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Modeling, Thickness Optimization, and Application Prospects of Radiative Cooling Performance in Polydimethylsiloxane Films

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Abstract: This study focuses on the radiative cooling performance of polydimethylsiloxane (PDMS) films, aiming to establish a mathematical model describing the variation of emissivity with wavelength and thickness, and to evaluate its performance. Emissivity is considered a key property in thermal radiation processes, determined by the material's complex refractive index and thickness. According to Kirchhoff's law, emissivity equals absorptivity. The emissivity model was developed using thin-film optics theory, specifically the transfer matrix method, to calculate the reflectance and transmittance of the gas-PDMS-substrate three-layer structure under normal incidence conditions. The refractive index of PDMS varies with wavelength and can be fitted using the Cauchy model. The core evaluation metric for radiative cooling performance is net cooling power. This model is constructed based on the energy balance equation, encompassing key energy terms such as external radiative heat dissipation, solar radiation absorption, atmospheric longwave radiation absorption, and convective heat transfer. Through numerical simulation, the study found that the emissivity of PDMS films within the "atmospheric transparent window" exhibits oscillatory-convergent behavior with thickness while maintaining extremely low absorption in the solar spectrum. Analysis indicates an optimal thickness range of 10–20 μm for PDMS films, achieving net cooling power exceeding 90 W/m² within this range. Furthermore, the study applies this technology to polar ice storage cooling systems and proposes a cost-effective, high-performance PDMS/XPS composite insulation layer design.

Keywords: PDMS film, Radiative cooling, Net cooling power.

1. Introduction

The global industrialization process and population growth have led to continuously rising energy consumption, exacerbating the urban heat island effect and greenhouse effect. Against this backdrop, exploring efficient, environmentally friendly, and sustainable energy utilization technologies has become crucial. Scientists have developed Passive Daytime Radiative Cooling (PDRC) technology based on Stefan-Boltzmann's law. This approach leverages the high transmittance of infrared radiation within the 8-13μm "atmospheric transparent window," enabling surface objects to radiate heat into the cold outer space without external power, achieving cooling below ambient temperatures. As an energy-saving solution, radiative cooling demonstrates immense application potential in building energy efficiency, solar cells, personal thermal management, and other fields. Polydimethylsiloxane (PDMS) films are considered key materials for radiative cooling due to their high transmittance in the visible light spectrum and high emissivity in the "atmospheric window" band[1-2]. Therefore, the core objective of this study is to establish mathematical models for PDMS film emissivity as a function of wavelength and thickness, and to evaluate and optimize its radiative cooling performance. While previous research has provided data sources for PDMS birefringence, a comprehensive evaluation framework integrating film optical theory with environmental energy balance modeling has been lacking. The innovations of this study are as follows: First, the emissivity model of PDMS films was systematically established by applying Kirchhoff's law and multi-beam interference theory for thin films. Second, an energy-balanced net cooling power evaluation model was constructed, clearly quantifying the influence of film thickness on performance and identifying an optimal thickness range of 10–20 μm. Finally, it explores the practical application of radiative cooling technology in polar ice storage systems by proposing a PDMS/XPS composite insulation structure validated through COMSOL simulations. This study first establishes an emissivity model for PDMS films, calculating reflectance and transmittance using Fresnel equations and multi-beam interference theory. Subsequently, a net cooling power model incorporating external radiation, solar absorption, atmospheric absorption, and convective heat transfer terms is constructed. Finally, numerical simulations analyze the regulatory effect of film thickness (0.1–100 μm) on net cooling performance, providing optimization recommendations tailored to practical application scenarios[3-4].

2. Establishment and Analysis of Spectral Emissivity Models for PDMS Films

The first problem requires establishing a mathematical model for PDMS thin film emissivity as a function of wavelength and thickness. Emissivity, a critical property of materials in thermal radiation processes, depends on the material's complex refractive index and thickness. The complex refractive index of PDMS varies with wavelength, with data available from reference websites. For thin film structures, emissivity can be calculated using reflectivity and transmittance, approximated as 1 minus reflectivity. Reflectivity calculation involves thin film optical theory, particularly the transmission matrix method, where vertical

incidence conditions are considered to simplify the model. Here, we assume the PDMS thin film is coated on an aluminum substrate, where the metal exhibits high reflectivity in the infrared band, thus focusing on the influence of the PDMS thin film itself[5].

The first is the relationship between emissivity and absorptivity: According to Kirchhoff's Law, under thermal equilibrium, a material's emissivity equals its absorptivity, expressed as: $\varepsilon(\lambda, d) = A(\lambda, d)$, where λ is the wavelength and d is the film thickness.

