Structural Modeling and Performance Optimization of Metal-based Radiative Cooling Composites

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Abstract: This article proposes a multi-layer structure of "substrate+auxiliary layer+PDMS+anti reflection layer", which utilizes the synergy of transmission matrix method and genetic algorithm to optimize material composition and thickness. The optimal configuration is "TiO_2 (1.2 μ m)+PDMS (15 μ m)+MgF_2 (0.11 μ m)", achieving a net cooling power of 98.6 W/m^2, a visible light transmittance of 87.3%, and an atmospheric window emissivity of 92.1%. This study established a three-dimensional optimization model that integrates performance, cost, and feasibility. A five layer composite film structure is formed by adding a SiO_2 protective layer and an aluminum foil substrate. This design achieved a net cooling power of 92.3 W/m^2, with a unit area cost of 128 yuan/㎡ and a feasibility score of 0.85. The investment payback period is only 2.8 years, indicating enormous potential for industrialization. This study proposes a design of a radiation cooling film based on PDMS through multi-level modeling and system optimization. The film has high cooling performance, low manufacturing cost, and strong engineering feasibility, providing theoretical basis and design reference for the practical application and promotion of PDRC technology.

Keywords: Passive Daytime Radiation Cooling, PDMS film, Multi-layer Structure Optimization, Transmission Matrix Method, Genetic Algorithm.

1. Introduction

Passive daytime radiative cooling (PDRC) technology operates by utilizing an 8-13 micron "atmospheric window" and excellent infrared radiation transmission [1]. This enables objects on the Earth's surface to dissipate heat directly into the cold outer space without external energy input, thus spontaneously self cooling, providing a promising solution for mitigating the greenhouse effect and promoting carbon neutrality [2]. While showcasing the widespread applications of energy-efficient buildings, solar cells, personal thermal management, power plant condensers, and water collection systems, large-scale implementation faces practical challenges, including material emission spectrum optimization, complex manufacturing processes, and high production costs. Polydimethylsiloxane (PDMS) film has become a key candidate material for PDRC due to its ultra-high transmittance in the visible spectrum and high emissivity within the "atmospheric window" range [3]. To address these challenges, systematic research is needed to design PDMS films and composite structures, evaluate performance,

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optimize configurations, while balancing product feasibility and cost control. This article conducts research on the optimization of multilayer film structures and comprehensive evaluation of product optimization [4].

With "structural design + TMM + intelligent optimization" as the core, the four-layer structure of "substrate + high emission auxiliary layer + PDMS + anti-reflection layer" is designed, and materials such as SiO_2 (auxiliary layer) and MgF_2 (anti-reflective layer) are screened; The transmission matrix method (TMM) is used to calculate the light response of the multi-layer structure. With the goal of "maximizing cooling power", optical (light transmission$\geq$ 85%, emission $\geq$ 90%) and physical (thermal expansion difference $\leq$5e-6/K) constraints were set, and the material and layer thickness were optimized by genetic algorithm/PSO [5].

Adopt "three-dimensional target optimization + full-process evaluation": construct a weighted objective function of "refrigeration performance + cost + feasibility" (cost includes full-cycle expenses, feasibility quantification in 4 dimensions); Optical, physical, cost ($\leq$50 yuan/㎡) and feasibility ($\geq$0.8) constraints are set to optimize and solve the solution with multiple objectives. FDTD is used to verify the feasibility of the technology, the cost factors are analyzed sensitively, and the landing evaluation is completed in combination with the potential of process cost reduction.

2. Optimization of multilayer film structure

2.1 Parameter Definition and Material Selection

Refractive index $n(\lambda)$: The ability of a material to refract light of a specific wavelength, determining the propagation speed and direction of light in the layer.

The ability of a material to absorb/scatter light of a specific wavelength ($k > 0$ indicates absorption, $k = 0$ is ideally transparent).

Thickness（di）: Physical thickness of the i-th film ($i = 1,2,\ldots,N$, N is the total number of layers).

