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PHYSICS-INFORMED SYNERGISTIC OPTIMIZATION OF PDMS-BASED RADIATIVE COOLING FILM FOR OPTICAL-THERMAL PERFORMANCE AND COST

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Abstract: Considering the passive thermal management of transportation infrastructures under high solar radiation during the daytime, optothermal coupling design on PDMS radiative cooling films is proposed. The radiative cooling potential of polymer, porous structure, fiber membrane systems, and other polymer membrane systems is proved in buildings, general outdoor surfaces and aerospace scenarios. Thickness optimization and collaborative design of multi-layer structures for transportation scenario are still not explored. In this paper, the transfer matrix method and steady state energy model combined with thickness dependent analysis and particle swarm multi- objective optimization algorithm are used to evaluate single layer and multi layer PDMS structure. Results show that under unified boundary conditions net cooling power of single layer PDMS film is 17.26 W/m2 at 49.5 μm thickness and 29.3 μm can be used as representative thickness for material use and performance. After constructing PDMS - dielectric - metal structure with particle swarm optimization, net cooling power of three layer structure increases to 56.38 W/m2.
Keywords: Passive Daytime Radiative Cooling (PDRC); Polydimethylsiloxane; Transfer matrix method; Particle swarm optimization; Transportation infrastructure; Pavement thermal management

1 INTRODUCTION

To address the problem that transportation infrastructure generates high thermal loads when high solar irradiance occurs during the day, we propose a PDMS passive daytime radiative cooling film for three possible applications: external protective layer of embedded pavement sensing modules, local surface of bridge monitoring components and outer shell of roadside signal or monitoring cabinets in non-load bearing cases. These facilities are usually exposed to continuous direct sunlight and generally lack active cooling capabilities, and have to operate stably in complex outdoors without human supervision. Therefore, low power maintenance-free film method is of practical use.

Passive daytime radiative cooling (PDRC) is a zero-energy thermal management technique, achieving cooling by the selectiveness of materials using spectral selectivity. Its goal is to maintain high reflectivity in the solar band and high emissivity in the 8-13 μm window, reducing solar radiation absorption surface and increasing heat dissipation to the window. Compared to conventional compression refrigeration methods, PDRC does not require additional energy consumption or refrigerant circulation and has become a major research direction in building energy conservation and outdoor thermal management recently [1-3]. Fiber membranes, porous polymers, silicon polymer hybrid metamaterials, coatings can regulate the reflectivity in the solar band and emissivity in the mid-infrared band and achieving daytime cooling effects [1-2, 4-6].

Similar research is conducted in the transportation field, which focuses more on temperature field simulation of asphalt pavements, ballastless track structures, design of heat-insulating pavements, and equipment ventilation and heat dissipation optimizations [7-10]. However, there is little research on radiative cooling materials in the transportation thermal management of transportation infrastructure. Already studies show that the temperature field of asphalt pavements is affected by solar radiation, wind speed and structural conditions [7]. Heat-insulating pavements and heat-reflective surfaces help reduce heat absorption of surface layer and improve thermal environment [8-9]. In railway engineering, sunlight and diurnal temperature differences can cause obvious temperature gradients in ballastless tracks which impact service performance and service life [10-11]. Therefore, if radiative cooling materials structure can be applied to surface thermal management of transportation infrastructure, it will provide a new cooler idea.

This paper constructs photo-thermal coupling for radiative cooling films made of polydimethylsiloxane (PDMS) and quantitatively analyzes the effect of the thickness of single layer PDMS on spectral emissivity and net cooling power. Combining transfer matrix method (TMM), steady state energy balance model and particle swarm optimization algorithm (PSO), a PDMS-dielectric-metal multilayer structure is designed and optimized. The thermodynamic benefit, thickness and cost are considered, engineering application value of the film on road surfaces, bridges and roadside equipment is discussed. This is a fundamental numerical design work and the conclusions are based on specific spectral data, uniform boundary conditions and simplified cost model to theoretical basis for experimental verification and engineering applications in transportation scenarios (Table 1 and Figure 1).

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Table 1 Main Symbols

Symbol	Description	Unit
$\varepsilon(\lambda)$	Spectral emissivity	-
$R(\lambda)$	Spectral reflectance	-
d_i	Film thickness of the i-th layer	μm
$\tilde{n} = n + i\kappa$	Complex refractive index	
P_{net}, P_{cool}	Net radiative cooling power	W/m^2
T_{eq}	Equilibrium temperature	K
T_{amb}	Ambient temperature	K
$I_{solar}(\lambda)$	Solar spectral irradiance	$W/(m^2 \cdot \mu m)$
$\tau_{atm}(\lambda)$	Atmospheric transmittance	-
$B(\lambda, T)$	Blackbody radiation flux (Planck's law)	$W/(m^2 \cdot \mu m)$
M_{total}	Total transfer matrix	-
δ	Phase shift	rad
θ	angle of incidence	rad
c_1, c_2	PSO Cognitive and Social Acceleration Coefficients	-
ω	PSO Inertia Weight	-
S	Comprehensive Evaluation Score	-
$J(x)$	PSO Objective Function	-

