Radiative Cooling of Solar Cells with Cement-Based Materials

RADIATIVE COOLING OF SOLAR CELLS WITH CEMENT-BASED MATERIALS

Matteo Cagnoni[a,1], Pietro Testa[a,2], Jorge S. Dolado[b,c,3] and Federica Cappelluti[a,4]

[a]Department of Electronics and Telecommunications, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Turin, Italy
[b]Centro de Física de Materiales, CSIC-UPV/EHU, Paseo Manuel de Lardizabal 5, San Sebastián 20018, Spain
[c]Donostia International Physics Center, Paseo Manuel de Lardizabal 4, San Sebastián 20018, Spain

[1]matteo.cagnoni@polito.it, [2]pietro.testa@polito.it, [3]j.dolado@ehu.eus, [4]federica.cappelluti@polito.it

ABSTRACT: Lowering the operating temperature of solar cells can increase efficiency and lifespan of these devices. Among the available thermal management options, radiative cooling shines because of its passive nature and systemic simplicity. Unfortunately, the applicability of most radiative coolers to industrial manufacturing is questioned by high cost or UV instability. We have recently shown that stable and cost-effective cement-based materials can be designed to be suitable radiative coolers for solar cells. However, we have done so in line with the literature, by modeling the solar cell in the radiative limit and neglecting the thermal contact resistance at the cell/cooler interface, which might actually be large enough to hinder heat transfer because of the poor adhesion properties of cement-based materials. In this work, we have generalized the model used to assess radiative coolers by incorporating solar cell non-radiative losses (Auger, Shockley-Read-Hall) and a thermal barrier between cell and cooler. The final model provides a description of the thermal behavior of a solar cell with radiative cooler closer to reality, while preserving the transparency of the detailed-balance approach, that has allowed us to better assess these systems and provide design guidelines, with focus on cement-based radiative coolers.
Keywords: solar cells, radiative cooling, cement-based materials, detailed-balance principle

1 INTRODUCTION

Radiative cooling has been drawing a lot of attention in the last decade as a thermal management solution for buildings and solar cells [1], after the experimental demonstration of sub-ambient temperatures under direct sunlight [2]. Radiative coolers are designed to dump excess heat directly into outer space by emitting thermal radiation within the atmosphere transparency window (AW) between 8 and 13 µm [3]. When thermally coupled to a solar cell, a radiative cooler can reduce the cell temperature by collecting the excess heat generated upon sunlight absorption and thermally radiating it out of the device [4]. This approach is extremely attractive because of potential efficiency and systemic simplicity, but its applicability beyond research is questioned by the reliance on expensive materials [5] or fabrication processes [6], or on organic polymers with potential UV instability [7].

Faced with this challenge, we have recently shown that, from an electromagnetic perspective, cement-based materials could be ideal candidates for highly effective radiative coolers of solar cells, fulfilling also economic and stability requirements for large-scale deployment [8]–[10]. In particular, by combining chemical kinetics, molecular mechanics, effective-medium theory and electromagnetic simulations, we have first explained how these materials can be equipped with optimal thermal emissivity by tuning their micro-structure. Then, we have shown how they can be exploited in a system like the one depicted in Figure 1 to reduce the temperature of standard silicon cells by up to 20 K, *de-facto* matching the performance of much more expensive meta-materials. The system in Figure 1 corresponds to the detailed-balance model commonly employed in the literature [11] to determine the operating temperature of a solar cell with a radiative cooler, by describing the energy exchange between cell, cooler, environment and end-user.

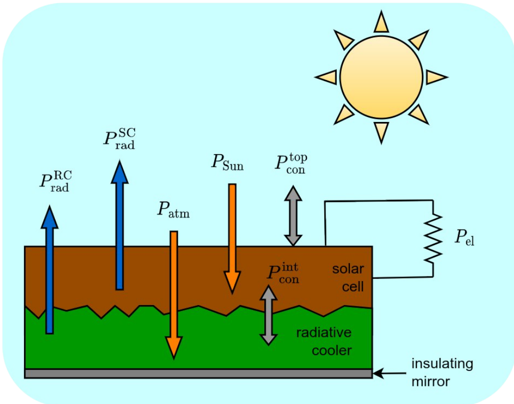

Figure 1: Solar cell with radiative cooler. The terms entering the corresponding detailed-balance model are shown.

