

Quantification of Spectral Emissivity of PDMS Thin Films Based on TMM and Research on Surface Thermal Environment Regulation Efficacy

Yuntan Chen^{*,#}, Meng Xu[#]

Department of Business Administration, Shanghai University of Finance and Economics Zhejiang College, Jinhua 321000, China

^{*}Corresponding author: Yuntan Chen (Email: 13706989635@163.com)

[#]These authors contributed equally.

Abstract: PDRC technology is of great significance for improving the surface thermal environment and achieving regional energy conservation. However, its core material, polydimethylsiloxane (PDMS), has limitations such as insufficient spectral selectivity and weak shielding against near-surface ambient thermal radiation, which restrict its engineering application. Based on the "surface-atmosphere radiative transfer" theory, this study employed the TMM to establish a spectral emissivity model of PDMS films, revealing the coupling mechanism among wavelength, thickness, and optical properties. Subsequently, by integrating the steady-state thermal balance equation of geographical factors, an energy exchange framework of "surface-film-atmosphere" was constructed. Results showed that PDMS films exhibit high emissivity in the atmospheric window and certain cooling effects under standard working conditions, but the lack of a high-reflectivity backsheet leads to significant parasitic thermal loads. This cross-scale integrated model provides theoretical support for enhancing the geographical adaptability and engineering feasibility of PDRC technology, contributing to the optimization of urban and rural microclimates.

Keywords: Passive Daytime Radiative Cooling (PDRC), Transfer Matrix Method (TMM), Surface Thermal Environment Regulation, Surface-Atmosphere Radiative Transfer.

1. Introduction

PDRC technology serves as a crucial green approach for improving the surface thermal environment and conserving regional energy, with remarkable application potential in geographical process regulation and urban-rural microclimate optimization [1][2]. However, PDMS its core material, suffers from issues such as insufficient spectral selectivity and weak shielding against near-surface ambient thermal radiation, which restrict the technology's cooling efficiency and engineering promotion in complex geographical environments [3]. Therefore, regulating the optical-thermal coupling properties of PDMS through material structure design and parameter optimization has become key to enhancing the technology's adaptability to geographical scenarios and engineering feasibility, as shown in Figure 1 [4].

Based on the TMM, this study established a spectral emissivity model for PDMS films, revealing the coupling mechanism among wavelength, thickness, and optical properties [5][6]. It was found that a 200 μm -thick PDMS film achieves an average emissivity of 0.94 in the 8–13 μm atmospheric window, demonstrating significant long-wave heat dissipation potential, yet it has limitations including non-zero infrared transmittance and high solar short-wave transmittance. By integrating geographical processes such as

surface-atmosphere radiative exchange, a thermal balance evaluation framework was constructed 错误!未找到引用源。 . Quantitative results showed that under standard working conditions ($T_{\text{amb}}=300\text{K}$), a pure PDMS film has a net cooling power of approximately 50.94W/m² and achieves a temperature reduction of 4°C. Nevertheless, the lack of a high-reflectivity backsheet leads to significant ambient heat input, limiting its application in geographical engineering [8][9].

To address the above bottlenecks, this study focused on the core of regulating surface-atmosphere radiative exchange, constructed an optical quantification model for single-layer PDMS films, optimized parameter preprocessing, and clarified the film's surface cooling potential and geographical constraints [10][11]. Furthermore, by coupling the steady-state thermal balance equation of geographical factors, an Ag metal substrate was introduced to build a double-layer composite structure, and a geographical process correlation model between optical properties and material parameters was established [12][13][14]. This model quantifies the interference effects of geographical factors, providing support for the application of PDRC technology in urban-rural microclimate optimization and surface thermal environment regulation [15][16].

