A comprehensive study on the cooling performance of the radiative cooling module with crossed compound parabolic concentrator

Ya Dan1, Mingke Hu2*, Qiliang Wang1, Saffa Riffat1, Yuehong Su1*

1 Department of Architecture and Built Environment, University of Nottingham, Nottingham NG7 2RD, UK
2 School of Electrical Engineering, Southwest Jiaotong University, Chengdu, 610031, China

Introduction

Radiative sky cooling (RC), utilizes the 'atmospheric window' between wavelengths of 8-13 μm to emit thermal infrared radiation to the deep universe (~3 K), thereby enabling self-cooling with significant application prospects. However, as depicted in Fig.1, the cooling power density (P_{cool}) for the RC module not only depends on the thermal radiation flux emitted by the RC emitter (P_{emi}) but also by the thermal radiation absorbed from the sky (P_{sky}) and surroundings (P_{sur}). Moreover, the most significant impact on its cooling performance is the solar thermal radiation (P_{sol}), which reaches approximately 1000 W/m^2, substantially exceeding the cooling flux of about 100 W/m^2 generated by the RC module at ambient temperatures.

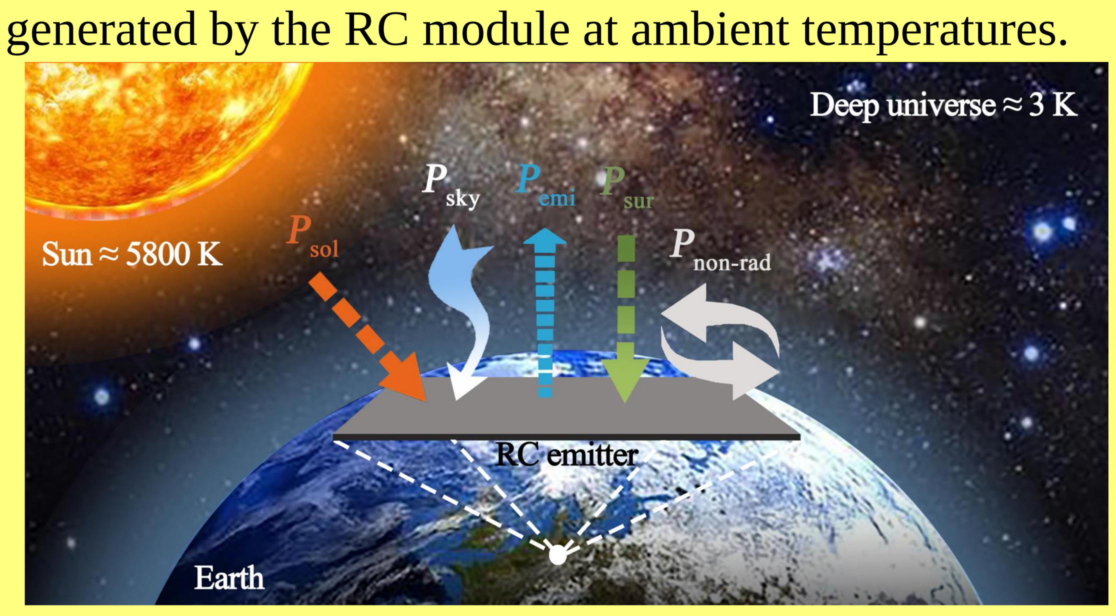


Fig. 1. Schematic diagram of heat transfer processes on a radiative cooling emitter.

To further improve the cooling power of RC technology, in addition to improving the spectral characteristics of RC materials to bring them close to ideal spectral characteristics, strengthening the structural design of RC modules to enhance their ability to block solar and external environmental thermal radiation can also achieve the goal.

In this context, a novel crossed CPC-RC module that is enclosed on all sides is proposed. This study evaluates the cooling performance of this innovative RC module alongside several others through numerical study. The combined impact of different ambient temperatures (T_{amb}) and solar absorptivity (α_{sol}) of emitter on RC modules is also discussed. Finally, due to the high sensitivity of concentrated RC modules to solar radiation, the cooling performance of crossed CPC-RC modules under various solar acceptance ratios (η_{con}) is studied.