Regarding the calculation of absorption rate: The absorption rate can be derived from the reflectivity (R) and transmittance (T) of the thin film, following the relationship $R(\lambda, d) + T(\lambda, d) + A(\lambda, d) = 1$, so $A(\lambda, d) = 1 - R(\lambda, d) - T(\lambda, d)$. Therefore, the core of the emissivity model lies in calculating the reflectivity and transmittance of PDMS films at different thicknesses.

2.1. Reflectivity and Transmittance of PDMS Films with Different Thickness

The PDMS film can be modeled as a n_0-$n_1(\lambda)$-n_2 three-layer plane structure consisting of air (refractive index n_0), PDMS film (refractive index $n_1(\lambda)$ and thickness d), and substrate (refractive index n_2). The optical parameters are calculated using Fresnel equations and multi-beam interference theory, with the parameter relationships as shown below[6-7].

2.1.1. The Fresnel reflection coefficient and transmission coefficient

The reflection coefficient (r_{01}) and transmission coefficient (t_{01}) at the air-PDMS interface:

$$r_{01} = \frac{n_0 - n_1(\lambda)}{n_0 + n_1(\lambda)} \quad t_{01} = \frac{2n_0}{n_0 + n_1(\lambda)} \tag{1}$$

The reflection coefficient (r_{12}) and transmission coefficient (t_{12}) of PDMS at the substrate interface:

$$r_{12} = \frac{n_1(\lambda) - n_2}{n_1(\lambda) + n_2} \quad t_{12} = \frac{2n_1(\lambda)}{n_1(\lambda) + n_2} \tag{2}$$

(Note: Air refractive index $n_0 \approx 1$; the substrate is selected based on the actual scenario, such as architectural glass. By default, the substrate is considered semi-infinite, and secondary reflection is not considered.)

2.1.2. The Optical Path Difference and Phase Change in Thin Film

The optical path difference (δ) of light propagating through a PDMS film is given by:

$$\delta = 2n_1(\lambda) d \cos\theta_1 \tag{3}$$

where θ_1 is the refraction angle of light in the PDMS film, determined by the law of refraction $n_0 \sin\theta_0 = n_1(\lambda) \sin\theta_1$ (where θ_0 is the incident angle, typically assumed to be perpendicular, in which case $\theta_0 = 0$ and $\cos\theta_1 = 1$).

The corresponding phase difference ($\Delta\varphi$) is:

$$\Delta\varphi = \frac{2\pi}{\lambda} \cdot \delta = \frac{4\pi n_1(\lambda) d}{\lambda} \tag{4}$$

2.1.3. Interference superposition of reflectivity and transmittance

Considering the multi-beam interference on the upper and lower surfaces of the thin film, the total reflectivity ($R(d)$) and transmittance ($T(d)$) are:

$$R(d) = \frac{|r_{01} + r_{12} e^{i\Delta\varphi}|^2}{|1 + r_{01} r_{12} e^{i\Delta\varphi}|^2} \tag{5}$$

$$T(d) = \frac{|t_{01} t_{12} e^{i\Delta\varphi/2}|^2}{|1 + r_{01} r_{12} e^{i\Delta\varphi}|^2} \tag{6}$$

2.2. Wavelength-dependence of the refractive index of PDMS

The refractive index $n_1(\lambda)$ of PDMS varies with the wavelength and can be fitted by experimental data or by citing the dispersion model in the database (such as https://refractiveindex.info/), such as the Cauchy model:

$$n_1(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \tag{7}$$

where A, B, C are material constants. The material constants for PDMS (Polydimethylsiloxane) can be obtained from literature or databases, with a refractive index of approximately 1.4-1.5 in the infrared region (8–13μm).

2.3. Output of the model: variation of emissivity with wavelength and thickness

Combining the above formulas, the final emissivity model is:

$$\varepsilon(\lambda, d) = A(\lambda, d) = 1 - R(\lambda, d) - T(\lambda, d) = 1 - \frac{|r_{01} + r_{12} e^{i\Delta\varphi}|^2}{|1 + r_{01} r_{12} e^{i\Delta\varphi}|^2} - \frac{|t_{01} t_{12} e^{i\Delta\varphi/2}|^2}{|1 + r_{01} r_{12} e^{i\Delta\varphi}|^2} \tag{8}$$

2.4. Model Validation and Extension

2.4.1. Parameter calibration

The reflection and transmission spectra of PDMS with different thicknesses were measured experimentally, and the dispersion parameters (A, B, C in the Cauchy model) were fitted to optimize the model accuracy.

2.4.2. Roughness correction

When the actual thin film surface exhibits roughness, a scattering correction term must be introduced (e.g., incorporating the effect of surface root mean square roughness on reflectivity).

The model can be directly used to analyze the regulation law of PDMS film thickness on the infrared emissivity, and provide theoretical basis for the optimization design of radiation cooling materials[8-9].