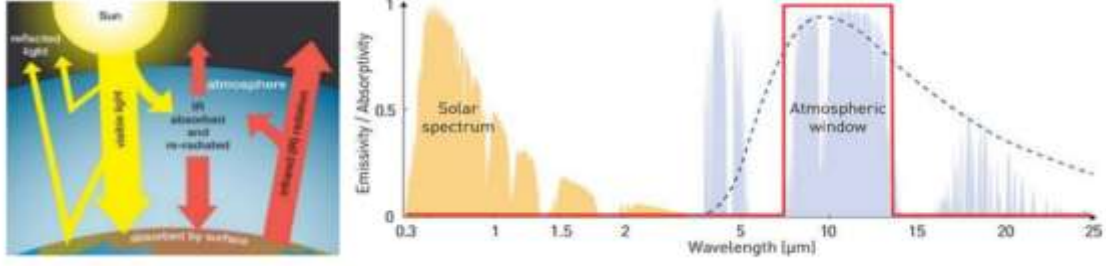


Figure 1 Radiative Cooling Technology

2. Geoscientific Logic for the Construction of an Integrated Model

To systematically quantify the engineering application potential of polydimethylsiloxane (PDMS) films in regulating the surface thermal environment, this study, based on the core theoretical paradigm of "surface-atmosphere radiative transfer-energy balance" in geoscience, constructed an integrated simulation model of "optical properties-thermal balance effect." This model enables cross-scale coupled simulation from the microcosmic optical response of materials to the macroscopic cooling efficiency in geographical contexts.

With the core logical chain of "surface cooling demand orientation-material optical property adaptation-geographical environment energy feedback," the model not only accurately reveals the coupling mechanism between PDMS films and the geographical radiative environment but also quantifies the cooling performance thresholds of PDMS films in typical geographical scenarios. It thus provides a scientific theoretical tool and quantitative support for geographical engineering practices such as urban-rural microclimate optimization and urban heat island mitigation.

2.1. Construction of a Spectral Emissivity Calculation Submodel Adapted to Geographical Radiation

This submodel is built on the physical laws of surface-atmosphere radiative exchange, using the Transfer Matrix Method (TMM). Its core objective is to quantitatively characterize the spectral emissivity of PDMS films in geographically critical radiation bands, providing core parameter support for subsequent cooling performance evaluation.

(1) Coupling of Physical Mechanisms: Based on Kirchhoff's law of thermal radiation and the law of conservation of energy, the core expression for spectral emissivity is derived theoretically:

$$\varepsilon(\lambda, d) = 1 - |r(\lambda, d)|^2 - |t(\lambda, d)|^2 \quad (1)$$

This formula accurately reflects the energy distribution mechanism of the film for solar shortwave radiation (2.8–25 μm, the dominant band for surface heat gain) and atmospheric window longwave radiation (8–13 μm, the key channel for surface radiative heat dissipation), laying a theoretical foundation for radiative regulation analysis in geographical scenarios.

(1) Adaptation to Geographical Scenarios: For the typical geographical layered structure of "air (surface environmental medium) | PDMS film | air (atmospheric environmental medium)", it is assumed that light waves are incident vertically (consistent with the radiative transfer

characteristics of horizontal underlying surfaces in natural geographical environments). By constructing a characteristic matrix, the coupling effect between film thickness (10–200 μm, covering the practical application range of geographical engineering) and complex refractive index ($N(\lambda) = n(\lambda) + ik(\lambda)$) is quantified, accurately characterizing the regulatory mechanism of interference phenomena on the film's geographical radiative response.

(1) Geographical Processing of Data: The selected optical constant dataset of PDMS material covers a wavelength range of 0.4 μm–20 μm. It has strong compatibility with the critical radiation bands of the geographical environment, and its data reliability has been academically verified. A cubic spline interpolation algorithm is used to reconstruct the original discrete data, mapping it to a continuous uniform grid of $\lambda = [0.3 \mu\text{m}, 25 \mu\text{m}]$ (with a step size of 0.01 μm). This grid fully covers the core bands of solar shortwave radiation (0.3–2.5 μm) and Earth's longwave radiation (8–13 μm), ensuring accurate matching between the model input parameters and surface-atmosphere radiative characteristics.

2.2. Geographical Energy Balance-Based Submodel for Cooling Performance Evaluation

Taking the spectral emissivity calculation results as the core input, this submodel integrates multi-path energy exchange processes in geographical environments and constructs a 3D thermal balance analysis system of "surface-film-atmosphere", realizing the geographically scenario-based evaluation of the cooling performance of PDMS films.

