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Performance comparison of different emissive layers in a combined photovoltaic-thermal and radiative cooling system

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ABSTRACT

Recent research suggests that the integration of radiative cooling (RC) technology in photovoltaic-thermal (PVT) systems, can improve the overall system efficiency during the day and provide additional cooling at night. Considering the potential benefits of such a combined system, this study measured the improvements that are achieved in a PVT system performance when using an ideally emissive top layer, and compared them to those achieved with regular glass encapsulation. Results showed that enhanced RC in a PVT system reduced the solar cell operating temperature by most 2 °C and increased total exergy efficiency by 0.65% during the day, and also provided an additional 4-8 W/m^2 cooling power at night. Although improvements were achieved in the system performance, it was found that when considering realistic atmospheric conditions and spectral properties, an enhancement in RC does not substantially improve the PVT system performance.

Keywords: Radiative cooling, Solar energy, Photovoltaic thermal, PVT, Exergy efficiency, Spectral emissivity

NOMENCLATURE

Abbreviations	
RC	Radiative Cooling
PV	Photovoltaic
PVT	Photovoltaic-Thermal
IR	Infrared
Symbols	
ε	Emissivity

1. *Introduction*

According to research, a rise in the solar cell operating temperature by just 1 °C results in a PV efficiency reduction of about 0.45% and that the degradation rate of a PV module doubles for every 10 °C rise in operating temperature [1]. These concerns make PV cooling an important area of study to ensure that solar energy systems perform well.

Objects on earth release thermal radiations in the mid-infrared band (3-25 µm), and since this band coincides with the atmospheric window (8-13 µm), which is the region where the atmosphere shows high transmissivity, terrestrial objects can radiate their heat into outer space and eventually get cooled by RC [2].

Apart from the numerous solar cell cooling techniques, RC of solar cells [3, 4] has gained much interest within the research community. This is because of the low cost and simple structure since this cooling method does not require any mechanical or electrical modifications to the overall system. RC technique modifies the emissivity profile of the PV module surface, which enhances heat removal and eventually improves cell efficiency [5, 6].

Another widely popular PV cooling technique, which was first developed in the 1970s, is the PVT system in which excess heat from the solar cell is removed by the fluid flowing underneath, generating electricity and thermal energy simultaneously. Some studies have integrated RC technology into PVT systems and have found a considerable rise in the systems' multi-functionality, total working time, and energy gain per unit area [7-9]. Fig. 1 shows the basic working principles of such combined systems in which thermal energy along with increased electrical efficiency is achieved during the day and additional cooling power is provided at night. According to these studies, the combined PVT and RC system in comparison to the individual PVT system is a promising future technology as it can substantially improve the system overall performance.

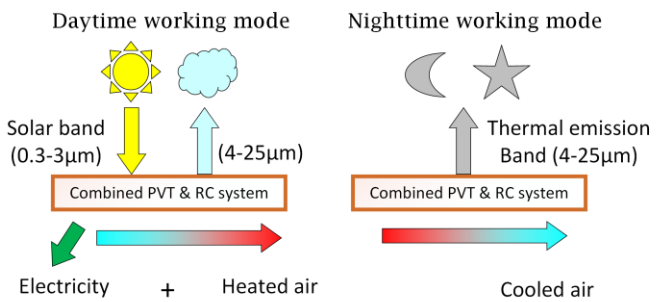

Fig. 1. Combined PVT and RC system that can provide electricity and heating energy during the day and cooling power during night.

Since the commonly used glass encapsulation in commercial PV/PVT systems has a fairly high emittance in the mid-IR band, it naturally has a considerable RC ability. The glass layer can radiate heat on its own without any spectral modifications, and thus the potential of increasing system performance by enhanced RC using novel highly emissive materials seems farfetched. Some studies [1, 10] examined the PV temperature reduction by comparing an ideal emissive surface to a conventional glass surface and found insignificant temperature reduction (about 1 °C). Gentle and Smith [11] compared the steady-state solar cell temperatures under a black body emitter surface and glass surface to assess the impact of hemispherical emissivity. They observed minor temperature reduction and also reasoned how the extra PV cooling achieved in Ref. [3] was made possible since a considerably low value for the emissivity of silica had been used.

