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# Field investigation of a hybrid photovoltaic-photothermic-radiative cooling system

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## HIGHLIGHTS

- A new collector that provides electricity, heat and cooling energy was proposed.
- An experimental rig was developed to investigate the performance of the collector.
- The collector showed favorable electrical and thermal efficiencies.
- The net radiative cooling power of the collector reached 72.0 W/m$^2$.

## ARTICLE INFO

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## ABSTRACT

Radiative cooling (RC) is a passive and green cooling technique dissipating heat to outer space, which is a natural heat sink. Yet most available radiative coolers are encountered with the challenges of low power density and daytime operating ability. In the meantime, solar photovoltaic/thermal (PV/T) collectors cannot work at night. To overcome this limitation, the present work proposed, designed and manufactured a practical-scale photovoltaic-photothermic-radiative cooling (PV-PT-RC) collector. The hybrid PV-PT-RC collector is capable of generating electricity and heat during the day and providing cooling energy at night. Subsequently, to study the performance of the collector, we developed an outdoor experimental system and performed experiments at various operation modes. As results suggest, the average electrical efficiency of the collector around noon was 10.3% and showed thermal efficiency at zero-reduced temperature of 55.3% in a diurnal collector mode test. The net RC powers of the collector in a clear night and overcast night reached 72.0 and 30.8 W/m$^2$, respectively. Multi-day daily system mode tests were performed, and the results suggest that the overall electrical/thermal efficiency of the PV-PT-RC system was ranged from 40.4% to 56.9%. The overall cooling energy gain of 2.90 MJ was obtained by the system at a typical clear night. The tri-functional collector is expected to provide indispensable electricity, heat as well as cooling energy in building and agriculture fields.

## 1. Introduction

The worsening energy crisis and environmental pollution worldwide, particularly in large developing economies (e.g., China and India), have propelled the development and the utilization of alternative energy resources. Solar energy plays a leading part in the renewable energy utilization nowadays since it is widespread, inexhaustible and non-polluting [1].

Photovoltaic (PV) technology is one of the dominant technologies employed to exploit solar energy [2]. PV conversion refers to a process that PV cells capture solar irradiance and subsequently convert it into electricity under photovoltaic effect. Various PV cells have been introduced and developed in recent decades (e.g., crystalline solar cells, polymer solar cells, perovskite solar cells and dye-sensitized solar cells) [3]. Yet only photons with greater energies than those of band gaps of PV cells can induce electron-hole pairs and be partially converted into current. Nearly 99% of solar radiation is ranged between 0.2 and 3 μm. Common PV modules apply crystalline silicon as the PV cell and can only convert partial solar irradiance at 0.2–1.1 μm range into electricity. Nearly 85% of solar energy is dissipated into heat, in turn aggravating PV efficiency [4]. Every 1 °C rise in the temperature of crystalline silicon PV cell can result in nearly 0.5% decrease of efficiency [5]. This efficiency reduction significantly depends from the type of the PV technology. Nizetic et al. [6] recently summarized relevant

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**Nomenclature**

| | |
|---|---|
| $A$ | area, m$^2$ |
| $a$ | cooling power loss coefficient, W/m$^2$ |
| $a_0$, $a_1$, $a_2$, $a_3$ | fitting coefficients, – |
| $b$ | cooling loss factor, – |
| $c$ | specific heat capacity |
| $E$ | radiation power, W/m$^2$ |
| $F_R$ | heat removal factor, – |
| $G$ | solar irradiance, W/m$^2$ |
| $H$ | total solar radiant energy received, MJ/m$^2$ |
| $I$ | current, A |
| $m$ | mass of water in the water tank, kg |
| $\dot{m}$ | mass flow rate, kg/s |
| $P$ | (cooling) power, W/m$^2$ |
| $Q$ | energy gain, J (MJ) |
| $T$ | temperature, K |
| $\bar{T}$ | average temperature, K |
| $\Delta T$ | temperature difference, °C |
| $\Delta t$ | recording interval of the data logger, s |
| $t_d$ | dew point temperature, °C |
| $U$ | voltage, V |
| $U_f$ | uncertainty, – |
| $U_L$ | heat loss coefficient of the collector, W/(K·m$^2$) |
| $U_{loss}$ | heat loss coefficient of the system, MJ/(K·m$^2$) |
| $w$ | precipitable water vapor amount, cm |
| $\Delta x_i$ | error of the variable |