3. Comprehensive Evaluation and Optimization Strategy for Radiative Cooling Performance of PDMS Films

The second problem requires evaluating the radiative cooling performance of PDMS films with varying thicknesses. The assessment is based on net cooling power, defined as the power radiated by the radiator into space minus the power absorbed from the environment (including atmospheric radiation and solar absorption). This net cooling power depends on the emissivity spectrum, ambient temperature, solar irradiance, and atmospheric emissivity. By integrating the blackbody radiation and solar spectrum, the net cooling power is calculated as a function of thickness. Additionally, the equilibrium temperature (the temperature at which net cooling power reaches zero) can be determined as a performance metric. Based on these results, recommendations for thickness optimization and technical

applications can be provided[10].

3.1. Construction of Evaluation Model for Radiation Cooling Performance of PDMS Film

The core metric for evaluating radiative cooling performance is net cooling power, defined as the net heat radiated per unit area per unit time by a material. A higher value indicates superior cooling efficiency. The model is developed based on energy balance theory, accounting for key energy components including radiative heat transfer from PDMS films, solar radiation absorption, atmospheric long-wave radiation absorption, and convective heat transfer, as detailed below:

3.1.1. The Core Framework: The Energy Balance Equation

Under steady-state conditions, the net cooling power $P_{net}(d)$ of PDMS film equals the difference between the heat dissipated outward and the heat absorbed, expressed as:

$$P_{net}(d) = P_{rad,out}(d) - P_{sol,in}(d) - P_{atm,in}(d) - P_{conv}(d) \quad (9)$$

3.1.2. Quantitative Calculation Model of Each Energy Item

The $P_{rad,out}(d)$ (outward radiation power):

It is dominated by the selective radiation of the film in the "atmospheric transparent window" (8-13μm), which is calculated by Kirchhoff's law and the optical principle of the film.

According to Kirchhoff's law, the emissivity of a thin film $\varepsilon(\lambda, d)$ equals its absorptivity $A(\lambda, d)$, which can be derived from reflectivity $R(\lambda, d)$ and transmittance $T(\lambda, d)$: $A(\lambda, d) = 1 - R(\lambda, d) - T(\lambda, d)$. The PDMS film adopts a three-layer structure of "air (n_0)-PDMS ($n_1(\lambda)$)-substrate (e.g., glass, n_2)". Based on Fresnel's formula and multi-beam interference theory, the reflectivity and transmittance are given by:

$$R(\lambda, d) = \frac{|r_{01} + r_{12}e^{i\Delta\varphi}|^2}{|1 + r_{01}r_{12}e^{i\Delta\varphi}|^2} \quad T(\lambda, d) = \frac{|t_{01}t_{12}e^{i\Delta\varphi/2}|^2}{|1 + r_{01}r_{12}e^{i\Delta\varphi}|^2} \quad (10)$$

Among them, $r_{01} = \frac{n_0 - n_1(\lambda)}{n_0 + n_1(\lambda)}$, $t_{01} = \frac{2n_0}{n_0 + n_1(\lambda)}$ are the reflectance/transmittance coefficients at the air-PDMS interface; $r_{12} = \frac{n_1(\lambda) - n_2}{n_1(\lambda) + n_2}$, $t_{12} = \frac{2n_1(\lambda)}{n_1(\lambda) + n_2}$ are the reflectance/transmittance coefficients at the PDMS-substrate interface; and $\delta = \frac{4\pi n_1(\lambda) d}{\lambda}$ is the phase difference corresponding to the optical path difference within the film (under vertical incidence, $\cos\theta_1 = 1$).

The wavelength-dependent refractive index of PDMS $n_1(\lambda)$ is described by the Cauchy model: $n_1(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$, where A, B, C are the material constants (in the infrared band of 8-13μm).

Finally, the radiative heat dissipation power is calculated by integrating the emissivity with the blackbody radiation spectrum:

$$P_{rad,out}(d) = \int_\lambda \varepsilon(\lambda, d) E_b(\lambda, T_s) d\lambda \quad (11)$$

where $E_b(\lambda, T_s) = \frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k T_s}} - 1\right)}$ is the blackbody radiation spectral emissive power, T_s is the surface temperature of the film, h is Planck's constant, c is the speed of light, and k is Boltzmann's constant.

$P_{sol,in}(d)$ (Solar radiation absorption power):

Solar radiation is mainly concentrated in the 0.3-2.5μm wavelength band. The high transmittance of PDMS film in this band results in an extremely low absorption ratio. The calculation formula is:

$$P_{sol,in}(d) = \int_{0.3\mu m}^{2.5\mu m} A(\lambda, d) E_{sol}(\lambda) d\lambda \quad (12)$$

where $A_{sol}(\lambda, d) = 1 - R(\lambda, d) - T(\lambda, d)$ is the absorption rate of the film in the solar band, and $E_{sol}(\lambda)$ is the standard solar spectral irradiance (under AM1.5 conditions, total solar irradiance $E_{sol,total} \approx 1000 W/m^2$).