In light of the two contrasting viewpoints regarding the feasibility of integrating enhanced RC in PV/PVT systems, this study investigates if substituting glass with an ideally emissive surface as the solar cell encapsulation could provide any significant performance improvement. Firstly, an experimentally verified transient thermal model for a PVT system was developed. Then, by using realistic atmospheric conditions, a comparative analysis between a regular glass layer and an ideal emitter as the module glazing was conducted to evaluate the system performance for daytime and nighttime working modes.

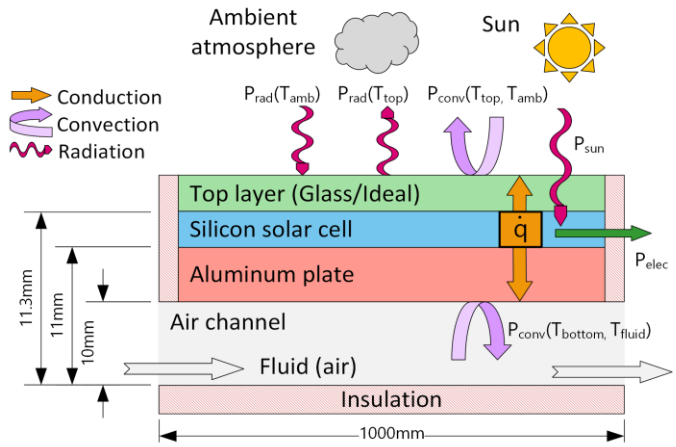

Fig. 2. A cross-sectional view of the combined PVT and RC system showing the dimensions and the boundary conditions used.

2. *Material and methods*

As illustrated in Fig. 2 the module consists of a top layer, silicon solar cells, aluminum plate, air channel, and insulation. The top layer was modified for the two cases considered. The first case hereafter denoted as “glass”, consists of a 3.2 mm glass layer on top of the solar cells as used in commercial PVT systems. The second case hereafter expressed as “ideal”, considers a material with an emissivity of one (ε = 1) in the thermal emission band (4-25 μm). With the recent progress in material science, such novel materials (i.e., photonic structures, nanoparticle-doped, metamaterials, etc.) that have very high emissivity values are a suitable choice for daytime and nighttime RC. The spectral emissivity profile for both cases is illustrated in Fig. 3.

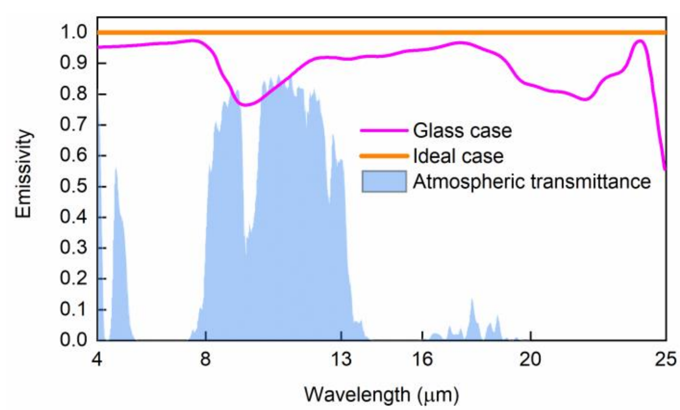

Fig. 3. Spectral emissivity profile for glass (pink) and ideal (orange) case in the mid-infrared band, with the typical atmospheric transmittance (blue) shown as a reference [10].

Since the focus of this study is to calculate the extra cooling gain, a fair comparison is made by taking the absorptivity for both cases to be equivalent in the solar band (0.3-3 μm). Considering the high emissivity of the ideal case, it is expected to radiate comparatively more heat to the sky as the glass case, eventually resulting in a greater temperature reduction of the solar cells during the day, along with incremental cooling at night.

