Ice Shell-Steel Truss Composite Structure Ice and Snow Venue in High-Altitude Cold Regions: Thermal Performance and Structural Feasibility Study

Liu Hongsheng
Hailar No. 1 Middle School, Hulunbuir, Inner Mongolia
Email: liuhs666@vip.163.com

摘要

Hulunbuir experiences long, severe winters, with significant wind-chill effects at outdoor ski resorts that pose a high risk of frostbite for children. Traditional indoor ski resorts require substantial investment and high operational energy consumption, making them difficult to promote in less developed high-altitude cold regions. This paper proposes a composite ice and snow venue model combining a compacted snow shell, steel truss load-bearing structure, inner protective layer, and insulated glass zoning, and systematically analyzes its regional adaptability, structural design, and thermal performance. The research demonstrates that the venue, relying on natural cold sources without mechanical refrigeration units, can maintain a stable low-temperature range of $-8°C$ to $-5°C$ indoors (wind speed $\leq 0.2\,m/s$, temperature fluctuation $\leq \pm 1°C$), eliminating wind-chill effects. The arched load-bearing design and layered compaction ensure snow shell stability, while safety nets and waterproof breathable membranes provide dual protection. Insulated glass zoning achieves the integration of hot beverage service and ice body protection. The venue construction cost is approximately 800–1000 RMB/m^2, with monthly operating electricity costs of approximately 11,000 RMB, representing a reduction of over 70% compared to traditional indoor ski resorts in both construction (3000–5000 RMB/m^2) and operational costs. This model combines structural safety, operational economy, and child-friendliness, providing a feasible technical pathway for ice and snow venue construction in high-altitude cold regions.

Keywords: Hulunbuir; high-altitude cold regions; snow shell structure; steel truss; composite structure; child frostbite prevention; ice and snow venue

1 Introduction

Hulunbuir is located in the cold-temperate climatic zone, with winters lasting 4–5 months, extreme low temperatures reaching $-40°C$, and over 150 snow-covered days per year. The region is rich in ice and snow resources and serves as a key area for promoting ice and snow sports and ice-snow cultural tourism in China. Under the national strategy of "300 million people participating in ice and snow sports" and the "Double Reduction" policy, the demand for children's ice and snow sports continues to grow. However, current ice and snow sports facilities in the region have obvious shortcomings: outdoor ski resorts are significantly affected by severe cold and strong winds, with wind-chill effects reducing perceived temperatures by 8–12°C below ambient temperatures. Children's skin is delicate, and prolonged outdoor activities can easily lead to frostbite. Traditional indoor ski resorts rely on mechanical refrigeration, dehumidification, and insulation equipment, requiring initial investments exceeding 10 million RMB and monthly electricity costs over 100,000 RMB, making large-scale promotion difficult.

International research on ice and snow architecture in cold regions has made significant progress. Yang et al. (2024) developed an early-stage design support system for ice shell architecture that integrates snow drift simulation tools to optimize structural morphology [15]. Wu et al. (2025) conducted combined experimental and numerical investigations on bamboo-reinforced ice beams, demonstrating a 239% increase in flexural strength compared to pure ice [16]. Domestic research has primarily concentrated on mechanical refrigeration technology for indoor ski resorts and energy-efficient design of cold-region buildings, with limited studies on composite venues combining natural snow with steel structures [4]. Existing achievements have failed to effectively address the core demand for safe, economical, and applicable venues for children's ice and snow sports in high-altitude cold regions.

This paper, grounded in Hulunbuir's climatic characteristics and resource advantages, proposes a snow shell-steel truss composite structure venue model. Through systematic analysis of its structural configuration, thermal performance, safety stability, and operational maintenance strategies, we provide a theoretical basis and practical reference for the construction of children's ice and snow sports venues in high-altitude cold regions. Following the United Nations Convention on the Rights of the Child, this paper defines children as individuals aged 0–18, with a focus on the 6–14 age group in the analysis.

2 Regional Construction Conditions Analysis

2.1 Climatic Conditions

Hulunbuir has a continental monsoon climate in the cold-temperate zone. The ice and snow season lasts from November to March each year, with average winter temperatures ranging from $-25°C$ to $-35°C$ and extreme minimum temperatures reaching $-40°C$. The sustained low temperatures provide abundant natural cold sources, enabling ice and snow structures to remain stable over long periods without mechanical refrigeration, forming the core climatic support for venue construction and operation.

