Cement-Based Radiative Coolers for Photovoltaics: Towards a Practical Design

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Cement-Based Radiative Coolers for Photovoltaics: Towards a Practical Design

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ABSTRACT

In 2014, the experimental realization of radiative coolers capable of reaching sub-ambient temperatures under direct sunlight has opened up new possibilities for the thermal management of solar cells. Radiative coolers eject excess heat by emitting thermal radiation within the so-called atmosphere transparency window. The completely passive nature of this process and its reliance on material properties only, make radiative coolers extremely attractive in terms of energy efficiency. Integrated with a photovoltaic cell, the radiative cooler can reduce the cell operating temperature, leading to high efficiency and lifetime gains. Yet, most radiative coolers in the literature are metamaterials with scarce elements or complex fabrications processes, or organic materials with potential UV instability, with questionable economic viability or reliability. To address this problem, we have recently proposed cement-based materials as a low-cost, scalable and stable solution for photovoltaics cooling, showing that their electromagnetic properties can be tuned to maximize their thermal emissivity by acting on their microstructure. In particular, using a detailed balance model, we have demonstrated that their cooling performance could increase the efficiency of silicon solar cells by up to 9% and extended their lifetime by up to 4 times. In this work, we take a further step towards the experimental realization of this attractive concept, by investigating possible approaches, requirements and prospects for the practical design of photovoltaic systems employing cement-based radiative coolers.

KEYWORDS: *cements and concretes, radiative cooling, solar cells, thermal simulations, electromagnetic simulations*

1. Introduction

In the last decade, radiative cooling has become a very attractive thermal management solution for buildings and solar cells (Zeyghami, Goswami, and Stefanakos 2018), after the experimental demonstration of sub-ambient temperatures under direct sunlight in 2014 (Raman et al. 2014). Radiative coolers are designed to emit a large amount of thermal radiation within the so-called atmosphere transparency window (AW). In this wavelength range between 8 and 13 µm, radiation propagates undisturbed toward outer space. By ejecting energy through this channel, radiative coolers can get rid of excess heat permanently and reduce their own temperature (Li and Fan 2019). Radiative coolers can be thermally coupled to a solar cell in the planar configuration shown in Figure 1. The cooler slab captures the excess heat generated within the cell during operation and ejects it from the system, reducing the temperature of the cell. This provides the two-fold advantage of increasing the solar cell efficiency and extending its lifetime (Zhu et al. 2014).

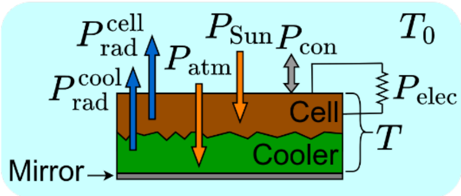

Figure 1. Solar cell with radiative cooler in planar configuration. The energy exchange terms entering the detailed-balance model used to determine the system operating temperature T are depicted. In particular, P_{Sun} is the power density absorbed by the cell from the Sun, P_{atm} is the one absorbed by the cooler from the atmosphere, $P_{\mathrm{rad}}^{\mathrm{cell}}$ and $P_{\mathrm{rad}}^{\mathrm{cool}}$ are the power densities emitted by the cell and the cooler, P_{elec} is the electrical power density delivered by the cell to the end user, P_{con} is the power density exchanged by the system with the environment by conduction/convection, and T_0 is ambient temperature.

Different kinds of radiative coolers have been proposed in the last few years (Hossain and Gu 2016), the most common ones being metamaterials made of stratified thin films or thick layers with a micro-patterned surface. Unfortunately, these technologies suffer from the use of scarce materials or expensive manufacturing processes, that might hinder scalability. Organic materials have been proposed as a low-cost alternative (Mandal et al. 2018), but their application might be jeopardized by UV-instability.

Looking for an alternative combining efficiency, low-cost and stability, we have recently proposed cementitious materials as extremely promising radiative coolers (Cagnoni, Tibaldi, Testa, et al. 2022; Cagnoni, Tibaldi, Dolado, et al. 2022), in the context of the EU-funded project MIRACLE (European Commission, n.d.). Not only cement-based solutions are cheap, scalable and robust, but also the complex nature of these materials, consisting of a heterogeneous porous matrix fillable with aggregates, provides many tuning knobs, from chemical to micro-structural modifications, to tailor their properties to fit radiative cooling applications. In our previous work, we have studied the interplay between microstructure and thermal radiation in slabs produced by alite hydration, used this knowledge to maximize their emissivity within the atmospheric window, and estimated their performance limit for the thermal management of solar cells, obtaining an impressive temperature reduction of 20 K for silicon-based devices, comparable with the more expensive metamaterials.

