

1 **Experimental study on a novel photovoltaic thermal system using** 2 **amorphous silicon cells deposited on stainless steel**

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10 **Abstract**

11 Amorphous silicon (a-Si) cells are able to perform better as temperature increases due to the
12 effect of thermal annealing. a-Si cells have great potential to solve or ease the problems of
13 high power temperature coefficient, large thermal stress caused by temperature fluctuation
14 and gradient, and thick layer of conventional crystalline silicon cell-related
15 photovoltaic/thermal (PV/T) collectors. In this paper, an innovative a-Si PV/T system is
16 developed. It is the first time that a-Si cells deposited on stainless steel have been used in a
17 practical PV/T system. The system comprises of two PV/T collectors. In each collector, there
18 are 8 pieces of solar cells in series. Long-term outdoor performance has been monitored.
19 Experimental results on the thermal efficiency (η_{th}), electrical efficiency (η_{PV}) and I-V
20 characteristic are presented. The peak instantaneous $\eta_{th,p}$ was about 42.49% with the
21 maximum $\eta_{PV,p}$ of 5.92% on April 2, 2017. The daily average $\eta_{th,a}$ and $\eta_{PV,a}$ were 32.8% and
22 5.58%. Accordingly, $\eta_{th,p}$, $\eta_{PV,p}$, $\eta_{th,a}$ and $\eta_{PV,a}$ on October 27 were 43.47%, 5.69%, 38.65%
23 and 5.22 %. During more than half a year operation, no technical failure of the system has
24 been observed. The feasibility of the a-Si PV/T is preliminarily demonstrated by the prototype.

25 *Keywords: amorphous silicon cell; photovoltaic/thermal collector; I-V characteristic; thermal*
26 *efficiency; electricity efficiency*

27 **1. Introduction**

28 Photovoltaic/thermal collectors (PV/T) have a higher utilization ratio of solar energy
29 compared to a solo PV module. The mainstream PV/T systems employ crystalline silicon (c-
30 Si) cells for power generation. There are several drawbacks:

31 First, efficiency decrement of the cells with the increment in the operating temperature is
32 significant. Common c-Si cells have high power temperature coefficients, which are about -
33 0.41 to -0.50%/°C at maximum power point (MPP) in standard test conditions (STC). Given
34 an efficiency of 18% at 25 °C, the absolute efficiency drop can be 5% if the temperature is
35 elevated to 75 °C. The decline is expected to be steeper at higher working temperature owing
36 to larger magnitude of the coefficient [1]. In case of c-Si cells, the PV/T working at medium-
37 high temperature calls for economic assessment [2], and it might not have advantage over side-
38 by-side PV and solar collector systems. The characteristic of c-Si cells has limited the PV/T
39 application and generally low grade energy can be supplied, in the form of domestic hot water
40 and air [3].

41 Second, c-Si PV/T may suffer from low electricity efficiency in the seasons when heat is
42 unfavorable. The consumers' demand on heat varies with time and season. Take glazed PV/T-
43 water system in Hefei, China for example. In summer there is remarkable reduction on demand
44 on domestic hot water compared with that in winter, though the solar radiation is more
45 attainable. Water in the storage tank can exceed 70 °C. Most heat is not desirable and eventually
46 wasted. Meanwhile, it is difficult for the PV/T to function near ambient temperature in regard
47 to the thermal insulation of the system, resulting in a relatively low cell efficiency. This is one
48 of the negative impact of the combined heat and power generation.

49 Third, c-Si PV/T may be easily broken in the long term operation due to fluctuation in the

50 temperature and its gradient. c-Si cells are commonly laminated on aluminum for the sake of
51 good thermal conductivity. However, coefficient of thermal expansion of c-Si (about 2.6×10^{-6}
52 /°C at 20 °C) is far less than aluminum's (about 23×10^{-6} / °C at 20 °C) [4]. Since PV/T is likely
53 to experience temperature from 0 to 80 °C and heat flux from 0 to 600W/m² through the year
54 [3, 5], it can be broken by the large mechanical stresses in long time usage. Abruption and
55 deformation have been monitored in some practical PV/T systems [6].

56 Amorphous silicon (a-Si) cells have attracted less attention than the c-Si cells in the PV/T
57 application. In general, a-Si cells have a low conversion efficiency than c-Si cells at room
58 temperature. The optical gap of a-Si cells is about 1.7eV, which causes photons with the
59 photoelectron energy below 1.7eV to directly pass through the a-Si layer and cannot be
60 absorbed by the intrinsic layer, thus contributing essentially no photocurrent and limiting the
61 conversion efficiency of the a-Si cells. One compelling characteristic of a-Si cells is the
62 degradation in the power output when exposed to the sunlight [7, 8], which is known as
63 Staebler-Wronski (S-W) effect [9]. The S-W effect is related with the light-induced degradation
64 of electrical performance and the creation of defect states. After prolonged exposure to sunlight
65 the defect states tend to saturate, and such stability is known as degraded steady state (DSS)
66 [10]. It is not difficult to achieve an initial a-Si cells efficiency of 10%, but it will drop to 7%
67 or lower at stabilized state, depending on the inner structure and operating temperature. The
68 phenomenon has limited the development of a-Si cell despite of its relatively low cost, and
69 makes it less competitive with c-Si cells. a-Si cells are mainly used for sole power generation
70 nowadays. Lower ambient temperature could contribute to more remarkable S-W effect.