(1) Modeling of Film Thermal Radiation Power: Based on the spectral integral form of the Stefan-Boltzmann law, it is assumed that both the upper and lower surfaces of the suspended PDMS film participate in radiative heat transfer and the internal temperature field is uniform. The total radiant power per unit area is the sum of the radiant contributions from the two surfaces, with the expression:

$$P_{\text{rad}}(T) = 2 \int_0^\infty I_{\text{BB}}(\lambda, T) \varepsilon(\lambda, d) d\lambda \quad (2)$$

where $I_{\text{BB}}(\lambda, T)$ is the spectral radiant exitance of a Planck blackbody. This formula quantifies the film's radiant heat dissipation capacity to outer space (a 3K cold source) through the 8–13 μm atmospheric window, which is consistent with the core physical principle of geographical radiative cooling.

(2) Modeling of Atmospheric Thermal Radiation Absorption Power: Based on the US Standard Atmosphere 1976 model and combined with Kirchhoff's law ($\varepsilon_{\text{atm}}(\lambda) = 1 - t_{\text{atm}}(\lambda)$), the geographical interference effect of key atmospheric components (H_2O , CO_2 , O_3) on surface cooling is quantified, with the expression:

$$P_{\text{atm}}(T_{\text{amb}}) = \int_0^\infty I_{\text{BB}}(\lambda, T_{\text{amb}}) \varepsilon_{\text{atm}}(\lambda) \varepsilon(\lambda, d) d\lambda \quad (3)$$

Only the downward atmospheric radiation absorbed by the film is considered, excluding the influence of the transmitted part.

(3) Modeling of Solar Radiation Absorption Power: The ASTM G173-03 standard AM1.5G global tilted solar spectrum (adapted to the radiative characteristics of tilted underlying surfaces in mid-latitude regions) is adopted. Combined with the translucent property of PDMS films, the expression for their solar radiation absorption power is:

$$P_{\text{sun}} = \int_0^{\infty} I_{\text{AM1.5}}(\lambda) \varepsilon(\lambda, d) d\lambda \quad (4)$$

This accurately characterizes the inhibitory effect of solar radiation on cooling in geographical environments.

(4) Modeling of Surface Thermal Radiation Absorption Power: Assuming the surface is an ideal blackbody ($\varepsilon_{\text{ground}} \approx 1$), the absorption of long-wave radiation from the surface by the lower surface of the film is quantified, with the expression:

$$P_{\text{ground}} = \int_0^{\infty} I_{\text{BB}}(\lambda, T_{\text{amb}}) \varepsilon(\lambda, d) d\lambda \quad (5)$$

This represents the core parasitic thermal load in geographical scenarios.

(5) Modeling of Non-Radiative Heat Exchange Power: A comprehensive heat transfer coefficient $h_c = 10 \text{ W}/(\text{m}^2 \cdot \text{K})$ (adapted to the natural ventilation environment in urban and rural outdoor areas) is selected to characterize the coupling effect of air convection and support structure conduction, with the expression:

$$P_{\text{non-rad}}(T, T_{\text{amb}}) = h_c (T_{\text{amb}} - T) \quad (6)$$

(6) Setting of Geographical Adaptability Evaluation Indicators: Two core indicators are defined: Net cooling power at ambient temperature $P_{\text{cool@amb}}$ (i.e., $P_{\text{net}}(T_{\text{amb}})$ when $T = T_{\text{amb}}$), which quantifies the initial cooling efficiency); Steady-state equilibrium temperature T_{eq} (obtained by solving $P_{\text{net}}(T) = 0$, which represents the ultimate cooling potential of the surface).

2.3. Construction of the Model's Collaborative Solution Logic

(1) Solution of Optical Parameters: Based on the TMM submodel, the full-band spectral emissivity curves of PDMS films with different thicknesses were systematically solved. Core parameters such as the average emissivity (ε_{atm}) in the atmospheric window (8–13 μm) were extracted, clarifying the geographical regulation law of film thickness on the radiative properties of the films.

(2) Solution of Cooling Performance: The spectral emissivity $\varepsilon(\lambda, d)$ was substituted into the thermal balance submodel. Combined with standardized geographical environment benchmark parameters ($T_{\text{amb}} = 300 \text{ K}$, AM1.5G solar spectrum, and atmospheric transmittance from the US Standard Atmosphere 1976), the net cooling power and steady-state equilibrium temperature of films with different thicknesses were calculated numerically.

(3) Feedback and Optimization Analysis: Through thickness sensitivity analysis, the internal correlation between the optical properties of PDMS films and geographical cooling performance was revealed. The optimal thickness threshold for geographical engineering was identified, and targeted structural optimization directions were proposed.