Description of the crossed CPC-RC module

The radiative heat exchange between the 2D CPC-RC module and the crossed CPC-RC module with the sun and external environment is illustrated in Fig.2. The crossed CPC structure, formed by placing two 2D CPCs perpendicularly and overlapping each other, consists of four parabolic surfaces and a square aperture. When the side openings of the two CPC-RC modules are aligned along the east-west direction, P_{sol} from the morning and evening, along with P_{sky} from the east or west, can reach the RC emitter of the 2D CPC-RC module through side openings. In contrast, such thermal radiations are effectively blocked by the wing frameworks of the crossed CPC structure, thereby enhancing its radiative cooling performance.

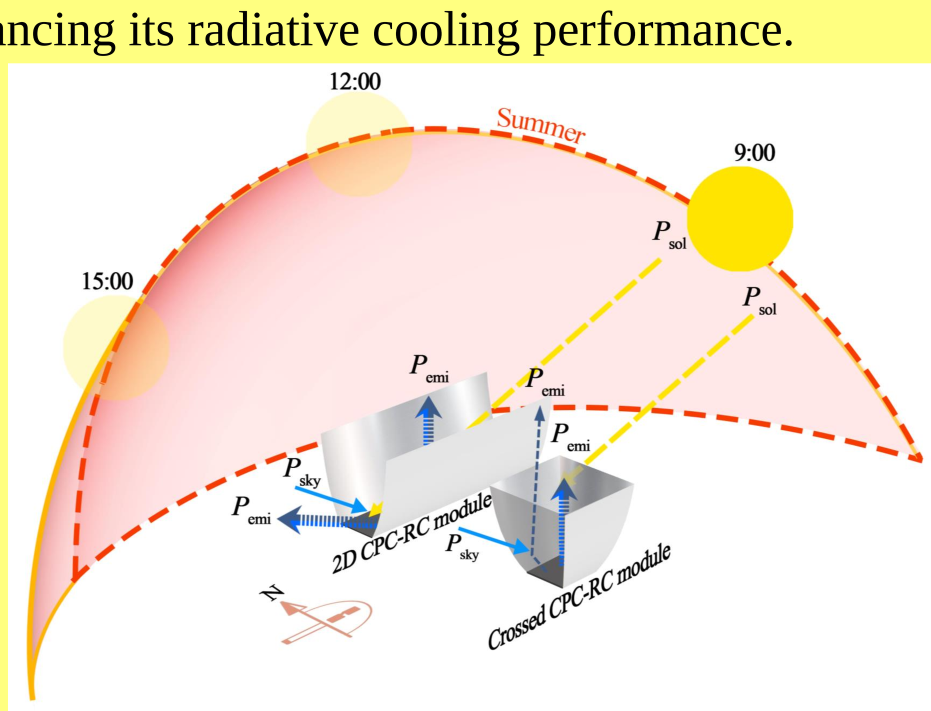


Fig. 2. Radiative heat exchange between 2D CPC-RC and crossed CPC-RC modules and external environment.

Results and discussion

COOLING POWER FOR RC MODULES UNDER DIFFERENT AMBIENT TEMPERATURE

A schematic diagram of the four RC modules evaluated for this section is shown in Fig.3. Additionally, Fig.4 displays the P_{cool} for RC modules with different RC emitters across various T_{amb} at night. It is revealed that the P_{cool} for four modules increases with rising T_{amb}, irrespective of the emitter used, with the two cross-structure RC modules showing excellent cooling performance. At 0 °C, the P_{cool} of 107.95 W/m^2 is exhibited by the crossed CPC-RC module with the ideal emitter, which is 20.43% and 7.21% higher than those exhibited by the flat-RC and 2D CPC-RC modules, respectively. As the T_{amb} gradually increases, the disparity among the four modules becomes more pronounced. When the T_{amb} is 40 °C, P_{cool} of 186.47 and 184.29 W/m^2 are shown obtained by the crossed CPC-RC and "V"-RC modules, respectively, while the P_{cool} for the flat-RC and 2D CPC-RC modules is only at 154.85 and 173.93 W/m^2.

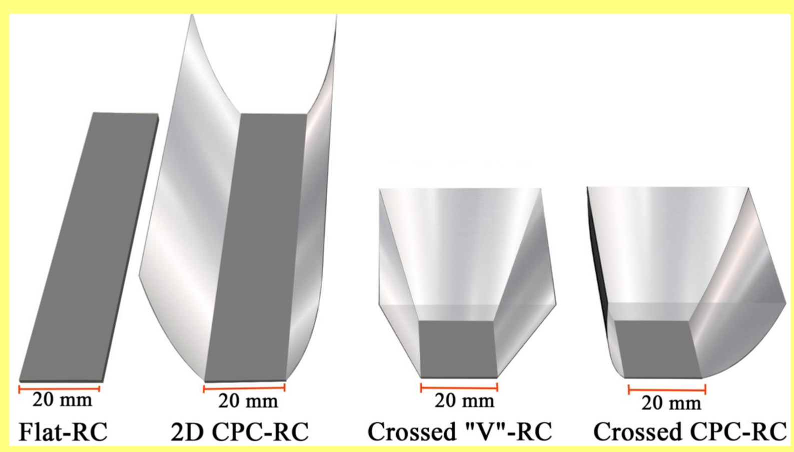


Fig..3. Schematic diagram of the four RC modules.