71 However, the aforementioned problems associated with the c-Si PV/T system can be solved
72 or eased by using a-Si cells. a-Si cells benefit from thermal annealing at high operating
73 temperature (>50 °C) and have the reversible ability to reduce defect states and even can be
74 restored to the original state, leading to an improved power generation. In contrast to c-Si cells,

75 a-Si cells may have positive power temperature coefficients. It has been demonstrated that the
76 S-W effect can be weakened in the high temperature stage [11]. According to the annual
77 performance of a-Si PV modules, the electrical efficiency of a-Si PV modules has seasonal
78 variation which is different from c-Si PV modules [12-14]. a-Si PV modules have a higher
79 electrical efficiency in summer months and lower electrical efficiency in winter months, and
80 the opposite is true for c-Si PV modules. The seasonal variation of a-Si PV modules is attributed
81 to the S-W effect and spectral effect [13]. The degradation at low temperature (22 ± 8 °C) for
82 about 1000h could be recovered upon the subsequent warm soaking (51 ± 8 °C) for about 500h,
83 resulting in an efficiency increment between 10% and 17% [15]. The operating temperature
84 during light-soaking has been deemed as the most important factor for determining stabilized
85 cell performance [16]. Based on tests on the PV systems over four years, it was concluded that
86 the a-Si cells exhibited positive power temperature coefficient. In some cases the power of a-
87 Si was increased by as much as 8.4% due to thermal annealing [17]. For a different climate or
88 cell configuration (e.g. i-layer thicknesses), the best a-Si cell at STC may not have the best
89 annual energy yield [18]. a-Si PV modules can operate up to 100 °C with only small amount of
90 power losses [19]. Higher temperature could result in faster stabilization and higher efficiency
91 at DSS [20].

92 The power temperature coefficient of a-Si cells at DSS may be positive, which is inconsistent
93 with results in the international standard test condition. The reason is duration of measurement
94 defined in such standard is typically short, and the cell is unable to proceed with a full annealing
95 as the operation temperature rises. Evidences have shown the power temperature coefficient of
96 a-Si cells for a short time scale of several hours is negative, while it is positive for a longer
97 time scale of seasons. In fact, a-Si modules continue to show further change in maximum power
98 even after they stabilize according to the international qualification standard IEC 61646 [21].
99 It indicates that the high operating temperature improves the electrical performance of a-Si PV

100 modules as a result of thermal annealing.

101 Aside from the unique positive power temperature coefficient in long term operation, the
102 thin-film a-Si cells can be easily deposited at low temperature onto a variety of substrates such
103 as glass, stainless steel sheet and plastic sheet [22] and there are savings on silicon material.
104 When deposited on stainless steel, the a-Si cells are flexible. The panels are used commercially
105 and can be rolled up and carried in a backpack and used to charge the electrical devices like
106 laptops. They may be able to cope with interruption at fluctuating temperature. Owing to the
107 thin-film, the cells should have lower thermal resistance than mainstream c-Si cells.

108 The above characteristics of a-Si cells are desirable in the PV/T application. a-Si PV/T
109 collectors shall normally work at higher temperature than ambient temperature, which will
110 facilitate better thermal annealing, and thus the electrical performance can be improved. The
111 cells may benefit from high temperature operation even in seasons of less demand on heat and
112 would not have a dramatic efficiency drop as c-Si cells. The modules possess good thermal
113 conductivity and can avoid huge thermal stress.

114 Above all, a-Si PV/T system is promising. Theoretical works have been reported. The
115 performances of a-Si and c-Si PV/T have been compared and analyzed by simulation [23]. The
116 effect of high-temperature annealing strategy on the annual yield of a-Si PV/T has been
117 examined. Significant amount of additional energy generation is possible over the year with an
118 appropriate dispatch strategy at thermal annealing temperature of 100 °C [20, 24]. The
119 thickness of a-Si intrinsic layer has also influence on the a-Si PV/T performance [25]. Upon
120 annealing, the grown-in SiH monohydride groups are partially transformed into SiH₂
121 dihydrides and polysilane chains which have been reported to impair the performance of a-
122 Si:H based PV/T devices [26]. Compared with c-Si cells, a-Si cells are more suitable for
123 operating at the medium-high temperature, and are promising in solar roof [27-29], PV glazing
124 [30] and photovoltaic-thermoelectric [31-34] applications.

125 So far, there have been a few reports on the experimental study of a-Si PV systems such as
 126 a-Si PV windows which can provide daylight illuminance and electricity generation
 127 simultaneously [35-36] and a-Si PV walls [37]. The field tests of systems for residential
 128 application have been done in Bangkok, Thailand, with an average electricity efficiency of 4.0%
 129 and thermal efficiency of 51% [38]. Investigation on a heat pipe a-Si PV/T system has been
 130 done in Changsha, China, with an average electricity efficiency of 4.8% and thermal efficiency
 131 of 41% [39]. In these studies, the substrate for the a-Si cells is glass or plastic.

132 Notably, experimental investigation on a-Si PV/T system using stainless steel as the substrate
 133 has not been reported yet. Its thermodynamic performance and technical practicability need to
 134 be demonstrated. In this paper, design and test of a novel PV/T system using a-Si cells is
 135 introduced. To the best of the authors' knowledge, it is the first time that a-Si cells deposited
 136 on stainless steel have been used in a practical PV/T system. Outdoor performance and
 137 simulation of the system is investigated. The thermal efficiency, electrical efficiency and the I-
 138 V characteristic are analyzed in detail. Feasibility of the system is discussed on the basis of
 139 over half a year running.

