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RESEARCH PAPER

Design and Performance of a Novel Hybrid Photovoltaic–Thermal Collector with Pulsating Heat Pipe (PVTPHP)

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Abstract

Hybrid photovoltaic–thermal collectors (PVT) are cogeneration components that convert solar energy into both electricity and heat. Pulsating heat pipe (PHP) is a fast-responding, flexible and high-performance thermal-conducting device. The aim of this work is design and performance of a novel hybrid photovoltaic–thermal collector with pulsating heat pipe (PVTPHP) for improving the electrical efficiency, by reducing the photovoltaic panel's temperature, as well as taking advantage of the thermal energy produced. An experimental setup of PVTPHP is constructed, and its operating parameters are measured. The measured parameters include solar radiation intensity, ambient temperature, filling ratio, inclination angle, PV module temperature, open-circuit voltage, short-circuit current, condenser inlet temperature, condenser outlet temperature, water flow rate, fill factor, electrical efficiency, heat delivery and combined efficiency. The results show that this new design has given a good thermal and electric performance compared to the traditional PV and PVT.

Keywords Photovoltaic–thermal collector · Pulsating heat pipe · Combined efficiency · Filling ratio · Inclination angle

Abbreviations

PVTPHP	Hybrid photovoltaic–thermal collector with pulsating heat pipe
PHP	Pulsating heat pipe
PV	Photovoltaic
FF	Fill factor
FR	Filling ratio

List of the symbols

A	Collector gross area, m^2
C_P	Specific heat, kJ/kg K
I_T	Instantaneous/hourly flux incident on top cover of collector, W/m^2
T_i	Condenser water inlet temperature (°C)
T_o	Condenser water outlet temperature (°C)
T_a	Ambient temperature (°C)
$\dot{m}$	Mass flow rate, kg/s

Greek symbols

η	Efficiency

Subscripts

a	Ambient
Cond	Condenser
el	Electrical
i	Inlet
mp	Maximum power
oc	Open circuit
RF	Standard test conditions
sc	Short circuit
th	Thermal

1 Introduction

Nowadays, renewable energies are widely used to reduce the environmental problems, maintain unrenewable resources and sustainable development. Solar energy is one of the main sources of renewable energies that has been attracting the attention of most countries. Conventional systems, which are used to utilize solar energy, include photovoltaic (PV) systems and solar collectors (Yazdanpanahi et al. 2015). PV technology is able to convert solar radiation in electricity with an efficiency ranging from 5 to 20%, meaning that a significant part of the incident solar

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energy is reflected or converted in thermal energy (Aste et al. 2015). So, the temperature of PV cells is increased by the absorbed solar radiation that is not converted into electricity, and consequently, efficiency and output power of a PV system decrease due to the increase in PV module temperature. For that reason, over the years, many research efforts have been spent on the development of hybrid photovoltaic–thermal (PVT) technology (water or air heat transfer fluid). A photovoltaic–thermal (PVT) module is a combination of a photovoltaic (PV) panel and a thermal collector for cogeneration of heat and electricity, with better overall performances of the two separated systems (i.e., thermal and photovoltaic) (Aste et al. 2015; Van Helden et al. 2004). A study of the thermal and electrical performance of PVT solar hot water system was carried out by Dupeyrat et al. (2014). They observed that in configuration of limited available space for solar collector area, the use of efficient PVT collectors in the building envelop can be more advantageous than standard PV and solar thermal collector. Design, modeling and performance monitoring of a photovoltaic–thermal (PVT) water collector with two roll-bonded aluminum absorbers were carried out by Aste et al. (2015), and finally, considerations about daily and annual yields of the proposed PVT collector, compared to a standard photovoltaic module, are discussed. Many investigations on flat-plate PVT collectors have been carried out theoretically as well as experimentally since the late 1970s (Kern and Russel 1978; Florschuetz 1979; Cox and Raghuraman 1985). As reported by different authors in recent reviews (Charalambous et al. 2007; Zondag 2008; Chow 2010; Ibrahim et al. 2011; Jones and Underwood 2001; Kalogirou 2001; Zondag et al. 2002; Tripanagnostopoulos et al. 2002; Bosanac et al. 2003; Tiwari et al. 2006), many types of flat-plate PVT collectors have already been developed. The most investigated PVT technology in recent times is based on systems using water as heat transfer fluid, because they achieve higher overall efficiencies than air systems (Herrando et al. 2014), due to higher heat capacity of water, so the system can be used during the whole year. Testing of two different types of photovoltaic–thermal (PVT) modules with heat flow pattern under tropical climatic conditions was carried out by Dubey and Tay (2013). The thermal part of type A is made of copper, whereas that of type B is made of aluminum. They observed that the average thermal efficiency and PV efficiency for Type A PVT module are 40.7 and 11.8%, respectively, and for Type B are 39.4 and 11.5%, respectively. The electrical efficiency of the PV modules was also compared with and without the thermal collector, and it was found that the average PV efficiency of the PVT modules is about 0.4% higher than the normal PV module. Several novel PVT arrangements were recently investigated (Sarhaddi et al. 2011; Mishra and Tiwari 2013; Fudholi et al. 2014; Fiorentini et al. 2015; Touafek et al. 2013).

Generally, all the above studies show that using the hybrid photovoltaic–thermal collectors is a proper solution for efficient and multi-purpose use of solar energy.

PV/heat-pipe combination has recently been studied. Khairnasov and Naumova (2016) carried out an analysis of the current state and prospects of heat pipes used in photovoltaic–thermal collectors and solar systems. The experiment research for solar PVT system based on flat-plate heat pipe has been performed by Quan et al. (2010). They proposed a photovoltaic–thermal collector with heat pipe for cogeneration of hot fluid (air/water) and electricity. Tang et al. (2009) reported the experimental research of using novel flat-plate heat pipe for solar cells cooling. This prototype module comprises a photovoltaic layer and a flat-plate heat pipe containing numerous micro-channel arrays acting as the evaporation section of the heat pipes. Zhang et al. (2012) presented a review of R&D progress and practical application of the solar photovoltaic–thermal (PVT) technologies. They reported the general comparison of the currently available PVT types and their technical characteristics. They claimed that PVT based on heat pipe can extract heat from PV cells instantly, and if the operating temperature of the heat-pipe fluid can be adequately controlled, the solar efficiency of the system could be significantly improved, and finally, the heat-pipe type retains the cost problem that may affect its wide deployment in practical projects. A novel heat-pipe photovoltaic–thermal system was designed and constructed by Gang et al. (2011), which can be used in cold regions without freezing as compared with the traditional water-type photovoltaic–thermal system. They performed a numerical and experimental study on their heat-pipe PVT system. Optimized design and operation of heat-pipe photovoltaic–thermal system with phase change material for thermal storage were carried out by Sweidan et al. (2016). Akachi (1990) introduced the pulsating heat pipe (PHP) as a heat transfer apparatus. This device was made of a long capillary tube bent into several turns which was filled partially with an operating fluid. A PHP consists of three sections: (1) evaporator, (2) adiabatic section and (3) condenser. In the evaporator, pressure increases due to boiling, while in the condenser, pressure decreases due to the condensation. Hence, self-sustainable pressure perturbations occur, which oscillate the operating fluid and enhance the rate of the convectional heat transfer. The sensible and latent heat transfer happened simultaneously due to phase change and convectional heat transfer. PHPs are similar to conventional heat pipes, with regard to their high conductivity and variable heat flux. Qian et al. (2010) carried out an analysis of a new photovoltaic–thermal building integration system and brought forward a new concept for building integrated PVT system utilizing pulsating heat pipe. Zhang et al. (2008) proposed a closed-loop capillary solar photovoltaic thermoelectric board. The system consists of the oscillating heat pipes, headers, finned tube, graphite conductive layer, metal frame, PV module and insulation.