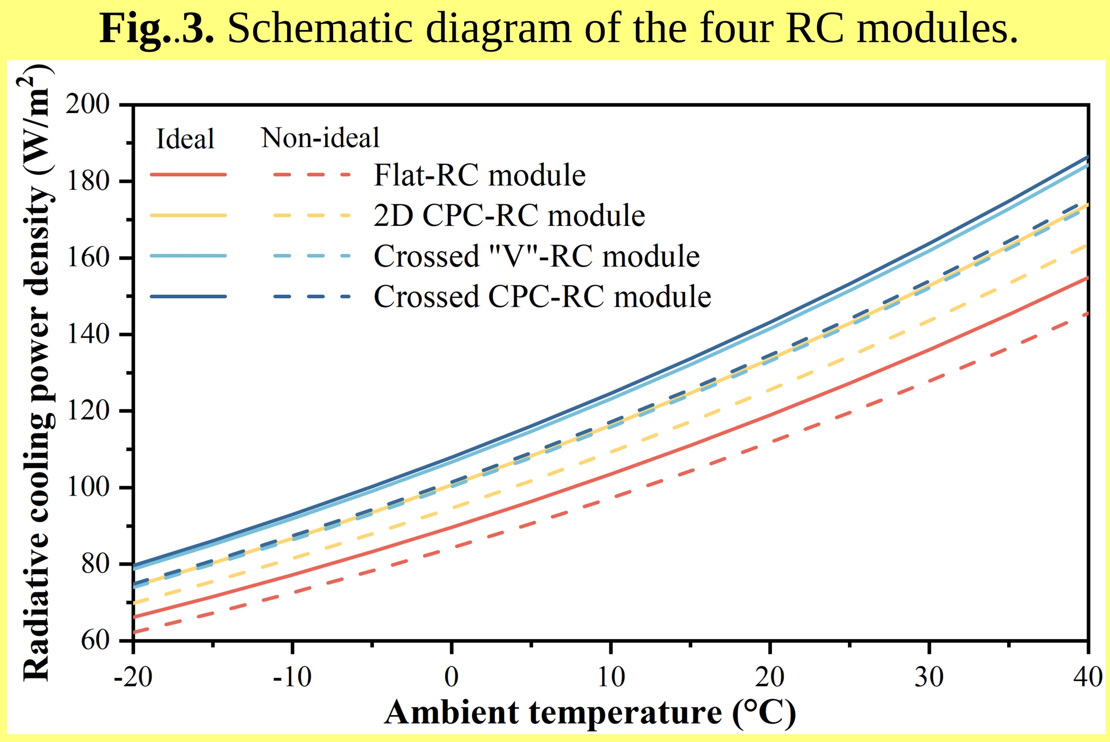
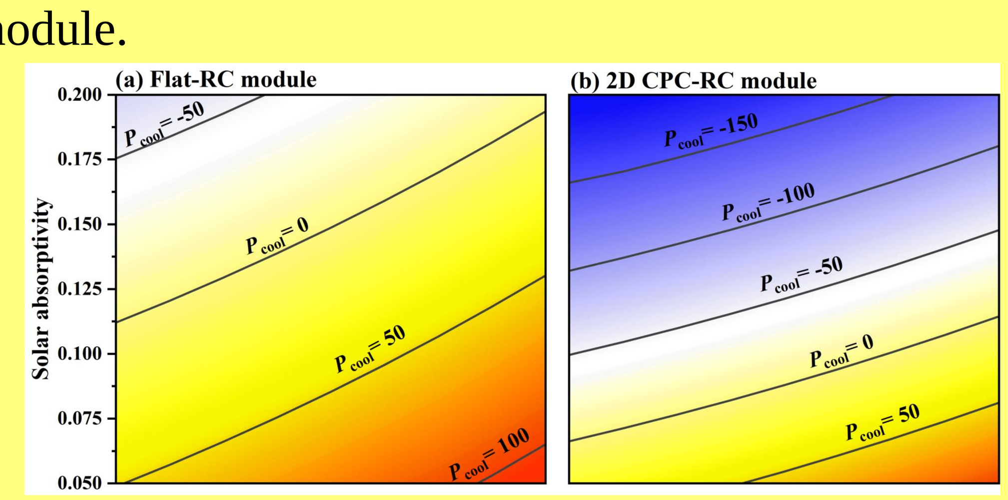


Fig. 4. Variation curves of radiative cooling power density for four RC modules at different ambient temperatures.