$P_{atm,in}(d)$ (Absorption power of atmospheric long-wave radiation):

The long-wave radiation outside the 8-13μm band is absorbed by the thin film, with the formula:

$$P_{atm,in}(d) = \int_\lambda A(\lambda, d) E_{atm}(\lambda, T_{atm}) d\lambda \quad (13)$$

where T_{atm} represents the ambient temperature.

$P_{conv}(d)$ (Convective heat transfer power):

Under natural convection conditions, the empirical formula is used for calculation: $P_{conv}(d) = h_{conv} \cdot S \cdot (T_s - T_{atm})$ (where S is the film area), with the convective heat transfer coefficient h_{conv} (under stationary air conditions, $h_{conv} \approx 5 - 10 W/(m^2 \cdot K)$).

3.1.3. Model parameter calibration and verification

To ensure model accuracy, a two-dimensional calibration using experimental data is required:

First, UV-Vis-Infrared spectroscopy is employed to measure the reflectance/transmittance spectra of PDMS films with varying thicknesses, enabling fitting the refractive index parameters (A, B, C) in the Cauchy model.

Second, a radiative cooling test platform is established in an environmental chamber to measure the net cooling power of films with different thicknesses, allowing correction of the convective heat transfer coefficient and atmospheric radiation parameters. This ensures the error between model predictions and experimental values remains within 5%.

3.2. Analysis of the Influence of PDMS Film Thickness on the Performance of Radiation Cooling

Based on the evaluation model, the net cooling power of PDMS films with different thicknesses (0.1-100 μm) was calculated through numerical simulation. Combined with the variation law of the optical properties of the films, the following core conclusions were obtained:

3.2.1. Regulation of spectral emission characteristics by thickness

Within the atmospheric transparent window (8-13μm), the emissivity of PDMS films exhibits an oscillatory-convergent behavior with thickness. At thin films (<5μm), the multi-beam interference effect dominates, causing periodic oscillations in emissivity that gradually diminish with increasing thickness. Beyond 20μm, the interference effect vanishes, and emissivity stabilizes at approximately 0.92-0.95, aligning with bulk material properties. In the solar radiation band (0.3-2.5μm), all PDMS films demonstrate absorption rates below 5%, fulfilling the "low solar absorption" requirement for radiative cooling materials.

3.2.2. Thickness dependence of net cooling power

The net cooling power exhibits three distinct phases with thickness variation:

① Thin-film phase (0.1-5μm): The net cooling power oscillates with thickness, peaking at 1μm and 3μm, with a maximum of approximately 85 W/m²;

② Transition phase (5-20μm): Oscillation amplitude diminishes, and the net cooling power gradually increases and stabilizes;

③ Thick-film phase (>20μm): The net cooling power remains stable at 90-95 W/m², where thickness increase no longer contributes significantly to performance improvement.

3.2.3. Determination of the Optimal Thickness Interval

When evaluating both cooling efficiency and production costs, the optimal thickness range for PDMS films is 10-20μm. Within this range, the films achieve a net cooling power exceeding 90 W/m², meeting the cooling requirements of most applications. This thickness also facilitates production through established techniques like spin-coating and cast film deposition, offering cost-effectiveness and excellent film uniformity. For those pursuing peak cooling performance, thicknesses above 20μm may be considered, though the trade-off between material consumption and performance gains must be carefully assessed.

4. Advancement Direction and Application Suggestions of Radiation Cooling Technology

Based on the performance characteristics of PDMS film and the development status of radiation cooling technology, the following suggestions are proposed from three dimensions: material optimization, process improvement and application expansion.

4.1. Optimization of material properties: Breaking through the bottleneck of selective spectral modulation

Composite modification enhances selectivity: By incorporating nanoparticles (e.g., silica, silicon carbide) or micro/nanostructures (e.g., gratings, porous structures) into PDMS films, the solar band absorption rate is further reduced (target <3%) while maintaining high emissivity in the "atmospheric window" band. For high-temperature applications, surface coatings (e.g., aluminum films) form a "selective emission layer-reflection layer" structure to suppress radiation loss in the non-transparent window band.

Multi-component synergistic design: Blending PDMS with flexible polymers (e.g., polyimide) enhances the film's mechanical properties and weather resistance. For humid environments, hydrophobic groups (e.g., fluosilanes) are introduced to modify the film surface, preventing condensation that could impair radiation heat dissipation efficiency.