The region is dominated by northwest winds in winter, with average wind speeds of 3.5–5.0 m/s, and significant wind-chill effects under strong wind conditions. The venue adopts a fully enclosed structure that effectively blocks outdoor cold winds, eliminating wind-chill effects and increasing indoor perceived temperatures by 8–10°C compared to outdoors, thereby effectively reducing frostbite risk in low-temperature, high-wind environments. Additionally, the regional frost depth is 2.5–3.5 m, requiring foundation designs with embedment depths below the frost line and anti-frost-heave measures [8].

2.2 Material and Construction Conditions

Hulunbuir has an extensive river system, with winter river ice thicknesses of 0.8–1.2 m. The ice is uniform in texture and high in strength, making it a high-quality ice material. Compacted snow can achieve densities of 0.4–0.6 g/cm^3, providing good thermal insulation and structural stability [3]. Natural ice and snow can be sourced locally without transportation, significantly reducing material costs.

Steel supply in the region is convenient, steel truss construction technology is mature, and local construction teams have extensive experience in cold-region engineering. Large-span steel structure construction in extremely cold environments must address challenges such as material brittleness, low-temperature welding, and frost heave deformation. The use of Q355B low-alloy steel with hot-dip galvanizing or epoxy zinc-rich primer protection can effectively ensure structural safety [14]. The venue construction period can be controlled within 15–20 days, suitable for rapid winter assembly. Spray water mist can freeze quickly under low-temperature conditions, providing favorable conditions for snow shell reinforcement and repair.

2.3 Market Demand Characteristics

According to statistics from the Hulunbuir Municipal Bureau of Culture and Tourism, winter parent-child ice and snow tourism accounts for over 60%, with visitors predominantly children aged 6–14 and their parents. Core demands focus on safety protection, comfort experience, and diversified services [6]. Current outdoor ski resorts in the region lack dedicated frostbite prevention facilities for children, while indoor experience halls are small in scale and single in function. There is currently no composite venue integrating ice and snow sports, leisure experiences, and hot beverage services. This model can effectively fill the market gap while serving as a practical base for ice and snow sports in primary and secondary schools, demonstrating good prospects for popularization and application.

2.4 Policy and Resource Support

Under the national “300 million people participating in ice and snow sports” strategy and the “Double Reduction” education policy, local governments in cold regions have introduced subsidy policies for ice and snow infrastructure. Hulunbuir’s abundant natural snow and ice resources, combined with mature steel processing industries and experienced cold-region construction teams, provide comprehensive resource support for the proposed composite venue model. The short construction period (15–20 days) aligns well with winter vacation schedules, enabling rapid deployment to meet seasonal demand peaks.

3 Composite Structure Design and Safety Protection System

This chapter integrates structural design and safety protection into a unified framework, systematically addressing four aspects: structural layers, load-bearing system, protection system, and functional zoning.

3.1 Overall Structural System

The venue adopts a multi-layer composite configuration of outer snow shell, middle steel structure, inner protection, and glass zoning. The functional positioning of each layer is shown in Table 1.

The venue occupies approximately $1500\,\mathrm{m}^2$ with an indoor clear height of 8–10 m. The overall form is a streamlined arch, balancing mechanical rationality and visual appeal.

3.2 Steel Truss Load-Bearing System

We adopt Q355B low-alloy high-strength structural steel, which maintains good tensile, compressive, and impact resistance properties at $-40°\mathrm{C}$ [2] (for cold-region engineer-

表 1: Venue structural layers and functional positioning

Layer	Material/Component	Primary Function
Outer layer	Compacted snow shell (0.6–1.0 m)	Thermal insulation, load bearing, weather resistance
Middle layer	Q355B steel truss system	Primary load-bearing structure
Inner layer	Waterproof breathable membrane + safety nets	Moisture barrier, fall protection
Zoning	Low-E insulated glass partition	Thermal environment isolation

ing applications, low-temperature impact toughness re-inspection should be conducted according to GB/T 4161). Differentiated design based on functional areas: the ice and snow sports zone has a span of 40–80 m with truss spacing of 3–4 m; the leisure experience zone has a span of 20–30 m with spacing of 4–5 m. Bolted-welded connections are used at joints, with reinforcement at connection points. All steel components undergo dual anti-corrosion and anti-freezing treatment: epoxy zinc-rich primer (each coat $\geq 80\,\mu$m, two coats) + polyurethane topcoat (each coat $\geq 60\,\mu$m, two coats).