The thermal model of the system was created using conjugate heat transfer and surface-to-surface radiation modules within COMSOL Multiphysics. Spectral profiles for the emissivity of the top surface and the sky were fed in as input functions. The thermal properties of the materials used were taken from the software material library. Boundary conditions used were updated for each time step and have been explained in section 3. Mesh independence was verified using adaptive mesh refinement. The assumptions considered and model accuracy was validated using experimental data from Ref. [12]. It was assumed that:

- Solar cells received all solar radiation absorbed by the top layer.
- Absorptivity and emissivity values were angularly independent.
- Thermal conductivity values were temperature independent.
- The temperature of inlet air in the channel was the same as ambient temperature.

Since a clear sky and dry atmosphere with low wind speed supports RC, weather data for the city of Las Vegas, which has similar atmospheric conditions, was taken from EnergyPlus software and used during the analysis as shown in Fig. 4. The daytime working mode was measured from 7:00 to 17:00 (10 hours) while the nighttime mode was studied from 19:00 to 5:00 (10 hours). Air mass flow rate was taken as 0.01 kg/s, to keep the flow laminar.

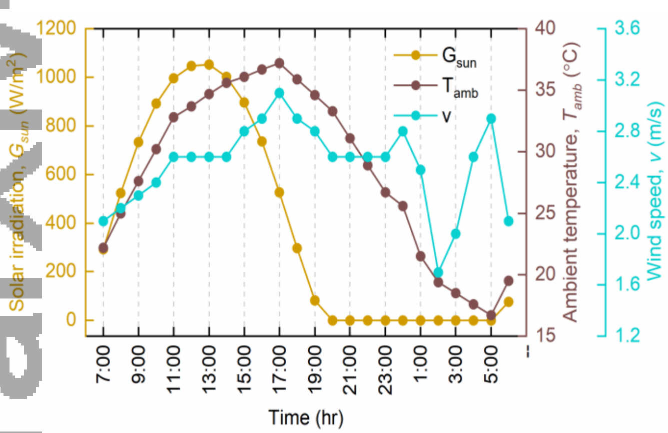

Fig. 4. Weather data for Las Vegas on a typical summer day in June, taken from EnergyPlus software.

3. *Theory/calculation*

Based on the assumptions taken, the heat diffusion equation for the model is expressed as follows [12] :

$$\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

Where T is temperature distribution across the model in vertical (z) direction, K; k is thermal conductivity, W/mK; ρ is density kg/m^3; c_p is specific heat capacity $J/(kgK)$; and $\dot{q}=P_{sun}-P_{elec}$, is the internal heat generated due to the difference between absorbed solar power and extracted electrical power, W/m^2; with P_{sun} being the solar radiation absorbed by the top layer, W/m^2, calculated as $P_{sun}=G_{sun}\alpha$, where G_{sun} is total solar irradiance and α is the absorptivity in solar radiation band taken as 0.9; P_{elec} is the electrical power generated by the solar cells, W/m^2, and is expressed as

$$P_{elec}=G_{sun}\eta_{ref}[1-\beta_r(T_{PV}-T_{ref})] \tag{2}$$

where η_{ref} is the solar cell reference efficiency at standard conditions taken as 0.20; β_r is temperature coefficient of PV efficiency taken as 0.0045 K^{-1}; T_{PV} is the operating temperature of solar cells, K; and T_{ref} is reference temperature, $298.15K$.