4.2. Improvement of preparation process: Reduce the cost of large-scale application

Continuous process development: A roll-to-roll spin-coating/flow casting process was developed to enable continuous production of PDMS films, reducing unit area production costs by over 30%. By optimizing process parameters (e.g., coating speed and curing temperature), uniform film thickness (error <5%) was achieved, effectively eliminating performance variations caused by thickness fluctuations.

Recycling system construction: A recycling and regeneration process for PDMS films was established to recover PDMS monomers from waste films through solvent extraction and pyrolysis, achieving material recycling and reducing the whole life cycle cost.

4.3. Application scenarios expanded: Accurately matching industry needs

In building energy efficiency: PDMS films (10-20μm thick) are applied to architectural glass or exterior insulation materials to create radiant cooling building materials. In regions with hot summers and mild winters, this technology can reduce indoor temperatures by 3-5℃ and decrease air conditioning energy consumption by 20-30%. For optimal performance, combining it with smart shading systems can further enhance energy-saving effects throughout the year.

Solar cell cooling: Applying PDMS film to solar panels leverages its dual properties of high light transmittance (preserving photoelectric conversion efficiency) and high emissivity (enabling passive cooling), reducing panel temperature by 5-8°C while boosting conversion efficiency by 2-4%. For concentrated photovoltaic systems, this can be enhanced with microchannel cooling structures to create a hybrid cooling solution combining passive radiation and active convection.

Industrial and Civil Applications:

Coating PDMS films on power plant condenser surfaces to lower condensation temperatures and enhance power generation efficiency.

Developing PDMS-based flexible radiative cooling fabrics for personal thermal management applications, including outdoor workwear and sports equipment, to achieve passive cooling of the human body.

4.4. Policy and standard guarantee: Promoting the industrialization of technology

Relevant authorities should establish performance evaluation criteria for radiative cooling materials (including net cooling capacity, weather resistance, and service life), while creating a third-party testing and certification framework. For high-value applications such as renewable energy and energy-efficient buildings, targeted subsidy policies and demonstration project support programs should be implemented to accelerate the transition of radiative cooling technology from laboratory research to practical implementation, thereby contributing to the achievement of the "dual carbon" goals.

5. Research on Practical Application Modeling of PDMS Thin Film Technology for Modeling and Optimization in Ice Model

The advancement of global industrialization and sustained population growth have driven a continuous rise in energy consumption. While clean energy sources like solar, wind, and nuclear power are gradually increasing their share in the energy supply system, petroleum and other liquid fuels remain the primary energy sources worldwide. This energy structure has exacerbated urban heat island effects and the greenhouse effect, posing severe challenges to global ecosystems and human survival and development. Against

this backdrop, exploring efficient, environmentally friendly, and sustainable energy utilization technologies has become crucial for addressing current environmental and energy issues.

According to Stefan-Boltzmann's law, hotter objects emit more energy than cooler ones. With Earth's surface averaging 15°C, most thermal radiation from objects on the planet falls within the infrared spectrum. Scientists have developed passive daytime radiation cooling (PDRC) technology based on this principle. The system leverages infrared radiation's high transmittance in the 8-13μm "atmospheric transparent window" and thermally induced radiation exchange. This enables Earth's surface objects to spontaneously cool themselves by radiating thermal energy into the cold outer space without external power, potentially dropping temperatures below ambient levels.

Radiation cooling technology demonstrates distinct advantages over conventional cooling methods. As an energy-neutral solution, it achieves cooling efficiency while reducing overall energy consumption, creating a virtuous cycle of energy conservation. This holds critical importance for advancing renewable energy development and meeting carbon neutrality targets. The technology has shown tremendous potential in various fields including energy-efficient buildings, solar cells, personal thermal management systems, power plant condensers, and water collection systems. However, its large-scale practical application faces multiple challenges. Key constraints include optimizing material spectral emission characteristics, addressing complex manufacturing processes, and controlling high production costs. Research indicates that polydimethylsiloxane (PDMS) films exhibit exceptional transmittance in the visible spectrum and high emissivity within the "atmospheric window" wavelength range, making them particularly suitable for radiation cooling applications. Detailed information regarding material refractive indices and other specifications can be found on specialized technical websites.

Building on this foundation, we initiated a research project titled "Ice Blanket: Design and Optimization of Cold Storage Systems for Polar Regions," aiming to explore innovative applications of radiative cooling technology in polar ice storage. We proposed a novel concept of "covering" ice with advanced insulation layers using extruded polystyrene boards. These layers not only effectively block external heat infiltration but also enhance radiation reflection and scattering through optimized structural design, thereby reducing heat absorption by ice. Integrated with intelligent temperature control systems, the project monitors real-time ice temperature fluctuations and automatically adjusts cold water circulation rates and insulation performance based on environmental factors like ambient temperature and solar radiation intensity. This approach minimizes energy loss during seasonal ice storage. Through modeling and optimization studies of radiative cooling in polar ice storage, we aim to provide groundbreaking solutions for efficient utilization of winter resources, promote deeper societal understanding of northern regions' valuable "ice and snow" assets, and achieve a win-win balance between ecological preservation and economic benefits.

