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Experimental comparison of two PV direct-coupled solar water heating systems with the traditional system

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HIGHLIGHTS

- A design approach of PV-coupled solar water heating system (SWHS) is presented.
- Two different designs of PV modules are proposed and investigated.
- A comparative test rig of PV-coupled SWHS and traditional SWHS is set up.
- A flow rate increasing with solar irradiation is recommended.

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ABSTRACT

Simple and reliable, PV direct-coupled DC pumps are promising in solar water heating systems (SWHS). However, there is limited experimental data on the performance comparison of PV-coupled SWHS with traditional SWHS. Hence in this study, a comparative test rig is set up to measure and analyze the performance of the PV-coupled SWHS and the traditional system under the same conditions. The experimental results show that on sunny days the PV-coupled SWHS has similar daily thermal efficiency as the traditional SWHS, and slightly higher efficiency after improving the design of the PV module. Under low irradiation, the PV-coupled SWHS gains much more heat than the traditional SWHS, which indicates the potential of the PV-coupled SWHS having much higher efficiency than the traditional SWHS on cloudy days. In order to improve the performance of the PV-coupled SWHS, two different designs of PV module are proposed, and their influence on the pump startup characteristics, the flow rate profile, and the thermal efficiency of the system is investigated. It is found that the modified design of the PV module can reduce the requirement of PV cells and increase the efficiency of the system.

1. Introduction

Solar collector has been a well-known product to reduce fossil energy consumptions for space and water heating [1] and has been widely used in China with far more than 1.5×10^8 m^2 collector areas installed [2]. Most solar water heating systems (SWHS) with collector arrays are forced circulation systems using AC pumps [3–6]. The heat transfer fluid flows at a constant rate, controlled by an ON/OFF differential temperature sensing controller. However, many technical obstacles still remain. The controller and the sensors lead to system malfunctions, and AC pumps cycle between ON and OFF frequently under low solar irradiation [7]. These operational instabilities bring harmful effects to power grid (like power grid voltage fluctuation) and reduce the lifetime of AC pumps and controllers [7]. Moreover, whatever the weather is like, the controller must keep working 24 h a day. Then, the SWHS utilizing PV directly-coupled DC pumps is proposed by previous researchers, since the flow rate requirement of the heat transfer fluid often has a natural relationship with the availability of solar energy [8]. The PV-coupled SWHS is simple and reliable, without the requirement of controller, temperature sensors, and auxiliary electric [9].

Several research have been conducted to evaluate the performance of PV-coupled SWHSs through simulations and/or experiments. Al-Ibrahim [7] conducted simulations on PV-coupled SWHSs with the assumption that the flow rate was a square-root function of solar irradiation. And the results show that the PV-coupled SWHS could have much higher solar fraction than traditional systems. Loxsom and Durongkaveroj [10] used two straight-line segments to represent the flow rate versus irradiation relationship in their study. Cardinale et al. [11] did the investigation with the assumption that the power supplied to the motor was fully trans-

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Nomenclature

Ac	total aperture area of collector array (m^2)
A_{pv}	total area of a PV cell product (include border) (m^2)
C_p	water heat capacity (J/(kg K))
G	solar irradiance (W/m^2)
H	daily solar radiation ($MJ/(m^2\ day)$)
I	output current of PV module (A)
m	mass of water in tank (kg)
n	number of PV cells used in a PV module (–)
Q	volume flow rate (L/s)
T_{avg}	average temperature of water in tank (°C)
$T_{initial}$	initial temperature of water in tank (°C)
T_{final}	final temperature of water in tank (°C)
T_{rise}	temperature rise of water in tank in a day (°C)
T_{in}	inlet temperature of collector array (°C)
T_{out}	outlet temperature of collector array (°C)
V	output voltage of PV module (V)
ρ	density of water (kg/m^3)
η	thermal efficiency of collector array (–)
η_{day}	daily thermal efficiency of system (–)
η_{DC}	DC pump efficiency (–)
η_{PV}	electric efficiency of PV module (–)
ΔP	hydraulic head (kPa)
σ	temperature stratification of the water in tank (°C)

