip is responsible for preventing wind

and water; the middle cavity balances the internal and external air pressure; the inner rubber strip ensures airtightness and heat-preservation performance; and the three sealing members can be attached to the surface of the sash profile in all directions. EPDM rubber strip adopts a low-temperature, weather-resistant modified formula, which can still maintain good elasticity at $-45\text{ }^{\circ}\text{C}$, and has no issues such as hardening, shrinkage, or deformation after 300 freeze-thaw cycles, ensuring the stability of building airtightness to reach the Grade 8 standard. A special drainage diversion channel is reserved in the middle isobaric cavity, so that the snowmelt water can be discharged outward along the cavity and will not penetrate into the indoor side structure, thus thoroughly solving the leakage and air leakage diseases caused by the freezing of accumulated water to open the sealing gap.

(2) No thermal bridge attached frame structure at the entrance of the wall

In the construction stage of doors and windows, the graphite polystyrene thermal insulation frame is embedded in advance, and the thermal conductivity of the frame is controlled at $0.032\text{ W}/(\text{m}\cdot\text{k})$, effectively isolating the annular thermal bridge between the concrete structure of the wall and the metal window frame. The outer side of the attached frame is flush with the external wall insulation layer, the splicing gap is filled with low thermal conductivity insulation mortar, and the surface layer is coated with weather-resistant waterproof sealant to complete the sealing treatment. The gap inside the hole is filled with high-density closed-cell foaming agent, which has extremely low thermal conductivity and will not form a heat conduction channel. The window sill area is designed with an outward-leaning, water-covered structure, which effectively avoids the problem of rain and snow accumulation and infiltration, and eliminates the frosting thermal bridge disease on the window sill from the installation node level.

2.3. Optimization of thermal insulation structure of high-performance glass

(1) High-light-transmission three-glass two-cavity Low-E insulating glass

The combination of three layers of tempered glass and two layers of 12mm inert gas cavities is adopted, and the inner glass is plated with a high light transmittance and low radiation film, so that the visible light transmittance can be maintained above 62%, ensuring that solar radiation can be fully received indoors in severe cold winter. The hollow cavity is filled with argon, which inhibits the convection heat transfer of air inside the cavity. The glass edge replaces the traditional metal aluminum strip, and the glass fiber warm edge spacer strip is used to eliminate the thermal bridge effect of the glass edge. The temperature of the inner surface of the glass can be increased by $6\text{--}8\text{ }^{\circ}\text{C}$, so as to prevent large-scale condensation and freezing in winter. The whole set of glass combination can reduce the heat transfer coefficient of the whole window to $1.2\text{ W}/(\text{m}^2\cdot\text{k})$, which is suitable for the construction requirements of various energy-saving buildings in cold regions.

(2) Application of vacuum glass integrated structure

The vacuum degree in the vacuum glass is kept within 0.1 Pa , which eliminates the heat dissipation path of gas conduction and convection heat transfer. The thermal insulation performance of a single piece of vacuum glass is equivalent to that of a 1.5 m thick brick wall, and the minimum heat transfer coefficient of the whole window can reach $0.4\text{ W}/(\text{m}^2\cdot\text{k})$. The inner side of the glass is coated with an infrared barrier coating, and the micro stainless steel support points are arranged in the vacuum cavity, which is suitable for the complex working conditions of long-term temperature difference deformation in cold areas. The overall thickness of vacuum glass is reduced by 70% compared with that of conventional three-glass insulating glass,

and the cross-section size of the window frame profile can be simultaneously optimized and narrowed, thus reducing the consumption of profile raw materials and the implied carbon emission of components. Vacuum glass with multi-cavity broken bridge aluminum profiles can meet the design index of zero-carbon building doors and windows in cold regions.