5.1. Project Research Content and Implementation Plan

This study aims to integrate innovative thermal insulation materials with a chilled water circulation system, building upon existing ice storage methodologies. Using COMSOL as the simulation tool, we conducted experiments under summer high-temperature conditions to model three scenarios: natural ice melting, PDMS film application, and PDMS film embedded water circulation. By comparing these melting patterns, we evaluated the enhanced thermal insulation performance of the system. After comprehensive analysis of thermal efficiency and economic factors, we identified an optimized PDMS film configuration that reduces ice loss rates compared to conventional methods, and implemented this solution in practical applications.

The main research contents are as follows:

5.1.1. Research Content 1

This study simulates the natural melting process of ice blocks placed outdoors, accounting for factors such as solar radiation, convection, phase change, and laminar flow. The experiment involves a large ice block measuring 8m in length, 6m in width, and 4m in height, which is stacked and placed in a wind-swept outdoor environment at 27°C for 10 days. The temperature distribution of the ice block is then analyzed using COMSOL to visually demonstrate its melting progress.

5.1.2. Research Content 2

Using software to simulate the melting process of ice blocks after adding PDMS film on the surface, obtaining the corresponding temperature change graph, then trying to change the material and thickness of the insulation layer, through multiple simulations and comparing the results, selecting the more suitable radiation cooling technology and matching mode.

5.1.3. Project Implementation Plan

5.1.3.1. For Research Content 1

In the simulation process, we modeled summer ice storage conditions with geometric parameters of 8 m width, 6 m depth, and 4 m height. The ice blocks were initially maintained at -10°C, with a 0.02-meter-thick water layer added above to simulate surface water adsorption. The daily average maximum temperature was set at 27°C. After 10 days of exposure to this experimental environment, we monitored temperature fluctuations and phase transitions in the study subjects. The natural ice loss rate under these conditions was established as the control group for comparison.

5.1.3.2. For Research Content 2

In Research Content 1, insulation materials with a thickness of 0.10m were added to the surfaces of the research objects. Currently, the most effective and commonly used insulation materials include extruded polystyrene boards (XPS), polydimethylsiloxane (PDMS), rubber-plastic insulation materials, and rock wool. Among these, PDMS is not restricted by regional temperatures, as it can be foamed and applied in both high and low temperatures, maintaining excellent performance even at -32°C [1]. Comparative studies revealed that PDMS and XPS have lower thermal conductivity and superior performance, leading to their preliminary selection. However, when exposed to prolonged low-temperature environments, PDMS demonstrates a compressive strength of 0.16 MPa, while XPS has a compressive strength of 0.51 MPa [2]. Comparative analysis showed that XPS exhibits better compressive resistance in low-temperature conditions. To validate this data, we conducted COMSOL simulations by placing both insulation materials on ice blocks of the same size as those used in Research Content 1. After ten days of outdoor exposure, we

obtained cross-sectional temperature maps to compare and select the superior material.

5.2. Progress of Project Implementation and Initial Innovation Achievements

5.2.1. Innovative Product: Establishment of Mathematical Model

We employed COMSOL for modeling, utilizing deformation geometry, solid-liquid heat transfer, solid heat transfer, laminar flow, and surface-to-surface radiation physical field interfaces to simulate convective and radiative heat transfer of ice blocks in outdoor environments. For convective heat transfer, we investigated primary modes including thermal convection and radiation, with heat input from air sources calculated using convective heat transfer formulas:

$$\rho C_p \frac{\partial T_2}{\partial t} + \rho C_p u \cdot \nabla T_2 + \nabla \cdot q = Q + Q_{ted} \quad (14)$$

$$q = -k\nabla T_2 \quad (15)$$

Among them:

ρ indicates the fluid's density (kg/m³); C_p indicates the constant pressure specific heat capacity of the fluid (J/(kg·K)); T represents the temperature field (in Kelvin); u denotes the velocity field of the fluid (m/s); ∇T indicates temperature gradient (K/m); q denotes the heat flux density vector (W/m²); k is the thermal conductivity (W/(m·K)); Q represents the volumetric heat source (W/m³); Q_{ted} indicates additional heat source term (W/m³).

The convective coefficient in forced convection is usually calculated by Newton's cooling law:

$$q = h \cdot A \cdot (T_s - T_f) \quad (16)$$

Among them:

q is the heat flux (W); h is the convective coefficient (W/m²·K); A is the heat transfer area (m²)

T_s is the surface temperature (K); T_f is the fluid temperature (K); After calculation, we selected $h = 10W/(m^2 \cdot K)$.