ferred to the pump. Besides simulation studies, there are many experimental studies on PV-coupled SWHSs. Many researchers studied solar photovoltaic/thermal systems which are similar as PV-coupled SWHSs [12–16]. Benghanem et al. [17], Mokeddem et al. [18], Kaldellis et al. [19], Sutthivirode [20] and et al. investigated the solar water pump system which used PV coupled pumps to pump water from a well. Swan and Allen [21] presented an experimental study of a new integrated solar pump design which had no dynamic seal. With the design, the total volume and mass of the solar DC pump was significantly reduced. A variety of design variations were tested and an electric to hydraulic efficiency of 32% was got. The authors used a pulse width modulation (PWM) to connect the PV module and the pump and maintain a constant PV module voltage. The results show that the solar pump is suitable for SWHS and the oversizing of PV module is wasteful. In the study of MacLeod [22], the experimental system is an indirect SWHS with two 6 m^2 flat plate solar collector and an internal coil heat exchanger. The authors connected the PV module and the pump with a linear current booster (LCB) to start the pump under low solar irradiation (about 250–300 W/m^2). Different configurations of the connection of the PV module and pump were investigated experimentally. They found the performance (ration of power supplied to the motor and power outputted by the PV module) of the LCB was about 1–2% higher than other configurations. Grassie et al. [23] proposed a PV-coupled SWHS with constant outlet temperature of the collector. The system is freeze tolerant and the water is circulated by a small PV directly coupled DC pump. To provide the desired outlet temperature, the method of shading the PV module is used. Bai et al. [24] investigated the startup phase of three PV-assisted SWHSs with different electronic devices (direct connection, LCB, MPPT), and the system performance was compared with traditional systems through simulations. From the results, the author found that the matched flow rate system with a temperature difference of 5 °C had the lowest consumption of the auxiliary heat. Regarding the energy performance, the PV-SDHW system with a solar circulation pump had better performance than traditional system and other PV-SDHW configurations.

In previous research, the experiments were conducted to measure the performance of some components, while the overall system performance were obtained through simulations. Most simulation studies were carried out with TRNSYS software [24,25], and the results need to be validated by experiments. And few research took into consideration the influence of the environment and the flow nonuniformity in collector arrays [26]. It appears that the PV-coupled SWHS has a better performance than the traditional SWHS in some studies [7], while on the contrary, the traditional SWHS has a better performance in others [24,27]. In other words, the previous studies have limited experimental data on the performance comparison of PV-coupled SWHS with traditional SWHS. In this study, two systems which are identical except for the fluid circulation method, are set up to compare and analyze the performance. One is a SWHS with a PV direct-coupled DC pump, the other is a traditional SWHS with an AC pump and an ON/OFF differential temperature sensing controller. Furthermore, in order to improve the PV-coupled SWHS, two different designs of PV modules are proposed and their influence on the pump startup characteristics, the pump flow rate profile and the thermal efficiency of the system is investigated.

2. The experimental setup

2.1. The configurations of the comparative systems

A PV-coupled SWHS and a traditional SWHS (Fig. 1) were built at Wuhu city (31°N, 118°E). The experimental setup of the PV-coupled SWHS comprises five flat-plate solar thermal collectors (1 m × 2 m) connected in parallel, which is shown in Fig. 2. The collector array is connected directly with a storage tank of 630 L. A PV directly-coupled DC brushless pump is used to circulate the heat transfer fluid. The PV module has the same inclination and orientation as the solar collector array.

The experimental setup of the traditional SWHS is shown in Fig. 3. It has the same configuration as the first system (Fig. 2), except that it uses an AC pump and an ON/OFF controller to circulate the fluid.

The inlet and outlet temperature, the fluid flow rate, the pump input voltage and current, and the pressure loss of each system are measured simultaneously. Seven T-type thermocouples are installed, distributed uniformly to monitor the temperature stratification of the water in each tank. The inlet and outlet temperature are measured with pt100 A-class sensors. The measurement data are collected by a data logger every 10 s from sunrise to sunset. The detailed characteristics of the components in the experimental setups are shown in Tables 1–3.

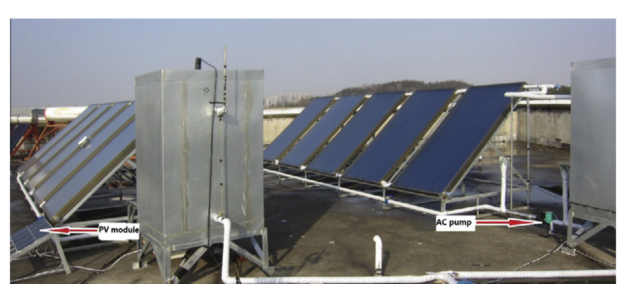

Fig. 1. Photo of experimental setup of the comparative systems.