Reinforced concrete independent foundations are adopted, with embedment depth ≥ 3.5 m (below the frost line). A 10 cm graded gravel cushion layer is placed at the bottom, and ≥ 5 cm polystyrene foam boards are used on the sides for frost heave prevention [8]. Rubber shock-absorbing pads are installed at the connections between steel trusses and foundations to buffer minor deformations caused by freeze-thaw cycles.

3.3 Outer Snow Shell Structure Design

The snow shell adopts an arched load-bearing design that distributes top loads to the steel trusses on both sides and the foundations, avoiding stress concentration. The top snow shell thickness is 0.8–1.0 m, and the side walls are 0.6–0.8 m, with thickness gradients adapted to load and insulation requirements at different locations [3].

The construction process consists of layered snow spraying, mechanical compaction, and low-temperature spray freeze-thaw reinforcement: each layer is sprayed to a thickness of 10–15 cm and compacted layer by layer. After forming, low-pressure spray water mist is applied in the morning and evening, which freezes rapidly below -20°C, forming an ice-snow composite structure with ice filaments interwoven with snow mass (i.e., compacted snow as the matrix and ice crystals as the reinforcing phase). This composite combines the lightweight toughness of snow with the strength and insulation advantages of ice, with self-weight only one-third that of pure ice structures [1].

3.4 Structural Mechanical Verification

According to the Load Code for the Design of Building Structures (GB 50009-2012) [12], the 50-year return period basic snow load in Hulunbuir is $0.55\,\mathrm{kN/m^2}$, and the basic wind load is $0.65\,\mathrm{kN/m^2}$ (terrain roughness Category B). Considering that the venue's safety class is Level 2 (corresponding to structural importance coefficient $\gamma_0 = 1.0$), and accounting for accidental load effects under extreme cold-region conditions, the most unfavorable load combination adopts the permanent load-controlled combination:

$$S = 1.35 S_{Gk} + 1.4 \times 0.7 S_{Qk,w} + 1.4 \times 0.7 S_{Qk,s} \tag{1}$$

where S_{Gk} is the self-weight (steel truss + snow shell + protective layers), $S_{Qk,w}$ is the wind load (corresponding to the basic wind pressure of $0.65\,\mathrm{kN/m^2}$ under extreme weather conditions), and $S_{Qk,s}$ is the 20 cm fresh snow load ($0.8\,\mathrm{kN/m^2}$, estimated at snow density $400\,\mathrm{kg/m^3}$). For wind-sensitive large-span structures, supplementary verification under variable load-controlled combinations is also conducted, with the larger value governing the design.

表 2: Main verification indices under most unfavorable load combination

Verification Item	Calculated Value	Limit Value
Steel truss max stress ratio	≤ 0.60	1.0
Mid-span deflection	$\leq L/450$	$L/400$
Elastic stability coeff. φ_b	≥ 0.92	≥ 0.6 (GB 50017-2017)
Snow shell max compressive stress	$\leq 0.10\,\mathrm{MPa}$	$0.25\,\mathrm{MPa}$

Load-bearing capacity verification is performed according to the Standard for Design of Steel Structures (GB 50017-2017) [10]; stress ratios are verified separately for strength and overall stability. The snow shell compressive stress limit refers to the uniaxial compressive strength test value of compacted snow at $-10°\mathrm{C}$ (0.25–0.35 MPa) [11]. Considering that snow shell materials may undergo creep and freeze-thaw cycle damage during long-term service, we adopt a design safety factor of 3.0 (higher than the conventional value of 2.5) to ensure long-term service safety.

3.5 Internal Safety and Protection

3.5.1 Passive Protection System

Reinforced safety nets (nylon high-strength yarn, mesh $\leq$ 5 cm, rope diameter $\geq$ 12 mm, breaking strength $\geq$ 16 kN) meeting Class 1 standards of Safety Nets (GB 5725-2009) [7] are fully suspended 2–3 m below the steel trusses. Fixing point spacing is $\leq$ 1.5 m. Additional fall-prevention nets (mesh $\leq$ 3 cm) are installed above children's activity areas, forming dual protection.

3.5.2 Envelope Sealing System

Waterproof breathable membranes (HDPE membrane, thickness $\geq$ 0.3 mm, tensile strength $\geq$ 15 MPa, no brittle fracture at -40°C) are fully laid inside the safety nets, with hot-weld lapping and lapping width $\geq$ 10 cm. Core functions include: (1) blocking warm moist air from penetrating the snow shell to prevent ice melting and corrosion; (2) intercepting snow and ice debris to improve indoor environmental cleanliness; and (3) enhancing airtightness to assist temperature stability.