The cooling power density for four RC modules as a function of the α_{sol} and T_{amb} is shown in Fig.5. Fig.5 (a) illustrates that in the flat-RC module, cooling power is still generated even if the α_{sol} increases to 0.18 as T_{amb} rises to 40 °C. However, sub-ambient cooling is not achieved by the flat-RC module when α_{sol} exceeds 0.18. In contrast, as depicted in Fig.5 (b), (c), and (d), obvious differences are exhibited by the other three concentrated RC modules. Cooling power is not generated by the three RC modules when α_{sol} exceeds 0.12, even with T_{amb} at 40 °C. This occurs because the impact of solar radiation on cooling performance is greater in the concentrated RC modules than in the flat-RC module. However, a slightly higher P_{cool} = 0 line is maintained by the crossed structure-based RC module due to their superior shielding effect against adverse external environmental thermal radiation. Specifically, the P_{cool} of 110.47 and 108.29 W/m^2 is shown by the crossed CPC-RC and crossed "V"-RC modules, respectively, at 40 °C with α_{sol} is 0.05, which is slightly lower than the 114.85 W/m^2 of the flat-RC module, but approximately 13% higher than that of the 2D CPC-RC module.



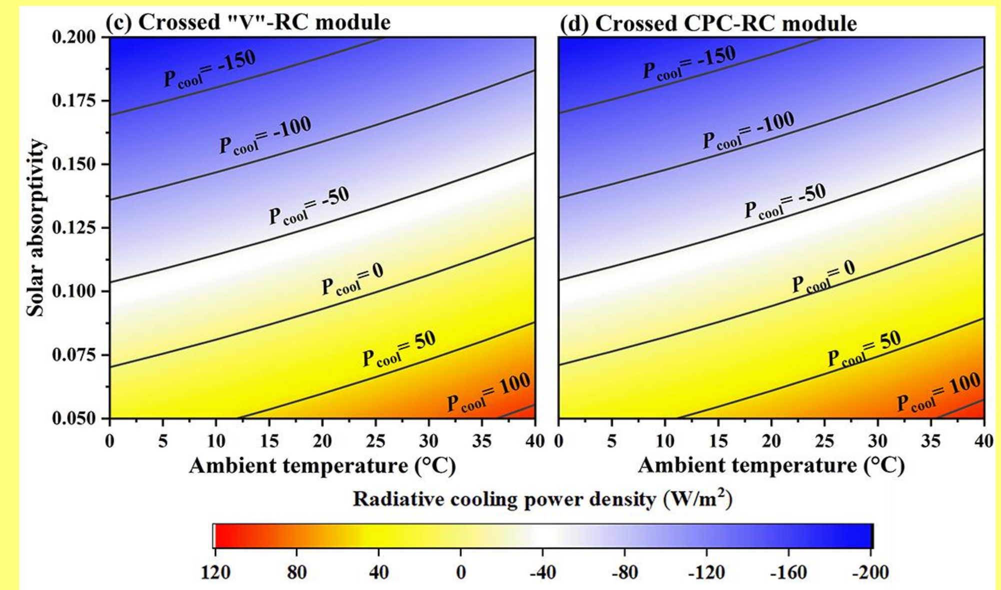


Fig. 5. Cooling power density for four RC modules as a function of the α_{sol} and the T_{amb}.