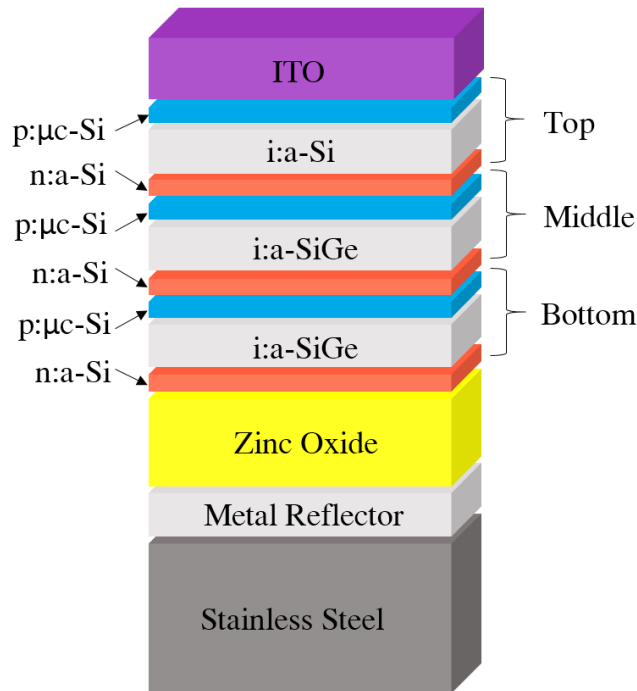
Nomenclature	
A	area, m ²
B	temperature coefficient, K ⁻¹
c	specific heat capacity, J/(kg·K)
D	diameter, m
d	thickness, m, inner diameter, m
E	electrical gain, W
G	solar irradiation, W/m ²
h	heat transfer coefficient, W/(m ² ·K)
L	length, m
\dot{m}	mass flow rate, kg/s
\dot{M}	total mass flow rate, kg/s
M	mass, kg
R	thermal resistance
T	temperature, K
t	time, s
u	flow velocity, m/s
Nu	Nusselt number, -
Ra	Raleigh number, -
λ	thermal conduction, W/(m·K)
ρ	density, kg/m ³ , reflectance, -
σ	Stefan-Boltzman constant, W/(m ² ·K ⁴)
τ	transmittance, -
$(\tau\alpha)$	effective absorptance, -
ξ	covering factor, -
<i>Subscripts</i>	
a	ambient, air
ad	adhesive layer
b	absorber plater
bt	welding layer
e	sky
g	glass
i	insulation layer
in	inlet of collector
out	outlet of collector
PV	PV module
ref	standard test condition
t	copper tube

P	Perimeter, m	tank	water-storage tank
<i>Greek letters</i>		TPT	black TPT
α	absorptivity, -	w	water
β	tilt angle of collector, °	wt	water in the tank
ε	emissivity, -		
η	efficiency, -		

140

141 **2. Description of the a-Si PV/T collector**

142 Triple-junction a-Si cells are employed (a-Si:H/a-SiGe:H/a-SiGe:H), provided by Xunlight
 143 Kunshan Co.,Ltd. The schematic structure is depicted in Fig.1. The peak quantum efficiencies
 144 of a-Si top-cell, a-SiGe middle-cell, a-SiGe bottom-cell are about 67% at 450nm, 55% at 580
 145 nm and 48% at 710 nm, with a total QE efficiency of up to 86% [40].



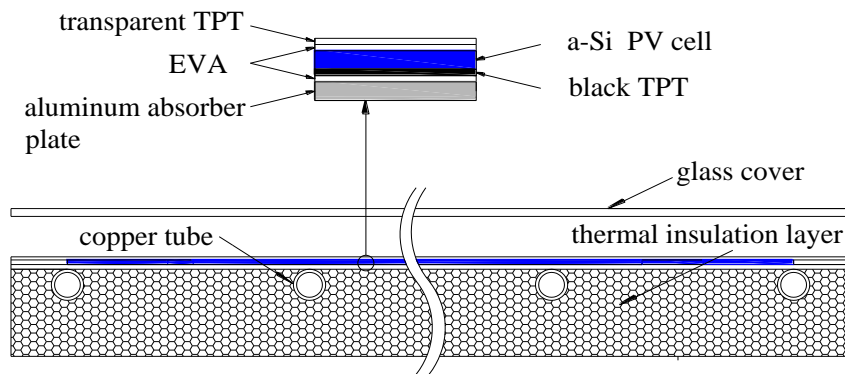
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Fig.1. Schematic diagram of the triple-junction a-Si cells

148 The cross section and the structure diagram of the novel PV/T module are depicted in Figs.
 149 2 and 3. The a-Si PV/T collector has the following components: glass cover, a-Si cells,
 150 aluminum absorber plate, copper tubes and thermal insulation layer. The glass cover utilizes a
 151 textured inner face. To encapsulate the a-Si cells, transparent tedlar-polyester-tedlar (TPT),
 152 black TPT and EVA are employed. The transparent TPT can make solar irradiation through and

153 protect the a-Si cells, and it can make the a-Si cells electrical insulated. The EVA plays a role
 154 in preventing water and dirt, as well as in tight bonding with other parts. The encapsulation of
 155 the a-Si PV/T is similar with that of c-Si ones.