3.6 Functional Zoning and Thermal Environment Isolation

Double-layer Low-E insulated glass (6 + 12A + 6, argon-filled) is used for flexible partitioning, with aluminum alloy frames treated for freeze protection and seamlessly connected to the waterproof breathable membrane. The Low-E coating effectively blocks radiative heat transfer, preventing heat from the hot beverage zone from spreading to the ice area.

We divide the venue into three functional zones as shown in Table 3. The stay time in the all-ice experience zone is based on the Guidelines for Human Tolerance Time in Low-Temperature Workplaces (GB/T 38063-2019, recommended guideline) [13], which gives a human tolerance time of approximately 30–40 minutes under conditions of temperature -8°C, wind speed $\leq$ 0.2 m/s, and light physical activity. Considering that children have larger body surface area-to-mass ratios and weaker thermoregulation abilities compared to adults, we shorten the safe stay time to 15–20 minutes.

The temperature control targets for each zone are as follows: the Ice Shell Sports Zone is controlled at -7°C to -5°C to meet skiing requirements; the All-Ice Experience Zone is controlled at -8°C to -6°C, slightly lower than the sports zone to preserve ice sculpture quality; and the Hot Enjoyment Glass Zone is controlled at -2°C to 0°C, near freezing but slightly below 0°C, providing a warming sensation for visitors while avoiding thermal radiation impact on the ice area. Hot beverage services utilize double-layer insulated cups and localized heating stations to ensure beverages maintain appropriate temperatures

表 3: Venue functional zoning

Zone	Function	Temperature (°C)	Safe Stay Time
Ice Shell Sports Zone	Skiing, ice sports	−7 to −5	Flexible
All-Ice Experience Zone	Ice sculpture viewing	−8 to −6	15–20 min
Hot Enjoyment Glass Zone	Hot beverages, rest	−2 to 0	Flexible

during consumption. Beverage preparation and storage are completed within dedicated insulated equipment in the glass zone, without affecting the ice area temperature.

4 Thermal Performance and Energy Efficiency Analysis

4.1 Temperature and Humidity Environment Creation

The outer compacted snow shell has a thermal conductivity $\lambda \leq 0.2\,\mathrm{W/(m \cdot K)}$ [3], providing good thermal insulation performance. The fully enclosed design blocks outdoor cold winds, with indoor wind speeds $\leq 0.2\,\mathrm{m/s}$, creating a near-windless environment. Relying on natural cold sources without mechanical refrigeration units, we configure only ventilation equipment with a total power of approximately 50 kW for air micro-circulation. The indoor temperature is stably controlled in the range of −8°C to −5°C, with fluctuation $\leq \pm 1$°C.

The waterproof breathable membrane maintains indoor relative humidity in the range of 40%–60%, avoiding both condensation and ice melting caused by excessive humidity and human discomfort caused by excessive dryness. In this environment, the human perceived temperature is 8–10°C higher than outdoors at the same temperature. Children can engage in activities for extended periods in the sports zone wearing standard cold-protection equipment, fundamentally reducing frostbite risk.

4.2 Heat Balance Analysis

The main heat sources in the venue include human body heat dissipation, lighting equipment heat dissipation, ventilation equipment heat dissipation, and heat transfer through the glass partition from the hot beverage zone.

Human body heat dissipation is estimated at 100 W per person (light activity), with a maximum occupancy of 200 persons:

$$Q_{\text{human}} = 100 \times 200 = 20.0\,\mathrm{kW} \tag{2}$$

Lighting equipment is estimated at $10\,\mathrm{W/m^2}$, totaling:

$$Q_{\text{lighting}} = 10 \times 1500 = 15.0\,\mathrm{kW} \tag{3}$$

Ventilation equipment heat dissipation is based on 50 kW equipment at 80% efficiency:

$$Q_{\text{ventilation}} = 50 \times (1 - 0.8) = 10.0\,\mathrm{kW} \tag{4}$$

Heat transfer through the glass partition from the hot beverage zone (detailed in Section 4.3):

$$Q_{\text{glass}} = 2.04\,\mathrm{kW} \tag{5}$$

Total heat input:

$$Q_{\text{total}} = 20.0 + 15.0 + 10.0 + 2.04 = 47.04\,\mathrm{kW} \tag{6}$$

This heat is dissipated outward through the snow shell envelope. Based on the arch geometry (span 40–80 m, rise height approximately 15 m), we estimate the total snow shell heat dissipation area, including roof and side walls, to be approximately $2500\,\mathrm{m^2}$. With thermal conductivity $\lambda = 0.2\,\mathrm{W/(m \cdot K)}$, average thickness 0.8 m (taking the side wall thickness as a conservative value), and indoor-outdoor temperature difference of 30°C (indoor −5°C, outdoor −35°C), the conductive heat dissipation is:

$$Q_{\text{cond}} = \frac{\lambda \cdot A \cdot \Delta T}{d} = \frac{0.2 \times 2500 \times 30}{0.8} = 18.75\,\mathrm{kW} \tag{7}$$

Considering natural convection and radiative heat dissipation on the snow shell surface, the actual heat dissipation is approximately 1.3–1.5 times the conductive heat dissipation:

$$Q_{\text{loss}} = 18.75 \times (1.3\text{–}1.5) = 24.4\text{–}28.1\,\mathrm{kW} \tag{8}$$

Heat balance comparison: $Q_{\text{total}} = 47.0\,\mathrm{kW} > Q_{\text{loss}} = 24.4\text{–}28.1\,\mathrm{kW}$, with a surplus of approximately 18.9–22.6 kW.

Quantitative verification of ventilation heat removal capacity: The ventilation equipment is rated at $Q_v = 20000\,\mathrm{m^3/h}$, with indoor-outdoor temperature difference $\Delta T = 30°\mathrm{C}$, air specific heat at constant pressure $c_p = 1.005\,\mathrm{kJ/(kg \cdot K)}$, and air density $\rho = 1.29\,\mathrm{kg/m^3}$. The heat removal capacity is:

$$Q_{\text{exhaust}} = Q_v \cdot \rho \cdot c_p \cdot \Delta T/3600 = 20000 \times 1.29 \times 1.005 \times 30/3600 = 216.2\,\mathrm{kW} \tag{9}$$

By adjusting the ventilation rate using variable frequency control, only approximately 10% of the rated airflow is required to remove 21.6 kW of excess heat, fully covering the 18.9–22.6 kW surplus range. During actual operation, we can dynamically adjust the ventilation equipment frequency based on indoor temperature sensor feedback, precisely matching heat removal to indoor thermal loads to achieve stable temperature control.

The above results demonstrate that the 50 kW ventilation equipment provides far more heat removal capacity than required while meeting air micro-circulation needs. Through variable frequency regulation, we can precisely control heat removal, verifying the feasibility of maintaining the venue's internal low-temperature environment without mechanical refrigeration through rational heat management strategies.

4.3 Quantitative Heat Flow Analysis Between Hot Beverage Zone and Ice Zone

The hot beverage zone temperature is controlled at -2 to $0°C$, while the ice zone is at -8 to $-5°C$, with a temperature difference of approximately 6–8°C. The heat transfer coefficient K of the double-layer Low-E insulated glass ($6 + 12A + 6$, argon-filled) can be taken as 1.6–1.8 $W/(m^2 \cdot K)$ (common engineering values; actual performance depends on Low-E coating position and argon concentration, and should be verified through factory test reports before construction). Ignoring frame thermal bridge effects (already treated for freeze protection), the one-dimensional steady-state heat flux density is:

$$q = K \cdot \Delta T = 1.7 \times 8 = 13.6\,\mathrm{W/m^2} \tag{10}$$

Based on a partition area of $150\,\mathrm{m^2}$:

$$Q_{\mathrm{glass}} = q \times A = 13.6 \times 150 = 2040\,\mathrm{W} = 2.04\,\mathrm{kW} \tag{11}$$

This value is far less than the heat loss through the envelope of traditional indoor ski resorts (typically $> 50\,\mathrm{kW}$), demonstrating that the glass partition can effectively control the thermal impact of the hot beverage zone on the ice zone at a very low level.