Generally, a pulsating heat pipe has the heat transfer capacity between the two sources with minimum temperature difference; no need for external force, and contrary to conventional heat pipes, needs no wick due to the small diameter and using the capillary. As a result, it has smaller weight and size compared to conventional heat pipes.

Therefore, considering the capabilities proposed for pulsating heat pipe, it seems that the pulsating heat pipe is a good choice to use in PVT collectors.

In the present study, the idea of a novel hybrid photovoltaic–thermal collector with pulsating heat pipe (PVTPHP) is proposed, and its performance has been analyzed and tested based on the weather data of city of Izeh in the southwest of Iran.

2 Experimental Setup

All the experiments were performed in Izeh, Iran (latitude: 31°8′; longitude: 49°87′). The experimental setup consists of one monocrystalline silicon PV module (100 W) integrated with a novel pulsating heat-pipe solar collector. Schematics of the PVTPHP and experimental setup are shown in Figs. 1a, b and 2. PVTPHP was placed outdoors in an unimpeded area and in a southern direction using a solar power meter. A water storage tank has been located below the experimental setup. The thermal section of PVTPHP is made of pulsating heat-pipe solar collector. The PV panel is simply mechanically clamped to the thermal collector. An insulation layer of 5 cm thickness is provided to reduce heat losses through the back of the PVTPHP. The design parameters of the PV are described in Table 1.

As shown in Fig. 1, condenser part of the PVTPHP is made of galvanized sheet in the form of a sealed cube box. This increases the amount of heat transfer between PV and thermal section and facilitates the use of the PVTPHP in active and thermosyphon systems, although most of the previous studies used a header or individual tank for condenser.

Details of fabrication materials of pulsating heat-pipe solar collector (thermal collector) are given below:

- Absorber material: copper sheet
- Collector mainframe material: galvanized sheet
- Dimension of absorber plate: 0.7 m × 1 m
- Condenser section: a box 0.7 m × 0.3 m × 0.03 m
- Length of evaporator: 70 cm
- Length of condenser: 30 cm
- Turns of PHPs: 19

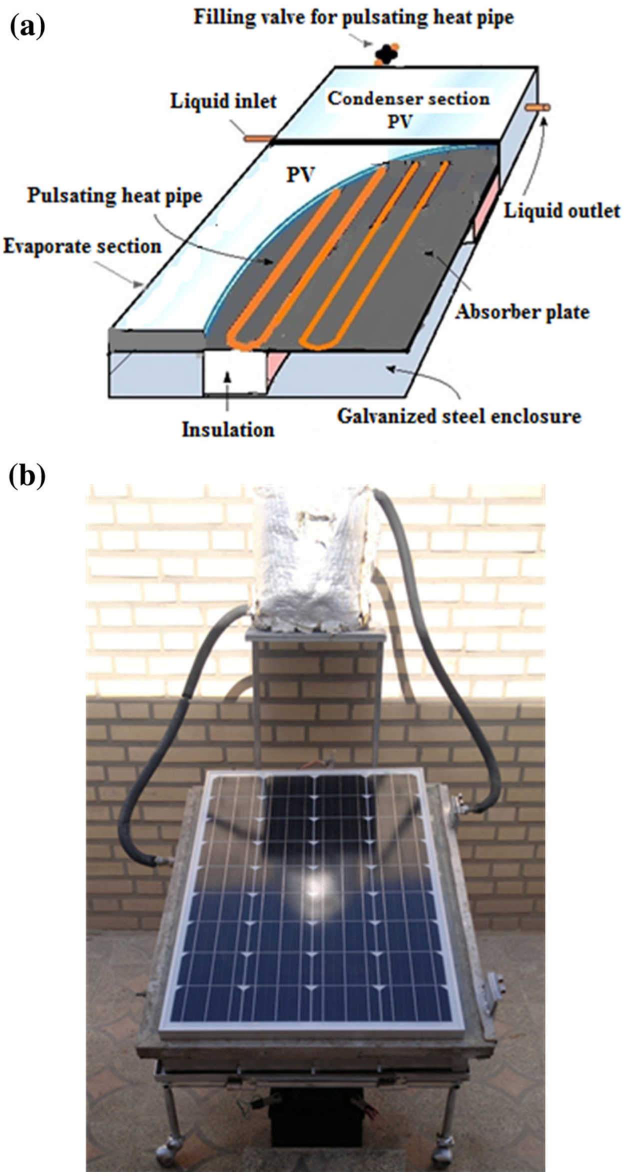


Fig. 1 Detailed configuration of PVTPHP (**a**). Hybrid photovoltaic–thermal collector with pulsating heat pipe (PVTPHP) (**b**)

- Back insulation: fiberglass wool and polystyrene (5 cm)
- PHP material: copper tube
- Inner diameter of PHPs: 2 mm
- Outer diameter of PHPs: 4 mm
- PHP working fluid: distilled water
- PVT working fluid: water

It has to be noted that the most advanced technique for the connection between PV section and the absorber is the lamination of the whole package (Glass, PV cells, electrical insulation and absorber) in one step (Aste et al. 2015; Dupeyrat et al. 2014). However, at the experimental stage, the above-mentioned technique was evaluated too expensive and difficult

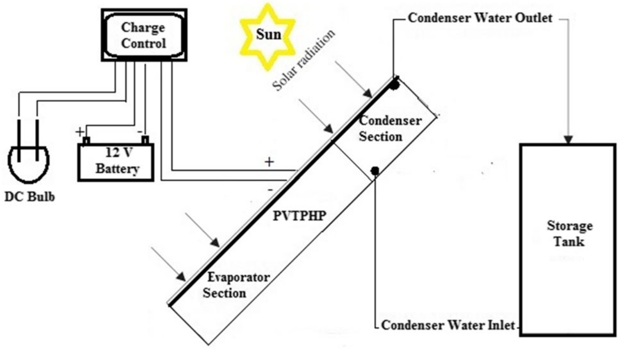


Fig. 2 Schematic diagram of PVTPHP system

Table 1 Design parameters of the PV system

Parameter	Value
PV module	Monocrystalline silicon glass-to-glass PV module (100 W)
$L \times b$	1.1 m × 0.67 m
$I_{\mathrm{sc,RF}}$	6.02 A
$V_{\mathrm{oc,RF}}$	22.1 V
$I_{\mathrm{MP,RF}}$	5.62 A
$V_{\mathrm{MP,RF}}$	17.8 V
η_0	0.135

to activate. So, to reach a good thermal contact between PV panel and thermal collector, thermal paste is applied instead.