*Greek symbols*

| | |
|---|---|
| $(\tau\alpha)$ | transmittance-absorptance product, – |
| $\tau$ | dimensionless temperature difference |
| $\varepsilon$ | emissivity, – |
| $\sigma$ | Stefan–Boltzmann constant, – |
| $\lambda$ | wavelength, μm |
| $\xi$ | packing factor |
| $\varphi$ | relative humidity, % RH |
| $\eta$ | efficiency, – |
| $\bar{\eta}$ | average efficiency, – |

*Abbreviation and subscripts*

| | |
|---|---|
| a | ambient air |
| b | blackbody |
| c | collector |
| cool | cooling |
| e | electrical |
| final | final time |
| in | collector inlet |
| initial | initial time |
| o | overall |
| out | collector outlet |
| p | panel/power plant |
| PV | PV module |
| s | sky |
| th | thermal |
| w | water |

references from the last two decades that are associated with various active cooling techniques for PV panels, and then performed a general economic-environmental evaluation on a 30 kW PV system running under Mediterranean climate conditions.

Given the limited photoelectric conversion band of conventional PV cells, a large number of researchers focused on increasing the conversion efficiency of PV cells by broadening the spectral response range of new-type solar cells [7,8]. For instance, Liu et al. [9] presented a method to increase the conversion efficiency of flexible PV devices in the NIR spectral region by incorporating Si nanowire arrays with plasmonic Ag nanoplates. Results suggested that the incorporation of Ag nanoplates increased external quantum efficiency by 59%. In the meantime, perovskite solar cells show high PV efficiency by comparatively narrow band gap. On that basis, Jeon et al. [10] incorporated formamidinium lead iodide ($FAPbI_3$) with methylammonium lead bromide ($MAPbBr_3$) as light-harvesting unit of perovskite solar cells; they could increase a photoelectric conversion efficiency by over 18% under an incident solar radiation of 1000 W/m$^2$.

The photothermal (PT) collector/system represents another major aspect of solar energy utilization. PT conversion can be performed in the full solar spectrum (i.e., 0.2–3 μm). Accordingly, a solar thermal collector is capable of absorbing and converting most of solar irradiance into heat on its absorber, which is usually coated with solar selective absorbing coatings [11]. Subsequently, the generated heat is removed by cooling fluids (e.g., water, air and refrigerant) [12].

The flat-plate solar collector is the most frequently used type of solar thermal installation, having aroused broad attention in the scientific community [13]. In general, improving solar absorbing performance [14], suppressing heat loss [15] and optimizing heat exchanging unit [16] are the three major methods of increasing the thermal efficiency of solar collectors. The introduction and development of solar selective absorbing coatings significantly decrease long wave radiant heat loss [17]. For instance, by conducting magnetron sputtering on stainless steel substrate, Ning et al. [18] prepared a novel Mo/ZrSiN/ZrSiON/$SiO_2$ solar selective absorbing coating. A high solar absorptivity of 0.94 and a low thermal emissivity of 0.06 at 25 °C were achieved. Advancements in nanotechnology have enabled the addition of nanoparticles with favorable heat transfer ability (e.g., metals, metal oxides and carbide) in working fluids to improve heat transfer coefficient [13]. For instance, Mirzaei et al. [19] experimentally investigated an $Al_2O_3$/water nanofluid-based flat plate solar collector. As results suggest, the nanofluid increased the collector efficiency by nearly 23.6% with an optimum flow rate of 2 L/min.

To maximize the overall utilization efficiency of solar energy, scholars have introduced and developed photovoltaic/thermal (PV/T) technologies [20]. A PV/T collector incorporates a PV panel and a solar thermal collector into a single module, capable of generating electricity and heat simultaneously. In a flat-plate PV/T collector, water and air are the two common heat carriers extracting heat from the absorber and then flowing into the water tank as domestic hot water [21] or streaming into the room for space heating [22]. The flat-plate PV/T collector has an overall efficiency greater than that of a conventional flat-plate solar collector [23].

To improve the thermal performance of flat-plate PV/T collector, various heat exchange structures have been developed by researchers. These structures include dual function water/air based PV/T collectors, heat pipe-based PV/T collectors, nanofluid based PV/T collectors as well as phase change material (PCM) based PV/T collectors [24]. Hu et al. [25] proposed a flat-plate PV blind-integrated Trombe wall module and examined its electrical and thermal performances under various air flow rates and PV blind angles. As the results suggest, the inlet air flow rate of 0.45 m/s and the angle of 50° were considered preferable for the module. Ji et al. [23] proposed a tri-functional PV/T collector capable of running in water heating and air heating mode. By performing tests, they investigated the performance of the collector and found that the collector is capable of operating efficiently under various conditions and shows better seasonal adaptability. By using experiments, Hu et al. [26] studied the impact of inclination angle on the