In this proceeding, we complement the aforementioned study focused on optimizing the cement-paste microstructure at fixed slab geometry (thickness = 100 μm, roughness = 0), by investigating the impact of thickness and roughness on the slab emission properties and cooling performance; this let us define geometric design rules for the cement slab.

2. Methodology

For this study, we have considered the cementitious material having the highest emissivity in the AW, characterized by (R_{CSH}, R_{CH}) = (0.6, 2.3) μm in our previous work (Cagnoni, Tibaldi, Dolado, et al. 2022); R_{CSH} and R_{CH} quantify the average size of the CSH and CH sub-domains forming the heterogeneous cement paste. The spectral directional absorbance/emissivity $A_{\Omega,\lambda}^{\mathrm{cool}}(\lambda,\theta)$ of a slab made of it has been determined as a function of thickness and roughness by inserting the previously determined complex permittivity into the transfer-matrix model (TMM) described in (Katsidis and Siapkas 2002), reformulated into scattering-matrix form to ensure numerical stability at large thickness and roughness.

Then, the calculated $A_{\Omega,\lambda}^{\mathrm{cool}}(\lambda,\theta)$ has been introduced into a detailed-balance model describing the energy exchange between cell, cooler, environment and end user as a function of the system temperature, by means of the power density terms introduced in Figure 1 and given by (Perrakis et al. 2021):

$$P_{\mathrm{Sun}} = \int_0^{hc/E_g} \mathrm{d}\lambda\, E_{e,\lambda}^{\mathrm{Sun}}(\lambda) \tag{1a}$$

$$P_{\mathrm{rad}}^{\mathrm{cell}} = \pi \int_0^{hc/E_g} \mathrm{d}\lambda\, L_{e,\Omega,\lambda}^{BB}\left(\lambda, T, V_{\mathrm{MPP}}(T, E_g)\right) \tag{1b}$$

$$P_{\mathrm{elec}} = J_{\mathrm{MPP}}(T, E_g)\, V_{\mathrm{MPP}}(T, E_g) \tag{1c}$$

$$P_{\mathrm{atm}} = \int_0^{2\pi} \mathrm{d}\Omega \int_0^{+\infty} \mathrm{d}\lambda \cos\theta\, A_{\Omega,\lambda}^{\mathrm{atm}}(\lambda,\theta)\, A_{\Omega,\lambda}^{\mathrm{cool}}(\lambda,\theta)\, L_{e,\Omega,\lambda}^{\mathrm{BB}}(\lambda, T_0) \tag{1d}$$

$$P_{\mathrm{rad}}^{\mathrm{cool}} = \int_0^{2\pi} \mathrm{d}\Omega \int_0^{+\infty} \mathrm{d}\lambda \cos\theta\, A_{\Omega,\lambda}^{\mathrm{cool}}(\lambda,\theta)\, L_{e,\Omega,\lambda}^{\mathrm{BB}}(\lambda, T) \tag{1e}$$

$$P_{\mathrm{con}} = h_c\,(T - T_0) \tag{1f}$$

where E_g is the solar cell band-gap, $E_{e,\lambda}^{\mathrm{Sun}}$ is the Sun spectral irradiance, $L_{e,\Omega,\lambda}^{BB}$ is the black-body spectral radiance, J_{MPP} and V_{MPP} are the solar cell current density and voltage at maximum-power-point calculated according to the Shockley-Queisser model, $A_{\Omega,\lambda}^{\mathrm{atm}}(\lambda,\theta)$ is the atmosphere spectral directional absorbance/emissivity, h_c is the conduction/convection coefficient, and Ω and θ are the solid and zenith angles. The solar cell temperature T is obtained by solving the equation:

$$P_{\mathrm{rad}}^{\mathrm{cell}} + P_{\mathrm{rad}}^{\mathrm{cool}} + P_{\mathrm{elec}} - P_{\mathrm{Sun}} - P_{\mathrm{atm}} + P_{\mathrm{con}} = P_{\mathrm{net}}(T) = 0 \tag{2}$$