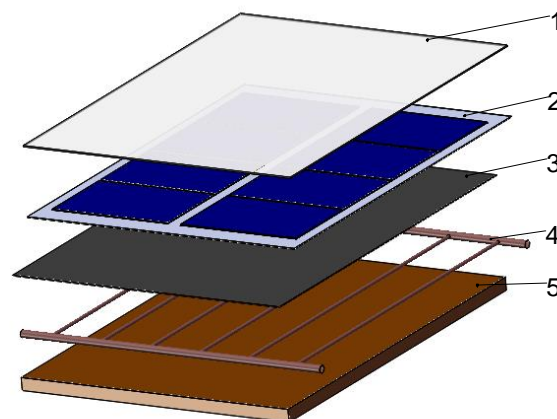
156 The thickness of the glass cover, transparent TPT, EVA, PV cell, black TPT, aluminum
 157 absorber plate is about 3.2, 0.2, 0.2, 0.6, 0.2 and 1.16 mm, respectively. There is a 26 mm air
 158 gap between the glass cover and the PV module to reduce the convective heat transfer. The
 159 bottom of the a-Si PV/T collector is a thermal insulation layer of 36 mm in order to reduce the
 160 conductive heat loss.



161

162

Fig. 2. Cross section of a-Si PV/T collector



163

164 Fig. 3. Structure diagram of the a-Si PV/T collector: 1-glass cover; 2-amorphous silicon cells; 3-aluminum
 165 absorber plate; 4-copper tubes; 5-thermal insulation layer

166 An unpacked a-Si cell is shown in the Fig. 4. The flexible cell has stainless steel as the
 167 substrate. Eight pieces of a-Si cells in series are laminated onto the surface of the aluminum

168 absorber plate. The size of one piece of a-Si cell is 356 mm × 239 mm. The photovoltaic
169 characteristics of an a-Si cell are listed in Table 1 in the standard test conditions (irradiation of
170 1000W/m² and temperature of 25 °C). The data are related to the cell performance prior to
171 degradation.



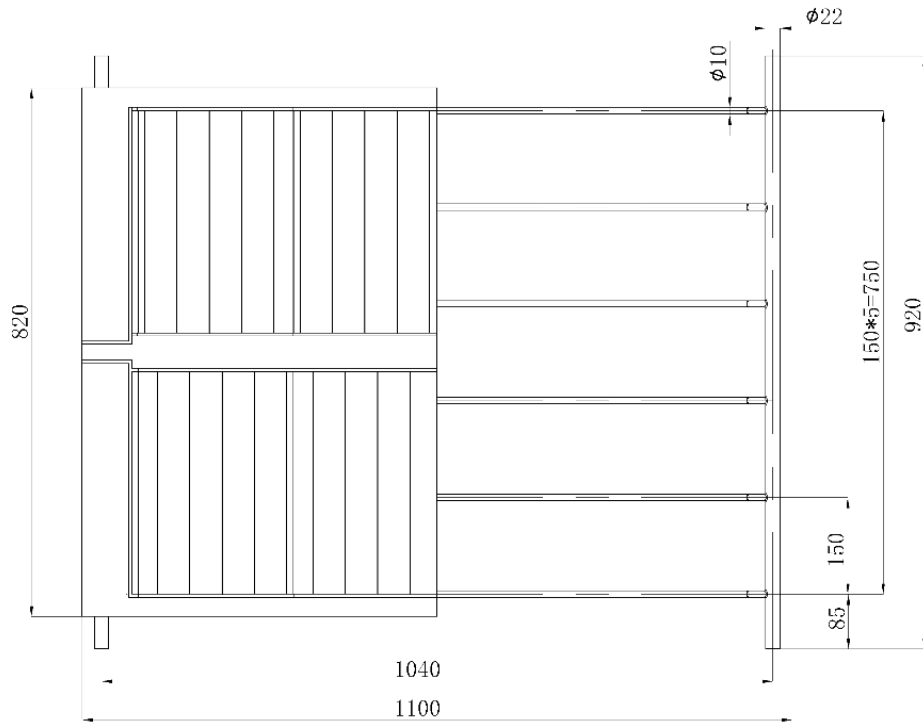
172
173 Fig. 4. An unpacked a-Si cell

174 Table 1 Photovoltaic characteristics of an amorphous silicon cell in standard test condition

Parameter	Value
Power ($\pm 10\%$)	$P_m=6.5W$
Open circuit voltage	$V_{oc}=2.1V$
Short circuit current	$I_{sc}=5.1A$
Voltage at max power	$V_m=1.6V$
Current at max power	$I_m=4.1A$

175

176 The outer dimension of the PV/T collector is displayed in Fig.5. The cells are laminated on
177 the aluminum absorber plate of 820 mm × 1100 mm. Six copper tubes are stuck on the back of
178 the plate by laser welding. The dimension of a copper tube is $\phi 10 \times 1040$ mm and the distance
179 between two adjacent tubes is 150 mm.



