Energy Conversion and Management 88 (2014) 650–656

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental investigation of tri-functional photovoltaic/thermal solar collector

Jie Ji *, Chao Guo, Wei Sun, Wei He *, Yanqiu Wang, Guiqiang Li

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, #96 Jinzhai Road, Hefei City, Anhui Province, China

ARTICLE INFO

Article history:
Received 7 June 2014
Accepted 9 September 2014
Available online 26 September 2014

Keywords:
Tri-functional photovoltaic/thermal collector
PV/air-heating
PV/water-heating
Performance evaluation

ABSTRACT

Photovoltaic/thermal (PV/T) solar collectors can provide electric power and thermal energy simultaneously. Either PV/T water collectors or PV/T air collectors can be left unused in some seasons because of the freezing problem of water and seasonal demand of hot air. In this paper, a novel design of tri-functional PV/T solar collector was proposed. The collector can work in PV/water-heating mode or PV/air-heating mode according to the seasonal requirements. Experiments were conducted in different working modes under variable conditions to evaluate the performance of collector. The results show that the daily thermal efficiency achieved 46.0% with the electrical efficiency of 10.2% in PV/air-heating mode. The temperature increase of air reached 20 °C with the flow rate of 0.033 kg/s on a sunny day. The instantaneously thermal efficiency at zero reduced temperature were 37.4% and 44.3% as the air flow rate was 0.026 kg/s and 0.032 kg/s respectively. In PV/water-heating mode, the thermal efficiency of the collector was 56.6% at zero reduced temperature, and the daily thermal efficiency of the system was around 36.0%. Compared with solar collectors presented by other authors, the tri-functional PV/T collector is able to operate efficiently in various conditions.

1. Introduction

PV cells are semiconductor devices that convert incident radiation into electricity directly. For each type of PV cells, only part of the solar irradiation can be utilized. The rest of the incident radiation converts to heat and induces a temperature rise of solar cells eventually. The PV efficiency decreases (typically 0.4% per degree centigrade rise for c-Si cells) as the cell temperature increases [1]. In order to cool the PV cells and make full use of the solar radiation, photovoltaic/thermal (PV/T) collectors have been developed [2,3]. The PV/T collector can collect electrical and thermal energy simultaneously which means double output with single area. The thermal energy extracted by PV/T collectors is used for water heating in domestic and industrial applications, or space heating and agricultural drying with air as working fluid [4–7]. Combined with absorption chiller or thermoelectric refrigerator, the PV/T water collector can also be used for space cooling [8,9]. Several theoretical and experimental studies have been performed on PV/T air or water collectors [10–13]. The results show that PV/T collectors can use solar energy more efficiently and cost-effective compared to convenient solar thermal collectors.

However, the PV/T water collector may be damaged without anti-freeze solutions when freezing temperatures occur in winter, especially at middle and high latitudes. And heated air for space heating is a more economical way to reduce the energy consumption in cold days. As for the PV/T air collector, it may be left unused in non-heating seasons. Especially in summer, the electrical efficiency of PV/T air collector would be limited because of the high temperature of PV cells without ventilation and overheating protection methods. Neither the PV/T water collector nor the PV/T air collector is able to work effectively all over the year. In view of this, the idea of dual-function solar collector was proposed by Ji et al. [14] and Ma et al. [15]. Air flow channel was introduced to conventional sheet-and-tube solar water collectors to perform the air heating function. The performance of dual-function solar collector has been investigated experimentally and theoretically. The collector was proved to be effective and could be modified to a building-integrated one. It showed good thermal performance in both air heating mode and water heating mode.

Inspired by this, a new design of tri-functional photovoltaic/thermal solar collector is presented in this paper. The collector is modified from sheet-and-tube solar collectors. This tri-functional PV/T collector is designed to provide electricity and hot air (PV/air-heating mode) in winter, and provide electricity and hot water (PV/water-heating mode) in the rest of year. The working mode of tri-functional PV/T collector is flexible to fulfill the

* Corresponding authors. Tel./fax: +86 551 63607346.
E-mail addresses: jijie@ustc.edu.cn (J. Ji), hwei@ustc.edu.cn (W. He).

http://dx.doi.org/10.1016/j.enconman.2014.09.030
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

