Solar Energy 155 (2017) 1084–1091

Contents lists available at ScienceDirect

Solar Energy

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

Building-integrated heat pipe photovoltaic/thermal system for use in Hong Kong

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ARTICLE INFO

Article history:
Received 6 April 2017
Received in revised form 9 July 2017
Accepted 19 July 2017

Keywords:
Heat pipe
Hybrid solar system
Building integration
Energy performance

ABSTRACT

Heat pipe is a high-efficiency heat transfer device being widely used in solar applications. In this study, an innovative building integrated heat pipe photovoltaic/thermal (BiHP-PVT) system, which offers electricity generation, services water pre-heating, and space air-conditioning load reduction, was investigated. Firstly, a dynamic model was developed for a heat pipe photovoltaic/thermal (HP-PVT) system, and the numerical accuracy was confirmed by experimental validation. Then the annual performance of the BiHP-PVT system was evaluated through a case study in Hong Kong based on the typical weather conditions. The simulation results show that the annual overall heat transmission through the external wall can be reduced to less than a quarter of the normal practice. The annual water heating efficiency and electricity generation efficiency are around 35% and 10% respectively. The overall electricity saving is 315 kW h/year per unit façade surface area. In addition to its attractive energy performance, the BiHP-PVT system presents larger climate adaptability.

1. Introduction

Photovoltaic (PV) cells can absorb solar radiation, but only a minor fraction of the absorbed energy is converted into electricity. A large amount is actually converted into heat, resulting in substantial temperature rise of the PV cells. The PV electrical efficiency decreases by 1–2% for every 30 °C rise in this temperature. A range of PV cooling methods have been proposed, like air and/or liquid flow, heat pipes, phase change materials, and thermoelectric devices (Makki et al., 2015). Hybrid photovoltaic/thermal (PVT) system is another alternative to lessen the performance degradation of the PV cells. From 1970s onwards, research publications on PVT have been escalating, including historical and thematic reviews on PVT applications (Charalambous et al., 2007; Zondag, 2008; Hasan and Sumathy, 2010; Tiwari et al., 2011; Chow, 2010). The coverage generally includes analytical and numerical modeling and simulation, experimental work and exergetic evaluation, parameters analysis and commercial development.

Using heat pipe to collect solar thermal energy was firstly introduced in 1970s. Since 1980s, research efforts have been on flat plate heat pipe solar collectors with the heat pipes mechanically bonded to the absorber plate, and also on the evacuated tubular heat pipe solar collectors with heat pipes inserted into the vacuum selective glass tubes (Ortabasi and Fehlner, 1980; Akyurt, 1984; Chow et al., 2011; Nkwetta and Smyth, 2012; Redpath, 2012). Heat pipe solar water heater has several advantages over the conventional flat plate solar water heater. These are namely, thermal diode benefit, easy freeze protection, lower pumping power, and higher thermal efficiency.

Using heat pipes for PV cooling however was firstly proposed in 1980s (Russell, 1982). The heat pipe cooling PV systems were firstly investigated for concentrated PV (CPV) systems (Akbarzadeh and Wadowski, 1996; Anderson et al., 2008; Kuo et al., 2009). In 2010s, the incorporation of heat pipes to conventional flat plate PV module came into picture. Wu et al. validated a theoretical model which relates the outlet water temperature with the absorber temperature using the ε-NTU method. They found that the solar cell temperature differences between different rows were less than 2.5 °C (Wu et al., 2011). Pei et al. developed a dynamic model for the HP-PVT system and validated it using experimental data; annual analysis were also performed (Pei et al., 2012). Zhang et al. combined the modular HP-PVT and the heat pump to overcome the 'dry-out' problem as observed in the conventional loop HP-PVT configurations (Zhang et al., 2013). The refrigerant in the evaporator of the heat pump cycle absorbs heat from the condenser section of the loop heat pipe. The thermal

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http://dx.doi.org/10.1016/j.solener.2017.07.055
0038-092X/

and photovoltaic efficiencies were found higher than the conventional loop HP-PVT system.

When the HP-PVT collectors are integrated with the building facade, this then becomes the building integrated HP-PVT system (BiHP-PVT). Our literature survey showed that this innovative concept, unlike the building integrated water-based PVT (BiPVT/w) systems, has not been adequately studied. In this paper, our HP-PVT simulation model was introduced with experimental validation. Further on, the annual performance of the BiHP-PVT system was analyzed through a case study, in which the energy performance can be readily compared with the BiPVT/w option.

2. Mathematical models

The HP-PVT collector is the core component of the HP-PVT system. Fig. 1 shows such a collector with a layer of solar cells laminated on to the absorber plate and an array of heat pipes adhered to the other side of the plate. Incoming solar beam can be transmitted through the front glass cover with electricity generation through photon conversion at the solar cells, and solar heat is also transferred to the heat pipes. Water flowing across the condenser sections of the heat pipes subsequently gain heat, and this recirculating water stream flows back to the storage tank and starts another cycle. The following describes the numerical model used in our system analysis.