Experimental realization of this concept would be technologically disruptive, since it could lead to efficiency relative gains up to 9% [12] and lifetime prolongation up to 4 times [13] at a very small additional cost, thanks to the reliance on cheap, available, stable and scalable materials.

In this work, we have extended the analysis done in [9] by including relevant non-idealities in the photovoltaic and thermal models, to obtain a more accurate evaluation of the cooling capability and derive useful guidelines at material/device level toward the practical realization of solar cells with cement-based radiative coolers.

First, the performance of radiative coolers is commonly assessed by describing the solar cell with the Shockley-Queisser model in the radiative limit [9], [11]. However, intrinsic and extrinsic non-radiative recombination mechanisms such as Auger [14] and Shockley-Read-Hall (SRH) [15] are often more prominent and strongly temperature dependent. By incorporating these terms into the description of the cell, we have obtained a thermal model for the whole system much closer to reality. Furthermore, by introducing these terms in a simple parametric form, we have eschewed the use of specific solutions and treated the problem on a rather general footing, which can provide the researchers with a broader view.

Second, the system is usually assumed to be isothermal in its stationary state, with a perfect thermal contact between the cell and the cooler. However, cement-based materials usually exhibit poor adhesion to surfaces [16], suggesting that the thermal resistance at the cell/cooler interface might be non-negligible; this might happen also in the case of good adhesion because of acoustic mismatch [17]. Unfortunately, a poor thermal contact is going to hinder heat transfer from the cell to the cooler, hence worsening the cooling performance. By extending the detailed-balance model to incorporate the effect of the thermal contact resistance at the cell/cooler interface, we have enabled a better assessment of the potential of cement-based radiative coolers and the definition of thermal contact requirements.

The extended detailed-balance model hereby developed should not be intended as applicable to cement-based radiative coolers only, but to any kind of radiative cooler, as long as the cooler-dependent quantities (*e.g.*, emissivity) are adapted to the specific case under consideration.

2 METHODS

In case of perfect thermal contact between cell and cooler, the net power density P_{net} ejected by the cell/cooler stack in terrestrial environment can be calculated as:

$$P_{\mathrm{net}} = P_{\mathrm{rad}}^{\mathrm{SC}} - P_{\mathrm{Sun}} + P_{\mathrm{el}} + P_{\mathrm{rad}}^{\mathrm{RC}} - P_{\mathrm{atm}} + P_{\mathrm{con}}^{\mathrm{top}}$$

where $P_{\mathrm{rad}}^{\mathrm{SC}}$ is the power density radiated by the solar cell, P_{Sun} the one absorbed from the Sun, P_{el} the one delivered to the end-user, $P_{\mathrm{rad}}^{\mathrm{RC}}$ the one radiated by the cooler, P_{atm} the one absorbed from the atmosphere, and $P_{\mathrm{con}}^{\mathrm{top}}$ the one exchanged with the environment by conduction and convection at the device top surface.

Explicit formulas to calculate these terms can be found in [9]. In particular, $P_{\mathrm{el}} = \max_V\{J(V)\,V\}$ can be obtained as the power density at maximum-power-point, where the $J(V)$ relation is usually described in the radiative limit considered by the original Shockley-Queisser model [18].