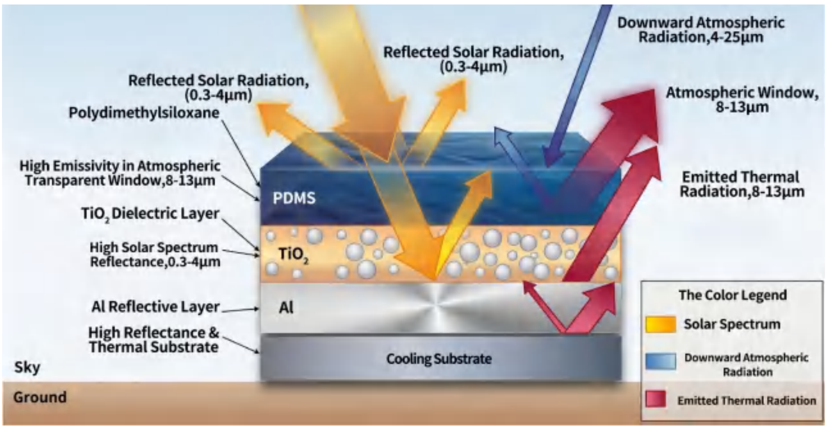


Figure 1 Schematic of PDMS Multilayer Radiative Cooling Film and Radiation Transfer Mechanism

2 MATERIALS AND METHODS

2.1 Input Parameters

The optical constants of PDMS, TiO2, Al, and related materials used in this study are all taken from the tabulated datasets used in this research. The PDMS data is based on the optical constant study by Zhang et al., while the TiO_2 and metal layers are represented by the wavelength - dependent complex refractive indices extracted from the literature. These datasets have been interpolated within the wavelength ranges required for solar band and thermal infrared calculations.

The boundary condition of daytime solar irradiance is taken from the ASTM G173 standard reference spectrum. The atmospheric radiative exchange in the thermal infrared region is characterized by the atmospheric transmittance data of the main atmospheric window band in the reference calculation. All the results reported in this paper correspond to the same reference dataset to ensure the direct comparability of the calculation results for single - layer and multi - layer cases (Table 2).

Table 2 Material Properties and Boundary Conditions Used in the Numerical Workflow

Materials/Inputs	Source	Role in the model
PDMS	Optical Constants of Zhang et al.	Radiation layer
TiO2	Optical constants of Siefke et al.	dielectric layer
Al	Rakic Optical Constants	Metal reflective layer
ASTM G173	Standard Solar Spectrum	Solar Irradiance Boundary
Atmospheric transmittance	Spectral data provided	Atmospheric Window Radiation Model

2.2 Transfer Matrix Model

To determine the spectral emissivity of PDMS-based thin films at different wavelengths, a transfer matrix model was established in this study. This model calculates the phase accumulation inside each layer of material and the reflection or transmission processes at adjacent interfaces, and represents them in matrix form. The optical response of the entire multilayer system is obtained by multiplying the matrices successively. Based on Kirchhoff's principle, the reflectance of the PDMS thin film is converted into emissivity.

To objectively evaluate the photothermal conversion limit of thin-film structures, calculations were carried out under the same wavelength range, thickness range, and incident conditions in this paper. The wavelength range for spectral calculation is 0.3 - 25.0 μm. The thickness range of the single-layer PDMS is 1.0–100.0 μm, and the default incident angle is taken as 30°. The dispersion characteristics of each layer of material in the model depend on its complex refractive index, and its expression is:

$$\tilde{n} = n + \mathrm{i}\kappa, \tag{1}$$

Among them, n represents the real part (refractive index), which determines the phase velocity; κ represents the imaginary part (extinction coefficient), which determines the absorption of light.

At the interface between two media i and j, the (Snell) coefficients of r and t depend on the polarization state of the incident light. For a light wave incident at an angle θ_i (measured relative to the normal), the incident angle θ_j can be obtained through the (Snell) law:

$$\tilde{n}_i \sin\theta_i = \tilde{n}_j \sin\theta_j \tag{2}$$

Among them, θ_i and θ_j are the propagation angles of the light wave in the i-th and the j-th layers, respectively.