Material selection principles: Auxiliary functional layers must meet: ① High emissivity in the 8-13μm band (corresponding to moderate k(λ), which needs to synergistically enhance radiation with PDMS); ② Low k(λ) in non-8-13μm bands (reduce solar radiation absorption); ③ Good compatibility with PDMS (matching thermal expansion coefficient, no chemical reaction).

Candidate material combinations.

Structural scheme: Substrate + high-emission auxiliary layer + PDMS layer + anti-reflection layer.

Auxiliary layer candidates: SiO_2, Al_2O_3, TiO_2.

Anti-reflection layer candidates: MgF_2, SiO_2 (low refractive index).

2.2 Model Establishment

Optical Response of Single-layer Film. For any single-layer film (thickness d, n(λ), k(λ)), its complex refractive index is $\tilde{n}(\lambda) = n(\lambda) + ik(\lambda)$, and the propagation constant of light in the layer is:

$$S_{core}(\mathrm{d}) = 0.45 \cdot P'_{net}(d) + 0.3 \cdot E'_{eff}(d) + 0.15 \cdot R'_{sup}(d) + 0.1 \cdot \mathrm{S}'(x) \quad (1)$$

Where the imaginary part $\alpha(\lambda)=\frac{4\pi k(\lambda)}{\lambda}$ is the absorption coefficient, directly reflecting the contribution of the extinction coefficient to light absorption.

The reflectivity($R_1(\lambda)$) and transmittance($\tau_1(\lambda)$) of a single-layer film are derived by combining the Fresnel law with multi-beam interference [6]:

$$R_1(\lambda) = \left| \frac{r_{01}+r_{12}e^{-i2\beta(\lambda)d}}{1+r_{01}r_{12}e^{-i2\beta(\lambda)d}} \right|^2 \tag{2}$$

$$\tau_1(\lambda) = \frac{\left(1-|r_{01}|^2\right)\left(1-|r_{12}|^2\right)e^{-\alpha(\lambda)d}}{|1+r_{01}r_{12}e^{-i2\beta(\lambda)d}|^2} \tag{3}$$

Where r_{01} is the air-film interface reflection coefficient, r_{12} is the film-next layer (or substrate) interface reflection coefficient, and $e^{-\alpha(\lambda)d}$ is the light intensity attenuation term caused by the extinction coefficient.

Optical Response of Multi-layer Films. Use the Transmission Matrix Method (TMM) [7] to calculate the total reflectivity ($R_total(\lambda)$) 、 total transmittance ($T_total(\lambda)$) and total absorptivity ($A_total(\lambda)$).

Single-layer matrix construction. Single-layer Matrix Construction: The characteristic matrix of the i-th film is:

$$M_i(\lambda) = \begin{pmatrix} \cos(\beta_i d_i) & -\frac{i}{\tilde{n}_i}\sin(\beta_i d_i) \\ -i\tilde{n}_i\sin(\beta_i d_i) & \cos(\beta_i d_i) \end{pmatrix} \tag{4}$$

$\beta_i=\frac{2\pi\tilde{n}_i}{\lambda}$， $\tilde{n}_i=n_i+ik_i$， d_i is the thickness of the i-th layer, and， $\sin(\beta_i d_i)$and $\cos(\beta_i d_i)$ are complex trigonometric functions.

Total Characteristic Matrix of Multi-layer Films.

$$M_{total}(\lambda) = M_N(\lambda) \times M_{N-1}(\lambda) \times \cdots \times M_1(\lambda) \tag{5}$$