In this work, we have first improved the description of the cell/cooler system by incorporating Auger and Shockley-Read-Hall non-radiative recombination into $J(V)$ according to the models developed in [14] and [15], respectively. Interestingly, by performing some algebraic manipulations, we could separate the dependence on temperature of these terms from the one on the solar cell band-gap E_g and the one on material- and technology-related parameters (*e.g.*, effective density-of-states, depletion region thickness). Then, we have incorporated the latter into a single parameter for each non-radiative recombination channel, denoted as β_{AUG} and β_{SRH}, which quantifies the T-normalized strength of the losses associated to the corresponding mechanism. More details on the math can be found in the Full Paper [19].

Finally, this approach has let us express P_{net} only as a function of the solar cell operating temperature T and the triplet $\left(E_g, \beta_{\mathrm{AUG}}, \beta_{\mathrm{SRH}}\right)$, given the emissivity of the radiative cooler and the environmental conditions. Then, one can determine the solar cell operating temperature T as a function of $\left(E_g, \beta_{\mathrm{AUG}}, \beta_{\mathrm{SRH}}\right)$ by solving $P_{\mathrm{net}} = 0$ with respect to T.

As a second extension, we have introduced a finite thermal contact resistance at the cell/cooler interface, to empirically account for acoustic mismatch and poor adhesion properties, quantified by the heat transfer coefficient h_c^{int}. Because of this, solar cell and radiative cooler are not isothermal anymore, having temperature T_{SC} and T_{RC}, respectively. Their net power densities are coupled through $P_{\mathrm{con}}^{\mathrm{int}}\left(T_{\mathrm{SC}}, T_{\mathrm{RC}}\right) = h_c^{\mathrm{int}}\left(T_{\mathrm{SC}} - T_{\mathrm{RC}}\right)$, as depicted in Figure 1. Their operating temperatures are again determined by the condition of zero net power density [20] according to the following system of equations, which we have used to study the impact of h_c^{int} on T_{SC} in the radiative limit:

$$\begin{cases} P_{\mathrm{net}}^{\mathrm{SC}}\left(T_{\mathrm{SC}}, T_{\mathrm{RC}}\right) = P_{\mathrm{rad}}^{\mathrm{SC}} - P_{\mathrm{Sun}} + P_{\mathrm{el}} + P_{\mathrm{con}}^{\mathrm{top}} + P_{\mathrm{con}}^{\mathrm{int}} = 0 \\ P_{\mathrm{net}}^{\mathrm{RC}}\left(T_{\mathrm{SC}}, T_{\mathrm{RC}}\right) = P_{\mathrm{rad}}^{\mathrm{RC}} - P_{\mathrm{atm}} - P_{\mathrm{con}}^{\mathrm{int}} = 0 \end{cases}$$

3 RESULTS

Although the methods developed are applicable to any radiative cooler, we have hereby considered the best cement-paste from our previous work [9] to perform the numerical calculations, as discussed in more detail in [19].

First, we have calculated the temperature reduction provided by the cement-based radiative cooler to the solar cell as a function of band-gap and strength of the non-radiative recombination losses, by calculating and comparing the cell operating temperature with and without radiative cooler; we have assumed that cell and cooler are isothermal.

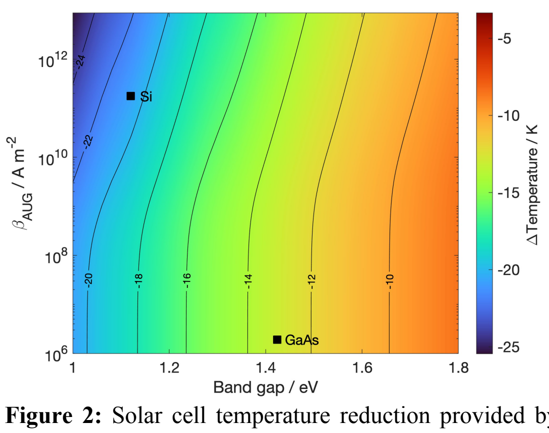

Figure 2: Solar cell temperature reduction provided by the considered cement-based radiative cooler as a function of band-gap and strength of the Auger recombination losses, for negligible SRH losses.

