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Annual performance of building-integrated photovoltaic/water-heating system for warm climate application

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ABSTRACT

A building-integrated photovoltaic/water-heating (BiPVW) system is able to generate higher energy output per unit collector area than the conventional solar systems. Through computer simulation with energy models developed for this integrative solar system in Hong Kong, the results showed that the photovoltaic/water-heating (PVW) system is having much economical advantages over the conventional photovoltaic (PV) installation. The system thermal performance under natural water circulation was found better than the pump-circulation mode. For a specific BiPVW system at a vertical wall of a fully air-conditioned building and with collectors equipped with flat-box-type thermal absorber and polycrystalline silicon cells, the year-round thermal and cell conversion efficiencies were found respectively 37.5% and 9.39% under typical Hong Kong weather conditions. The overall heat transmission through the PVW wall is reduced to 38% of the normal building facade. When serving as a water pre-heating system, the economical payback period was estimated around 14 years. This greatly enhances the PV market opportunities.

1. Introduction

Direct electricity generation from solar radiation through photovoltaic (PV) is more expensive than conventional power generation. The situation is expected to remain for some years and currently the commercial applications rely heavily on government subsidies and/or intangible income sources. By integrating PV modules with solar thermal collectors, the increased energy yield per unit collector area is able to shorten the economical payback period. Such photovoltaic/thermal (PVT) hybrid products are considered to be more promising than the separated side-by-side installations. Research activities on PVT collectors and systems have been on and on in the past decades [1–3] and these are growing rapidly, primarily in European [4–7] and Asian [8–11] countries. A thorough literature review on flat-plate PVT collectors and systems can be found in Zondag [12]. As a heat absorbent, water is more effective than air.

The energy performance of photovoltaic/water-heating (PVW) systems with natural circulation of water has been examined by the authors based on the weather conditions of two cities in China, i.e. in Hong Kong and Hefei [13–15]. These studies reported that the PVT technology is promising in supporting hot-water services systems. In particular, the use of a flat-box-type thermal absorber design, as in Fig. 1, is very effective to operate with the thermosyphon mode. The device is therefore very suitable for the warm and hot climate locations. In Hong Kong for a stand-alone PVW collector system with mono-crystalline solar cells, the daily thermal efficiency was found 48.3% in winter and 45.4% in summer at zero reduced-temperature (i.e. when the initial water temperature in the storage tank is as cold as the mean ambient temperature on the day of measurement). This was corresponding to a water-storage to collector-area ratio (M/A_c) of 96.6 kg/m^2.

In order to evaluate its integrative energy performance and economic payback period as compared to the plain PV panel and solar water-heating collector, a dynamic simulation model of the PVW collector system was developed. Details of the numerical approach have been described in Chow et al. [16]. The numerical results showed that a payback period of 12 years for the PVW collector system is achievable and is comparable to the side-by-side system with the equivalent surface areas of PV module and solar water-heating collector. This is then much shorter than the estimated 52-year payback period of the plain PV application in Hong Kong.

Building-integrated photovoltaic/thermal (BiPVT) system designed for water-heating is one step further in our research study. When a part of the solar radiation fallen on the building façade is directly converted to useful thermal and electric power, the portion of solar energy transmitted through the external facade

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Nomenclature

A	area, m^2
C	specific heat capacity, J/(kg K)
D	diameter; thickness, m
G	incident solar radiation, W/m^2
H	mean height, m
h	heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
L	mean length, m
l	wet perimeter of water channel, m
$\dot{m}$	mass flow rate, kg/s
r	packing factor, –
T	temperature, °C
t	time, s
U	overall heat transfer coefficient, W/(m^2 K)
U	flow velocity, m/s
V	volume, m^3
W	mean width, m
W	width, m
x,y	distance, m