In actual engineering, the K-value of insulated glass is affected by coating position, cavity thickness, gas concentration, and sealing technology. We recommend thermal performance re-inspection before construction and consideration of thermal bridge effects of the glass frame. In the design phase, we can adopt $K = 1.8\,\mathrm{W/(m^2 \cdot K)}$ as a conservative value:

$$q_{\mathrm{conservative}} = 1.8 \times 8 = 14.4\,\mathrm{W/m^2}, \quad Q_{\mathrm{conservative}} = 14.4 \times 150 = 2.16\,\mathrm{kW} \tag{12}$$

4.4 Energy Efficiency and Economic Benefits

The venue construction cost is approximately 800–1000 RMB/m² (main construction and installation costs, including steel trusses, snow shell construction, protective layers, and glass partition installation; excluding land acquisition fees, ice sculpture artistic modeling fees, and internal business equipment procurement costs). The total cost for 1500 m^2 is approximately 1.2–1.5 million RMB, representing a reduction of approximately 66.7%–84% compared to traditional indoor ski resorts (3000–5000 RMB/m^2, total cost 4.5–7.5 million RMB), i.e., over 70% reduction.

Operational energy consumption is detailed in Table 4. Ventilation equipment only maintains air micro-circulation during non-spraying periods, with a power of approximately 50 kW; spraying equipment only operates during water replenishment operations, with a power of approximately 30 kW. Ventilation operates 9 hours daily (business hours); spray equipment operates 2 hours per operation every 10–15 days. Based on a general industrial and commercial electricity price of 0.8 RMB/kWh:

表 4: Operational energy consumption comparison

Item	This Venue	Traditional Indoor Ski	Reduction
Monthly electricity cost	$\approx 11,000$ RMB	$> 100,000$ RMB	$> 89\%$
Construction cost	800–1000 RMB/m^2	3000–5000 RMB/m^2	$> 70\%$
Refrigeration units	None required	Required	100%

Ventilation monthly consumption:

$$E_{\text{vent}} = 50 \times 9 \times 30 = 13500\,\text{kWh} \tag{13}$$

Ventilation monthly cost:

$$C_{\text{vent}} = 13500 \times 0.8 = 10800\,\text{RMB} \tag{14}$$

Spray monthly consumption (3 times per month):

$$E_{\text{spray}} = 30 \times 2 \times 3 = 180\,\text{kWh} \tag{15}$$

Spray monthly cost:

$$C_{\text{spray}} = 180 \times 0.8 = 144\,\text{RMB} \tag{16}$$

Total monthly electricity cost:

$$C_{\text{electricity}} = 10800 + 144 = 10944\,\text{RMB} \approx 11000\,\text{RMB} \tag{17}$$

Labor cost estimate: 5–8 staff members at local monthly salary of 3,500 RMB:

$$C_{\text{labor}} = (5\text{–}8) \times 3500 = 17500\text{–}28000\,\text{RMB/month} \tag{18}$$

Total monthly operation and maintenance cost:

$$C_{\text{O\&M}} = C_{\text{electricity}} + C_{\text{labor}} = 10944 + (17500\text{–}28000) = 28444\text{–}38944\,\text{RMB/month} \tag{19}$$

5 Child Frostbite Prevention Design

The thermal environment described in Chapter 4 (stable low-temperature range, near-windless, suitable humidity) provides the physical foundation for child frostbite prevention. Based on this, we construct a systematic frostbite prevention system from four dimensions: environmental control, behavioral guidance, active protection, and emergency support.

5.1 Environmental Control (Passive Frostbite Prevention)

- Fully enclosed near-windless environment eliminates wind-chill effects, increasing perceived temperature by 8–10°C;
- Three-level temperature transition spaces (outdoor → foyer → hot enjoyment zone → sports zone) reduce thermal shock and adapt to children's physiological regulation capabilities;
- Precise temperature control in each zone avoids localized cold spots.

5.2 Behavioral Guidance and Information Display

- Temperature displays and frostbite prevention signs in each zone indicate appropriate stay times and precautions;
- All-ice experience zone signage states: "Recommended stay 15–20 minutes; children must be accompanied by parents;"
- Staff conduct regular patrols; upon detecting early signs of frostbite (facial redness/purpling, hand stiffness), they immediately guide individuals to the warm zone.

5.3 Active Protection Facilities

- Categorized frostbite prevention supplies are provided free of charge in all activity zones (gloves, scarves, face masks, hand warmers, snow boots);
- Free hot water supply points are located in the hot enjoyment glass zone and dedicated transition zones;
- All children's activity areas use compacted snow or non-slip ice surfaces, with ice edges rounded (radius $\geq 5\,\text{cm}$);
- Soft protective fences and sponge cushions are installed at the sides and bottoms of ice slides and ski slopes.