For s-polarization (the electric field is perpendicular to the incident plane), the reflection coefficient and transmission coefficient are respectively:

$$r_s = \frac{n_i cos\theta_i - n_j cos\theta_j}{n_i cos\theta_i + n_j cos\theta_j}, \tag{3}$$

$$t_s = \frac{2n_i cos\theta_i}{n_i cos\theta_i + n_j cos\theta_j}, \tag{4}$$

For p-polarization (the electric field is parallel to the incident plane), the reflection coefficient and transmission coefficient are respectively:

$$r_p = \frac{n_j cos\theta_i - n_i cos\theta_j}{n_j cos\theta_i + n_i cos\theta_j}, \tag{5}$$

$$t_s = \frac{2n_i cos\theta_i}{n_j cos\theta_i + n_i cos\theta_j}, \tag{6}$$

The interface matrix between the i-th layer and the j-th layer is:

$$\boldsymbol{M}_{ij} = \frac{1}{t_{ij}}\begin{bmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{bmatrix}, \tag{7}$$

Among them, r_{ij} and t_{ij} are the Fresnel coefficients (Snell) corresponding to the polarization state respectively. The interface matrix $\boldsymbol{M}_{ij}$ describes the reflection and transmission of light waves on both sides of the interface.

When a light wave propagates through an isotropic layer with a thickness of d, the phase generated is:

$$\delta = \frac{2\pi}{\lambda}\tilde{n} d \cos\theta\,, \tag{8}$$

Among them, θ is the propagation angle within this layer.

The propagation matrix $\boldsymbol{L}$ is:

$$\boldsymbol{L} = \begin{bmatrix} e^{-\delta i} & 0 \\ 0 & e^{\delta i} \end{bmatrix}, \tag{9}$$

This propagation matrix reflects the phase change of the light wave during its propagation within a single-layer medium. Therefore, the film thickness directly affects the interference relationship between the reflected light and the transmitted light.

For the multi-layer structure, the interfaces include air, PDMS layer, dielectric layer, metal reflective layer, and cooling substrate. The total transfer matrix can be represented by the product of individual matrices:

$$\boldsymbol{M}_{total} = \boldsymbol{M}_{01} \cdot \boldsymbol{L} \cdot \boldsymbol{M}_{12} ... \boldsymbol{L_i} \cdot \boldsymbol{M}_i \cdot \boldsymbol{M}_{i+1}, \tag{10}$$

Among them, $\boldsymbol{M}_{01}$ is the interface matrix between the incident medium air and the PDMS layer, and so on.

Calculate the total reflection coefficient r of the structure based on each element of the total transmission matrix.

$$r = \frac{\boldsymbol{M}_{total}[1,0]}{\boldsymbol{M}_{total}[0,0]}, \tag{11}$$

The reflectance is $R = |r|^2$. Natural light can be approximately regarded as non-polarized incident light. Since the bottom metal reflective layer makes the transmittance of the structure approximately zero, the spectral emissivity is

$\varepsilon = 1 - R$. In this study, the emissivities under s - polarization and p - polarization conditions are calculated respectively:

$$\varepsilon_s = 1 - R_s \tag{12}$$

$$\varepsilon_p = 1 - R_p \tag{13}$$

The arithmetic mean of the two values is taken as the effective spectral emissivity.

$$\varepsilon_{unpolarized} = \frac{\varepsilon_s + \varepsilon_p}{2}, \tag{14}$$

It can also be equivalently written as

$$\varepsilon_{unpolarized} = 1 - \frac{\varepsilon_s + \varepsilon_p}{2}, \tag{15}$$

Among them, $\varepsilon_{unpolarized}$ is the average emissivity of unpolarized light.

As shown in Figure 2, the calculation process of the TMM is as follows: Input the complex refractive index of the material, film thickness, incident wavelength, and incident angle, establish a multi - layer model of air, PDMS layer, TiO2 dielectric layer, and metal reflective layer, and obtain the total transfer matrix by multiplying the interface matrix and the propagation matrix layer by layer. The transfer matrix method describes the reflection, transmission of light waves at the inter - layer interface and the phase accumulation process in the thin film, so as to calculate the spectral reflectance R of the structure, and then obtain the spectral emissivity $\varepsilon_{unpolarized}$. This result is used as the input for the subsequent steady-state energy model to calculate the net cooling power.