2.1 Experimental Method

In Izeh, more than 90% of solar heat is gained between 8:00 AM and 6:00 PM. Hence, all experiments were carried out during this time period on sunny days during August and September 2015. The measured data include solar radiation intensity, ambient temperature, condenser water inlet and condenser water outlet temperature, filling ratio, inclination angle, solar cells temperature, water flow rate, open-circuit voltage, short-circuit current, fill factor and efficiency. Solar radiation intensity has been measured by a digital solar power meter (ST-1307) at the same incident plane of the PVTPHP. An infrared thermometer (FLUKE-62) has been used to measure the temperature of various points of PV module surface. Three digital thermometers (Built-In-Thermometer 50–200 °C) have been used to measure condenser water inlet and outlet temperatures, ambient temperature and water storage tank. Two digital multi-meters (HONEYTEK-A830L) have been used to measure current and voltage. The battery was charged during daytime using the power from the PV module and discharged during nighttime using DC bulbs. The uncertainty of the measured parameters is given in Table 2.

Table 2 The uncertainty of the measured parameters

Parameter	Unit	Uncertainty
Ambient temperature (T_{a})	°C	± 0.1
Condenser water inlet temperature (T_{i})	°C	± 0.1
Condenser water outlet temperature (T_{o})	°C	± 0.1
Solar cell temperature (T_{C})	°C	± 0.1
Solar radiation intensity (I_{T})	W/m^2	± 1
Voltage (V_{oc})	V	± 0.005
Current (I_{sc})	A	± 0.012
Mass flow rate ($\dot{m}$)	kg/s	± 0.001

3 Efficiency of PVTPHP

Analysis of PVTPHP with reference to Fig. 1a, b indicates two sections: the pulsating heat-pipe solar collector (thermal collector) and PV panel. In general, for experimental investigation the following algorithm can be implemented to calculate the efficiency of this PVTPHP:

Instantaneous thermal efficiency of a collector is expressed as (Zhang et al. 2012; Duffie and Beckman 2005):

$$\eta_i = \frac{\dot{m} C_P \int_{t_1}^{t_2} (T_{\mathrm{o}} - T_{\mathrm{i}}) \mathrm{d}t}{A \int_{t_1}^{t_2} I_{\mathrm{T}} \mathrm{d}t} \tag{1}$$

Hence, the thermal efficiency can be obtained as (Zhang et al. 2012; Duffie and Beckman 2005):

$$\eta_{\mathrm{th,PHP}} = \frac{Q_{\mathrm{u}}}{A I_{\mathrm{T}}} \tag{2}$$

where, Q_{u} is the useful energy gain of collector:

$$Q_{\mathrm{u}} = \dot{m} C_p (T_{\mathrm{O,Cond}} - T_{\mathrm{i,Cond}}) \tag{3}$$

The electrical efficiency of PV is defined as the ratio of actual electrical output power to the input rate of solar energy incident on the PV surface as follows (Yazdanpanahi et al. 2015; Zhang et al. 2012; Duffie and Beckman 2005):

$$\eta_{\mathrm{el,PV}} = \frac{V_{\mathrm{mp}} I_{\mathrm{mp}}}{A I_{\mathrm{T}}} \tag{4}$$

Hence, the combined efficiency of the PVTPHP can be obtained as:

$$\eta_{\mathrm{PVTPHP}} = \eta_{\mathrm{th,PHP}} + \eta_{\mathrm{el,PV}} \tag{5}$$

4 Results and Discussion

In general, experimental results show that the performance of a pulsating heat pipe (PHP) directly depends on the filling ratio of the operating fluid and its orientation. On the other hand, the electrical performance of a PV is strongly dependent on PV module temperature and intensity of solar radiation.

So, in the presentation of the results and investigation of the performance of PVTPHP, the above parameters are taken into account.

4.1 Performance of PVTPHP

Figure 3 shows the experimental results of temperature variations of individual PV without using thermal collector compared to the variations of ambient temperature and solar radiation during the day. Also the aforementioned figure shows that, as the ambient temperature and solar radiation increase, PV temperature will dramatically increase. In the mid-hours of the day with the maximum solar radiation, maximum use of the solar energy in individual PV, that is one of the main goals of solar systems, is not possible due to an increase in temperature.

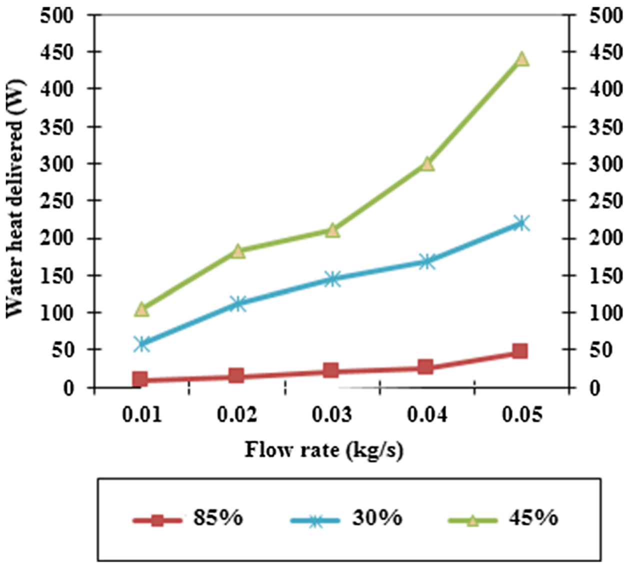
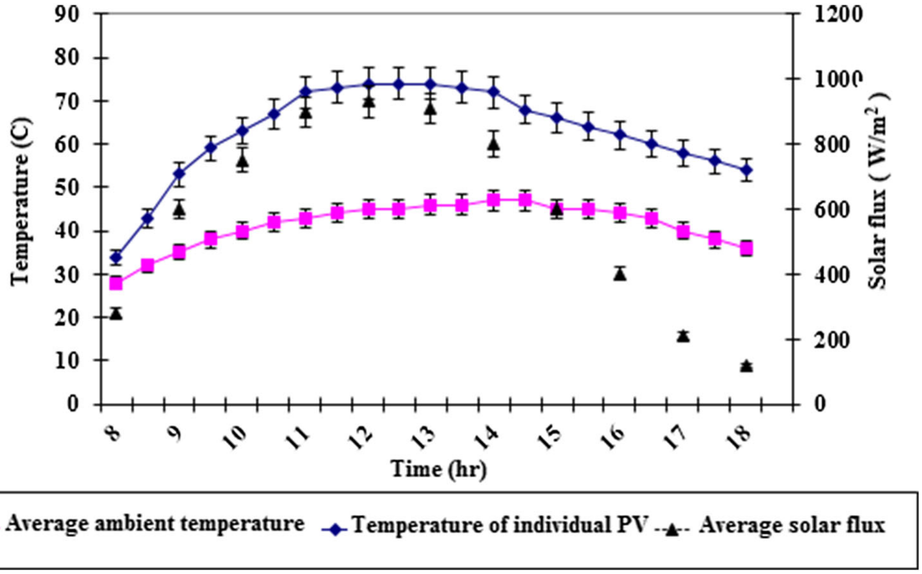


