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Enhancing PV Efficiency through Scalable Radiant Cooling with Optimized Randomly Doped Particle Structures

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ABSTRACT

Solar energy is a critical resource in the fight against climate change, yet a significant portion of solar radiation is dissipated as heat in photovoltaic (PV) systems, impairing their performance. Conventional solar cell cooling technologies are energy-intensive and demand regular maintenance. Here, we propose a scalable and economically viable radiative cooling cover employing randomly doped particle structures to combat these issues. The cover's solar transmittance and "sky window" emissivity were investigated numerically, using a combination of Mie theory and Monte Carlo method. The optimal design yields a solar transmittance of 94.8% and a "sky window" emissivity of 95.3%, resulting in a power generation of 147.8 W/m² for the radiative cooling PV (RCPV) module. A comparison of this module's power efficiency under various environmental conditions with bare crystalline silicon solar cells and covered glass covers indicated that the PV surface temperature was 10.3 K lower in our module, closely approximating the ideal scheme. This innovative approach offers a pathway for enhancing the efficiency and sustainability of PV systems, contributing to the broader adoption of solar energy in combating climate change.

Keywords: Radiative cooling, Solar cell, Structural optimization

NONMENCLATURE

Abbreviations

Radiative cooling	RC
PDMS films with a randomly doped particle structure	PDMS-p
PDMS films with randomly doped soda glass particle structure	PDMS-SG
Photovoltaic	PV

Symbols

d	Particle diameter
f_v	Volume fraction
t	Film thickness
$\overline{\varepsilon}_{\mathrm{LWIR}}$	"Sky window" emissivity
$\overline{\tau}_{\mathrm{solar}}$	Solar transmittance

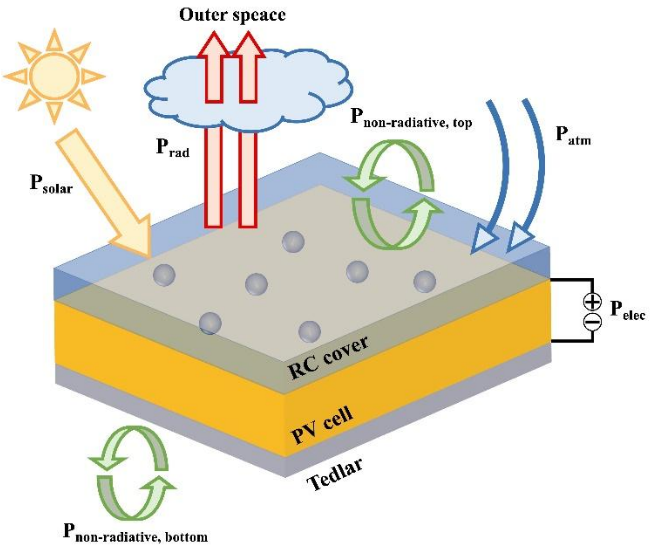

Fig. 1. Schematic diagram of a solar cell covered with radiative cooling film with randomly doped particle structure

1. INTRODUCTION

Harnessing the power of renewable energy is key in addressing climate change and ensuring a secure energy future. Solar energy stands out among renewable energy sources due to its ubiquity and immense potential [1]. Photovoltaic (PV) power systems, which convert sunlight directly into electricity, play an essential role in utilizing solar energy. The International Energy Agency (IEA) predicts that global PV capacity will reach 1,721 GW by 2030 and surge to 4,670 GW by

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2050. However, due to efficiency constraints, only a fraction of the solar radiation is converted into electricity, with the remainder dissipating as heat. This rise in temperature not only decreases power output, but also affects the overall performance and lifespan of the system [2].

Effective thermal management solutions are needed for solar cells. Existing cooling methods, such as jet impingement and thermoelectric cooling, often require significant energy inputs and maintenance, adding to operational costs [3]. To address this, radiative cooling, which provides passive cooling without requiring extra energy, has been explored. The concept of radiative cooling utilizes a transparent atmospheric window to transmit thermal radiation into space. The efficacy of radiative cooling emitters, however, depends on the transmittance of the solar spectrum to avoid any interference with the solar cells' absorption of solar radiation [2]. While theoretical and experimental studies suggest that radiative cooling can lower cell surface temperature, the fabrication of these emitters of the currently studied often involves complex and costly techniques, hindering their scalability and application. To accelerate the practical implementation of these emitters in PV, it is necessary to develop cost-effective, scalable solutions. One promising alternative is to use randomly doped particle structures, which are not only simpler to design but are also compatible with existing manufacturing technologies [4]. However, further investigation is needed to understand how microstructures affect the performance of these emitters.