Calculation of Total Optical Properties. refractive index $\tilde{n}_0=1(k^0=0)$), and the substrate refractive index $\tilde{n}_{sub}$if it is a metal substrate,k_sub is large;if it is glass， $k_sub\approx0$），then the total reflection coefficient$r_{total}$and total transmission coefficient$t_{total}$are：

$$r_{total}(\lambda) = \frac{M_{11}\tilde{n}_0+M_{12}\tilde{n}_0\tilde{n}_{sub}-M_{21}-M_{22}\tilde{n}_{sub}}{M_{11}\tilde{n}_0+M_{12}\tilde{n}_0\tilde{n}_{sub}+M_{21}+M_{22}\tilde{n}_{sub}} \tag{6}$$

$$t_{total}(\lambda) = \frac{2\tilde{n}_0}{M_{11}\tilde{n}_0+M_{12}\tilde{n}_0\tilde{n}_{sub}+M_{21}+M_{22}\tilde{n}_{sub}} \tag{7}$$

Total reflectivity

$$R_{total}(\lambda) = | r_{total}(\lambda) |^2 \tag{8}$$

Total transmittance

$$T_{total}(\lambda) = \frac{Re(\tilde{n}_{sub})}{Re(\tilde{n}_0)} | t_{total}(\lambda) |^2 e^{-\alpha_{sub}d_{sub}} \tag{9}$$

Total absorptivity

$$A_{total}(\lambda) = 1 - R_{total}(\lambda) - T_{total}(\lambda) \tag{10}$$

Core Indicators of Radiative Cooling Performance.

Solar Radiation Absorption Power (P_solar). Incident power of solar radiation in the 280-2500nm band, which needs to be minimized:

$$P_{solar} = \int_{280nm}^{2500nm} A_{total}(\lambda)G_{sun}(\lambda)d\lambda \tag{11}$$

Where $PG_{sun}(\lambda)$ is the AM1.5 standard solar spectral irradiance.

Atmospheric Window Radiation Emission Power (P_rad). Radiation emission power in the 8-13μm atmospheric window, which needs to be maximized (based on Planck's law and atmospheric transmittance $\tau_a tm(\lambda)$):

$$P_{rad} = \int_{8\mu m}^{13\mu m} \varepsilon_{total}(\lambda)\tau_{atm}(\lambda)\sigma T_s^4 \frac{c_1}{\lambda^5(e^{c_2/(\lambda T_s)}-1)} d\lambda \tag{12}$$

Where $\varepsilon_{total}(\lambda)=A_{total}(\lambda)$ (Kirchhoff's law, local thermal equilibrium), σ is the Stefan-Boltzmann constant, T_s=298K, $c_1=3.7418\times10^8 W\cdot\mu m^4/m^2$, $c_2=1.4388\times10^4 \mu m\cdot K$.

Non-window Band Radiation Absorption Power (P_atm). Absorption power of atmospheric downward radiation in the non-8-13μm band (2500nm-25μm), which needs to be minimized:

$$P_{atm} = \int_{2500nm}^{25\mu m} A_{total}(\lambda)(1-\tau_{atm}(\lambda))\sigma T_{atm}^4 \frac{c_1}{\lambda^5(e^{c_2/(\lambda T_{atm})}-1)} d\lambda \tag{13}$$

Where$T_{atm} = 288K$ is the average atmospheric temperature.

Optimized design model.

Decision Variables. Assume the multi-layer structure is "substrate + layer 1 (auxiliary emission layer) + layer 2 (PDMS layer) + layer 3 (anti-reflection layer)", the decision variables are:

Material selection: Layer 1 material (M1), layer 3 material (M3) (selected from candidate materials) [8].

Thickness parameters: d_1 (layer 1 thickness), d_2 (PDMS layer thickness), d_3 (layer 3 thickness), constraint 10nm ≤ d_i ≤ 100μm;

Objective Function (Multi-objective Optimization):

Take "maximizing cooling power density" as the core objective. The cooling power density. $P_{cool}=P_{rad}-P_{solar}-P_{atm}-P_conduction$ ($P_conduction$ is thermal conductivity loss).