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Fig. 5. Outer dimensions of the PV/T

182 3. Experimental setup

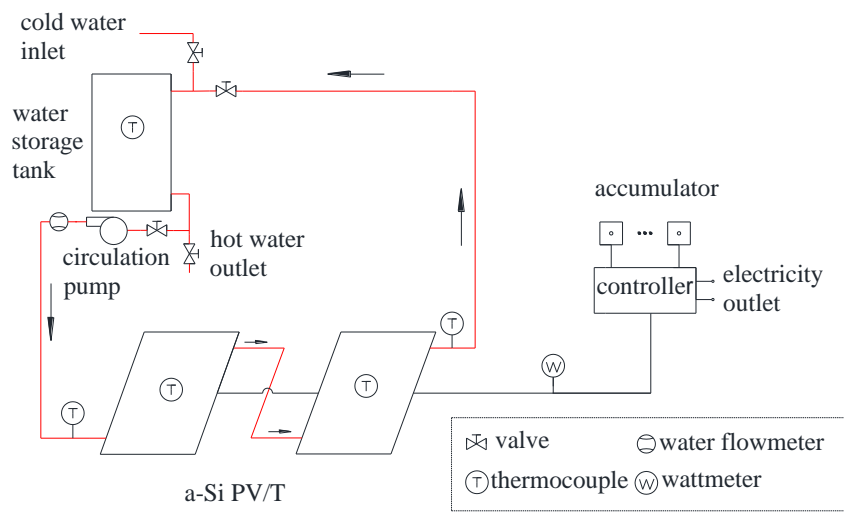
183 To estimate the performance of the a-Si PV/T collectors, the experimental system has been
 184 established on the roof of a building in Hefei which is located at 117.27E longitude and 31.86
 185 N latitude. The test rig and schematic diagram of the a-Si PV/T system are presented in Figs.
 186 6 and 7. The cooling water of the PV/T system circulates in a closed loop. Two a-Si PV/T
 187 collectors in series, a water-storage tank with the capacity of 80 L, a water pump, pipes, a water
 188 flowmeter and a maximum power point tracking (MPPT) PV controller (SSCM-1224-5A) are
 189 used in the experiment. The two a-Si PV/T collectors faced the south with a tilt angle of 30°
 190 for better utilization of solar irradiation [41]. Details on the measuring instruments are given in
 191 the Table 2. The installation angle of the radiometer was the same as that of the collectors to
 192 measure the global solar radiation (direct radiation and diffuse radiation) received on the
 193 surface of the collectors. The measurement data are recorded and stored on a disk via Agilent
 194 Bench Link Date Logger, a computer data-acquisition system.



195

196

Fig. 6. Test rig of the a-Si PV/T system



197

198

Fig. 7. Schematic diagram of the a-Si PV/T system experimental setup

199

Table 2 Types of related measuring instruments

Instruments	Types	Measurement accuracy	Location
Thermal resistance	Pt 100	± 0.1 °C	Collector inlet and outlet
Thermocouple	Type T	± 0.5 °C	Water-storage tank; ambient ; aluminum absorber
Flowmeter	LWGY	$\pm 5\%$	Water-storage tank output
Radiometer	TBQ-2	$\pm 2\%$	Solar collector
Current sensor	HKK-13-I	$\pm 0.1\%$	PV module output current

200 4. Mathematic models

201 4.1 Mathematic models of the a-Si PVT system

202 Simulation is carried out to provide a closer view of the heat transfer and power generation

203 in the system. The following assumptions are made [6]:

204 1) The water flow rate in the copper tube is uniform.

205 2) The heat capacities of the adhesive layers (EVA and TPT) are neglected.

206 3) The temperature gradients of the glass cover, PV module, absorber plate and copper pipe in
207 thickness are negligible.

208 The energy balance equation of glass cover can be expressed as:

$$209 \quad \rho_g c_g d_g \frac{\partial T_g}{\partial t} = h_a(T_a - T_g) + h_{e,g}(T_e - T_g) + h_{g,PV}(T_{PV} - T_g) + G\alpha_g \quad (1)$$

210 Where h_a , $h_{e,g}$, $h_{g,PV}$ are the convective heat transfer coefficient between the glass cover and
211 the surrounding air, the radiant heat transfer coefficient between the glass cover and the sky,
212 and the heat transfer coefficient between the glass cover and the PV module, respectively,
213 expressed as:

$$214 \quad h_a = 2.8 + 3.0u_a \quad (2)$$

$$215 \quad h_{e,g} = \varepsilon_g \sigma (T_e^2 + T_g^2)(T_e + T_g) \quad (3)$$

$$216 \quad h_{g,PV} = \sigma (T_{PV}^2 + T_g^2)(T_{PV} + T_g) \left(\frac{\xi}{1/\varepsilon_{PV} + \xi(1/\varepsilon_g - 1)} + \frac{1 - \xi}{1/\varepsilon_{PV} + (1 - \xi)(1/\varepsilon_g - 1)} \right) + \frac{Nu \cdot \lambda_a}{d_a} \quad (4)$$

217 Where ξ is covering factor defined as:

$$218 \quad \xi = \frac{A_{PV}}{A_b} \quad (5)$$

219 For inclination angle of the collector ranging from 0° to 75° , the Nusselt number can be
220 calculated as [42]:

$$221 \quad Nu = 1 + 1.14 \left(1 - \frac{1708(\sin 1.8\beta)^{1.6}}{Ra \cdot \cos \beta} \right) \left[1 - \frac{1708}{Ra \cdot \cos \beta} \right]^+ + \left[\left(\frac{Ra \cdot \cos \beta}{5830} \right)^{1/3} - 1 \right]^+ \quad (6)$$

222 Where $[\]^+$ indicates that only positive values for terms within square brackets shall be used;

223 in the case of negative values, zero is used.