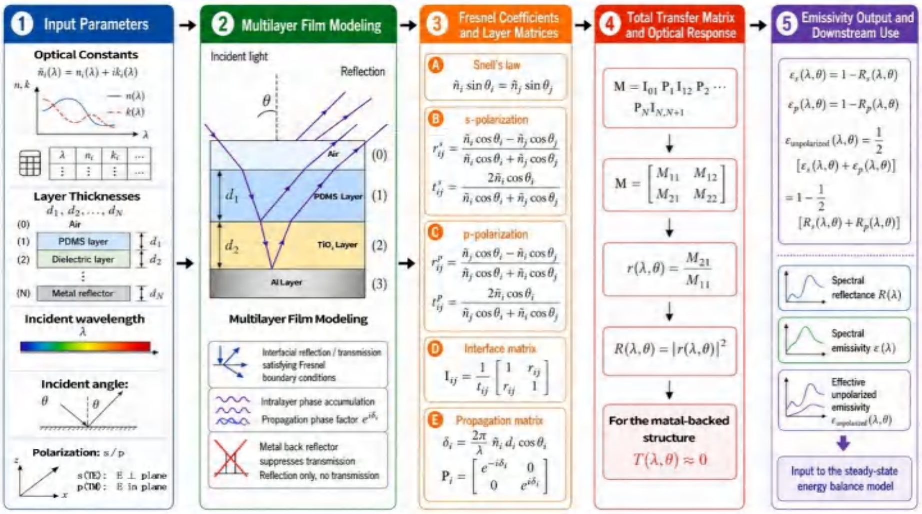


Figure 2 Schematic Diagram of the Forward Matrix Method

2.3 Steady-State Photothermal Coupling Model

To ensure the comparability of the cooling performance of different structures, this study uniformly simulates the typical boundary layer environment of the near - surface pavement under low wind speed under the conditions of ambient temperature $T_{amb} = 300\ K$ and convective heat transfer coefficient $h_c = 5W/(m^2{\cdot}K)$, reducing the influence of external environmental fluctuations on the net cooling power of the structures.

To evaluate the cooling performance of PDMS-based films, a steady-state energy balance model was established in this study. For the PDRC film with a surface temperature of Ts, the formula for calculating its net cooling power density P_{net} is as follows:

$$P_{net} = P_{rad} - P_{atm} - P_{solar} - P_{nonrad}, \tag{16}$$

Among them, P_{net} is the net cooling power; P_{rad} is the thermal radiation power emitted by the structure to the outside; P_{atm} is the absorbed downward atmospheric radiation; P_{solar} represents the absorbed solar irradiance; P_{nonrad} is the non - radiative sensible heat exchange, mainly air convection and conduction heat transfer, which follows Newton's law of cooling, and the formula is as follows:

$$P_{nonrad} = h_c(T_{amb}\text{-}T_s), \tag{17}$$

In the formula, h_c is the comprehensive non-radiative heat transfer coefficient. To evaluate the ultimate cooling capacity of engineering thin films, the equilibrium temperature T_{eq} is defined as the surface steady-state temperature when the system reaches thermal equilibrium:

$$P_{net}(T_{eq}) = 0, \tag{18}$$

When conducting practical calculations under standard conditions, the net cooling power is obtained by calculating the integral of the spectrum:

$$P_{cool} = \int_0^\infty \varepsilon(\lambda)\left[B\left(\lambda, T_{sky}\right) - B(\lambda, T_{amb})\right]\tau_{atm}(\lambda)d\lambda - \int_0^\infty \varepsilon(\lambda)I_{solar}(\lambda)d\lambda, \tag{19}$$

2.4 Particle Swarm Optimization Algorithm Model

To determine the optimal structure for multi-layer radiative cooling, this study introduces the Particle Swarm Optimization (PSO) algorithm, a robust metaheuristic algorithm inspired by the behavior of biological swarms. The PSO algorithm operates by maintaining a population (swarm) of candidate solutions (particles), which iteratively explores the search space. The position $\boldsymbol{x}_i^k$ of each particle represents a potential design configuration, and its velocity $\boldsymbol{v}_i^k$ determines its movement trajectory. In each iteration, each particle updates its position based on its own known best solution and the best solution found by the entire swarm.

The core update equation for the k-th iteration is:

$$\boldsymbol{v}_i^{(k+1)} = \omega \boldsymbol{v}_i^k + c_1 r_1\left(\boldsymbol{pbest}_i - \boldsymbol{x}_i^k\right) + c_2 r_2\left(\boldsymbol{gbest}_i - \boldsymbol{x}_i^k\right), \tag{20}$$

$$\boldsymbol{x}_i^{(k+1)} = \boldsymbol{x}_i^k + \boldsymbol{v}_i^k, \tag{21}$$

Among them, ω is the inertia weight, c_1 and c_2 are the cognitive acceleration coefficient and the social acceleration coefficient respectively, and r_1, r_2 are random numbers uniformly distributed in the interval 0–1.

The position vectors of the particles encode the thicknesses of each layer in the multi-layer stack, and the material types at each position have been predetermined. The optimized configuration uses a swarm size of 30 particles and a maximum of 40 iterations. The effectiveness of this algorithm in handling such non-linear, constrained optimization problems makes it suitable for photonics structure design (Figure 3).