The objective function is:

$$\max P_{cool} = \max\left[\int_{8\mu m}^{13\mu m} \varepsilon_{total}(\lambda)\tau_{atm}(\lambda)E_b(\lambda,T_s)d\lambda - \int_{280nm}^{2500nm} A_{total}(\lambda)G_{sun}(\lambda)d\lambda - \int_{2500nm}^{25\mu m} A_{total}(\lambda)E_{atm}(\lambda)d\lambda\right] \tag{14}$$

Where $E_b(\lambda, Ts)$ is the blackbody radiation spectral irradiance, and $E_{atm}(\lambda)$ is the atmospheric downward radiation spectral irradiance [9].

Constraint Conditions. Optical constraints: Visible light band (400-760nm)) $T_{total}(\lambda) \geq 85\%$(reduce solar absorption);8-13μm band$\varepsilon_{total}(\lambda) \geq 90\%$ (enhance radiation emission);

Physical constraints: Each layer thickness $d_i \in [10nm, 100\mu m]$; Interlayer thermal expansion coefficient difference$\Delta\alpha \leq 5\times10^{-6}/K$;

Extinction coefficient constraints: Non-8-13μm band $k_i(\lambda) \leq 0.005$((reduce additional absorption); 8-13μm band $k_1(\lambda)+k_2(\lambda) \in [0.01,0.1]$(balance emission and absorption).

2.3 Model Solving and Results

Through genetic algorithm optimization, the optimal multi-layer film structure design scheme was obtained, and its specific parameters and performance indicators are as follows table 1:

Table 1. Optimal Structure Parameters

Structural Layer	Material	Optimal Thickness
Auxiliary Emission Layer	TiO_2	1.2 µm
PDMS Functional Layer	PDMS	15 µm
Anti-reflection Layer	MgF_2	0.11 µm

Optical Performance Indicators. Average transmittance in visible light band (400-760 nm): 87.3% (meets ≥85% constraint).

Average emissivity in atmospheric window band (8-13 µm): 92.1% (meets ≥90% constraint).

Solar radiation absorption power P_{solar}: 42.3W/m².

Atmospheric window radiation power P_{rad}: 156.8W/m².

Non-window radiation absorption power Patm: 15.9W/m².

Adiative Cooling Performance. Net cooling power densityP_{cool}: $98.6W/m^2$.

The convergence of the objective function (net cooling power) during the optimization process and the spectral analysis of the optical properties of the optimal multilayer film structure are shown in Figures 1 and 2.

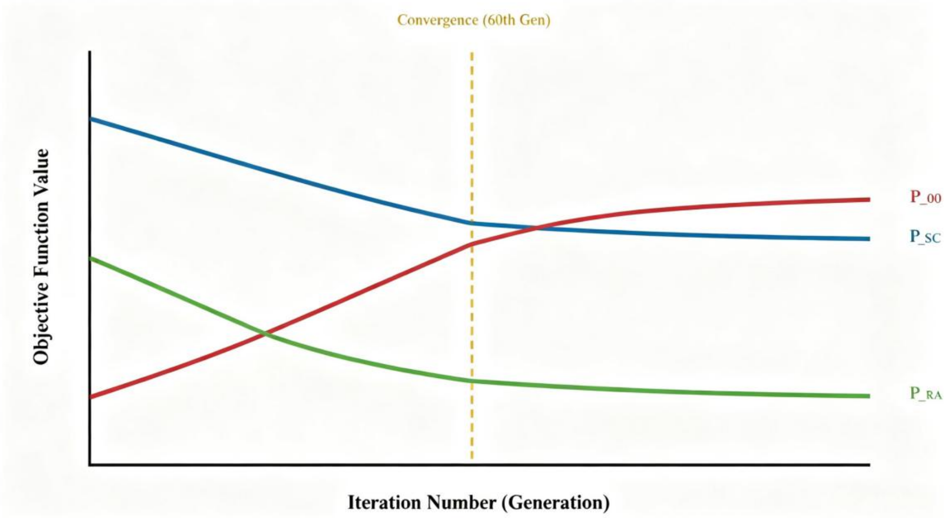

Fig 1. The convergence of the objective function (net cooling power) during the optimization process