5.4 Emergency Support

- Two emergency medical points (in the hot enjoyment glass zone and ice shell sports zone) are staffed with first aid personnel and supplies for frostbite and trauma;
- Children must be accompanied by parents throughout the entire time in sports zones, with dedicated staff supervision in key areas;
- On-site medical staff assess conditions according to frostbite classification standards; mild frostbite is treated on-site, while severe cases are immediately transferred to hospital with full follow-up.

6 Operation and Maintenance Model

We adopt a low-cost, routine, and refined maintenance strategy with targeted management systems.

6.1 Regular Water Replenishment Reinforcement and Erosion-Ice Accretion Balance Model

Spray water replenishment reinforcement is performed every 10–15 days, scheduled for 0:00–6:00 (outdoor temperatures −30°C to −40°C for optimal freezing). Industrial-grade spray pump pressure is set to 0.2–0.3 MPa, applied uniformly to the outer surface of the snow shell.

According to field measurements by our project team in the winter of 2023, the annual average erosion rate on the outer surface of the snow shell is $v_e \leq 0.5\,\text{cm/month}$, while erosion on the inner side is significantly lower due to the waterproof breathable membrane barrier. Each reinforcement adds $h_s = 0.5\text{–}1.0\,\text{cm}$ of thickness, with $n = 24\text{–}36$ annual reinforcement cycles. The annual net thickness increase model is:

$$\Delta H = n \cdot h_s - 12 \cdot v_e \tag{20}$$

Substituting the values:

$$\Delta H_{\min} = 24 \times 0.5 - 12 \times 0.5 = 6\,\text{cm/year} \tag{21}$$

$$\Delta H_{\max} = 36 \times 1.0 - 12 \times 0.5 = 30\,\text{cm/year} \tag{22}$$

Under long-term service conditions, taking the median value of the thickening range, approximately 18 cm/year, the cumulative thickening over 10 years is approximately 1.8 m.

After deducting the initial thickness of 0.8 m, the net thickening is 1.0 m, with a corresponding self-weight increase of approximately $1.0\,\text{m} \times 500\,\text{kg/m}^3 = 500\,\text{kg/m}^2$. We recommend conducting structural safety assessments at the 5-year and 10-year milestones, and mechanically thinning the shell to control thickness within 1.5 m if necessary. On weekends and holidays, ice replenishment demonstrations can be arranged as a special experiential activity.

6.2 Hot Beverage Zone Operational Specifications

- Hot beverage service is strictly confined to the glass zone; hot beverage cups are not permitted to be taken out;
- Double-layer insulated cups are used, with outer surface temperature $\leq 40°\text{C}$, and cup sleeves provided to prevent burns;
- Dedicated exhaust equipment in the hot beverage zone exhausts hot air and moisture outdoors to prevent them from affecting the ice structure;
- Non-slip mats are installed on the floor, with prompt cleanup of spills.

6.3 Zone-Based Inspection Management

During open hours, inspections are conducted at the frequencies shown in Table 5; during non-open hours, one comprehensive inspection is performed after closing each day. Maintenance records are established to enable traceable management.

表 5: Zone-based inspection management

Zone	Inspection Frequency	Key Items
Snow shell exterior	Every 2 days	Erosion, cracks, ice accretion
Steel truss system	Weekly	Corrosion, deformation, connections
Safety nets	Daily	Integrity, fixing points
Glass partition	Daily	Seal integrity, condensation
Indoor environment	Continuous	Temperature, humidity, wind speed

6.4 Safety Emergency Management

We establish a comprehensive emergency response plan system covering extreme weather (blizzards, $\geq$ Grade 9 winds), structural anomalies (monitoring data exceeding warning thresholds), personnel frostbite/injury, and fire scenarios. The venue is equipped with dry powder fire extinguishers, fire sand, and other facilities; open flames are strictly prohibited; and electrical equipment adopts explosion-proof and leakage-proof designs. We organize two to three comprehensive emergency drills each winter to ensure effective implementation of the emergency protocols.

7 Structural Safety Assurance System

The venue builds comprehensive safety assurance from four dimensions: anti-collapse, anti-fall, anti-ice-erosion, and anti-frost-heave.

7.1 Anti-Collapse

The arched load-bearing structure distributes loads to both sides, with the steel truss bearing all primary loads. Q355B steel has sufficient strength reserves, with a stress ratio ≤ 0.6 under the most unfavorable working condition verification. The ice-snow interwoven composite structure has good toughness and deformation resistance. We install twelve monitoring points (steel truss nodes, snow shell top, foundation locations) with real-time monitoring using total stations and settlement gauges. When settlement $\geq 5\,\text{mm}$ or deformation $\geq 3\,\text{mm}$, the emergency response is triggered immediately.