3. Results

3.1. Spectral Emissivity Submodel

Based on the TMM submodel results, this section focuses on analyzing the geographical radiation adaptability characteristics and thickness regulation rules of PDMS films's pectral emissivity:

(1) Band Adaptability Characteristics: All films exhibit an $\varepsilon_{\text{atm}} \approx 0$ in the visible band (0.3–0.7 μm), corresponding to extremely low absorptivity. This effectively suppresses solar shortwave radiation absorption and reduces surface heat gain. In the 8–13 μm atmospheric window band, the integrated average emissivity of the 200 μm -thick film reaches 0.94, demonstrating excellent surface longwave radiation heat dissipation potential, which meets the core demand for geographical radiative cooling.

(2) Thickness Regulation Rules: As film thickness increases, the average emissivity in the atmospheric window rises but gradually saturates. The largest increase (20.35%) occurs from 10 μm to 25 μm , while the increase from 100 μm to 200 μm is only 1.08%. This identifies the optimal thickness threshold (around 100 μm) for balancing efficiency and cost in geographical engineering. Additionally, increased thickness smoothens interference fringes in the infrared band, stabilizing radiation properties and enhancing adaptability to complex geographical environments.

(3) Limitations in Geographical Application: All films show non-zero transmittance in the full infrared band, leading to surface thermal radiation loss. Moreover, their high solar shortwave radiation transmittance fails to effectively block surface heat gain, which becomes a core shortcoming for geographical engineering applications.

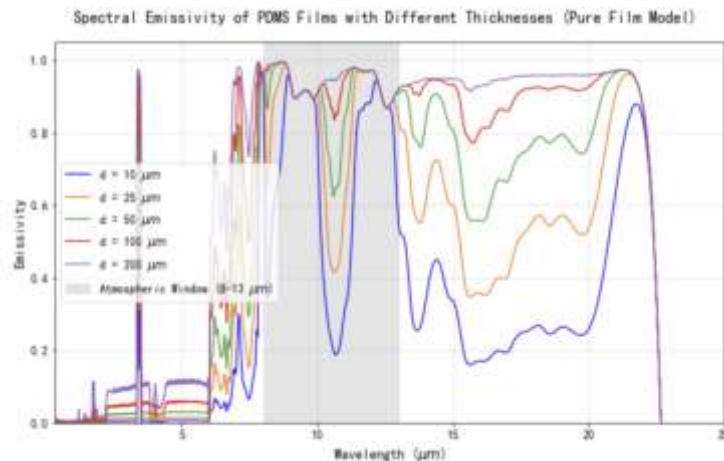


Figure 2 Spectral Emissivity of PDMS Films with Different Thicknesses

3.2. Thermal Balance Submodel

Combined with spectral emissivity parameters, the cooling performance results under the standard geographical condition ($T_{\text{amb}}=300\text{K}$) were quantified via the thermal balance submodel, with the analysis as follows:

(1) Core Cooling Performance: For pure PDMS films, the net cooling power increased from 30.92W/m^2 to 50.94W/m^2 as thickness rose, while the steady-state equilibrium temperature decreased from 297.29K (24.14°C) to 296.02K (22.87°C). The equilibrium temperature was $3\text{--}4^\circ\text{C}$ lower than the ambient temperature, indicating a certain potential for surface cooling and verifying the material's application value in geographical scenarios.

(2) Analysis of Geographical Influencing Factors: Surface thermal radiation absorption (P_{ground}) and atmospheric

thermal radiation load (P_{atm}) were the main parasitic thermal loads, offsetting approximately 50% of the cooling power in total. Non-radiative heat exchange ($P_{\text{non-rad}}$) varied with the ambient temperature gradient, further weakening cooling efficiency—highlighting the significant interference of complex geographical environments on cooling performance.

(3) Limitations in Engineering Adaptability: Due to the lack of a high-reflectivity backsheets, pure PDMS films insufficiently shield thermal radiation in the near-surface environment. Additionally, solar radiation transmission leakage prevents cooling of the target objects beneath the film, making it difficult to adapt to the practical needs of geographical engineering such as urban-rural building roofs and outdoor facilities.