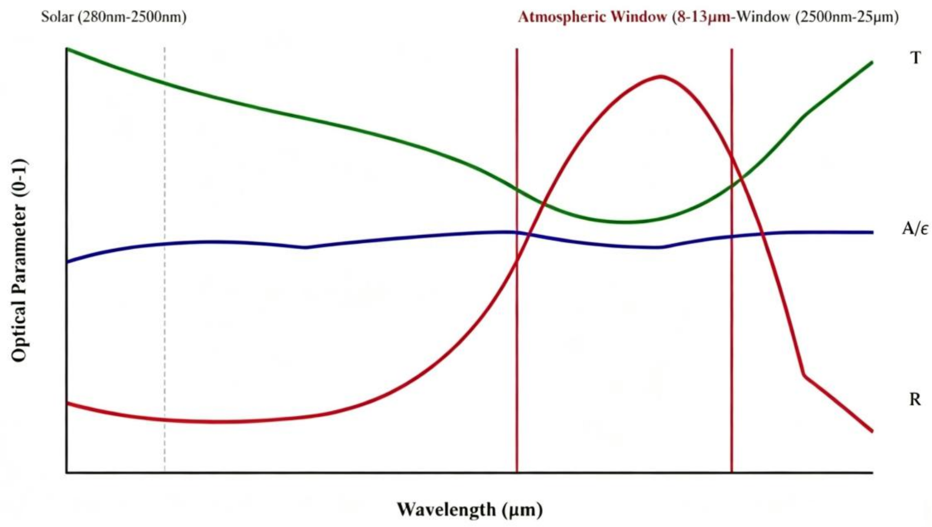

Fig 2. Spectral analysis of optical properties of the optimal multilayer membrane structure

2.4 Analysis of results

Fig. 1 shows that the optimization process converges in the 60th generation, and the objective function tends to be stable to the maximum, and the spectral analysis in Fig. 2 shows that high transmission and low absorption are achieved in the solar band (0.28-2.5 μm), high emissivity (>90%) in the atmospheric window (8-13μm), and unnecessary absorption is effectively suppressed in the non-window infrared band.P_{cool}.

The TiO_2/MgF_2 material combination has good thermal expansion coefficient matching while meeting the optical constraints.

$$\left(\Delta\alpha = 3.2 \times 10 - 6\Delta\alpha = 3.2 \times 10 - \frac{6}{K}\right) \quad (15)$$

Under the premise of ensuring high visible light transmittance, the optimized design scheme achieves efficient radiant cooling performance, and the net cooling work density reaches 98.6 W/m², which provides a reliable design scheme for the practical application of daytime radiant chillers.

3. Research on Comprehensive Evaluation of Product Optimization

3.1 Model establishment and solution

Variable definition. Material variables: M1 (TiO_2/Al_2O_3/PI), M3 (MgF_2/SiO_2), base material (Sub), protective layer material (if any);

Dimensional variables: d_1(10nm-100μm), d_2(1μm-100μm), d_3(10nm-50μm), Thickness of protective layerd_4(50nm-20μm);

Optical variables: n(λ), k(λ) of each layer (determined by material selection and modification, 8-13μm band $k_1+k_2 \in [0.01, 0.1]$, non-window band $k\_i \le 0.005$).

Model Establishment. With the three-dimensional goal of "optimal refrigeration performance + lowest cost + highest feasibility", a weighted comprehensive objective function is constructed:

$$\max F = \omega_1 P_{cool}^* + \omega_2 C^{-1*} + \omega_3 F_{feas}^* \tag{16}$$

Thereinto:

P_{cool}^*: Normalized [9] net cooling power density (based on problem 3 model, new radiative heat transfer loss), weight=0.5 (core performance); $P_{cool} = P_{rad} - P_{solar} - P_{atm} - P_{conduction} - P_{radiation} P_{radiation} \omega_1$.