Fig. 4 Comparison of heat delivery for various filling ratios and water flow rate of PVTPHP, data recorded on August 2015

The results show that, in the hybrid photovoltaic–thermal collector with pulsating heat pipe (PVTPHP) as the filling ratio increases from 30 to 50%, a significant enhancement in the production rate of hot water and electrical efficiency was observed. However, higher filling ratios of 50–80% reduced the rate of production. The PHP generates bubbles to pulsate and move the liquid slug and transfer the heat to the condensation section. Therefore, high filling ratios prevent the pulsation of the bubbles. Thereupon the heat transfer rate will not be sufficient. Although low filling ratios make bubbles pulsate, they may result in the pipe drying out. So, the output power of PVTPHP decreases due to the increase in PV module temperature. Thus, the PHP must have an optimum value for the filling ratio. Figure 4 shows that, in this work, maximum heat delivery and optimized filling ratio are measured as 45%. Figure 4 also shows that for PVTPHP, heat delivery and thermal efficiency increase as condenser water mass flow rate increases; however, at the same time condenser water outlet temperature decreases. The inclination angle of the PVTPHP, which is parallel to PHP, affects the amount of solar heat gain to the PVTPHP. Experimental results show that the electrical performance of PV module is strongly dependent on intensity of solar radiation. On the other hand, the thermal performance of a PHP is strongly dependent on its orientation and its best thermal performance is attainable in a vertical orientation. Therefore, the effect of inclination of the PVTPHP on the

Fig. 3 Temperature variations of individual PV compared to the variations of solar radiation and ambient temperature during the day



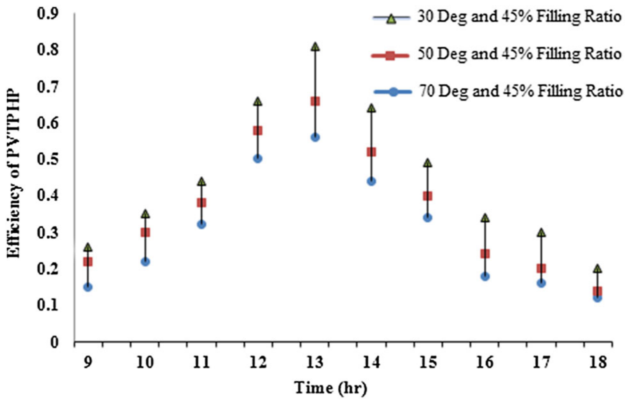


Fig. 5 Comparison of total efficiency for various PVTPHP inclination angles, August 2015

rate of production has been investigated. As shown in Figs. 5 and 7, the maximum efficiency is achieved at an inclination of 30°. Higher inclination angles (reaching to a vertical orientation) lead to higher performance in PHP. In contrast, the intensity of solar radiation decreases for any angle other than 30°, which is the latitude of the location. However, it is observed that the maximization of the gained solar intensity is more effective than the verticality of the PHP for PVTPHP. Figures 6 and 7 show that heat delivery and efficiency decrease as condenser water inlet temperature increases. Such a situation occurs in thermosyphon systems. Experimental results of PVTPHP show that the maximum rate of production occurred at midday between 12:30 PM and 2:30 PM.

Figure 7 shows that efficiency decreases as condenser water inlet temperature increases. In addition, it represents the efficiency of PVTPHP for 45% filling ratio at various PVTPHP inclination angles. It is seen that the efficiency for PVTPHP with an inclination angle of 30° is less affected by water inlet temperature, and in this case we have 14% increase in efficiency.

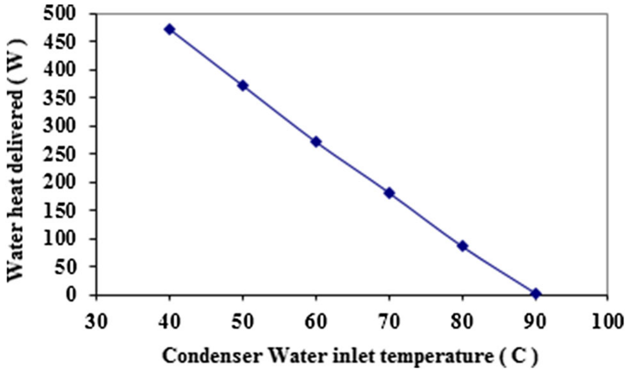


Fig. 6 Water heat delivery at various condenser water inlet temperatures

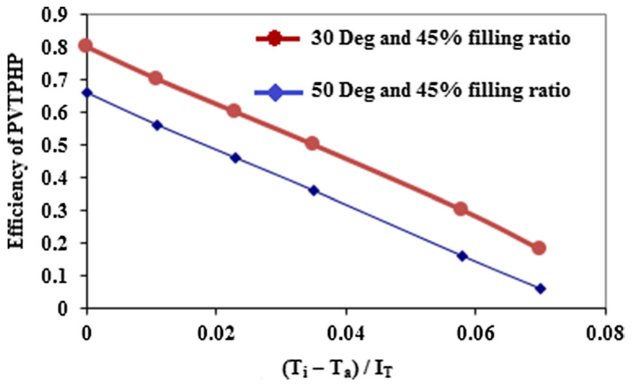


Fig. 7 Comparison of total efficiency for various condenser water inlet temperatures and various PVTPHP inclination angles. August 2015