Figure 2 shows the results for the cases with negligible Shockley-Read-Hall recombination, *i.e.*, $\beta_{\mathrm{SRH}} = 0$. Interestingly, the temperature reduction provided by the radiative cooler increases for larger values of β_{AUG}, suggesting that the cooling performance of the latter is underestimated in the radiative limit on the one hand, and that the presence of a radiative cooler is more beneficial for solar cells whose behavior departs more from the radiative limit. Clearly, the same conclusions can be reached concerning the efficiency gains provided by the radiative cooler, which are larger for stronger non-radiative recombination because of the larger temperature reduction attainable by the radiative cooler and the larger efficiency temperature coefficient due to increasing non-radiative recombination; this latter point is shown and discussed in more detail in [19]. We have observed a similar behavior for the cases with negligible Auger recombination, *i.e.*, $\beta_{\mathrm{AUG}} = 0$, but $\beta_{\mathrm{SRH}} > 0$ [19], suggesting that these conclusions are qualitatively independent from the non-radiative recombination channels considered.

Second, we have estimated the impact of a finite thermal contact resistance at the cell/cooler interface as a function of the associated heat transfer coefficient h_c^{int}. To minimize the number of parameters affecting the results and preserve a simple data visualization, we have performed this step by modeling the solar cell in the radiative limit.

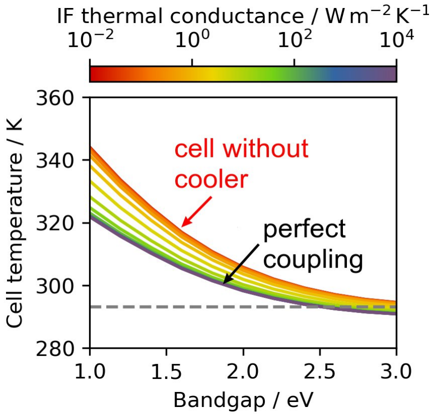

Figure 3: Solar cell operating temperature vs band-gap as a function of the heat transfer coefficient at the cell/cooler interface. The solar cell is modeled in the radiative limit.

Figure 3 shows the solar cell operating temperature T_{SC} as a function of its band-gap E_g for several h_c^{int} values. As expected, as the heat transfer coefficient decreases, the solar cell temperature approaches the one of the system without radiative cooler, suggesting that a too large thermal barrier completely inhibits the effect of the radiative cooler by decoupling it from the solar cell. Although not surprising, this model and the corresponding data allow one to quantify the temperature reduction that can be achieved as a function of the thermal contact resistance and define specifications for the values of the latter depending on the temperature reduction required for the application of interest. Therefore, it provides important design guidelines concerning a critical but often overlooked aspect of these systems. A more in dept discussion can be found in [19].

4 CONCLUSION

In conclusion, we have generalized the detailed-balance model commonly employed in the literature to assess the performance of radiative coolers by incorporating non-radiative recombination losses in the Shockley-Queisser model of the solar cell and by introducing an empirical finite heat transfer coefficient between cell and cooler to model an eventual non-negligible thermal contact resistance at their interface due to acoustic mismatch or poor adhesion properties.

Although general, we have applied this model to the specific case of cement-based materials, in particular to the best cement-based radiative cooler that we have designed in our previous work [9]. Our choice to focus on these materials has been driven by the disruptive potential of this solution due to its stability and low-cost, which are problems affecting current state-of-the-art radiative coolers.

This model extension and the corresponding simulations and data analysis have enabled us to obtain a description of the thermal behavior of a solar cell with radiative cooler closer to reality, while preserving the transparency of the detailed-balance approach, and to better assess these systems while providing design guidelines. Our results show that the beneficial impact of radiative cooling and the subsequent efficiency gain are relevant for all solar cell technologies, but more significant for devices that depart more from operation in the radiative limit. Moreover, some amount of non perfect-thermal coupling between radiative cooler and cell can be accommodated without hindering the cooling performance.

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