The boundary conditions for the top and bottom surfaces of the model are shown in Fig. 2 and evaluated as:

$$-k\frac{\partial T}{\partial z}_{top}=P_{rad}(T_{top})+P_{conv}(T_{top},T_{amb})-P_{rad}(T_{amb}) \tag{3}$$

$$k\frac{\partial T}{\partial z}_{bottom}=P_{conv}(T_{bottom},T_{fluid}) \tag{4}$$

Where $P_{rad}(T_{top})$ is the power radiated out by top surface; $P_{rad}(T_{amb})$ is power absorbed from the ambient atmosphere; $P_{conv}(T_{top},T_{amb})$ and $P_{conv}(T_{bottom},T_{fluid})$ is power removed by convective heat transfer with ambient atmosphere and fluid, respectively. All powers are evaluated in terms of W/m^2.

For performance evaluation, electrical efficiency (η_{elec}) and thermal efficiency (η_{elec}) are evaluated as:

$$\eta_{elec}=\frac{P_{elec}}{G_{sun}} \tag{5}$$

$$\eta_{ther}=\frac{\dot{m}c_p(T_{out}-T_{in})}{G_{sun}} \tag{6}$$

Where $\dot{m}$ is the mass flow rate of fluid, kg/s; T_{in} and T_{out} are the average inlet and outlet temperatures of the working fluid in the channel. For nighttime working mode, system performance is evaluated using cooling power, $P_{cool} = \dot{m}c_p(T_{in} - T_{out})$.

Since electrical energy and thermal energy have different thermodynamic qualities, the total system efficiency (η_{total}) during daytime working mode can be evaluated using exergy efficiency as follows [13]:

$$\in_{total} = \in_{elec} + \in_{ther} \quad (7)$$

Where $\in_{total}$ is total exergy efficiency of the system; $\in_{elec}$ is electrical exergy efficiency; and $\in_{ther}$ is thermal exergy efficiency.

Electrical exergy efficiency $(\in_{elec})$ can be calculated as:

$$\in_{elec} = \frac{X_{elec}}{X_{sun}} \quad (8)$$

Where X_{elec} is electrical exergy rate per unit area, W/m^2 and is the same as P_{elec}; and X_{sun} is the solar exergy rate calculated as $X_{sun} = \left(1 - \frac{T_{amb}}{T_{sun}}\right) G_{sun}$.

Thermal exergy efficiency $(\in_{ther})$ in Eq. (7) is calculated as:

$$\in_{ther} = \frac{X_{ther}}{X_{sun}} \quad (9)$$

where X_{ther} is the thermal exergy rate, W/m^2, calculated as $X_{ther} = \dot{m}c_p \left[(T_{out} - T_{in}) - T_{amb} \ln\left(\frac{T_{out}}{T_{in}}\right) \right]$.

4. Results and discussion

4.1 Daytime performance

Fig. 5 shows that the PV operating temperature (red), T_{PV}, for the ideal case is continuously lower from 0.96 °C to 2 °C than that in the glass case, because of the improved thermal emittance. However, the temperature difference between the outlet and inlet air (blue), denoted by $\Delta T_{out\text{-}in}$, is slightly lower with about 1 °C for the ideal case than the glass case. It can be deduced that the enhanced RC obtained with the ideal case improves the electrical efficiency but simultaneously reduces the thermal efficiency of the system.

Since electricity and heat have different thermodynamic qualities, their combined efficiency is calculated from the viewpoint of exergy, which is the sum of electrical and thermal exergy efficiencies and gives an idea of the overall performance of the system. It can be seen that the total efficiency (black), ε_{total}, of the ideal case is greater than that of the glass case throughout the day. However, the relative difference between them is small (about 0.65 %).