COOLING POWER FOR CROSSED CPC-RC MODULE UNDER DIFFERENT SOLAR ACCEPTANCE RATIOS

Fig.6 shows the P_{cool} at different η_{con} for crossed CPC-RC modules with different emitters at T_{amb} is 30 °C. It can be seen that a decrease in P_{cool} with an increase in η_{con} when α_{sol} is greater than 0, regardless of whether RC module uses the ideal or non-ideal emitters. When α_{sol} is 0.05, good cooling performance is achieved by both emitters, with the module using the ideal emitter reaching 83.77 W/m^2 and module with the non-ideal emitter reaching 73.95 W/m^2, even if η_{con} equals 1. However, at this time, P_{cool} is only half of what it is when η_{con} is equal to 0. As α_{sol} increases to 0.10, a faster decrease in P_{cool} with increasing η_{con}. When η_{con} reaches 1, the P_{cool} of 3.77 W/m^2 is still obtained by the module with the ideal emitter, while the P_{cool} for the module with the non-ideal emitter cannot obtain cooling power when η_{con} is 0.96. Furthermore, if α_{sol} is further increased to 0.15 or 0.20, no cooling power is obtained by the module with the ideal emitter when η_{con} is larger than 0.69 and 0.52, respectively.

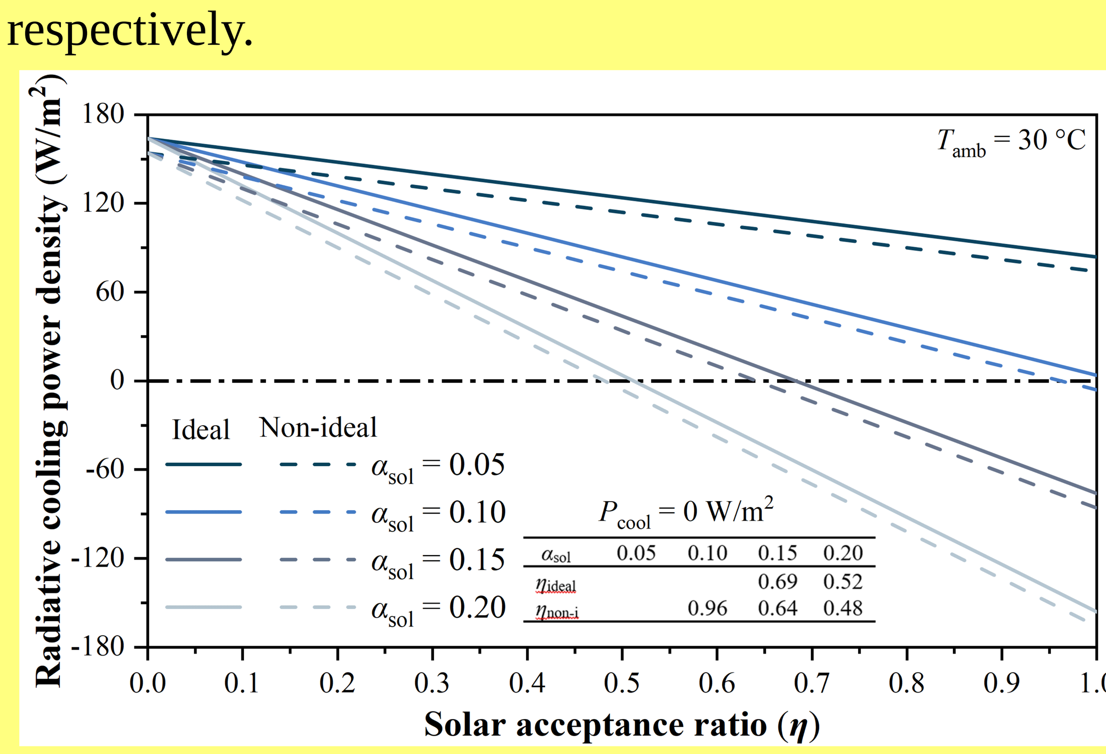


Fig. 6. Cooling power for crossed CPC -RC modules with different emitters under different solar acceptance ratios

Conclusions

●The comparative results of the cooling power density (P_{cool}) for four RC modules under varying ambient temperatures (T_{amb}) at night show that even at T_{amb} is 0 °C, the P_{cool} for the crossed CPC-RC module can reaches 107.95 W/m^2, outperforming the flat-RC and 2D CPC-RC modules by 20.4% and 7.2% respectively.

●The variations in P_{cool} for the crossed CPC-RC module under different solar acceptance ratio (η_{con}) reveal that even with an η_{con} set at 1, the module's P_{cool} remains at 83.77 W/m^2 when T_{amb} is 30 °C and the emitter' solar absorptivity (α_{sol}) is 0.05. As α_{sol} increases to 0.15 or 0.20, the RC module fails to achieve any cooling power when η_{con} exceeds 0.69 and 0.52, respectively.

Acknowledgments

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