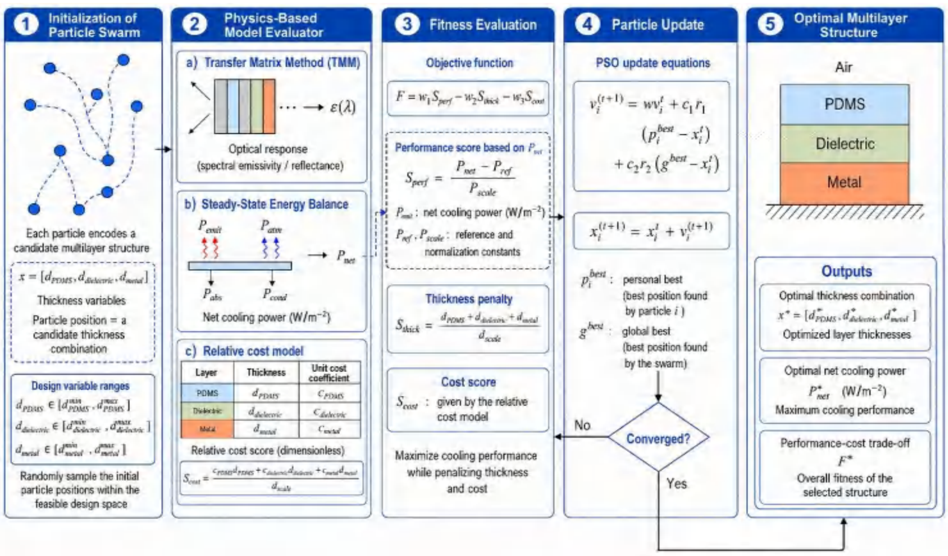


Figure 3 Schematic Diagram of the PSO Algorithm

2.5 Multilayer Structure Optimization Model

To enhance the radiative cooling performance of the multilayer thin-film structure, this study established a multilayer structure optimization model based on the transfer matrix method and constructed an optimization framework for the multilayer structure of PDMS, TiO2, and metal reflector. The optimization objective function needs to balance multiple competing objectives.

$$minimize\ J(\mathbf{x}) = -P_{net}(\mathbf{x}) + \alpha \cdot \bar{\varepsilon}_{solar}(\mathbf{x}) + \beta \cdot [1 - \bar{\varepsilon}_{window}(\mathbf{x})] + \gamma \cdot \frac{d_{total}(\mathbf{x})}{d_{max}}, \tag{22}$$

Among them, $\mathbf{x}$ represents the design variables, including material selection and thickness, α、β、γ is the weight coefficient. To consider the limits of actual manufacturing, the thickness of PDMS is constrained within 100 μm. Penalty values are added to overly thick or complex structures to avoid complex designs and obtain the optimal thin-film structure.

To screen the optimal thickness considering refrigeration performance and cost factors, this study established a multi-objective evaluation model.

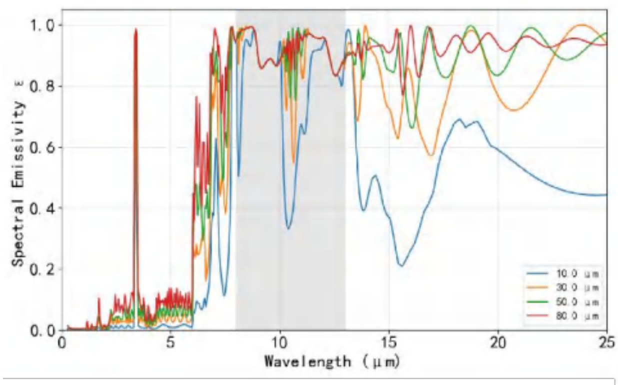
$$S = 0.4 \cdot S_{perf} + 0.3 \cdot S_{temp} + 0.2 \cdot S_{cost}, \tag{23}$$

Among them, S_{perf} represents the refrigeration performance; S_{temp} represents the film thickness; S_{cost} represents the cost.