A_c	collector aperture area, m^2
A_{PV}	PV area of collector, m^2
c_p	specific heat capacity, J/(kg K)
F_R	heat removal factor of collector, –
G	solar irradiance, W/m^2
I	current of PV module, A
H	daily solar radiation, MJ/(m^2 day)
$\dot{m}$	air/water mass flow rate, kg/s
M	mass of water in tank, kg
P_{flow}	mechanical work, W
T_{cell}	cell temperature, °C
T_{final}	final water temperature in tank, °C
T_{in}	air/water inlet temperature, °C
$T_{initial}$	initial water temperature in tank, °C
T_{out}	air/water outlet temperature, °C
T_{p1}, T_{p2}, T_{p3}	absorber plate temperature, °C
U	voltage of PV module, V
U_L	energy loss coefficient of collector, °C m^2/W
U_{loss}	energy loss coefficient of system, °C m^2/MJ
Δp	pressure drop, Pa
Δt	data acquisition interval, s
η_f	energy saving efficiency, –
η_{PV}	electrical efficiency, –
η_{total}	total efficiency, –
η_{th}	thermal efficiency, –
η_{power}	energy conversion efficiency of conventional power plant, –
ρ	density of air, kg/m^3
ς	packing factor, –
$(\tau\alpha)_e$	effective transmittance-absorptance product, –

requirements in different seasons, regions and applications. In the present work, experiments have been conducted to investigate the thermal and electrical performance of tri-functional PV/T solar collector in different working mode. The effect of solar radiation, flow rate, and inlet temperature are discussed. The efficiencies in PV/air-heating mode and PV/water-heating mode are calculated and compared with latest works.

2. Description of the tri-functional PV/T collector and the experimental set-up

2.1. Description of the tri-functional PV/T collector

The structure and cross section of the PV/T collector are shown in Fig. 1. The collector has the following components: glass cover, mono-crystalline silicon cells, aluminum absorber plate, copper tubes, air inlet, air outlet, and insulation layer. The PV cells are packaged and attached to the absorber plate with a packing factor of 0.59. The aperture area of the collector is 1.89 m^2 and the cell area is 1.12 m^2. The rest of the absorber plate is covered by black painted surface. Between the glass cover and the PV cells, there is air gap to reduce the heat loss from upper surface and prevent the dust deposition caused by air flow. The copper tubes are welded at the bottom of the absorber plate by laser welding machine. In PV/air-heating mode, the collector is connected to a ventilation system and both ends of the copper tubes are closed. While in PV/water-heating mode, the inlet and outlet of the air flow channel are closed. The heights of air gap and air flow channel are 0.02 m and 0.03 m, respectively. The collector is properly insulated by glass fiber with the thickness of 0.03 m.

2.2. Experimental setup

The experimental setup of PV/air-heating mode is shown in Fig. 2. A fan is located downstream of the collector to produce a negative gauge pressure and steady air flow. The temperature of air entering the collector is controlled by an air heater. As the flow rate of the blower is fixed, an air bypass valve is mounted downstream to adjust the flow rate. The flow rate is measured by a vortex shedding flowmeter (VSF).

For PV/water-heating mode, both the tests of collector working under forced circulation and natural circulation have been conducted. As shown in Fig. 3a), a water tank with storage capacity of 120 L is located near the collector. For forced circulation, the water flow is driven by a brushless DC pump using an external power and the flow rate is controlled by a valve and measured by a water meter. As for natural circulation system, a water tank of same capacity is located above the collector, which is shown in Fig. 3b). The water circulation is driven by density difference when water is heated and temperature gradients occur.

The test rigs are mounted in Hefei (32°N, 117°E) and the tilted angle of collectors is fixed at 35°. A list of experimental testing and monitoring devices is given in Table 1. Three thermocouples are adhered to the back of absorber plate evenly along the axis (marked as T_{p1}, T_{p2}, T_{p3} from entrance to exit). Five thermocouples are arranged in the water tank at different altitude to measure the water temperature. The PV cell temperature is measured by a thermocouple adhered to the center of PV panel. The instantaneous thermal and electrical performance of collectors under quasi-steady-state and the daily performance of the PV/T system were tested with a range of inlet or initial temperature and flow rate in both PV/air-heating and PV/water-heating mode. All the data were recorded in good weather conditions with an interval of 30 s from AM 8:00 to PM 16:00 during October to December in 2013. The test procedures refer to the recommendation of ASHRAE 93-2010 [16].

3. Performance evaluation of the tri-functional PV/T collector

In the present study, both the performance of PV/T collector and daily performance of PV/T system are evaluated. The performance of PV/T collector can be characterized by thermal efficiency and electrical efficiency. All the thermal efficiencies are based on aperture area of the PV/T collector. The instantaneous thermal efficiency of collector can be defined as the heat gain of the working fluid between outlet and inlet divided by incident solar radiation, expressed as:

$$\eta_{th} = \frac{\dot{m}c_p(T_{out} - T_{in})}{GA_c} \quad (1)$$

In order to reduce the effect of variation of ambient temperature and solar radiation and get general conclusions, the Hottel–Whillier model is applied and the heat gain of PV/T collector can be expressed as[1]:

$$Q_u = A_c[GF_R(\tau\alpha)_e - F_R U_L(T_{in} - T_a)] \quad (2)$$