224 The two-dimension energy balance equation for PV module is expressed as:

$$225 \quad \xi \rho_{PV} c_{PV} d_{PV} \frac{\partial T_{PV}}{\partial t} = \lambda_{PV} d_{PV} \left(\frac{\partial^2 T_{PV}}{\partial x^2} + \frac{\partial^2 T_{PV}}{\partial y^2} \right) + h_{g,PV} (T_g - T_{PV}) + (T_b - T_{PV}) / R_{b,PV} \quad (7)$$

$$+ G(\tau\alpha)_{PV} - \xi E_{PV}$$

226 Where $(\tau\alpha)_{PV}$ and E_{PV} are the effective absorptance and the output power of the PV cells
227 (W/m²), respectively, and expressed as:

$$228 \quad (\tau\alpha)_{PV} = \frac{\tau_g \tau_{ad} \alpha}{1 - (1 - \alpha) \rho_d} \quad (8)$$

$$229 \quad E_{PV} = G \tau_g \tau_{ad} \eta_{ref} [1 - B(T_{PV} - T_{ref})] \quad (9)$$

230 Where ρ_d is the reflection of glass cover for diffuse radiation; α is the comprehensive
231 absorptance, expressed as:

$$232 \quad \alpha = \xi \alpha_{PV} + (1 - \xi) \alpha_{TPT} \quad (10)$$

233 The $R_{b,PV}$ is the thermal resistance of the adhesive layer between the PV module and the
234 absorber plate (m²·K/W) and expressed as:

$$235 \quad R_{b,PV} = \frac{d_{ad}}{\lambda_{ad}} \quad (11)$$

236 For the absorber plate, some nodes are in connection with the copper tubes and heat is
237 transferred directly from the nodes to the tubes. Meanwhile, some nodes are set between the
238 tubes. There are two types of energy balance equations, which are related to the connection
239 nodes and middle nodes, respectively.

240 The energy balance equation of the middle nodes is expressed as:

$$241 \quad \rho_b c_b d_b \frac{\partial T_b}{\partial t} = \lambda_b d_b \left(\frac{\partial^2 T_b}{\partial x^2} + \frac{\partial^2 T_b}{\partial y^2} \right) + (T_{pv} - T_b) / R_{b,PV} + (T_a - T_b) / R_{b,a} \quad (12)$$

242 The energy balance equation of the connection nodes is expressed as:

$$\rho_b c_b d_b \frac{\partial T_b}{\partial t} = \lambda_b d_b \left(\frac{\partial^2 T_b}{\partial x^2} + \frac{\partial^2 T_b}{\partial y^2} \right) + (T_{pv} - T_b) / R_{b,pv} + \frac{T_t - T_b}{R_{b,t} \cdot A_{ij}} \quad (13)$$

Where A_{ij} is the area of a single controller (m^2), $R_{b,a}$ and $R_{b,t}$ are the thermal resistance between the absorber plate and the air ($m^2 \cdot K/W$), and the thermal resistance between the absorber plate and the copper pipe (K/W), expressed as:

$$R_{b,a} = d_i / \lambda_i + 1 / h_a \quad (14)$$

$$R_{b,t} = d_{bt} / (\lambda_{bt} \cdot A_{bt}) \quad (15)$$

The energy balance equation of the copper tube is expressed as:

$$\pi \frac{(D_i + d_i)}{2} \frac{(D_i - d_i)}{2} \rho_t c_t \frac{\partial T_t}{\partial t} = \pi \frac{(D_i + d_i)}{2} d_i \lambda_t \frac{\partial^2 T_t}{\partial x^2} + \pi d_i h_{w,t} (T_w - T_t) + \frac{T_b - T_t}{R_{b,t}} \cdot dx \quad (16)$$

Where $h_{w,t}$ is the convective heat transfer coefficient between the copper tube and flowing water.

For the flowing water in the copper tube, the energy balance equation is expressed as:

$$A_t \rho_w c_w \frac{\partial T_w}{\partial t} = -\dot{m} c_w \frac{\partial T_w}{\partial x} + A_t \lambda_w \frac{\partial^2 T_w}{\partial x^2} + P_t h_{w,t} (T_t - T_w) \quad (17)$$

The energy balance equation of water in the tank is expressed as:

$$A_{tank} \rho_w c_w \frac{\partial T_{wt}}{\partial t} = -\dot{M} c_w \frac{\partial T_{wt}}{\partial x} + A_{tank} \lambda_w \frac{\partial^2 T_{wt}}{\partial x^2} + P_{tank} h_{tank} (T_a - T_{wt}) \quad (18)$$

Where h_{tank} is the heat transfer coefficient between the surrounding air and water in the tank.

4.2 Performance evaluation

The thermal and electrical efficiencies are two important parameters in evaluating the system performance. The instantaneous thermal efficiency of the a-Si PV/T collectors is defined as ratio of the heat gain to the incident solar radiation.

$$\eta_{th} = \frac{Q_w}{GA_b} = \frac{c_w \dot{M} (T_{out} - T_{in})}{GA_b} \quad (19)$$

The fitted curve of the instantaneous thermal efficiency under quasi-steady-state conditions

264 is displayed. A linear correlation between the instantaneous thermal efficiency and the reduced
 265 temperature $(T_{in} - T_a)/G$ is built, expressed as [43]:

$$266 \quad \eta_{th} = F_R(\tau\alpha)_e - F_R U_L \frac{T_{in} - T_a}{G} \quad (20)$$

267 Where $F_R(\tau\alpha)_e$ is the intercept efficiency when the inlet temperature is equal to the ambient
 268 temperature, $F_R U_L$ is the coefficient of heat loss.