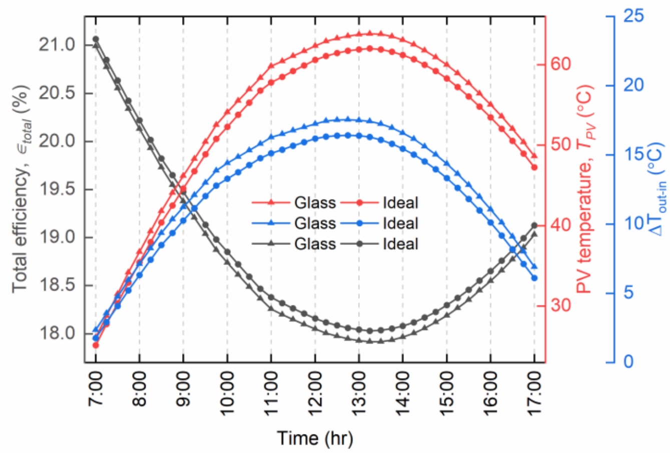

Fig. 5. Daytime performance of the glass and ideal cases, showing the PV operating temperature (red), temperature difference between outlet and inlet air (blue), and total exergy efficiency of the PVT-RC system (black).

4.2 Nighttime performance

During nighttime working mode, sub-ambient cooling is achieved due to the absence of solar irradiation and fall in the ambient temperature. As heat is removed from the top surface of the module, the air in the channel gets cooled, and therefore $\Delta T_{out\text{-}in}$ (blue) shows negative values as seen in Fig. 6. Due to higher emittance, flowing air in the channel for the ideal case cools down more than the glass case, and therefore $\Delta T_{out\text{-}in}$ for the ideal is lower as compared to the glass case. The average temperature of the aluminum plate (red), T_{plate}, that is in direct contact with the flowing air is also calculated. T_{plate} for the ideal case is continuously lower (about 0.9 °C) than the glass case.

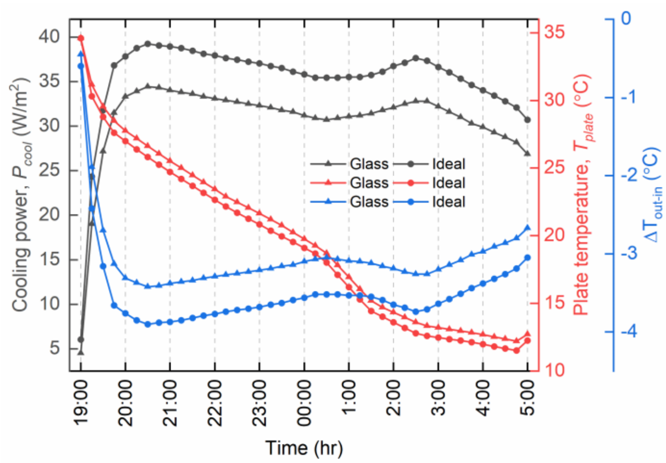

Fig. 6. Nighttime performance of the glass and ideal cases, showing the aluminum plate temperature (red), temperature difference between outlet and inlet air (blue), and cooling power (black) of the PVT-RC system.

Cooling power (black), P_{cool}, for both systems is considerably low during the initial cooling hours from

19:00 to 19:45 due to the system's thermal inertia and presence of some scattered solar irradiation. At later times, even though P_{cool} for the ideal case is higher than that for the glass case, the difference between them is not substantially large and varies from 4 to 8 W/m^2.

5. Conclusions

This study investigated if the integration of enhanced RC in present-day PVT modules can substantially improve system performance. A transient thermal analysis was carried out for two cases to evaluate their performance using total exergy efficiency for daytime working and cooling power for nighttime working. The first case consists of a regular 3.2 mm glass encapsulation on the solar cells while the second case considers an ideally emissive layer. The results show that:

1. During the day, the RC of solar cells markedly improves the electrical efficiency of the system. However, thermal emission to the sky results in a loss of thermal efficiency, which makes the net rise in the total exergy efficiency of the ideal system fairly small (about 0.65%).
2. During the night, the small difference of 4 to 8 W/m^2 in the cooling power gain between the two cases explains that the regular glass layer in PVT modules has an inherent ability to provide cooling at night, and that the use of highly emissive materials as the module glazing would not provide any significant increment in the cooling power gain.

In summary, spectrally modifying the PVT systems by replacing the conventional glass cover of the module with highly emissive materials, would not significantly improve system performance and therefore other application areas such as RC of space solar cells could be investigated in the future.

Acknowledgments

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6. References

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