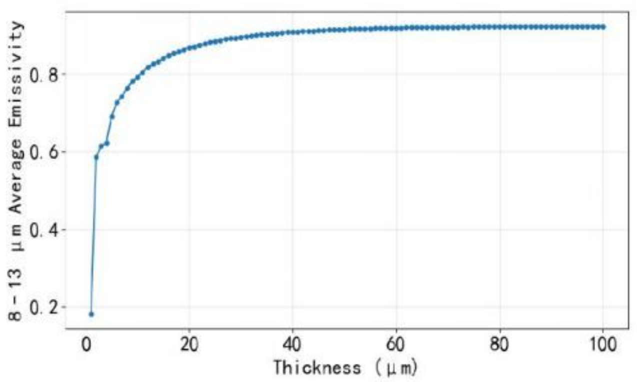
3 RESULTS AND DISCUSSION

3.1 Thickness-Dependent Optical Behavior of Single-Layer PDMS

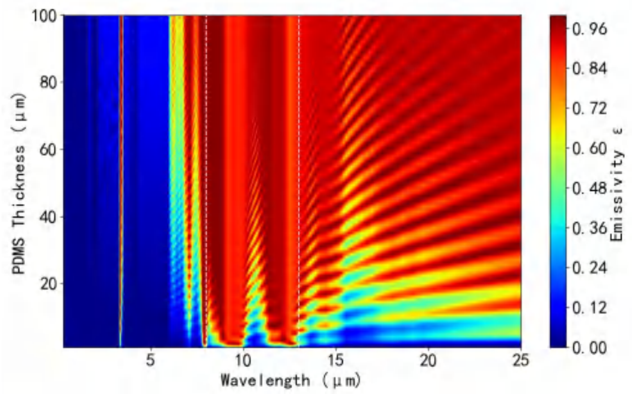
As shown in Figure 4(a), the spectral emissivity distribution ε(λ) of the single-layer PDMS structure exhibits significant spectral dichotomy between the solar band and the mid-infrared band. In the short-wave solar band, due to the wide electronic band gap of the siloxane backbone, the interband electronic transitions are effectively blocked, resulting in an emissivity close to zero and suppressing the heat generation from solar radiation. In contrast, in the 8-13 μm atmospheric window, influenced by the resonant excitation of the asymmetric stretching of the Si-O-Si bond and the rocking vibration mode of the -CH3 group, PDMS shows strong thermal emission characteristics, combining low absorption in the solar band and high emission in the mid-infrared band. Therefore, PDMS has good radiative cooling performance and can serve as an ideal radiative cooling emitter.
As shown in Figure 4(b), the geometric thickness (d) of the PDMS layer is the core parameter controlling the optical phase accumulation and electromagnetic wave attenuation, resulting in a highly nonlinear trajectory of the radiation response. In the sub - wavelength region, affected by the volume absorption kinetics of the Beer - Lambert law, the average emissivity in the 8–13 μm band rises sharply. When the physical thickness exceeds the optical penetration depth of the material, the system changes from an optically thin state to an optically thick state, and the emissivity gradually converges to saturation. As shown in Figure 4(c), the Fabry-Perot interference fringes reflect the coherent electromagnetic wave reflection effect between air and PDMS, and between PDMS and the metal reflective layer. The emissivity converges to saturation as the thickness increases. Therefore, there is little gain when the physical thickness exceeds the critical optical threshold, and the reasonable thickness range is between 29.3 μm and 49.5 μm.



(a) Spectral Emissivity of PDMS Films at Various Thicknesses



(b) Sea Average Emissivity in the Atmospheric Window vs. PDMS Film Thickness)

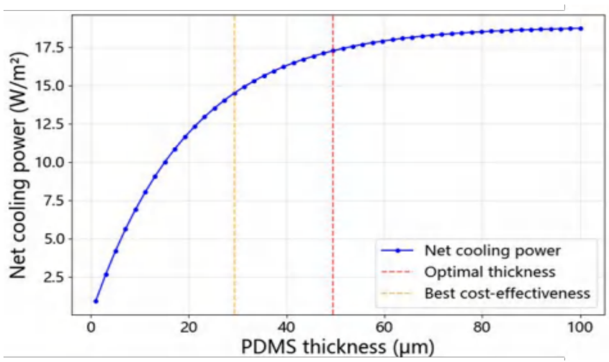


(c) Contour Map of PDMS Emissivity as a Function of Wavelength and Film Thickness

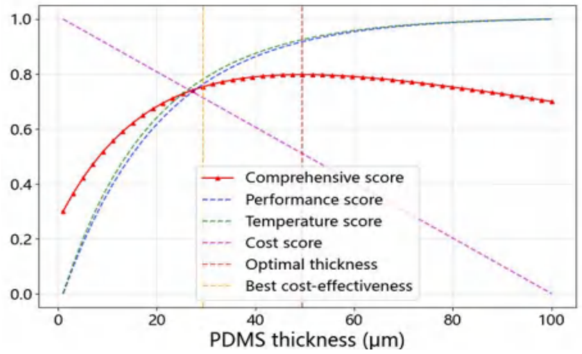
Figure 4 Spectral Emissivity Characteristics of PDMS Films with Different Thicknesses

