Applied Energy 205 (2017) 626–634

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Conceptual development of a building-integrated photovoltaic–radiative cooling system and preliminary performance analysis in Eastern China

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HIGHLIGHTS

- A specific spectral characteristic for both PV and RC was proposed.
- The PV/RC hybrid system based on spectral characteristic is original.
- A thermal model of the system was established and the performance was analyzed.
- The performance comparison with the conventional PV system was conducted.
- The system shows considerable performance for both PV and RC.

ARTICLE INFO

Keywords:
Photovoltaic
Radiative cooling
Building
Spectral selectivity

ABSTRACT

Building-integrated photovoltaic/thermal (BIPV/T) technology has been receiving considerable research attention because of its ability to generate electricity and thermal energy simultaneously. However, space cooling is crucial for buildings in hot regions where space heating is of little use. This study proposed a building-integrated photovoltaic–radiative cooling system (BIPV–RC) that can generate electricity via photovoltaic (PV) conversion during daytime and generate cooling energy via radiative cooling (RC) during nighttime to satisfy the demand in such areas. The selective plate, which is the main component of the BIPV–RC system, exhibits high spectral absorptivity (emissivity) in the PV conversion band of crystalline silicon solar cells and in the atmospheric window band (i.e., 0.3–1.1 μm and 8–13 μm), as well as low spectral absorptivity (emissivity) in other bands. A quasi-steady-state mathematical model was built, and its performance under realistic ambient conditions was analyzed. The electrical efficiencies of the BIPV–RC and conventional BIPV systems were then compared under different solar radiations. Comparison results show that the annual electricity production and cooling energy gain of the BIPV–RC system in Hefei reached 156.74 kW h m^{-2} (equivalent to 564.26 MJ m^{-2}) and 579.91 MJ m^{-2}, respectively. The total electricity production and cooling energy gain of this system are 96.96% higher than those of the BIPV system. Parametric studies show that the precipitable water vapor amount has remarkable effects on the nocturnal RC performance of the BIPV–RC system. A small precipitable water vapor amount corresponds to a high nocturnal RC power, thereby implying that a dry climate condition benefits the nocturnal RC of this system.

1. Introduction

Buildings account for approximately 40% of the annual global energy consumption [1]. This energy is mostly used to provide lighting, heating, and cooling, thereby emphasizing the need to develop renewable energy technologies. For example, the building-integrated photovoltaic (BIPV) [2–6] and building-integrated photovoltaic/thermal (BIPV/T) techniques [7–11] have been rapidly developed recently. In the BIPV system, only solar irradiation with a certain wavelength range can be converted into electricity, and the remaining absorbed solar irradiation is dissipated into heat, which increases the temperature of the solar cells. However, every 1 K increase in temperature decreases the relative efficiency of the crystalline silicon solar cells by approximately 0.45% [12]. The BIPV/T system was first examined in the 1990s and has been attracting increasing attention since 2000 because of its potential to promote net-zero energy buildings [13]. This system can also simultaneously generate electricity and useful heat for buildings by a single unit.

BIPV and BIPV/T systems have recently been theoretically and experimentally studied. Ref. [3] analyzed the power efficiency of a BIPV

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http://dx.doi.org/10.1016/j.apenergy.2017.08.011
Received 31 May 2017; Received in revised form 4 August 2017; Accepted 6 August 2017
0306-2619/

Nomenclature

T	temperature, K
G	solar irradiance, W m^{-2}
Q	thermal power, W m^{-2}
c_p	heat capacity, J kg^{-1} K^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
U	overall heat transfer coefficient, W m^{-2} K^{-1}
u	wind speed, m s^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number, –
Pr	Prandtl number, –
Ra	Rayleigh number, –
De	equivalent diameter, m
L	distance, m
l	length, m
A	area, m^2
E	electric power, W m^{-2}

Greek symbols

α	absorptivity, –
ε	emissivity, –
ρ	reflectance, –
τ	transmittance, –
η	efficiency, –
σ	Stefan–Boltzmann constant, –
ζ	packing factor, –
λ	wavelength, μm
γ	inclination angle, rad
θ	radiation angle, rad