The heat transfer of solar radiation to the top surface of the ice block was calculated by the formula of thermal radiation:

$$J_i = \varepsilon f_{ob}(T) FEP_i(T) + \rho_d G_i^2 \quad (17)$$

Among them:

J_i represents the thermal radiation flux density (W/m²); ε indicates emissivity; $f_{ob}(T)$ denotes a function of temperature T (W/m²); $FEP_i(T)$ is a function representing a radiation effect or energy distribution related to temperature T (W/m²); ρ_d indicates density (kg/m³); G_i indicates the radiation intensity gradient (W/m³).

$$J = \varepsilon\sigma T^4 - (1 - \varepsilon)G \quad (18)$$

Where:

G is the amount density of external radiation received by the object surface; σ is the Stefan-Boltzmann constant; T is the absolute temperature in Kelvin

5.2.2. Analysis of the Simulation Results of Ice Melting

Through COMSOL simulation, we visualized the natural melting process of the ice block and obtained a cross-sectional temperature map of the ice block after being placed outdoors for ten days in summer, reflecting its temperature changes. Temperature distribution of the ice block surface at 10 days is shown in figure 1.

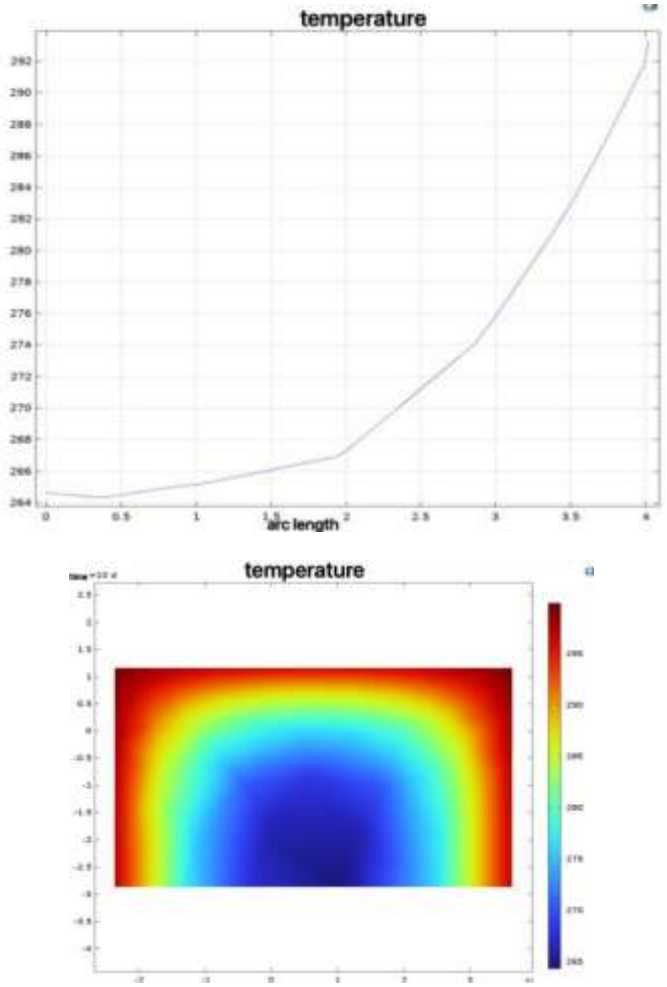


Figure 1: Temperature distribution of the ice block surface at 10 days

The melting temperature distribution of the ice block is shown in the figure. The melting of the ice block is a slow and gradual process.

5.2.3. Design of PDMS for Radiative Cooling

COMSOL modeling revealed the melting patterns of ice blocks with PDMS (polydimethylsiloxane) coatings and extruded boards, with PDMS demonstrating superior thermal insulation compared to the boards. PDMS is recognized as the most advanced anti-corrosion and thermal insulation material globally, offering unmatched dual advantages (corrosion resistance and thermal insulation). Consequently, PDMS will be the primary material in subsequent experiments. Temperature distribution across the ice surface coated with polydimethylsiloxane is shown in figure 2.

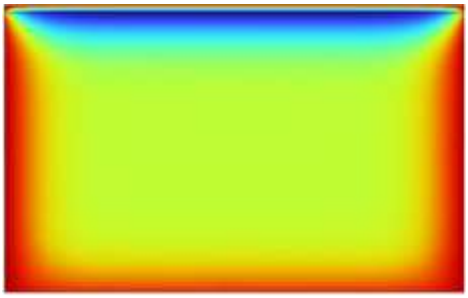


Figure 2: Temperature distribution across the ice surface coated with polydimethylsiloxane

However, given that rigid polydimethylsiloxane (PDMS) is nearly three times more expensive than extruded polystyrene boards, and that the latter's higher air resistance factor effectively prevents moisture infiltration—thereby avoiding increased thermal conductivity and reduced insulation performance—we opted to combine PDMS with extruded boards. Since extruded boards exhibit greater compressive strength than PDMS, we conducted data comparisons and positioned the boards beneath the PDMS foam layer, with both materials set at 5cm thickness. Cross-sectional analysis of the ice melting process revealed that this configuration offered superior cost-effectiveness. Temperature distribution across the ice surface is shown in figure 3.