This study focuses on designing a radiative cooling overlay for solar cells using a randomly doped particle structure, as shown in Fig. 1. We numerically investigate the solar transmissivity and emissivity of the film using the Mie theory and the Monte Carlo method. The results suggest that optimized design can effectively lower the operating temperature of silicon solar cells, improving their efficiency and power output while reducing complexity and cost. The findings also provide valuable insights into the future integration of these systems into energy infrastructures.

2. METHODS

In this study, Polydimethylsiloxane (PDMS) is used as a substrate for a film with randomly distributed particles to enhance the radiative cooling of solar cells. The radiative properties of the particles within the film are evaluated using Mie theory and Maxwell's equations [5]. The article models radiative transfer within the film to determine its transmittance and emissivity by solving the radiative transfer equation using a Monte Carlo method. Additionally, the electrical efficiency of solar cells incorporating the radiative cooling film is evaluated by considering the radiative cooling power, the electrical power generated, and the incident solar power, along with the heat diffusion equation to simulate temperature distribution [6].

3. *RESULTS AND DISCUSSION*

3.1 Model validation

In our previous studies [4], the accuracy of combining Mie theory with the Monte Carlo method for calculating radiative transfer properties has been established. The model has been demonstrated to effectively determine the solar transmittance and infrared emissivity of RC films. To further validate the PV efficiency model, results from the literature were chosen for comparison with the model outcomes, using a visibly transparent ideal thermal emitter covered by a PV cell as the test case. Fig. 2 presents a comparison between the results obtained from the proposed PV efficiency model and those found in the literature [6]. The average deviation between the method and the experimental data is within 1.1%, demonstrating that the model can reasonably predict the temperature of the PV panel under various environmental conditions.

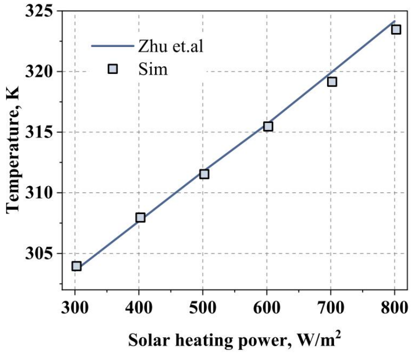

Fig. 2. Validation of heat transfer model for PV module surface temperature

3.2 Doped particle material selection

PDMS films with a randomly doped particle structure (PDMS-p) are required to demonstrate high solar transmittance and considerable "sky window" emissivity. Consequently, the chosen doped particles should display minimal absorption and maximal transmittance in the solar band, ideally with the material's extinction coefficient in this band being extremely low or nearly zero. On the other hand, to achieve high emissivity in the mid-infrared band, the material should exhibit a substantial extinction coefficient in this band. The performance of various films is evaluated using the "sky window" emissivity $\overline{\varepsilon}_{\mathrm{LWIR}}$ and the solar transmittance $\overline{\tau}_{\mathrm{solar}}$. These quantities are defined as follows

$$\overline{\varepsilon}_{\mathrm{LWIR}} = \frac{\int_{8\mu\mathrm{m}}^{13\mu\mathrm{m}} I_{\mathrm{bb}}(T,\lambda)\varepsilon(T,\lambda)\mathrm{d}\lambda}{\int_{8\mu\mathrm{m}}^{13\mu\mathrm{m}} I_{\mathrm{bb}}(T,\lambda)\mathrm{d}\lambda} \tag{1}$$

$$\overline{\tau}_{\mathrm{solar}} = \frac{\int_{0.3\mu\mathrm{m}}^{2.5\mu\mathrm{m}} I_{\mathrm{AM1.5}}(\lambda)\tau(\lambda)\mathrm{d}\lambda}{\int_{0.3\mu\mathrm{m}}^{2.5\mu\mathrm{m}} I_{\mathrm{AM1.5}}(\lambda)\mathrm{d}\lambda} \tag{2}$$

This study considers candidate doping materials including TiO_2, Ta_2O_5, Soda glass, SiO_2, PVC, and PS, with the optical constants of these materials obtained from RefractiveIndex.INFO [7]. The solar transmittance and "sky window" emissivity of various PDMS-p films were calculated using a doping particle size d of 6 μm, volume fraction f_v of 4%, and a film thickness t of 75 μm as a case study, as illustrated in Fig. 3. The figure reveals that among the candidate materials, soda glass delivers the highest solar transmittance and "sky window" emissivity. Furthermore, Soda glass is a prevalent glass type, constituting over 90% of the global market, thus offering excellent availability and cost-effectiveness. Given these considerations, Soda glass was ultimately selected as the dopant materials.