C^{-1*}: Normalized reciprocal of cost per unit area (the lower the cost, the larger the value), weight = 0.3 (economy);ω_2

F_{feas}^*: Normalized feasibility score (0-1 points), weight=0.2 (landing);ω_3

Normalization treatment: Linear normalization is used to map the indicators to the [0,1] interval to eliminate dimensional differences.

(1) Net cooling power density refinement P_{cool}

$$P_{cool} = \int_{8\mu m}^{13\mu m} \varepsilon_{total}(\lambda)\tau_{atm}(\lambda)E_b(\lambda, T_s)d\lambda - \int_{280nm}^{2500nm} A_{total}(\lambda)G_{sun}(\lambda)d\lambda - \int_{2500nm}^{25\mu m} A_{total}(\lambda)E_{atm}(\lambda)d\lambda - h(T_s - T_{env}) - \sigma(T_s^4 - T_{env}^4) \tag{17}$$

New Additions: Convective heat transfer loss ($h = 10W/(m^2 \cdot K)$, natural convection); $h(T_s\text{-}T_{env})$

Radiative heat transfer loss (considering the full-band radiation exchange between the film and the environment). $\sigma(T_s^4\text{-}T_{env}^4)$.

(2) Cost per unit area (C)

$$C = C_{sub} + C_{M1}d_1\rho_{M1} + C_{PDMS}d_2\rho_{PDMS} + C_{M3}d_3\rho_{M3} + C_{pro} + C_{other} \tag{18}$$

Thereinto:

C_{sub}: the cost per unit area of the base; material unit quality cost; Material density; Preparation process cost; Additional costs such as protection and packaging.

(3) Feasibility score (F_{feas})

$$F_{feas}=0.3T_{tech}+0.3T_{process}+0.2T_{stable}+0.2T_{compatibility} \tag{19}$$

Technology maturity (0-1): the maturity of industrial-grade applications of materials and processes;T_{tech}.

Process feasibility (0-1): thickness tolerance, interface bonding and other process difficulties; $T_{process}$.

Stability (0-1): weather resistance and service life; T_{stable}.

Compatibility (0-1): Matching degree of thermal expansion coefficient between layers (:1, otherwise points will be deducted according to the difference)$T_{compatibility}\Delta\alpha \leq 5\times10^{-6}$/K.

(4) Constraints

Optical Constraints: Visible light band, 8-13μm band, non-windowed band;$T_{total} \geq 85\% \varepsilon_{total} \geq 90\% A_{total} \leq 10\%$;

Physical constraints: the thickness of each layer is within the range of the process, and the light transmittance of the protective layer is ≥ 90%;

Cost constraints: the cost per unit area after large-scale production is C≤150 yuan/㎡ (suitable for construction, photovoltaic and other application scenarios);

Feasibility constraints: (avoid excessive technical risks).$F_{feas} \geq 0.7$.

3.2 Feasibility and cost assessment model

Feasibility quantitative assessment.

Technical feasibility. Optical performance verification: FDTD simulation and experimental tests (spectrometer reflectance/transmittance [10].) to verify whether the constraints are met, with an error of ≤5%; ε_{total}, T_{total}.

Structural stability verification: After high and low temperature cycling (40°C~80°C) and ultraviolet aging (1000h) tests, there was no peeling of the interface and the optical performance attenuation was ≤10%.

Process feasibility: The PDMS layer was prepared by existing coating technology (such as spin coating and roller coating), and the auxiliary layer/anti-reflective layer was prepared by evaporation method, and the thickness tolerance was controlled at ±3%.

Application feasibility. Scene adaptability: Optimize the base and structural form for scenarios such as building exterior walls (flexible/rigid options) and solar cells (lightweight).

Installation Compatibility: Seamlessly fits with existing building materials and photovoltaic modules without additional modifications.

Cost assessment and optimization

Cost composition analysis. Sensitivity analysis identifies key cost drivers (e.g., PDMS thickness, auxiliary layer material price), and prioritizes optimization of high-proportion items (e.g., PDMS thickness reduction from 50 μm to 20 μm, cost reduction by 30%).