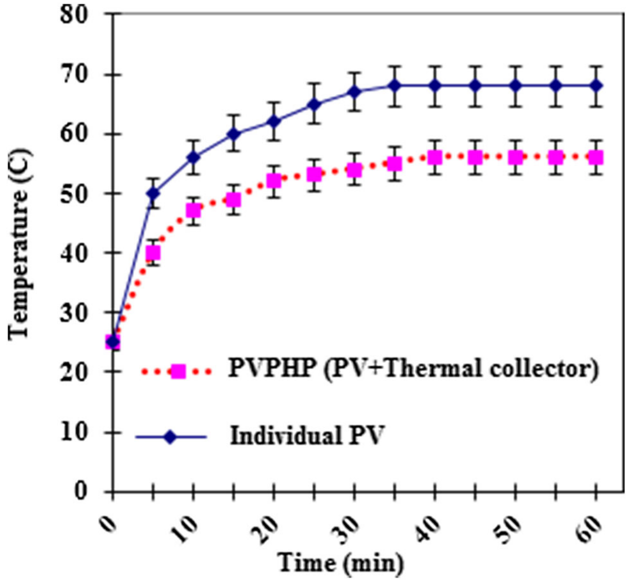


Fig. 8 Comparison of variations and the temperature increase trend in individual PV with PVTPHP compared to the time that it is used

Figure 8 compares the increase in temperature in individual PV and PVTPHP for 60 min for a fixed amount of radiation. It also shows that despite the same initial temperatures, after a few minutes, their temperatures will significantly differ. The results show that after almost 40 min, maximum temperature of PVTPHP increases to 56 °C, while in individual PV almost after 30 min, its maximum temperature increases to 68 °C which in somehow indicates the proper functioning of the PVTPHP design to reduce the temperature of the PV and better use of solar energy.

Figure 9 shows the comparison of the average temperature for the condenser and evaporator when using it as thermosyphon during the day. The results indicate that variations of the amount of solar radiation received during

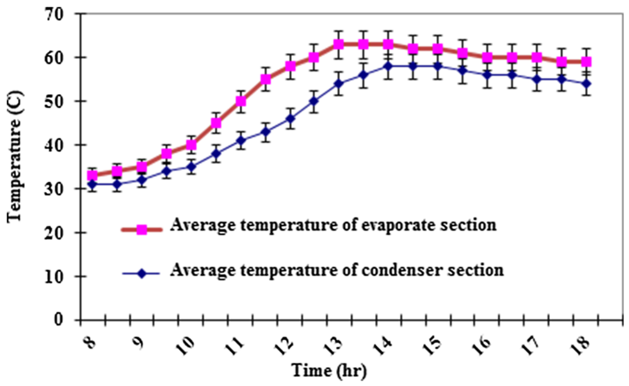


Fig. 9 Comparison of variations in average temperature of the condenser and the evaporator for the thermal part during the day

the day and the temperature of inlet water of condenser affect the temperature difference between the two parts. When using as thermosyphon, inlet water of condenser is equal to the temperature of the storage tank. As the tank temperature increases during the day, the condenser water temperature also increases.

4.2 Electrical Performance of PVTPHP

The nominal efficiency of PV cells is a parameter measured at standard test conditions (STC), with cells temperature of 25 °C, normal irradiance of 1000 W/m^2 and a solar spectrum corresponding to air mass (AM) of 1.5 (Aste et al. 2015; Zhang et al. 2012). However, the real operating conditions can be remarkably different from those of reference, influencing meaningfully the performance and therefore the electric power production. For these reasons, it is useful to define the value of real efficiency, taking into account variations of operative temperature of the cells, incident angle of solar irradiance. Figure 10 shows the I–V characteristic curve of PVTPHP. The current from PVTPHP depends on the external voltage applied and amount of sunlight and PV module temperature. When the PV is short-circuited, the current is at maximum (short-circuit current, I_{sc}), and the voltage across the PV is 0. When the PV cell circuit is open, with the leads not making a circuit, the voltage is at its maximum (open-circuit voltage, V_{oc}), and the current is 0. The typical current–voltage curve of PVTPHP shown in Fig. 10 represents the range of combinations of current and voltage.

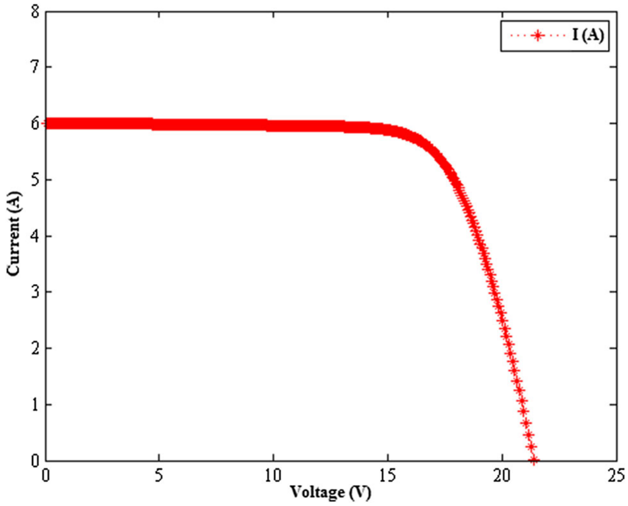


Fig. 10 Electrical current versus voltage for PVTPHP

Figure 11 shows the operation of the PVTPHP at its maximum power operating point. The power can be calculated by the product of the current and voltage. If this calculation is performed and plotted on the same axes, then Fig. 12 can be obtained.

Maximum power operating point in Fig. 12 is the operating point $P_{\max}$, $I_{\max}$, $V_{\max}$ at which the output power

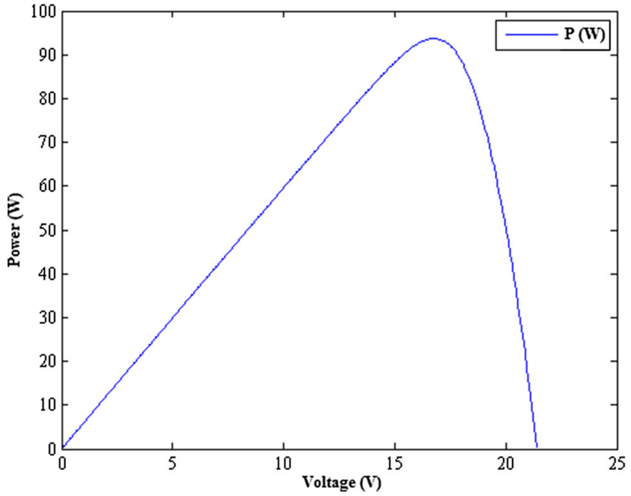


Fig. 11 Power versus voltage for PVTPHP

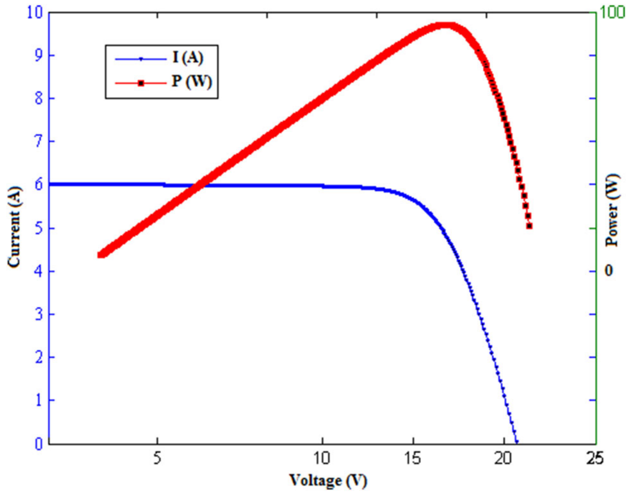


Fig. 12 Instantaneous power of PVTPHP at different current versus voltage

is maximized. Given $P_{\max}$, an additional parameter, called the fill factor (FF), can be calculated such that (Yazdanpanahi et al. 2015; Aste et al. 2015; Zhang et al. 2012):