7.2 Anti-Fall

Triple protection includes: the layered compaction plus spray-reinforced snow shell structure is dense and stable, reducing falling objects at the source; safety nets and fall-prevention nets provide full interception; dedicated personnel conduct inspections every 2 hours, promptly removing floating snow and ice accumulation and repairing any damage.

7.3 Anti-Ice-Erosion

Triple measures include: insulated glass zoning achieves complete thermal environment isolation; the waterproof breathable membrane blocks warm moist air from penetrating the snow shell; periodic ice replenishment offsets natural erosion. The measured erosion rate is far lower than the ice accretion rate, ensuring long-term structural stability (see the balance model in Section 6.1).

7.4 Anti-Frost-Heave

Foundation embedment depth $\geq 3.5\,\mathrm{m}$ (below the frost line), with graded gravel cushion layer at the bottom and polystyrene foam boards on the sides for frost heave prevention [8]. Rubber shock-absorbing pads are installed at the connections between steel trusses and foundations. We install a buried insulated drainage system around the venue to effectively avoid freeze-thaw cycle damage to the foundation and subgrade.

8 Conclusions

Based on the climatic characteristics of Hulunbuir's high-altitude cold region and the demand for children's ice and snow sports, this paper proposes a snow shell-steel truss composite structure ice and snow venue model. Through systematic analysis, we draw the following conclusions:

1. **Structural feasibility**: The composite system of arched snow shell and steel truss has reliable mechanical performance. According to GB 50009-2012 [12] and GB 50017-2017 [10] verification, under the most unfavorable load combination, the steel truss maximum stress ratio is ≤ 0.6, mid-span deflection calculated value is $\leq L/450$ (satisfying the $L/400$ limit), and elastic overall stability coefficient $\varphi_b \geq 0.92$. The safety nets and waterproof breathable membrane provide dual protection, ensuring long-term stable operation under extreme low-temperature and high-wind conditions.

2. **Thermal and frostbite prevention performance**: Relying on natural cold sources, we achieve a stable low-temperature range of $-8°\mathrm{C}$ to $-5°\mathrm{C}$ (wind speed $\leq 0.2\,\mathrm{m/s}$, temperature fluctuation $\leq \pm1°\mathrm{C}$). Heat balance analysis shows that the total heat input is approximately $47.0\,\mathrm{kW}$, and the natural heat dissipation through the snow shell envelope is approximately 24.4–28.1 kW, requiring active heat removal through the 50 kW ventilation equipment to maintain temperature stability. Under variable frequency control, only 10% of rated airflow is needed to meet heat removal requirements. The Low-E insulated glass partition can control the heat flow from the hot beverage zone to the ice zone at approximately 2.0 kW. The three-level temperature transition and systematic frostbite prevention design effectively reduce the risk of frostbite in children. The recommended safe stay time in the all-ice experience zone is 15–20 minutes [13].

3. **Long-term stability**: We establish an annual net thickness increase balance model, with a theoretical net increase of approximately 6–30 cm/year. Attention should be

paid to the self-weight increase caused by long-term thickening. We recommend conducting structural safety assessments every 5 years and mechanically thinning the shell if necessary.

4. **Economic efficiency**: The glass partition achieves physical isolation between the thermal environment and the ice environment. Operational energy consumption is reduced by more than 70% compared to traditional models. Construction and maintenance costs are significantly lower than those of indoor ski resorts. The total monthly operation and maintenance cost (electricity $\approx 11,000$ RMB + labor $17,500$–$28,000$ RMB) is approximately $28,500$–$39,000$ RMB (2.85–3.9 ten thousand RMB).

5. **Promotion value**: This model is suitable for economically less developed high-altitude cold regions and can serve as a reference for ice and snow venue construction in Heilongjiang, Xinjiang, Jilin, and other regions. It can also serve as a practical base for ice and snow sports in primary and secondary schools, supporting the national strategy for promoting ice and snow sports.

Future research may further focus on the optimization of ice and snow material properties (e.g., fiber-reinforced snow shells), refined structural simulation (CFD coupled heat and moisture transfer analysis), and intelligent operation and maintenance management systems, providing more comprehensive technical support for the high-quality development of the ice and snow industry in high-altitude cold regions.

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