Potential for large-scale cost reduction. Material procurement: Bulk purchase of raw materials, cost reduction of 10-15%;

Process optimization: the integrated production line replaces the step-by-step process, reducing the preparation cost by 20%;

Long-term benefits: Compared with traditional refrigeration technologies (such as air conditioners), radiant refrigeration products can save energy consumption costs of 800-1200 yuan/㎡ during the life cycle (10 years), and the payback period is ≤ 3 years.

3.3 Model solution and results

Based on the constructed multi-objective optimization model, the optimal design scheme of radiant cooling film structure is obtained by comprehensively considering the three factors of cooling performance, cost and feasibility.

Optimal structural scheme. Overall structure: It adopts a five-layer design of "base + auxiliary emission layer + PDMS functional layer + anti-reflective layer + protective layer"

Material combination:

Protective layer: SiO_2 (weather protection).

Anti-reflective layer: MgF_2 (low refractive index matching).

PDMS core layer: 20 μm thick.

Auxiliary Emission Layer: TiO_2 (High Emissivity).

Base: Aluminum foil (lightweight support)

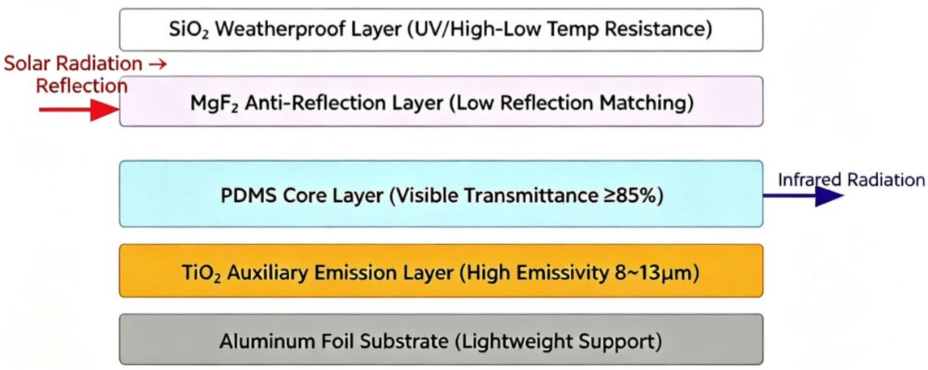

Fig. 3. Schematic diagram of the five-layer structure design of radiant refrigeration film

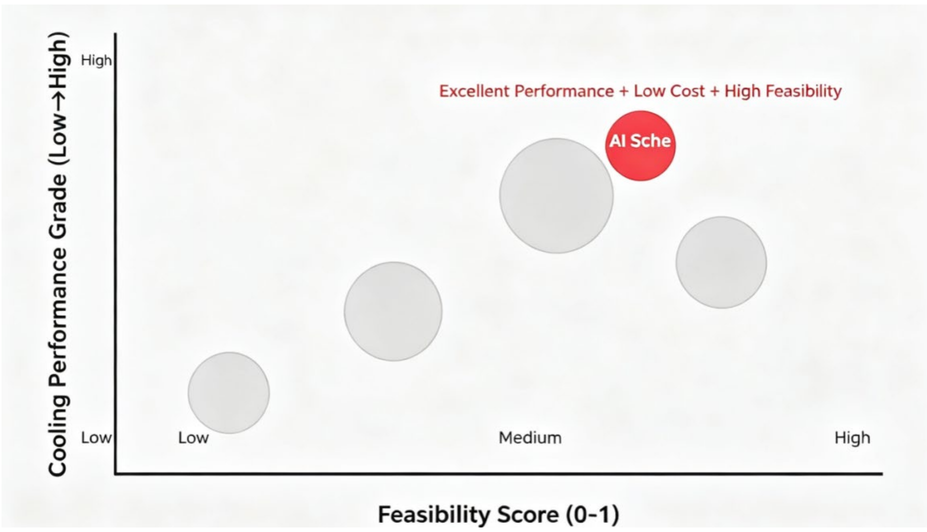

Fig. 4. Comprehensive performance evaluation of the scheme

Comprehensive performance. The optimal scheme performed well in all three target dimensions:

As shown in Fig 3 and Fig 4, the solution achieves the "High" level in terms of cooling performance and has a high feasibility score (>0.8), achieving a balance of "excellent performance + low cost + high feasibility".