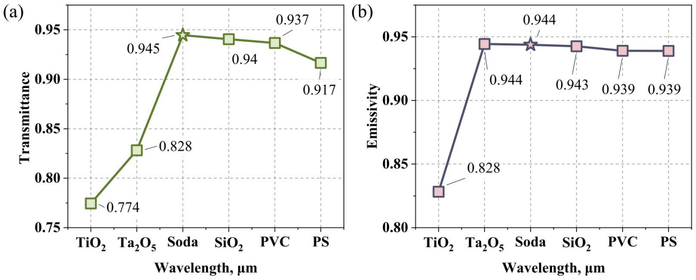

Fig. 3. Comparison of radiative properties among candidate doping materials.

3.3 Structural Parameter Influence on the Radiative Properties

To further investigate the coupling effects of different parameters, solar transmittance and "sky window" emissivity were calculated across an array of volume fractions (1-4%), particle diameters (4-10 μm), and thicknesses (50-150 μm). As depicted in Fig. 4, PDMS-SG films display superior solar transmittance when doped with smaller particle diameters and volume fractions within the studied range. However, the "sky window" emissivity appears to be largely indifferent to these parameters, primarily hinging on the film thickness. The maximum achievable solar transmittance and "sky window" emissivity of PDMS-SG films within the studied range were 94.8% and 95.3%, respectively.

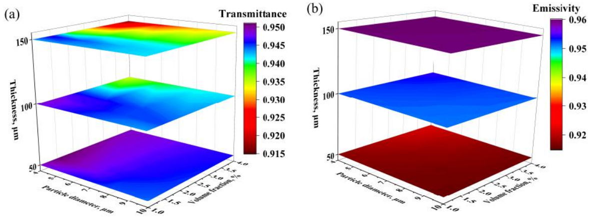

Fig. 4 Effect of the microstructure of RC films on (a) solar reflectance and (b) “sky window” emissivity.

3.4 Performance Analysis and Environmental Adaptability of RCPV

The power generation of radiative cooling photovoltaic (RCPV) modules with varying structural parameters was calculated. As illustrated in Fig. 5, the color contour plots detail the power generation across different thicknesses of radiative cooling (RC) films integrated with photovoltaic (PV) modules. These plots distinctly illustrate the variability of power generation contingent upon volume fraction and particle diameter. Intriguingly, the RCPV module exhibits peak power generation efficiency when parameters are optimized - with an RC film thickness of 100 μm, a doped particle diameter of 4 μm, and a volume fraction of 1.5%. Under these conditions, power generation can reach a maximum of 147.8 W/m^2.

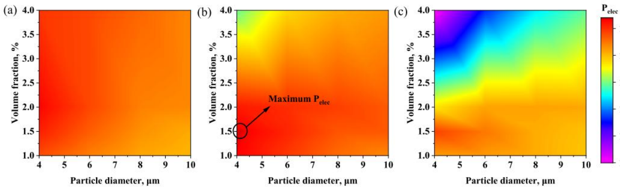

Fig. 5 Variation of power generation in RCPV modules for different RC film thicknesses: (a) 50 μ m, (b) 100 μ m, (c) 150 μ m

Furthermore, it was imperative to assess the performance of RCPV components under varying environmental conditions. Consequently, we calculated the panel surface temperatures of RCPV modules designed with optimal structural parameters under diverse environments, and juxtaposed these with the heat dissipation scheme that employs a glass cover and that of bare crystalline solar cells. Fig. 6 elucidates the variation in cell surface temperatures for these three schemes in the context of distinct environmental conditions. Notably, the figure reveals that the RCPV module consistently maintains a substantially lower solar cell surface temperature compared to both the glass cover thermal solution and the bare crystalline solar cell under corresponding environmental parameters. This underscores the efficacy of the RC thin film integrated with an optimized structural design in significantly reducing operating temperatures, thereby catalyzing an enhancement in power generation efficiency. This finding is pivotal as it opens avenues for deploying RCPV modules in diverse environments to achieve optimal performance.