2.1. Thermal model

The control volume finite difference modeling approach was adopted. The HP-PVT collector is represented by eight nodes. The node 'g' represents the glass cover; 'p' is for the PV plate; 'b' is for the absorber plate; 'e' is for the evaporator wall of heat pipe; 'f' is for the working fluid in heat pipe; 'i' is for the insulation layer, 'c' is for the condenser wall of heat pipe; 'w' is for the cooling water steam flowing across the heat pipe condenser. Accordingly, its temperature distribution can be computed using a matrix equation set derived from the instantaneous energy balance at these nodes. The following two assumptions were made in the model development:

(i) Heat conduction in the longitudinal direction of the aluminum absorber plate is negligible; and
(ii) The temperatures of the PV cells and the adhesive layers are the same, including the layers of ethylene-vinyl acetate (EVA) and tedlar-polyester-tedlar (TPT).

For the nodes 'g', 'p', 'b', 'e', 'i', 'c', 'w', the set of energy balance equations is then:

$$\begin{cases} M_g c_g \frac{dT_g}{dt} = h_{ag}A_{ag}(T_a - T_g) + h_{eg}A_{eg}(T_{sky} - T_g) + h_{gp}A_{gp}(T_p - T_g) + Q_g \\ M_p c_p \frac{dT_p}{dt} = h_{gp}A_{gp}(T_g - T_p) + h_{bp}A_{bp}(T_b - T_p) + Q_{pv} + Q_{ad} - P \\ M_b c_b \frac{dT_b}{dt} = h_{bp}A_{bp}(T_p - T_b) + h_{be}A_{be}(T_e - T_b) + h_{bi}A_{bi}(T_i - T_b) \\ M_e c_e \frac{dT_e}{dt} = h_{be}A_{be}(T_b - T_e) + h_{ie}A_{ie}(T_i - T_e) + (T_c - T_e)/R_{hp} \\ M_i c_i \frac{dT_i}{dt} = h_{bi}A_{bi}(T_b - T_i) + h_{ie}A_{ie}(T_e - T_i) + h_{ai}A_{ai}(T_a - T_i) \\ M_c c_c \frac{dT_c}{dt} = (T_e - T_c)/R_{hp} + h_{cw}A_{cw}(T_w - T_c) \\ M_w c_w \frac{dT_w}{dt} + c_w \dot{m}(T_{out} - T_{in}) = h_{cw}A_{cw}(T_c - T_w) + h_{wa}A_{wa}(T_a - T_w) \end{cases} \quad (1)$$

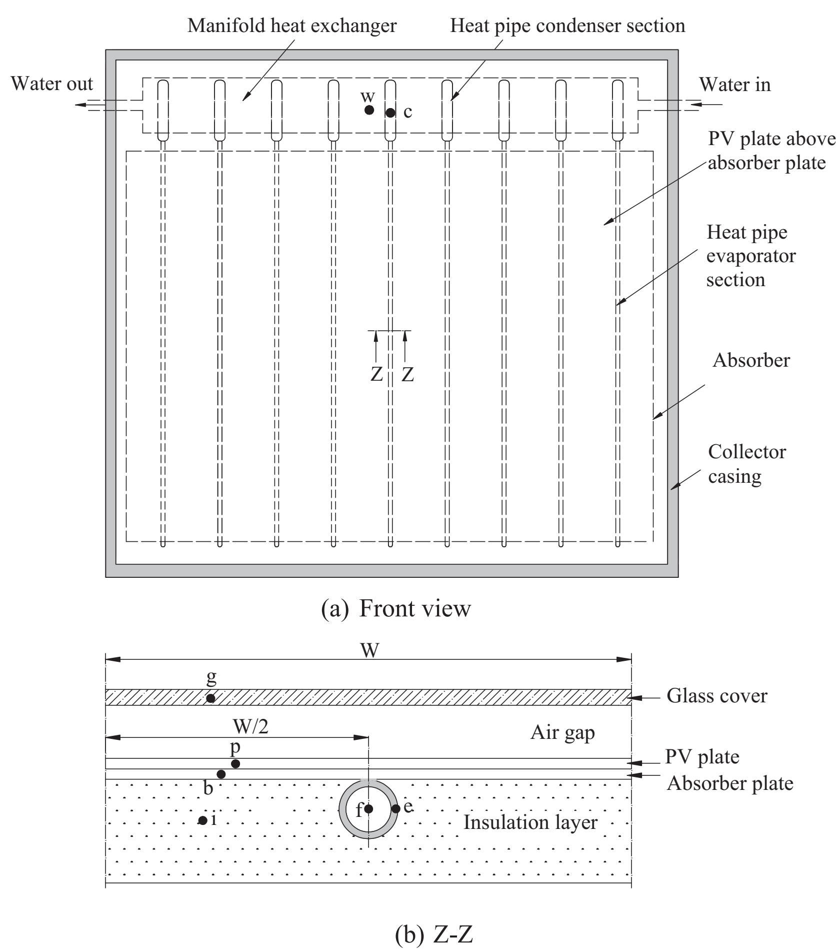

Fig. 1. The HP-PVT collector: (a) front view and (b) section Z-Z (across one heat pipe).