Subscripts and abbreviation

c	cover
p	aluminum plate
pv	solar cell
a	air
r	radiation
RC	radiative cooling
TPT	Tedlar–polyester–tellar
BIPV	building-integrated photovoltaic
BIPV–RC	building-integrated photovoltaic–radiative cooling
s	sky
b	back insulator
f	fluid
ref	reference
r_net	net radiation
PV	photovoltaic
EVA	ethylene–vinyl–acetate

system under actual operating conditions, and annual monitoring of south-facing vertical BIPV systems revealed the factors of its performance decreased. Results showed that extruded louvers decreased average insulation loss by 4.5% over a year. Ref. [4] presented an experimental study of cooling BIPV modules by forced convection in the air channel. The influence of air gap size and forced ventilation on the cell temperature of a BIPV system were investigated. A critical channel aspect ratio close to 0.11 was obtained for the given system to minimize overheating of PV cells. A power output increase of 19% over the natural ventilation case was observed for a duct velocity of 6 m/s. The sustainability of a rooftop BIPV system in Hong Kong was studied by [5] by using evaluation indicators of energy payback time (EPBT) and greenhouse gas payback time (GPBT). Results showed that the EPBT and GPBT were 7.3 and 5.3 years, respectively, based on a large amount of measured weather data. A discussion on the influence of orientation on EPBT indicated that choosing locations and orientations with high-incident solar irradiance is the key for the sustainability of BIPV applications. Ref. [7] used a full-scale solar simulator to investigate the thermal characteristics of a novel two-inlet air-based open-loop BIPV/T system. Such a system can increase thermal efficiency by 5% compared with a conventional one-inlet system. The annual performance of a BIPV/T (water-based) system was numerically analyzed in [9]. Thermal and electrical efficiencies of 37.5% and 9.39% year-averages, respectively, were obtained with a normal building façade.

The space heating and cooling demands of buildings vary across different areas and seasons. For instance, space cooling is more important for buildings in hot regions, such as Sudan and Egypt, than for those in cold areas. Radiative cooling (RC) [14–22], a passive cooling technique, has drawn considerable research attention in recent decades because of its capability to satisfy the demand in such areas. The atmosphere exhibits a relatively high transmittance within a wavelength band of 8–13 μm (i.e., atmospheric window). Thus, objects that are exposed to the sky are capable of radiating heat to outer space, where the temperature is close to absolute zero.

The cooling potential of RC in buildings was first utilized by societies in 400 BCE. Night sky cooling was used in yakh-chal by Persians to produce ice despite high ambient air temperatures [14]. The consumption of fossil fuels and concerns regarding the environment have caused RC to draw considerable attention in recent years. Ref. [15] investigated a lightweight aluminum nocturnal radiator painted in white for space cooling in Agrinio. Experimental results showed that such a nocturnal radiation system can be effectively used for space cooling. Ref. [16] used polyethylene mesh as a nocturnal radiator for a roof, which has good mechanical stability and is self-supporting; this method reduced the ambient air temperature by 5–7 °C. Ref. [17] presented a composite surface for a combined diurnal solar heating and nocturnal RC system (SH–RC). The proposed system can obtain a net cooling power of approximately 50.3 W m^{-2} on a clear night in Hefei. Refs. [21,22] extended the RC during daytime under direct sunlight by using a selective radiator. Ref. [21] used an integrated photonic solar reflector and thermal emitter that consists of seven layers of HfO_2 and SiO_2 to cool the radiator to 4.9 W m^{-2} below the ambient temperature under 850 W m^{-2} of solar radiation. Ref. [22] randomly embedded resonant polar dielectric microspheres in a polymeric matrix, thereby creating a metamaterial with spectral selectivity characteristics. The metamaterial showed a noontime net cooling power of 93 W m^{-2}.

Following the aforementioned technologies, a hybrid system (PV–RC) that can generate electricity by diurnal PV conversion should then be developed to achieve space cooling via nocturnal RC for buildings in hot regions. Unfortunately, studies on hybrid systems that combine PV conversion and RC are few. Ref. [23] developed a new PV/T system to produce electricity and cooling energy. They applied large PV/T frameless modules to a residential zero-energy building and experimentally tested the performance of the system in Madrid. Their experiments yielded nocturnal RC power levels of 60–65 W m^{-2}. Ref. [18] presented a combined photovoltaic–photothermic–nocturnal RC system (PV–PT–RC) and conducted a preliminary thermal analysis. A temperature difference of approximately 8 °C between the environment and the collecting surface was experimentally achieved. Ref. [24] presented a microphotonic approach to decrease the operating temperature of a solar cell via RC by applying a microphotonic crystal on top of a cell. Calculated results showed that the ideal case can passively decrease the operating temperature by 18.3 K. Nevertheless, the RC in [24] is only for the diurnal cooling of a solar cell.