3.2 Optimization of the Thickness of a Single-Layer PDMS Film

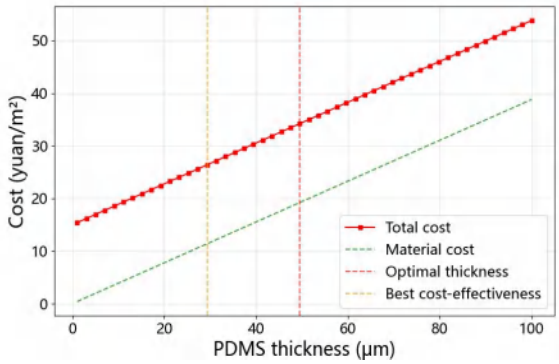
As shown in Figure 5(a), the thickness of PDMS has a significant impact on the cooling performance. Within a relatively thin thickness range, the cooling performance is significantly improved. This is because the volume absorption effect is enhanced, the number of molecules participating in resonance excitation surges, and the infrared emissivity is increased. When the thickness of the PDMS layer is greater than 49.5 μm, the growth rate of the infrared emissivity tends to be stable, and the performance improvement rate decreases significantly. This is because when the thickness is large enough, the proportion of the light intensity of multiple reflections and absorptions in the total incident light intensity gradually stabilizes. As shown in Figure 5(b), when the processing cost is fixed, the material cost increases linearly with the increase of the thickness. As shown in Figure 5(c), the comprehensive evaluation result achieves the highest total score of 0.798 points at a thickness of 49.5 μm. As shown in Figure 5(d), when the thickness is 29.3 μm, the cost is 0.5497 W/yuan, reaching the best cooling efficiency. That is, about 85% of the maximum heat dissipation performance can be achieved with only 65% of the cost. Therefore, the optimal thickness of the PDMS layer is 49.5 μm, and the net cooling power can reach 17.26 W/m² at this time. When deploying on a large scale, considering cost - effectiveness, the optimal thickness of PDMS is 29.3 μm.



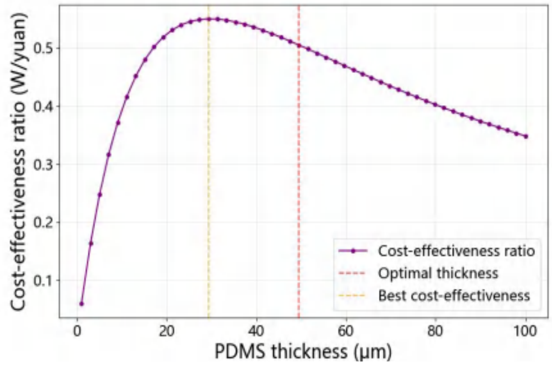
(a) Relationship Between Net Radiative Cooling Power and PDMS Thickness



(b) Multi-Objective Comprehensive Evaluation of Cooling Performance



(c) Cost Structure Analysis for PDMS Thin Films



(d) Cost-Effectiveness Analysis of Radiative Cooling Films

Figure 5 Thermodynamic Performance Evolution and Multi-Objective Topological Optimization of Radiative Cooling Films

3.3 Optimization of the Multi-Layer PDMS Thin Film Structure

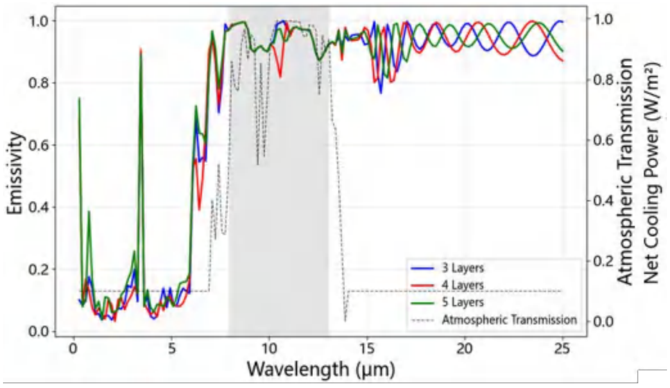
To enhance the performance of single-layer PDMS films between solar reflection and mid-infrared emission, this paper introduces the particle swarm optimization algorithm (PSO) to optimize the PDMS-dielectric layer-metal multilayer structure. The results show that the optimized multilayer structure can maintain a high reflectance in the solar spectral range and strong thermal emission ability within the 8 - 13 μm atmospheric window. Therefore, adjusting the thickness of each layer can effectively improve the spectral selectivity of the structure and enhance the cooling performance.

Based on the multi-objective optimization model established in Section 2.5, this study further compares the differences among three-layer to five-layer structures under the constraints of net cooling power, average emissivity in the atmospheric window, and cost. The results are shown in Table 3. As shown in Figure 6(a)-(d), the net cooling powers of the three-layer, four-layer, and five-layer structures are 56.38, 56.00, and 57.08 W/m², respectively. The corresponding average emissivities in the atmospheric window are 0.949, 0.937, and 0.945, all remaining above 0.93. Meanwhile, the average emissivities of each structure in the solar band are all below 0.158, indicating that the multi-layer PDMS structures all have high emissivity within the 8-13 μm atmospheric window but maintain low average emissivity in the solar band. The change range of the equilibrium temperature of structures with different numbers of layers is small. Compared with the three-layer structure, the net cooling power of the five-layer structure only increases by about 1.24%, suggesting that the increase in the number of layers has limited improvement on the net cooling power, while the cost and structural complexity also increase accordingly. For the design of radiative cooling films for transportation infrastructure, moderately simplifying the number of layers and optimizing the structural complexity are more conducive to balancing performance and cost.