$$\mathrm{FF} = \frac{P_{\max}}{I_{\mathrm{sc}} V_{\mathrm{oc}}} = \frac{I_{\max} V_{\max}}{I_{\mathrm{sc}} V_{\mathrm{oc}}} \quad (6)$$

The fill factor is a measure of the real I–V characteristic. For PVTPHP, this exercise is performed and plotted; then, Fig. 13 can be obtained. Figure 13 shows the fill factor of PVTPHP decreases as ambient temperature and PV temperature increases. But the fill factor for individual PV without PHP section at the same ambient temperature is 0.5. It is seen that the fill factor for PVTPHP with an inclination of 30° is less affected by PV panel temperature and ambient temperature. In this case, we have 0.14 increase in fill factor compared to individual PV without PHP section. Figure 14 shows the maximum power of PVTPHP at various ambient temperatures with an inclination of 30° and a condenser water flow rate of 0.05 kg/s. Figure 14 shows that the maximum power of PV and PVTPHP decreases as ambient temperature and PV panel temperature increase. But the maximum power for individual PV without PHP section at the maximum temperature is 67.5 W, while in this condition the maximum power for PVTPHP is 85 W. In this case, we have 17.5 W increase in maximum power compared to the individual PV without PHP section.

Experimental results for the influence of the PV panel temperature on the PV characteristics are shown in Figs. 15 and 16. Experimental results show that the main effect of the increase in PV panel temperature is on open-circuit voltage, which decreases linearly with the PV panel temperature; thus, the PV panel efficiency drops. As can be seen, the short-circuit current increases slightly with the increase in the PV panel temperature.

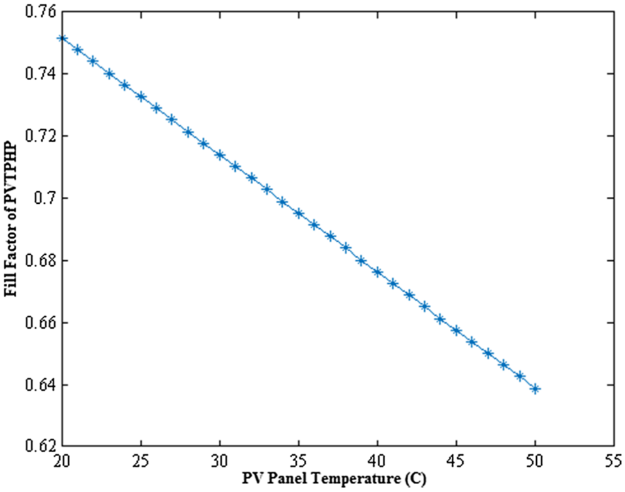


Fig. 13 Fill factor of PVTPHP at various ambient temperatures with an inclination angle of 30° and a condenser water flow rate of 0.05 kg/s

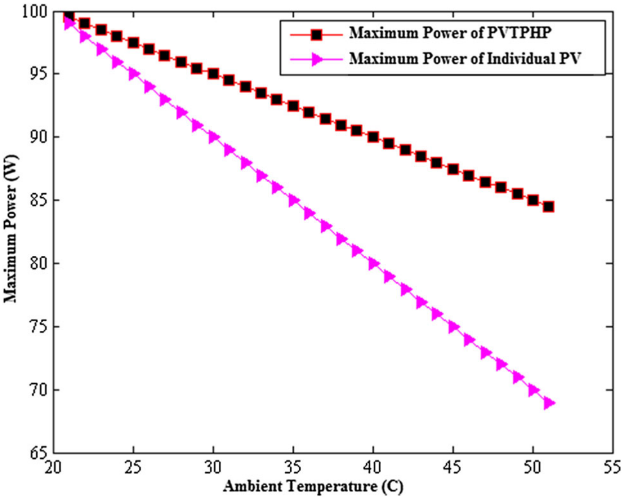


Fig. 14 Maximum power of PVTPHP and individual PV at various ambient temperatures with an inclination angle of 30° and a condenser water flow rate of 0.05 kg/s

The electrical efficiency of the PV panel without the thermal section (PHP) was also measured, in order to be able to compare it with the situation where it was integrated with the thermal section (PHP). The PV panels were disintegrated from the thermal collector and tested separately to measure their PV efficiencies. Electrical efficiency of individual PV without PHP section and electrical efficiency of PVTPHP at hourly variation of solar radiation and ambient temperature for typical test day are shown in Figs. 17 and 18.

Figure 17 shows the electrical efficiency of individual PV without thermal section (PHP) sharply reduced by increasing the PV panel temperature and ambient temperature. In addition, it shows that the increase in ambient