269 The instantaneous electrical efficiency is represented by:

$$270 \quad \eta_{PV} = \frac{E_{PV}}{GA_{PV}} = \frac{U_{mp} I_{mp}}{GA_{PV}} \quad (21)$$

271 A flowmeter is present in the system to measure the water flow rate and a considerable
 272 pressure drop exists, thereby leading to more pump power. In the PV/T performance analysis,
 273 the pump power is generally not taken into account [3, 5].

274 For a PV/T system using water as a circulation working fluid and storing solar energy in the
 275 tank, the daily average thermal and electrical efficiency can be given by:

$$276 \quad \eta_{th,a} = \frac{c_w M (\overline{T_{w,f}} - \overline{T_{w,i}})}{HA_b} \quad (22)$$

$$277 \quad \eta_{PV,a} = \frac{\sum E_{pv} \Delta t}{HA_{PV}} = \frac{\sum U_{mp} I_{mp} \Delta t}{HA_{PV}} \quad (23)$$

278 Where Δt is the time interval of data acquisition (s), $\overline{T_{w,i}}$ and $\overline{T_{w,f}}$ are the initial and final
 279 average water temperature in water-storage tank ($^{\circ}\text{C}$).

280 Since electricity is a higher grade energy compared to thermal energy, the daily efficiency
 281 of the a-Si PV/T system is calculated by the following equation [44]:

$$282 \quad \eta_{PVT,a} = \eta_{th,a} + \zeta \frac{\eta_{PV,a}}{\eta_{power}} \quad (24)$$

283 Where $\eta_{PVT,a}$ is the daily comprehensive efficiency of the a-Si PV/T system, η_{power} is the
 284 electrical efficiency from the conventional heat-engine plant and its value is 38%.

285 The fill factor (FF) is defined as the ratio of the product of the current and voltage at the
286 maximum power point to the product of the short circuit current and the open circuit voltage.
287 The FF is an important parameter that affects the output performance of the cells. When the
288 open circuit voltage and short circuit current are constant, the electrical efficiency of the cells
289 depends on the FF. The FF is expressed as:

$$290 \quad FF = \frac{I_{mp} U_{mp}}{I_{sc} U_{oc}} \quad (25)$$

291 To evaluate the degree of agreement between the simulation and the experiment, the relative
292 error (RE) is calculated by:

$$293 \quad RE = \frac{X_{exp} - X_{sim}}{X_{exp}} \times 100\% \quad (26)$$

294 Where the X_{exp} and X_{sim} is the values of experiment and the simulation, respectively.

295 **5. Results and discussion**

296 The construction of the a-Si PV/T system comprised of prolonged work. It started in April
297 2015. Few lessons could be learned from experiences. Manufacturers of a-Si cells deposited
298 on metal are rare. One module of length of 2.0 m and width of 1.0 m, which was the similar
299 size with conventional solar collectors, had been fabricated previously. However, it failed to
300 function properly, mainly due to the electrode damage in the laminating process. The a-Si cells
301 were much thinner than c-Si cells and the technical requirements on lamination seemed to be
302 higher in order to guarantee uniform pressure and good electric insulation.

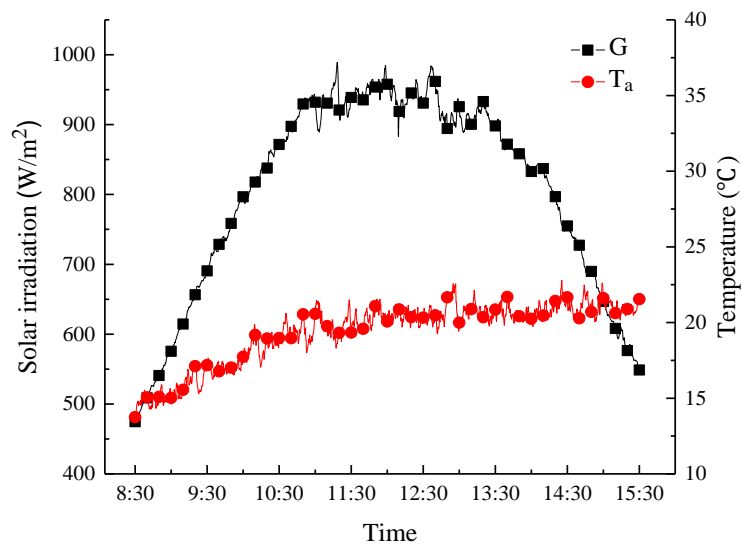
303 To facilitate easier fabrication, the size of the modules was reduced (about 1m×1m). This
304 paper is focused on the recent PV/T modules that were developed in October 2016. It took a
305 few months further to build and commission the whole test rig with proper sensor, battery
306 storage, water tank. During the installation and commission, the modules were carefully
307 covered to avoid exposure to solar radiation. In March 2017, the system was ready for long

308 term operation.

309 In the following sections, the test results for two sunny days (April 2, 2017 and October 27,
310 2017) are summarized, which represent the system performance at early-stage degradation and
311 after prolonged exposure, respectively. The variations of a-Si cells' operating temperature,
312 maximum power point current and voltage, inlet and outlet temperature of collectors, water-
313 storage tank temperature together with solar irradiation, water mass flow rate, ambient
314 temperature are displayed. The thermal efficiency, electrical efficiency and the I-V
315 characteristic are examined.