Greek Symbols

α	absorptivity, -
β	temperature coefficient, %
η	efficiency, –
ρ	density, kg/m^3

Subscripts

a	ambient air
b	beam
c	PV encapsulation
cell	standard solar cell testing condition
d	diffuse
eff	effective
f	channel fluid flow
g	front glazing
ins	insulation material
p	thermal absorber
r	radiation
tk	tank
w	wall

is reduced. Hence the space cooling load is reduced. On the other hand an external façade dominated by crystalline silicon solar cells in dark blue color can share the same aesthetical effect as in BiPV system. Funded by a Competitive Earmarked Research Grant from the Research Grants Council of Hong Kong, an experimental rig was constructed at the City University of Hong Kong for investigating the electrical and thermal performance of the BiPVW system. This paper first gives a brief review of the experimental findings; the simulation results based on validated numerical models are then presented.

2. Experimental works on BiPVW

Fig. 2 shows the experimental set up. To compare the thermal performance of two different building facade elements, an environmental chamber consisted of an outer chamber and enclosed within it, two identical inner chambers (test cells) was used. It was positioned with the external walls of the two test cells facing southwest – the orientation richest in year-round solar radiation in Hong Kong [17]. All internal walls of the test cells were thermally insulated. The air-conditioning provisions maintained all inner/outer chambers at a pre-set temperature of 22 ± 0.5 °C. The heat transmission through the internal walls of the test cells was therefore negligible. This set-up allowed an accurate assessment of the thermal performance of any specific features provided at the front wall of the test cells.

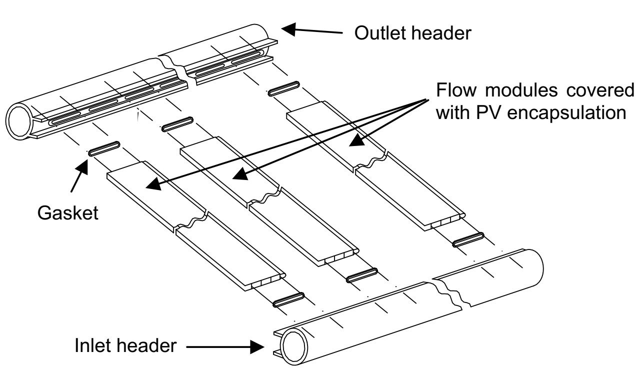

Fig. 1. Assembly of flow modules at the flat-box type thermal absorber.

In Fig. 2, the portion of the front wall at the right covered the test cell with a PVW wall, and the other bare wall at the left covered the reference test cell. The PVW wall was composed of six PVW collectors mounted on a 100 mm brick wall with plastering on both interior and exterior wall surfaces. The PVW collector adopted the flat-box thermal absorber design and provided with polycrystalline silicon PV cells. The water circuitry of the PVW collectors included a water storage tank and a circulation pump with manual bypass located at the roof of the environmental chamber. A direct digital controlled automatic drain valve was provided to imitate the daily pattern of water consumption through the storage tank. Natural circulation and forced circulation operating modes were used alternatively and periodically so that their seasonal system performance could be compared.

The following gives a summary of the major findings from the experiments [18]:

(i) According to the experimental measurements during the late summer period, the system thermal efficiency was found 38.9% at zero reduced-temperature, and the corresponding average electricity conversion efficiency 8.56%.
(ii) Good thermal insulation performance was observed at the PVW facade in both summer and winter periods. Comparing with the reference wall, the interior surface temperature of the PVW wall was much lower and fluctuated at smaller amplitude; the reduction of space cooling load in peak summer via the external wall was found 50%.
(iii) The collector performance of the system in natural circulation can be as good as that in the forced circulation mode for simple vertical PVW collector arrays in Hong Kong. This made natural circulation more attractive since forced circulation consumed extra electric power for pump operation and required additional investment on the pump and control system.

Besides, the experimental works provided the necessary measured data to validate and/or calibrate the computer simulation models, which were developed later on to evaluate the annual energy performance of a BiPVW system that served as