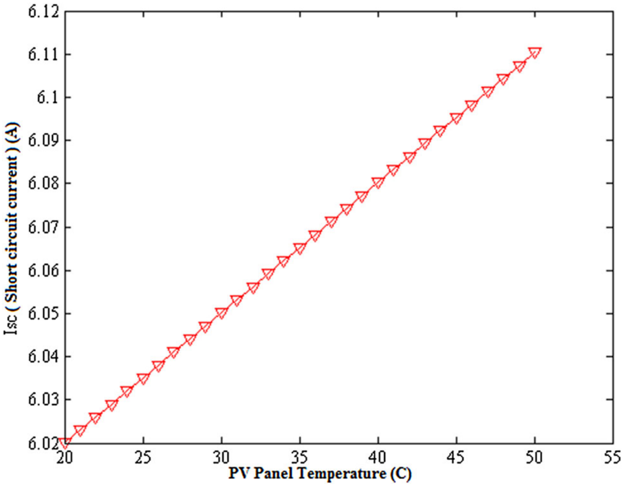


Fig. 15 Effect of increased PV panel temperature on I_{SC}

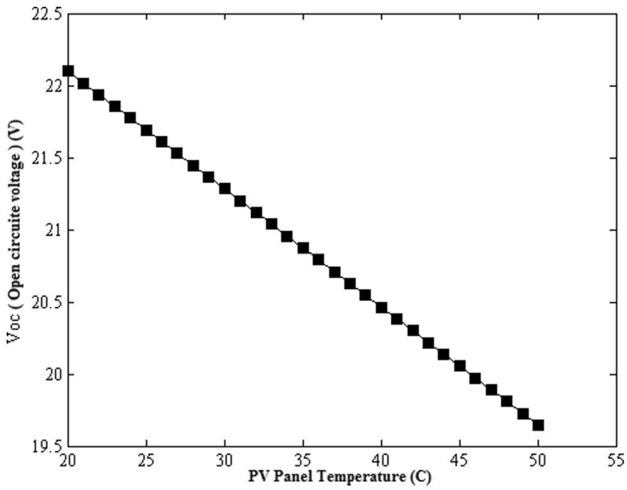


Fig. 16 Effect of increased PV panel temperature on V_{oc}

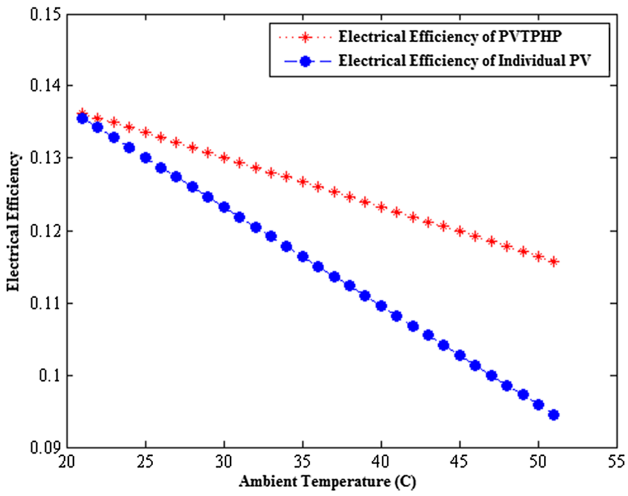


Fig. 17 Comparison of electrical efficiency of the individual PV and electrical efficiency of PVTPHP at hourly variation of solar radiation and ambient temperature for typical test day

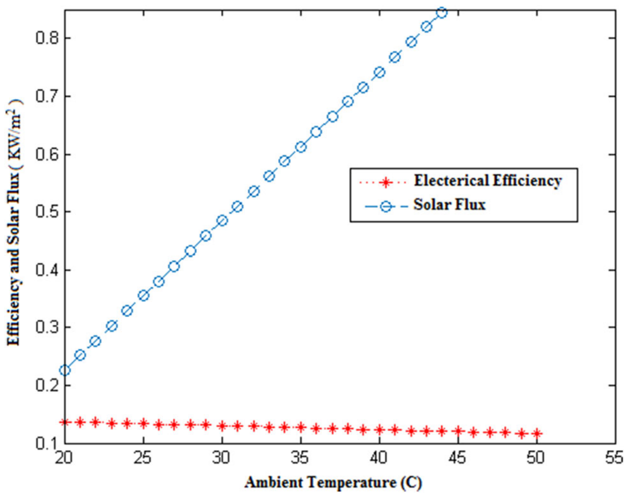


Fig. 18 Electrical efficiency of PVTPHP at hourly variation of solar radiation and ambient temperature for typical test day

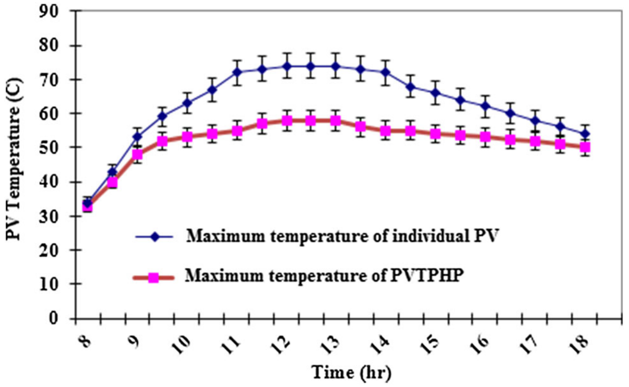


Fig. 19 Comparison of variations in maximum temperature of individual PV and PVTPHP during the day

temperature during the day can increase the PV panel temperature, and therefore, in this case the efficiency of photovoltaic panels without thermal section (PHP) is reduced from 0.135 to 0.095. Figure 18 shows, however, the maximum solar radiation coincides with the maximum ambient temperature, and this is a major problem for the traditional PV panels.

Figure 19 shows a comparison of the experimental results obtained from temperature variations of PVTPHP and individual PV during the day. The results obtained from the previous figures and Fig. 19 show that adding the thermal collector by the pulsating heat pipe to the PV for reducing the temperature and using the produced heat are efficient. The aforementioned figure shows the difference between maximum temperature of the PV and PVTPHP at 16 °C. This study demonstrated that the maximum temperatures of the PV and PVTPHP are dependent on several parameters such as temperature and flow rate of water to condenser, filling ratio of the pulsating heat pipe, inclination angle of PVTPHP, the way that thermal section and PV are connected, the amount of radiation received and operation hours. So, one of the main problems of this design is its complexity and multiple number of the parameters affecting its performance.

5 Conclusions

The present investigation indicates the effectiveness of a novel hybrid photovoltaic–thermal collector in combination with pulsating heat pipe as a cogeneration component that converts solar energy into both electricity and heat. From the obtained experimental results, it can be easily seen that in photovoltaic modules a significant part of the solar energy converted to thermal energy and electrical performances of PV modules deteriorate significantly with the increase in its temperature. But experimental results obtained from the PVTPHP show that in PVTPHP compared to individual PV panel, there is a chance for obtaining simultaneously highest thermal efficiency and electrical efficiency. However, our experiments demonstrate that the maximum rate of production occurred in midday 12:30 PM–2:30 PM with filling ratio of 45% and the water flow rate 0.05 kg/s. In addition to previous parameters, the effect of inclination angle of PVTPHP on the rate of production is investigated. It is observed that the maximum hourly yield occurs when the inclination angle of PVTPHP and the attached PHP is equivalent to latitude of the location, 30° (in this case Izeh, Iran). Experimental results show that the short-circuit current increases slightly with the increase in the PV panel temperature and open-circuit voltage and decreases linearly with the PV panel temperature; thus, the PV panel efficiency drops. Fill factor for PVTPHP with an inclination angle of 30° is less affected by PV panel temperature and ambient temperature. In this case, we have 17.5 W increase in maximum power compared to the individual PV without PHP section. Experimental results show that in this design maximum of electrical efficiency, thermal efficiency, fill factor, power, condenser water outlet temperature, heat delivery and combined efficiency occurred with filling ratio of 45% and the water flow rate 0.05 kg/s and an inclination angle of 30°.

