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Research Paper

Dynamic performance of high concentration photovoltaic/thermal system with air temperature and humidity regulation system (HCPVTH)

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HIGHLIGHTS

- An HCPVTH system is proposed to maximize solar energy resource utilization.
- The maximum overall HCPVTH efficiency and corresponding operating parameters are determined.
- Performance parameter dynamic variations of subsystems are measured over time.
- Coupling mechanisms among subsystems under various meteorological parameters are determined.
- The heat pipe recovery function is found to be largely responsible for improvement in overall HCPVTH efficiency.

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ABSTRACT

A high concentration photovoltaic/thermal system with air temperature and humidity regulation system (HCPVTH) is proposed as a means to maximize the utilization of solar energy resources. The HCPVTH consists of several subsystems: high concentrating photovoltaic power generation, thermal storage, absorption heat pump, and heat recovery air regulation. A complete energy conversion model of the HCPVTH is established which includes a photovoltaic efficiency model and waste heat utilization thermodynamics model. Variations in efficiency across the system and subsystems with respect to the PV cell surface temperature reveal the maximum overall HCPVTH efficiency. Meteorological parameters and corresponding inter-subsystem coupling mechanisms are obtained according to changes in subsystem performance indicators with respect to time. We reach a maximum overall efficiency of 49.77% (photoelectric conversion and refrigeration efficiency of 35.15% and 78.25%, respectively), tank water mass changing range of 0.82–17.52 L, and maximum energy-savings of 15.40% in the heat recovery air regulation subsystem when PV cell operating temperature is 101 °C, tank capacity is at least 16.7 L, and the air conditioning subsystem is equipped with a heat pipe component. The total provided refrigerating and dehumidifying capacities are respectively 1.189 GJ and 264.907 kg under these conditions. The findings reported in this study may provide guidance for design and operation regulations of each subsystem in HCPVTH.

1. Introduction

Concentrated photovoltaic (CPV) power generation [1,2] has become a popular research topic in recent years due to its many advantages including high power generation efficiency, compact structure, and relatively low levels of environmental pollution. CPV technologies substitute expensive PV cells for cheaper optical equipment, which markedly reduces the cost of photovoltaic (PV) power generation [3]. PV systems well exercise these advantages wherein carbon emissions are reduced as the concentration ratio (CR) increases.

Systems with CR greater than 200 are high concentration PV systems (HCPVs) [4]. An HCPV system concentrates the sunlight mainly via three types of equipment: the parabolic dish concentrator [3,5–7], tower-heliostat [8,9], and spot Fresnel lens [10–14]. The spot Fresnel lens planarization concentrator is lightweight, inexpensive, has high light transmittance, and is environmentally friendly – advantages which make it popular for use in HCPV systems [4]. HCPV systems are also typically equipped with III-V multi junction solar cells, on which

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Nomenclature

Abbreviations

A	absorber
AHP	absorption heat pump
AS	adiabatic section
AWS	air water separator
C	condenser
CS	condensation section
CT	cold tank
E	evaporator
EE	electric equipment
ES	evaporation section
FL	Fresnel Lens
G	generator
H	house
HC	heat collector
HP	heat pipe
HT	hot tank
IHX	intermediate heat exchanger
OVC	overcooling section
P	pump
PRC	precooling section
PVC	photovoltaic cell
REC	reheating section
S	solar
SAC	surface air cooler
T	throttle valve
Wi	water inlet
WJ	water jacket
Wo	water outlet

Symbols

A	surface area of PV cell (m^2)
C	concentration ratio
C_0	reference concentration ratio equal to 1
COP	refrigeration efficiency
E_0	direct normal irradiance ($W\ m^{-2}$)
h	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
I	short circuit current of the PV cell (A)
i	enthalpy ($kJ\ kg^{-1}$)
Q	energy (kW)
Q_{ES}	energy conservation of heat recovery air regulation system (kW)
T	temperature (°C)
V	PV cell open circuit voltage (V)

Greek symbols

α	energy saving efficiency
β	photoelectric conversion parameter temperature coefficient
ε	PV cell surface emissivity
η	energy ratio
σ	blackbody radiation coefficient
Φ	photoelectric conversion parameters

Subscripts

0	reference condition
A	ambient
AHP	absorption heat pump
c	actual temperature of PV cell surface
cc	convective energy loss on cell surface
cell	PV cell surface
cr	radiation energy loss on cell surface
HP	heat pipe
OC	traditional air conditioner
oco	overcooling section outlet
PV	photovoltaic
pc	pipe energy loss
pipe	pipe surface
tot	total
water	water inside pipe

photoelectric conversion occurs, to effectively receive highly concentrated optical energy [9,13–15]. These cells have higher thermal stability compared to silicon solar cells [16,17]. A dual-axis tracker may also be installed in the concentrator to make full use of solar energy throughout the day [4].

The temperature of the PV cell surface increases as CR increases, while in turn severely deteriorating the photoelectric conversion efficiency of the PV cell – even to the point of “burning up” the cell. Photoelectric conversion efficiency and PV power output linearly decay as PV cell temperature increases [18]. This limits the practical operation of PV power generation. The high concentration PV/thermal system (HCPVT), as per the cascade utilization of energy absorbed by its PV cells, has garnered a great deal of research attention in recent years [12,19–23]. Cogeneration systems not only enhance comprehensive utilization efficiency, but also allow for the safe operation of PV cells.

Renno and Petito [14] studied the electrical parameters and concentration factor of an HCPVT experimentally. They also simulated the temperature distribution of the coolant medium in ANSYS-CFX software; the PV cell temperatures measured by experimental means were used to set boundary conditions in the numerical model. Zimmermann [3] studied the thermal performance of an HCPVT system containing a microchannel heat sink via experimental measures. The total hybrid conversion efficiency of solar radiation in this system is 60%; the energy content of overall output power can be increased by 50% by waste heat recovery with hot water temperature of 70 °C. According to Chen et al. [24], the overall efficiency of the HCPVT system may exceed 70%–52% of which is shared by the thermal conversion efficiency. Xu et al. [10] established simulation models for both electrical and thermal conversions based on Shockley diode and 2D steady-state heat transfer equations, respectively. They investigated the influence laws of meteorological parameters (ambient temperature, wind speed, and irradiance) and cooling medium parameters (water temperature and mass flow rate) on both electrical and thermal efficiencies, which reached 28% and 60% per their calculations, respectively. Hot water temperature of 70 °C is generally agreed to yield maximum efficiency.

Lower quality energy recovered from the PV cell can be reused in a few different ways. Ong and Escher [25], for example, studied an HCPVT system with a multi-effect membrane distillation desalination system which converts 85% solar energy into use. The energy can also be reused as space heating or domestic hot water [26]. The heat storage tank is the critical component in this type of HCPVT system [27]. The energy may also be used for driving chillers. Garcia-Heller and Paredes [9] observed 87.5% overall reuse of waste heat in a PV cell by absorption chiller system, the PV efficiency of which is 25%. Their model has CR of 2000, which is concentrated in the tower-heliostat collector. Buonomano et al. [28] similarly studied the parameter-matching characteristics of solar thermal energy and an absorption/adsorption chiller.

PV cell energy can also be transformed into electric energy. Li et al.