3. Results and Discussion

Figure 2 summarizes our findings. First, the spectral emissivity (angularly-averaged) of the cement-based slab as a function of thickness is depicted on the left for the case of a smooth surface. As expected, increasing the thickness enhances the emission properties and enables one to approach unit emissivity within the AW. Interestingly, one can obtain significant emission also for non-bulk thickness, even lower than the previously studied case of 100 µm. However, as a thickness of a few micrometers is approached, the layer starts to become transparent and the emission properties are lost. Although a very large thickness (~ cm) can be easily achieved for cementitious materials, sub-mm geometries can be an advantage for integrating the cement-based cooler into the photovoltaic system. Moreover, our results show that the emission loss due to a reduced thickness can be compensated for by a controlled surface roughness (Figure 2, center). For example, unit emissivity can be achieved with a 100 µm layer having approximately 2% roughness (RMS). Finally, the right image of Figure 2 shows the temperature reduction experienced by a solar cell when coupled to the cement-paste under study with the structural features reported in the legend. Clearly, a too much thin layer is unable to provide an appreciable cooling performance. On the other hand, little difference is found between the previously studied case of 100 µm and a much thicker layer (10 cm), which is encouraging concerning the possibility of integrating a cement-based radiative cooler with a solar cell. Remarkably, we observe that a realistic roughness (2%) enables one to reach the temperature reduction brought by an ideal solar cell radiative cooler (black-body in IR spectral range (Zhao et al. 2019)).

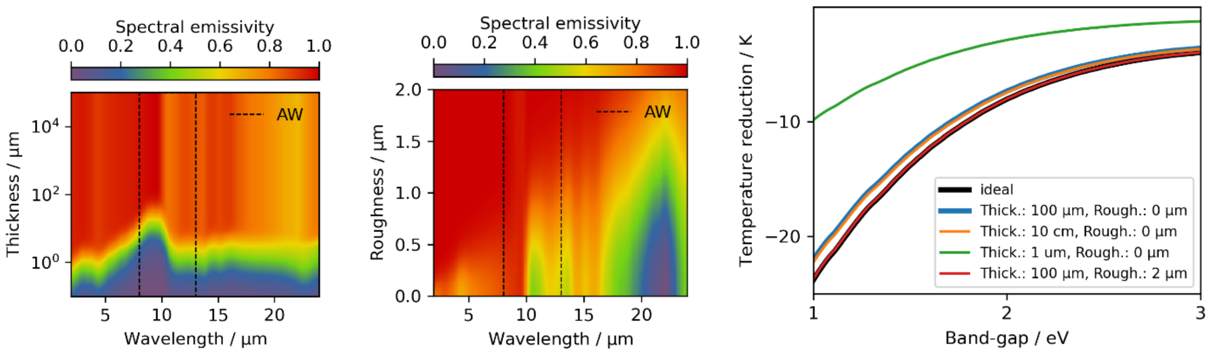

Figure 2. Spectral emissivity of cement-based radiative coolers vs thickness (left) and roughness (center, 100 µm thickness), and solar cell temperature reduction vs bandgap (right) for different thickness-roughness values. The atmospheric window (AW) is highlighted, as well as the temperature reduction brought by an ideal cooler.

4. Conclusions

Cement-based materials are a very attractive solution for realizing radiative coolers for the thermal management of solar cells because their thermal emissivity can be optimized by tuning their micro-structure. In this work, we have systematically studied the impact of the cement slab geometry on the cooling performance of a practical system consisting of a solar cell mounted on top of a cement slab. Interestingly, we have confirmed that satisfying cooling performance can be preserved by resorting to relatively small thickness, which is encouraging in view of integration of cement-based radiative coolers into photovoltaic systems. Furthermore, we have shown that possible emissivity losses due to the reduced size of the cooler can be compensated for by introducing a controlled surface roughness, which leads to enhanced emission and enable us to approach ideal emissivity and significant solar cell temperature reduction. These findings bring us closer to the practical realization of this concept, by clarifying structural design requirements for the cement-based radiative cooler. Therefore, high efficiency and lifetime gains could be pursued by photovoltaic systems integrating radiative coolers relying on the cheap, scalable and robust class of cementitious materials.

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