In addition, analyzing the experimental results indicates that temperature difference of condenser parts and evaporator during the day depends on parameters such as temperature and flow rate of water to condenser, variations of the amount of solar radiation received and the way thermal part of PVTPHP is used. Analysis of the amount of heat and the received efficiency, comparison of temperature variations during the day and comparison of the process of temperature increase within an hour to individual PV and PVTPHP, proves the proper functioning of the design. This study shows that adding thermal collector with pulsating heat pipe to PV to reduce its temperature and the use of the generated heat has a good performance. However, due to the effect of several parameters on its performance, this design is considered to be complicated. Therefore, given that in solar systems, manufacturing, maintaining and easy exploiting the equipment are very important for the public acceptability; it is acknowledged that despite the suitable research performance of the PVTPHP design, if we take a more general perspective, the use of simpler designs for PVT may be more useful practically.

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References

Akachi H Structure of a heat pipe, U.S. Patent 4921,041 Patent, 1990

Aste N, Lenonforte F, Del Pero C (2015) Design, modeling and performance monitoring of a photovoltaic–thermal (PVT) water collector. Sol Energy 112:85–90

Bosanac M, Sorensen B, Ivan K, Sorensen H, Bruno N, Jamal B (2003) Photovoltaic/thermal solar collectors and their potential in Denmark. Final Report, EFP Project, 1713/00-0014

Charalambous PG, Maidment GG, Kalogirou SA, Yiakoumetti K (2007) Photovoltaic thermal (PV/T) collectors: a review. Appl Thermal Eng 27(2–3):275–286

Chow TT (2010) A review on photovoltaic/thermal hybrid solar technology. Appl Energy 87(2):365–379

Cox CH, Raghuraman P (1985) Design considerations for flat-plate-photovoltaic/thermal collectors. Sol Energy 35(3):227–241

Dubey S, Tay AAO (2013) Testing of two different types of photovoltaic–thermal (PVT) modules with heat flow pattern under tropical climatic conditions. Energy Sustain Dev 17:1–12

Duffie JA, Beckman WA (2005) Solar energy of thermal processes, 3rd edn. Wiley, Hoboken

Dupeyrat P, Menezo C, Fortuin S (2014) Study of the thermal and electrical performances of PVT solar hot water system. Energy Build 68:751–755

Fiorentini M, Cooper P, Ma Z (2015) Development and optimization of an innovative HVAC system with integrated PVT and PCM storage for a net-zero energy. Energy Build 94:21–32

Florschuetz LW (1979) Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. Sol Energy 22(4):361–366

Fudholi A, Sopian K, Yazdi MH, Ruslan MH, Ibrahim A, Kazem HA (2014) Performance analysis of photovoltaic thermal (PVT) water collectors. Energy Convers Manag 78:641–651

Gang P, Huide F, Tao Z, Jie J (2011) A numerical and experimental study on a heat pipe PV/T system. Sol Energy 85:911–921

Herrando M, Markides CN, Hellgardt K (2014) A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: system performance. Appl Energy 122:288–309

Ibrahim A, Othman MY, Ruslan MH, Mat S, Sopian K (2011) Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. Renew Sustain Energy Rev 15(1):352–365

Jones AD, Underwood CP (2001) A thermal model for photovoltaic systems. Sol Energy 70(4):349–359

Kalogirou SA (2001) Use of TRYNSYS for modeling and simulation of a hybrid PV thermal solar system for Cyprus. Renew Energy 23:247–260

Kern EC Jr, Russel MC (1978) Combined photovoltaic and thermal hybrid collector systems. In: Proceedings of the 13th ISES photovoltaic specialists. Washington, pp 1153–1157

Khairnasov SM, Naumova AM (2016) Heat pipes application to solar energy systems. Appl Sol Energy 52(1):47–60

Mishra RK, Tiwari GN (2013) Energy matrices analyses of hybrid photovoltaic thermal (HPVT) water collector with different PV technology. Sol Energy 91:161–173

Qian J-F, Ji-Li Z, Liang-dong MA (2010) Analysis of a new photovoltaic thermal building integration system and correlative technology. Build Energy Environ 29(2):12–16

Quan Z, Li N, Zhao Y, Tang X (2010) The experiment research for solar PV/T system based on flat-plate heat pipes. In: Proceedings of the 17th Chinese national HVAC&R academic conference

Sarhaddi F, Farahat S, Ajam H, Behzadmehr A (2011) Exergetic optimization of a solar photovoltaic thermal (PV/T) air collector. Int J Energy Res 35(9):813–827

Sweidan A, Ghaddar N, Ghali K (2016) Optimized design and operation of heat-pipe photovoltaic thermal system with phase change material for thermal storage. J Renew Sustain Energy 8:023501. https://doi.org/10.1063/1.4943091

Tang X, Zhao Y, Quan Z (2009) The experimental research of using novel flat-plate heat pipe for solar cells cooling. In: Proceedings of the Chinese thermal engineering physics of heat and mass transfer conference, pp 239–241

Tiwari A, Sodha MS, Chandra A, Joshi JC (2006) Performance evaluation of photovoltaic thermal solar air collector for composite climate of India. Sol Energy Mater Sol Cells 90(2):175–189

Touafek K, Haddadi M, Malek A (2013) Design and modeling of a photovoltaic thermal collector for domestic air heating and electricity production. Energy Build 59:21–28

Tripanagnostopoulos Y, Nousia T, Souliotis M, Yianoulis P (2002) Hybrid photovoltaic thermal solar systems. Sol Energy 72:217–234

Van Helden WGJ, Van Zolingen RJC, Zondag HA (2004) PV thermal systems: PV panels supplying renewable electricity and heat. Prog Photovolt Res Appl 12:415–426

Yazdanpanahi J, Sarhaddi F, Mahdavi Adeli M (2015) Experimental investigation of exergy efficiency of a solar photovoltaic thermal (PVT) water collector based on exergy losses. Sol Energy 118:197–208

Zhang J et al (2008) Closed loop capillary solar photovoltaic board, Patent CN 2008 102 28 051 A: 08.10.08

Zhang X, Zhao X, Smith S, Xu J, Yu X (2012) Review of R&D progress and practical application of the solar photovoltaic/ thermal (PV/T) technologies. Renew Sustain Energy Rev 16:599–617

Zondag HA (2008) Flat-plate PV-thermal collectors and systems: a review. Renew Sustain Energy Rev 12(4):891–959

Zondag HA, De Vries DW, Van Helden WGJ, Van Zolingen RJC, Van Steenhoven AA (2002) The thermal and electrical yield of a PV–thermal collector. Sol Energy 72(2):113–128