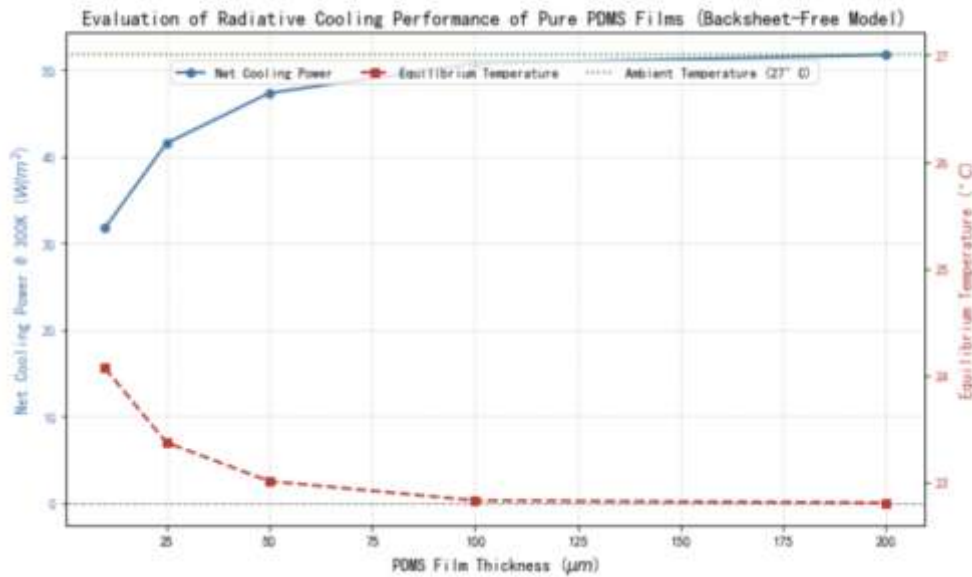


Figure 3 Radiative Cooling Performance Evaluation Diagram of Pure PDMS Films

3.3. Analysis of the Geographical Science Application Value of the Model

(1) Cross-Scale Coupling Innovation Value: It enables integrated simulation from the microscale optical mechanism of materials to the macroscale geographical cooling effect, breaking through the limitation that traditional optical models are disconnected from geographical application scenarios. This fills the gap in quantitative connection between microscale material properties and macroscale geographical effects, and enriches the technical method system for geographical process regulation.

(2) Geographical Engineering Practice Support Value: The core parameters of the model are set based on international standards and characteristics of typical geographical environments. With high reliability and universality of calculation results, the model can directly provide quantitative support for the design of geographical engineering schemes such as cooling of urban and rural building roofs and thermal environment regulation of outdoor facilities, improving the scientificity and targeting of engineering design.

(3) Technology Optimization Guidance Value: Through model simulation, the geographical application bottlenecks of pure PDMS films (solar radiation transmission leakage, significant geographical parasitic thermal load) are accurately

identified. This provides a solid theoretical basis for the design of the "film + high-reflectivity metal backsheets" composite structure, and promotes the engineering application and innovative development of passive daytime radiative cooling technology in geographical science fields such as regional thermal environment improvement and urban sustainable development.

4. Conclusions

The core advantages of this study lie in the construction of a cross-scale integrated model that incorporates core geographical principles such as surface-atmosphere radiative transfer and regional energy balance. It achieves accurate connection between microcosmic material properties and macroscopic geographical cooling effects through interdisciplinary methods. Relying on authoritative geographical environment datasets to ensure accuracy, a multi-dimensional evaluation system is established to realize the collaborative assessment of performance, cost, and geographical scenario adaptation. Guided by the needs of geographical engineering such as urban heat island mitigation, low-cost technical paths and a full-process design system are proposed. Its limitations are mainly reflected in the following aspects: idealized assumptions ignore complex geographical factors such as surface roughness and dynamic meteorology;

parameter processing does not consider the attenuation of material performance under geographical environment stress; and optimization objectives do not fully incorporate key indicators required for geographical engineering, such as mechanical strength and weather resistance. These factors restrict the applicability of the model in complex geographical scenarios and its long-term prediction accuracy.