2.4. Composite structure of passive heat collection and sunshade

The south-facing doors and windows of the building are equipped with a manually retractable built-in louver structure. In winter, the louver components are put away to maximize the reception of solar short-wave radiation, and the indoor base temperature is improved by solar energy, thus reducing the overall running time of heating equipment. In summer, the louver members are deployed to block direct sunlight indoors, reduce the indoor heat storage temperature, and reduce the energy consumption of refrigeration equipment. No sunshade component is added to the north-facing doors and windows, so as to reserve the heat intake channel in winter to the maximum extent. The sunshade louver adopts a lightweight recycled aluminum substrate, and the cavity of the blade is filled with thermal insulation cotton. The whole sunshade system does not need a continuous power supply and relies on passive solar energy resources to achieve energy saving and carbon reduction.

3. Innovative technology for carbon reduction in the whole process of supporting doors and windows in severe cold areas

3.1. Low-carbon raw material selection technology

Recycled aluminum materials are preferred in the production of door and window profiles. The energy consumption of smelting recycled aluminum materials is only 30% of that of primary aluminum, and the carbon dioxide emissions in the smelting process are greatly reduced ^[7]. The application ratio of recycled aluminum is increased to over 70%, which can reduce nearly half of carbon emissions in the raw material production stage. Thermal insulation materials replace traditional petroleum-based polyurethane, and solid wastes such as straw-based and mineral wool are used to regenerate thermal insulation base materials, so the preparation process of raw materials does not need to consume fossil energy. In the glass production process, Shi Ying tailings and other industrial solid wastes are used to replace some natural Shi Ying ores, and the melting furnace is equipped with photovoltaic power supply equipment to reduce the carbon increment caused by thermal power consumption. Waterborne solvent-free environmental protection products are selected for sealant, high-carbon organic solvent raw materials are eliminated, and the carbon footprint of door and window components in the whole life cycle is controlled from the source ^[8].

3.2. Low-energy processing and manufacturing technology

The door and window processing workshop is fully equipped with energy-saving equipment such as frequency conversion cutting and numerical control drilling to reduce the power loss caused by the no-load operation of the equipment ^[9]. The profile cutting process adopts precision simulation typesetting technology, and the waste rate of raw materials can be controlled within 5%, thus reducing the indirect carbon emissions caused by material waste. The surface treatment of components abandons high-temperature oily spraying technology and adopts electrostatic powder circulating spraying technology. Powder coating can be recycled, no liquid waste pollutants are discharged, and the overall energy consumption of the spraying process is

reduced by 40%. The production plant is equipped with wind power and distributed photovoltaic generator sets, and the production electricity depends entirely on clean energy, so as to eradicate carbon emissions from thermal power in the processing link. The hardware fittings for doors and windows are made of lightweight and high-strength recycled materials to reduce the overall input of metal raw materials.

3.3. Passive carbon reduction control in the operation stage

Passive sunshade and heat collection composite structure can fully tap solar energy resources in winter and reduce the consumption scale of heating energy such as gas and coal. The doors and windows are equipped with intelligent micro-ventilation components, which can realize small ventilation on low-temperature, sunny days and avoid large-scale heat loss caused by window opening in the whole house. In extreme cold weather, the ventilation gap can be automatically closed to stably accumulate indoor heat^[10]. The building is equipped with an intelligent energy consumption monitoring module, which can collect the heat loss data of doors and windows in real time, and dynamically adjust the operating power by linking heating equipment to avoid the energy waste caused by excessive heating and continuously reduce the carbon emission level in the operation stage of the building.

4. Comparative analysis of application effect of severe cold engineering

4.1. Application data of newly built ultra-low energy consumption residential buildings

A passive residential project in Mohe, Heilongjiang Province, adopts a complete set of optimized structures of five-cavity broken-bridge aluminum profiles with a 35 mm-wide heat-insulation bar, vacuum glass, EPDM three-way seal, graphite-framed thermal bridge, recycled aluminum profiles, and built-in sunshade blinds. The measured heat transfer coefficient of the whole window is 0.68 W/(m² k), the airtightness reaches the Grade 8 standard, and there is no frost or ice on the inner surface of the glass in winter. The annual heating gas consumption of a single-family residence decreased by 32%, and the carbon emissions of doors and windows in the whole life cycle decreased by 46% compared with those of traditional single-layer aluminum windows. The profiles of the project are all made of recycled aluminum, and the production workshop relies on a photovoltaic power supply, and the carbon emission reduction rate of raw material preparation and component processing reaches 38%.