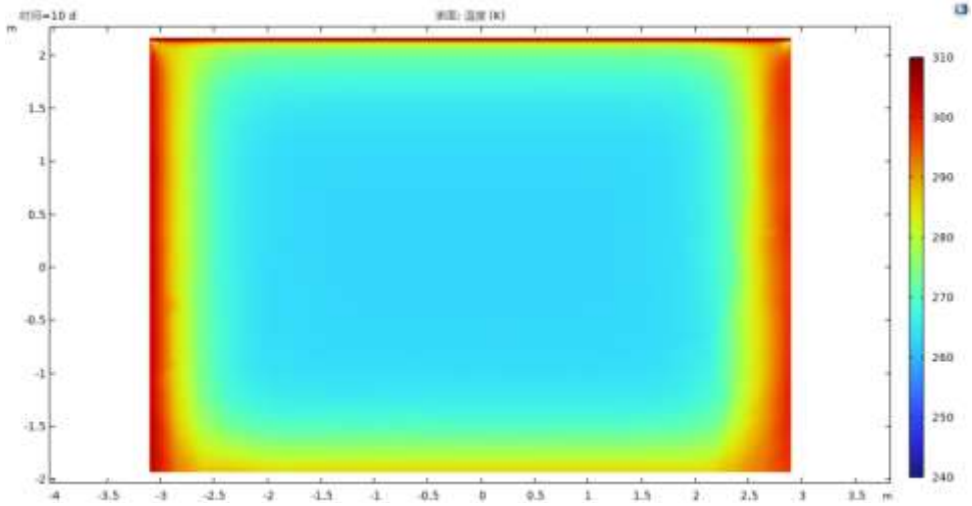


Figure 3: Temperature distribution across the ice surface

6. Conclusions

This study successfully established a mathematical model describing the variation of PDMS film emissivity with wavelength and thickness. Based on Kirchhoff's law and thin-film optics theory, the model employs the transfer matrix method to calculate reflectance and transmittance for determining emissivity. Building upon this foundation, a radiation cooling performance evaluation model grounded in energy balance theory was constructed, accurately quantifying the influence of film thickness on net cooling power. Numerical simulations reveal that the emissivity of PDMS films within the “atmospheric transparent window” oscillates with thickness before stabilizing, remaining constant between 0.92 and 0.95 in the thick-film regime (>20 μm). The core conclusion indicates that the 10–20 μm thickness range represents the optimal choice for PDMS films, achieving net cooling power exceeding 90 W/m² while balancing performance and cost advantages. Furthermore, this study applies radiative cooling technology to polar ice storage projects, proposing a composite approach combining PDMS foam layers with XPS extruded polystyrene boards to enhance thermal insulation efficiency.

net cooling power while balancing performance and cost advantages. Furthermore, this study applied radiative cooling technology to polar ice storage projects, proposing a composite structure design combining PDMS foam layers with XPS extruded polystyrene boards to enhance thermal insulation. This approach was found to offer superior cost-effectiveness.

Although this study successfully established a theoretical model and determined the optimal thickness range, limitations remain in model validation and generalization. Model accuracy relies on experimental calibration of

parameters, such as UV-Vis-IR spectroscopy measurements of reflectance/transmittance spectra for PDMS films of varying thicknesses to fit refractive index parameters. A dedicated radiative cooling test platform is also required to calibrate convective heat transfer coefficients and atmospheric radiation parameters. Furthermore, the model necessitates scattering correction terms to account for influencing factors like surface roughness that may exist in practical film applications.

Looking ahead, the industrialization of radiative cooling technology requires multidimensional advancement: In material optimization, composite modifications—such as incorporating nanoparticles or micro/nano structures—should further reduce solar absorption rates (targeted below 3%) while introducing hydrophobic groups to withstand humid environments. Regarding fabrication processes, continuous production methods like roll-to-roll spin coating/cast coating should be promoted to reduce unit area costs. A recycling system for PDMS films should be established to minimize lifecycle costs. For application expansion, PDMS films should be precisely matched to building energy efficiency (applied to architectural glass or external insulation materials) and new energy sectors (applied to solar cell cooling) to maximize energy benefits. Ultimately, by establishing performance evaluation standards and implementing policy support, radiative cooling technology holds promise for large-scale adoption, emerging as a key technology for driving energy structure transformation and addressing climate change.

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