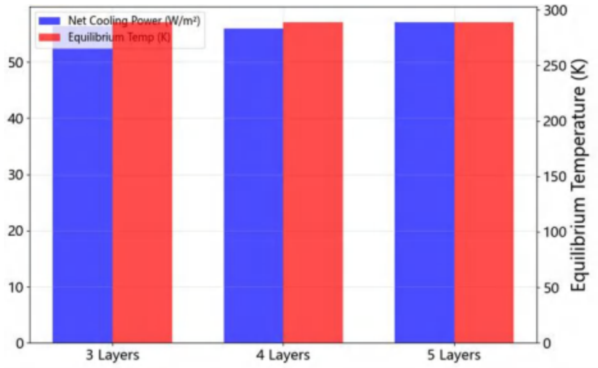
Based on the results of particle swarm optimization, the three-layer structure of PDMS-dielectric layer-metal layer is the most optimal structure. The three-layer thin-film structure is composed of a 70.804 μm PDMS layer, a 0.43 μm dielectric layer, and a 0.246 μm metal layer, with a total thickness of approximately 71.48 μm and a net cooling power of 56.38 W/m².

Table 3 Comparison of the Properties of PDMS Films with Three to Five Layers

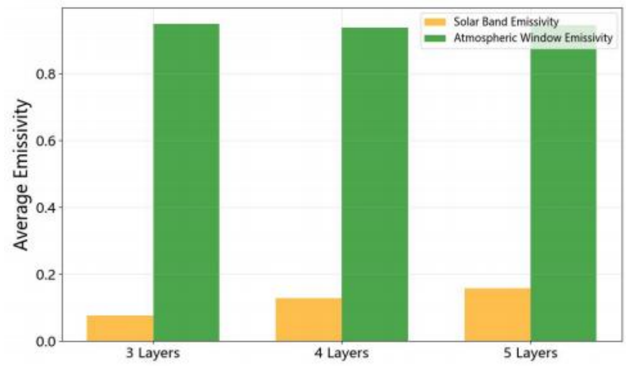
Number of floors	Net cooling power(W/m²)	Average emissivity of the atmospheric window	Equilibrium temperature(K)
3	56.38	0.949	288.7
4	56.00	0.937	288.6
5	57.08	0.945	288.6



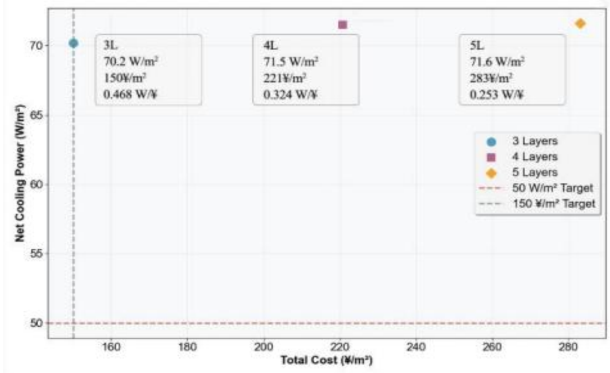
(a) Spectral Emissivity Profiles of Optimized Multilayer Structures



(b) Cooling Performance Metrics Versus Layer Configuration Complexity



(c) Comparative Analysis of Solar and Atmospheric Window Emissivity



(d) Layer Count Impact on Cooling Performance and Cost

Figure 6 Performance Comparison of Optimized Multilayer PDMS Radiative Cooling Structures

4 CONCLUSIONS

In summary, this study established a photothermal coupling design method based on PDMS radiative cooling films and analyzed the cooling performance of single - layer and multi - layer structures. First, based on the transfer matrix method, the influence of the thickness of the single - layer PDMS film on the spectral emissivity and net cooling power was investigated. The results show that the net cooling performance first increases and then levels off with the increase of thickness, reaching the optimal single -layer net cooling power of 17.26 W/m² at 49.5 μm. Considering the material usage, cost, and performance, the optimal thickness of the PDMS layer is 29.3 μm. Subsequently, the cooling performance of the film was quantitatively evaluated using the steady - state energy balance model, and the PDMS - dielectric - metal multi - layer structure was optimized by the particle swarm optimization algorithm. The results indicate that the optimal solution is a three - layer film structure with a 70.804 μm PDMS layer, a 0.43 μm dielectric layer, and a 0.246 μm metal layer, with a total thickness of approximately 71.16 μm and a net cooling power of 56.38 W/m². The above research shows that the method constructed in this study can provide an effective solution for the structural design and performance prediction of radiative cooling films and offer a theoretical reference for the passive thermal management of transportation infrastructure surfaces. The results of this paper are mainly applicable to the comparison of structural performance under the boundary conditions of high solar irradiation during the day. For road service issues such as rain and snow, low temperature, anti-skid and wear-resistance, and long-term adhesion reliability, further sample preparation and field experiments are still needed for verification.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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