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Performance study on a novel hybrid solar gradient utilization system for combined photocatalytic oxidation technology and photovoltaic/thermal technology

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HIGHLIGHTS

- A novel solar gradient utilization system;
- Preparation of photocatalytic-glass module;
- Effect of TiO_2 coating density on performance of PC-PV/T system;
- Comparisons of PC-PV/T system with conventional two PV/T systems.

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ABSTRACT

A novel hybrid solar photocatalytic, photovoltaic and thermal recovery system that meets the domestic demands for air purification, electricity generation, space heating and hot water supply in one integrated is proposed (PC-PV/TAW). The photocatalytic module uses ultraviolet part to drive photocatalytic degradation of indoor pollutants, and the photovoltaic/thermal module absorbs visible and infrared parts to generate electricity, warm air and hot water. In this article, three photocatalytic-glass modules with different TiO_2 coating density are prepared and the effect of TiO_2 coating density on the performance of electrical, thermal and formaldehyde degradation for PC-PV/TAW system is investigated. In addition, comparisons of PC-PV/TAW system with two conventional systems of photovoltaic/thermal water system (PV/TW) and photovoltaic/thermal air and water system (PV/TAW) are conducted. Finally, the associated losses of PC-PV/TAW system and two conventional PV/T systems are analyzed. Results are as follows: (1) PC-PV/TAW system with TiO_2 coating density of 1.86 g/m^2 behaves the best thermal and electrical performance while a little reduction of formaldehyde degradation performance among three PC-PV/TAW systems; (2) The electrical efficiency of PC-PV/TAW system approaches 0.174 both considering generated electricity by PV modules and saving electricity by purifying air; (3) The overall thermal and electrical efficiency of PC-PV/TAW, PV/TAW and PV/TW system is 0.644, 0.696 and 0.677, respectively, while PC-PV/TAW system can generate total volume of fresh air of 248.040 $m^3/(m^2{\cdot}day)$; (4) The loss analyses show the solar spectral characteristics of TiO_2 coating is the key to system performance of PC-PV/TAW system.

1. Introduction

The photovoltaic/thermal (PV/T) technology, as an integration of photovoltaic (PV) modules and solar thermal collector, can collect not only electrical energy but also thermal energy. Many studies have shown the increase of PV cell temperature leads to a significant reduction of open circuit voltage then reduces the solar electrical conversion efficiency [1,2]. The cooling by using water [3], air [4] or refrigerant [5] can efficiently decrease the PV cell temperature to increase the electrical conversion efficiency.

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Nomenclature

T	temperature, °C
I	solar radiation intensity, W/m^2
c	specific heat capacity, J/(kg·K)
t	time, s
h	heat transfer coefficient, W/(m^2·K)
δ	thickness, m
u	air or water flow velocity, m/s
A	area, m^2
d	hydrodynamic diameter or diameter, m
Q	rate of heat flow, W/m^2, volumetric flow rate of gas, m^3/h
E	electric power, W/m^2; reaction activation energy, J/mol
R	thermal resistance, (m^2·K)/W
B	temperature coefficient, K^{-1}
H	height, m; adsorption heat, J/mol
C	formaldehyde concentration, ppb
n	the mass transfer rate, ppb·m/s
r	reaction rate, ppb·m/s
k	reaction rate coefficient, m/s
K	extinction coefficient or adsorption constant
V	volume, m^3
m	mass flow, kg/s
Re	Reynolds number
Pr	Prandtl number
Nu	Nusslet number
Ra	Rayleigh number
Sh	Sherwood number
Le	Lewis number
D	HCHO diffusion coefficient, m^2/s

Greeks

σ	Stefan-Boltzmann constant, W/(m^2·K^4)
λ	thermal conductivity, W/(m·K)
ε	formaldehyde once-through conversion
α	absorptivity
τ	transmissivity
η	efficiency
β	coefficient of thermal expansion, K^{-1}
ν	dynamic viscosity, m^2/s
ξ	packing factor
θ	angle
ρ	density, (kg/m^3); reflectivity

Subscripts

g	glass plate
a	air
p	absorber plate
c	copper tube
f	water flow in copper tube
a	air
p	absorber plate
c	copper tube
f	water flow in copper tube
w	water in tank
b	back plate
ta	water tank
amb	ambient
sky	sky
df	diffuse
dr	direct
e	equivalent
ins	thermal insulation material
W	welding
s	surface
m	mass transfer
$HCHO$	formaldehyde
app	apparent
H_2O	water vapor
th	thermal
in	inlet
out	outlet
e	electrical
tot	total
te	thermal and electrical

Abbreviations

UV	ultraviolet
Vis	visible
IR	infrared
PV	photovoltaic
PC	photocatalytic
PCO	photocatalytic oxidation
EVA	ethylene-vinyl acetate
CADR	clean air delivery rate, m^3/h
ppb	parts per billion
PV/T	photovoltaic/thermal

In the past 40 years, PV/T collectors have been widely investigated because of several advantages such as the higher overall efficiency compared with any individual system, the less thermal stresses for PV cells, and the less installation cost compared to installing two individual systems [2,6]. An indoor standard test of the PV/T air collectors conducted by Solanki showed that the thermal and electrical efficiency were 42% and 8.4%, respectively [7]. Slimani et al. [8] conducted the theoretical and experimental studies by comparing four types PV/T air collectors, which provided guidance to the design of PV/T air collectors. Yang et al. [9] found that PV/T air collector with two air inlets had an increase of about 5% for thermal efficiency and marginal increase for electrical efficiency compared with PV/T air collector with single air inlet. Kamthania et al. [10] presented the performance evaluation of a hybrid PV/T air collector in New Delhi and results showed that the annual thermal and electrical energy were 480.81 kWh and 469.87 kWh, respectively. And other performance analyzes of hybrid PV/T air collector by exergy analysis [11], life cycle cost assessment [12] and key parameters analysis [13] have also been conducted. As for PV/T water collectors, water is more effective for cooling PV/T systems due to its cooling characteristics of higher thermal mass compared with air [14]. Ji's group investigated a variety of factors that influencing the electrical and thermal performance of PV/T water collector such as the water mass flow and transmittance of glazing cover [15], the PV coverage ratio [16], the types of PV cells [17], and the PV module position [18]. They also proposed a novel tile-shaped dual-function solar water collector, which was very suitable for the Chinese traditional buildings [19]. Many researchers have conducted the detailed investigations on the thermal and electrical, and exergy efficiencies of PV/T water collectors, which provided valuable information on the design and operation of PV/T water collectors [20–23].

Recently, to enhance the overall performance and functionality of conventional PV/T system, the dual channel type PV/T collectors using air and water as cooling fluids simultaneously have been proposed [24–27]. Feng et al. [24] proposed a novel photovoltaic (PV) fresh air and domestic hot water system to improve indoor air quality and supply hot water. Ji and Guo proposed a novel design of tri-functional PV/T