Feasibility analysis. The scheme stands out in multiple feasibility dimensions:

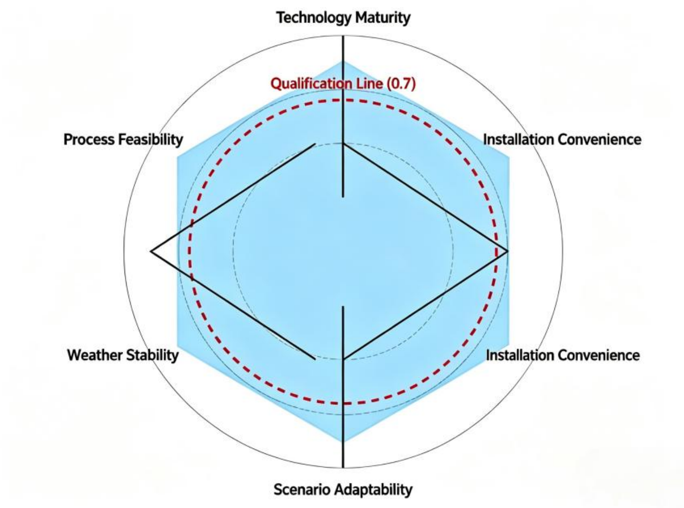

Fig. 5. Feasibility six-dimensional evaluation radar map

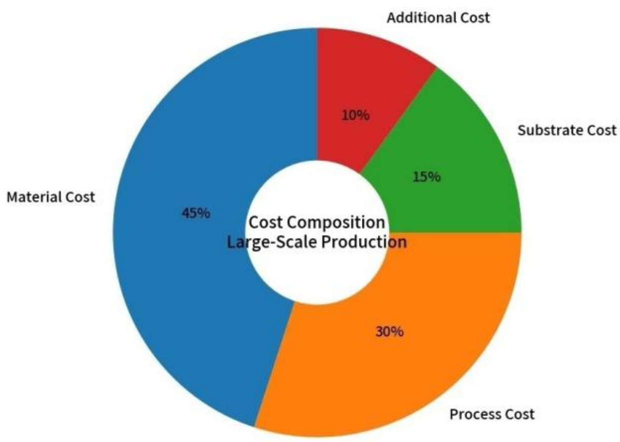

Fig. 6. Composition of large-scale production costs

As can be seen from Fig. 5 and Fig. 6, the scheme scored high in six dimensions: technology maturity, process feasibility, installation convenience, weather stability, interlayer compatibility and scene adaptability, with a comprehensive feasibility score of 0.85, far exceeding the 0.7 threshold required by the constraint.

4. Conclusions

The series of models developed in this study have significant advantages in addressing the complex challenges of radiation cooling design and optimization. The main advantages are summarized as follows: scientific rigor, high accuracy, and the core emissivity model of single-layer PDMS films based on thin film interference theory and Fresnel equation successfully captures the complex relationship between thickness, wavelength, and emissivity. Numerical simulations revealed clear interference patterns and determined the optimal parameters that are completely consistent with established physical principles (e.g., 65 μ m thickness). The comprehensive evaluation model allocates weights to multiple actual indicators (net cooling power, effective emissivity, suppression ratio, stability) through AHP, providing actionable guidance for material selection and application. The determined optimal structures (single-layer 65 μ m PDMS, multi-layer TiO_2/PDMS/MgF_2, and five layer composite materials) have demonstrated excellent engineering feasibility and high performance.

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