4.2. The measured benefits of the renovation of doors and windows in old residential areas

The original doors and windows of an old residential area in northern Inner Mongolia are single-layer ordinary plastic-steel structures. In the reconstruction project, six-cavity modified PVC profiles and three-glass Low-E hollow sealed doors and windows were replaced, and the construction treatment of a non-thermal bridge-attached frame at the entrance of doors and windows was completed simultaneously. Before the renovation, the average monthly consumption of coal for heating in winter was 1.2 tons, and after the renovation, the average monthly consumption decreased to 0.73 tons, and the annual coal-fired carbon emission of single-family houses decreased by about 1.1 tons. The doors and windows used in the renovation are made of low-carbon profiles, which can be completely recycled after being scrapped, and the renovation cost of the project can be fully recovered by saving energy consumption in heating within four years.

4.3. Summary of comprehensive benefits of various technologies

The multi-cavity thermal insulation profile structure can reduce the heat transfer coefficient of the whole window by 40% to 65%, and block the heat dissipation channel of the profile metal thermal bridge from the source. A multi-layer sealing structure with an attached non-thermal bridge frame can reduce cold air infiltration by more than 70% and effectively reduce the building heating load. Vacuum glass and triple-glass Low-E insulating glass can inhibit the loss of infrared radiation heat, and the annual energy-saving range of a single window can reach more than 30%. Low-carbon renewable raw materials and photovoltaic energy-saving processing technology can reduce nearly half of the hidden carbon in door and window components. Passive solar shading and heat collection structures rely on natural energy to reduce the consumption of fossil fuel for heating. The closed-loop recovery system can reduce carbon emissions in the component scrapping treatment stage. The synergistic application of multiple technologies can simultaneously achieve the dual construction goals of improving the thermal insulation performance of doors and windows and reducing carbon emissions in the whole cycle. Different types of buildings in severe cold areas can match different technical schemes. Vacuum glass with recycled broken bridge aluminum profiles is preferred for new zero-carbon buildings, and a modified multi-cavity PVC triple-glass structure can be adapted for low-cost renovation of old houses. A wood-aluminum composite low-carbon profile system can be adopted for high-end passive houses. All kinds of schemes can adapt to the complex working conditions of severe cold, low temperature, strong wind, and freezing and thawing, and their engineering practical value is more prominent.

5. Conclusion

In summary, the energy-saving and carbon-reducing technologies for doors and windows in severe cold areas will continue to be iteratively upgraded around two dimensions: material innovation and intelligent empowerment. The low-temperature and high-performance composite substrate is the core direction of material research and development in the future. With the popularization and application of photovoltaic-integrated intelligent doors and windows, the deep integration of transparent photovoltaic modules and glass structures can be realized. In winter, photovoltaic power generation can supplement building heating electricity and achieve the effect of reducing carbon in the independent production capacity of doors and windows. In the future, the industry will continue to improve the unified standard of carbon accounting for doors and windows in severe cold areas, build a regional recycling and processing industrial chain for recycled doors and windows, promote the deep integration of energy-saving structures for doors and windows and low-carbon technologies, and help comprehensively promote the near-zero carbon renovation of buildings in severe cold areas in the north.

Funding

Heilongjiang Provincial Natural Science Foundation Project: “Application Research on Key Technologies for Low-Energy Consumption and Carbon Reduction in Building Doors and Windows in Severely Cold Regions” (Project No.: LH2022E101)

Disclosure statement

The author declares no conflict of interest.

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