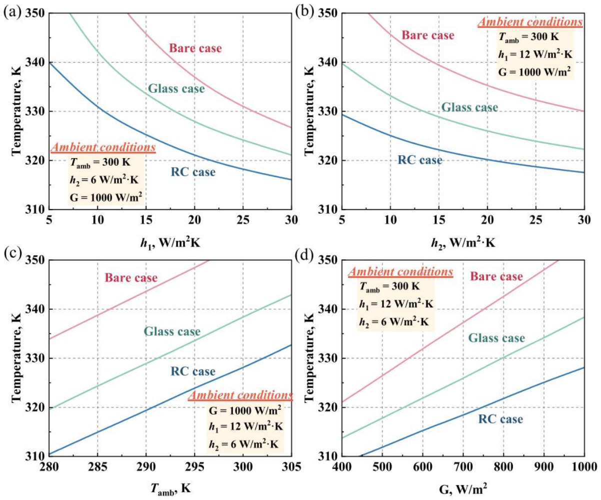

Fig. 6 Variation of Cell Surface Temperatures in RCPV Modules: Influence of Environmental Factors (a) h1, (b) h2, (c) Tamb, and (d) G.

4. CONCLUSIONS

This study presents an in-depth investigation into the incorporation of radiative cooling technology within photovoltaic (PV) systems using randomly doped particle structures. The integration of radiative cooling films made from PDMS and Soda glass as the dopant material demonstrated a significant reduction in the operating temperature of the solar cells, which is instrumental in enhancing power generation and the overall efficiency. The optimal structural parameters for the radiative cooling film were determined to be a thickness of 100 μm, a doped particle diameter of 4 μm, and a volume fraction of 1.5%. Under these conditions, a peak power generation of 147.8 W/m² was attained. Moreover, the comparative analysis showed that the radiative cooling photovoltaic (RCPV) module's surface temperature was significantly lower than that of traditional cooling solutions, underlining the effectiveness of the proposed approach.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] S.H. Lin, L. Ai, J. Zhang, T.L. Bu, H.G. Lia, F.Z. Huang, J. Zhang, Y.H. Lua, W.J. Song (2019) Silver ants-inspired flexible photonic architectures with improved transparency and heat radiation for photovoltaic devices. Sol. Energy Mater Sol. Cells 203: 110135. https://doi.org/10.1016/j.solmat.2019.110135

[2] X. Sun, T.J. Silverman, Z. Zhou, M.R. Khan, P. Bermel, M.A. Alam (2017) Optics-based approach to thermal management of photovoltaics: selective-spectral and radiative cooling, IEEE J. Photovoltaics 7: 566 – 574. https://doi.org/10.1109/JPHOTOV.2016.2646062

[3] M. Li, D. Zhong, T. Ma, A. Kazemian, W.B. Gu (2020) Photovoltaic thermal module and solar thermal collector connected in series: Energy and exergy analysis, Energy Convers. Manag. 206: 112479. https://doi.org/10.1016/j.enconman.2020.112479

[4] M. Du, M.Q. Huang, X.Y. Yu, X.J. Ren, Q. Sun (2022) Structure Design of Polymer-Based Films for Passive Daytime Radiative Cooling, Micromachines, 13:2137. https://doi.org/10.3390/mi13122137

[5] S. Wen, H. Qi, Y. Li, Y. Ren, L. Ruan (2020) An on-line extended Kalman filtering technique for reconstructing the transient heat flux and temperature field in twodimensional participating media. Int. J. Therm. Sci. 148: 106069. https://doi.org/10.1016/j.ijthermalsci.2019.106069

[6] L.X. Zhu, A. Raman, K. X. Wang, M.A. Anoma, S.H. Fan (2014) Radiative cooling of solar cells, Optica 1: 32-38. https://doi.org/10.1364/OPTICA.1.000032

[7] M. Polyanskiy, RefractiveIndex.INFO, [Online; accessed on <2023.05>] (2023). URL https://refractiveindex.info\