This study will focus on optimizing the geographical adaptability of the model in the future. Specifically, it will expand the dynamic simulation system by integrating long-term meteorological observation data, and correct the material performance attenuation parameters under different geographical environments through outdoor aging experiments. Meanwhile, it will optimize the mechanical strength and weather resistance of the nanoporous structure to enhance the resistance to geographical environmental stress. Efforts will be made to promote the in-depth integration of passive radiative cooling technology and geographical engineering. Customized composite structures will be developed for building needs in different climate zones, and a photovoltaic-cooling synergy system adapted to specific geographical regions will be constructed. In addition, the study will explore the integration path of materials and geographical energy storage technology, and build a regional thermal environment regulation system by combining geographical elements such as urban green spaces and water bodies. This is expected to provide innovative support for green building planning, sponge city construction, and other related fields.

References

- [1] Chen M, Pang D, Chen X, et al. Passive daytime radiative cooling: Fundamentals, material designs, and applications[J]. *EcoMat*, 2022, 4(1): e12153.
- [2] Yang M, Ren C, Wang H, et al. Mitigating urban heat island through neighboring rural land cover[J]. *Nature Cities*, 2024, 1(8): 522-532.
- [3] Douglas L D, Rivera-Gonzalez N, Cool N, et al. A materials science perspective of midstream challenges in the utilization of heavy crude oil[J]. *ACS omega*, 2022, 7(2): 1547-1574.
- [4] Sung C H, Hao T, Fang H, et al. Biological and Biologically Inspired Functional Nanostructures: Insights into Structural, Optical, Thermal, and Sensing Applications[J]. *Advanced Materials*, 2025: e09281.
- [5] Zhou S, Meng B, Yuan C. Polydimethylsiloxane (PDMS)-assisted non-destructive transient thermoreflectance characterizations[J]. *Review of Scientific Instruments*, 2024, 95(5).
- [6] Luo X, Li F, Qiao C, et al. Research on the energy-saving effect of composite film materials on smart windows based on optical properties[J]. *Thermal Science*, 2023, 27(3 Part A): 2183-2194.
- [7] Shi H, Xiao Z, Wen J, et al. An optical-thermal surface-atmosphere radiative transfer model coupling framework with topographic effects[J]. *IEEE Transactions on Geoscience and Remote Sensing*, 2020, 60: 1-12.
- [8] Shang J, Zhang Y, Zhang J, et al. Hydrogel-based stimuli-responsive radiative and/or evaporative cooling materials for carbon neutrality[J]. *ACS Energy Letters*, 2024, 9(2): 594-626.
- [9] Yousuf H, Mohammed S A, Jony J A, et al. Application of high-efficiency III-V/Si bifacial tandem solar cells: A new approach to photovoltaic energy enhancement under diverse environmental conditions[J]. *Sustainable Energy Technologies and Assessments*, 2025, 82: 104481.
- [10] Huang J, Zhou X, Wu G, et al. Global climate impacts of land-surface and atmospheric processes over the Tibetan Plateau[J]. *Reviews of Geophysics*, 2023, 61(3): e2022RG000771.
- [11] Clough R, Fisher A, Gibson B, et al. Atomic spectrometry update: review of advances in the analysis of metals, chemicals and materials[J]. *Journal of Analytical Atomic Spectrometry*, 2023, 38(11): 2215-2279.
- [12] Lin L, Zheng H, Luo Q, et al. Regulating lithium nucleation at the electrolyte/electrode interface in lithium metal batteries[J]. *Advanced Functional Materials*, 2024, 34(24): 2315201.
- [13] Cheng P, An Y, Jen A K Y, et al. New nanophotonics approaches for enhancing the efficiency and stability of perovskite solar cells[J]. *Advanced Materials*, 2024, 36(17): 2309459.
- [14] Mondal I, Jha I, Hossain S K A, et al. Variability of bio-optical properties of Sundarbans mangrove estuarine ecosystem using elemental analysis, Sentinel 3 OLCI imageries and neural network models[J]. *Advances in Space Research*, 2025, 75(2): 2028-2047.
- [15] Lin L, Zhao Y. Optimizing Local Climate Zones to Mitigate Urban Heat Risk: A Multi-Models Coupled Approach in the Context of Urban Renewal[J]. *Building and Environment*, 2025: 113282.
- [16] Liu C, Lu S, Tian J, et al. Research overview on urban heat islands driven by computational intelligence[J]. *Land*, 2024, 13(12): 2176.