316 5.1 Test on April 2, 2017

317 A full day test of the a-Si PV/T system was commenced at 8:30 and concluded at 15:30. The
318 mass flow rate of the two collectors in series was around 0.058 kg/s. Fig. 8 shows the variation
319 of solar irradiation and ambient temperature during the day. Both direction and diffusion are
320 taken into account. The solar irradiation gradually increased in the morning and decreased in
321 the afternoon. At the beginning and end of the test, it was about 474.6 W/m² and 426.9 W/m²,
322 respectively. The maximum value was 989.2 W/m² at 11:18. The daily total solar irradiation
323 was 20.33 MJ/m². The ambient temperature fluctuated from 13.7 °C to 20.5 °C and the average
324 value was about 19.4 °C.



325

326

Fig. 8. Variations of solar irradiation and ambient temperature on April 2

327

The simulation and experiment results of the temperature of aluminum plate and the water

328

in the water-storage, and the temperature of the inlet and outlet during the day are shown in the

329

Fig. 9 and Fig. 10. Simulation results are in good agreement with the test data. Two

330

thermocouples were placed on the middle of the aluminum plate back and the center of the

331

water-storage tank. The test temperature of the water-storage tank increased from 20.2 °C to

332

56.0 °C which can fulfill the domestic demand on hot water. The final temperature of the water

333

in the tank in the simulation is 56.5 °C. The tested temperature of aluminum plate gradually

334

increased from 25.0 °C to 62.0 °C and the simulated values climbed from 25.6 °C to 61.0 °C.

335

According to the test results, the inlet and outlet temperature of the PV/T system had a same

336

trend with the temperature of water-storage tank. The outlet and inlet temperature difference

337

increased in the beginning from 1.1 °C to 2.9 °C and then decreased to 0.6 °C in the afternoon.

338

The tank and water inlet temperatures were very close, indicating that the temperature gradient

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in the tank was small. On the other hand, there was a difference of about 2-8 °C between

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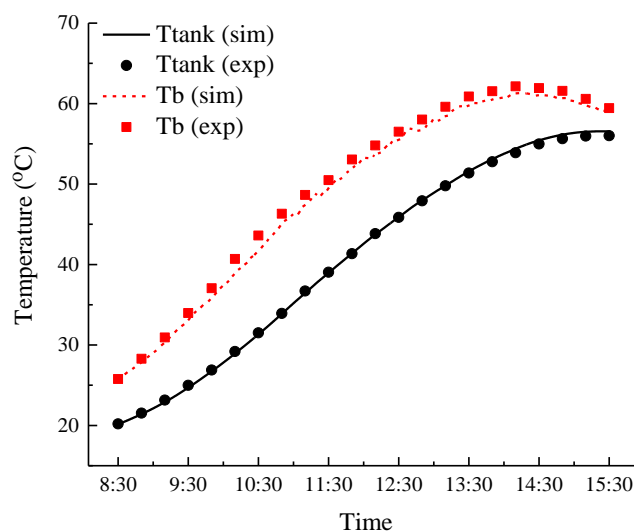
aluminum plate temperature and water inlet/outlet temperature, which was due to the thermal

341

resistance between the plate and water. The difference reached the maximum at the noontime

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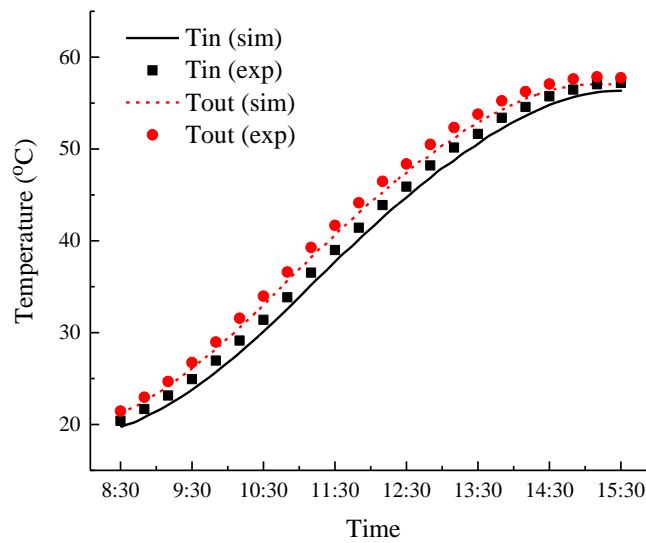
when the heat flux was largest. The daily total heat gain of water-storage tank was 12.03MJ.



343

344 Fig. 9. Simulation and experiment results of the temperatures of the aluminum plate and water in the tank

345 on April 2



346

347 Fig. 10. Simulation and experiment results of water temperatures at the inlet and outlet of the PV/T
348 system on April 2

349 Fig. 11 displays the variation of heat gain and thermal efficiency with time. The maximum
350 heat gain was 693.61W, corresponding to the maximum thermal efficiency of 42.49% at 11:02.
351 Unlike the solar irradiation which was approximately symmetrical, the thermal efficiency had
352 a drop in the afternoon that was steeper than the increment in the morning. This was attributed
353 to the weaker solar radiation and higher water temperature in the water-storage tank. The daily
354 average thermal efficiency of the a-Si PV/T system was 32.8%. The thermal efficiency was not
355 high in comparison with conventional flat plate collector and there are some reasons: First, the
356 size of a-Si PV/T is relatively small, resulting in more significant heat loss. Second, there is no
357 selective absorption coating on the surface of a-Si cells and the cell has a higher long-wave
358 emissivity and radiative heat loss. Third, since two collectors are connected in series, the
359 connection between the two collectors leads to certain heat loss.

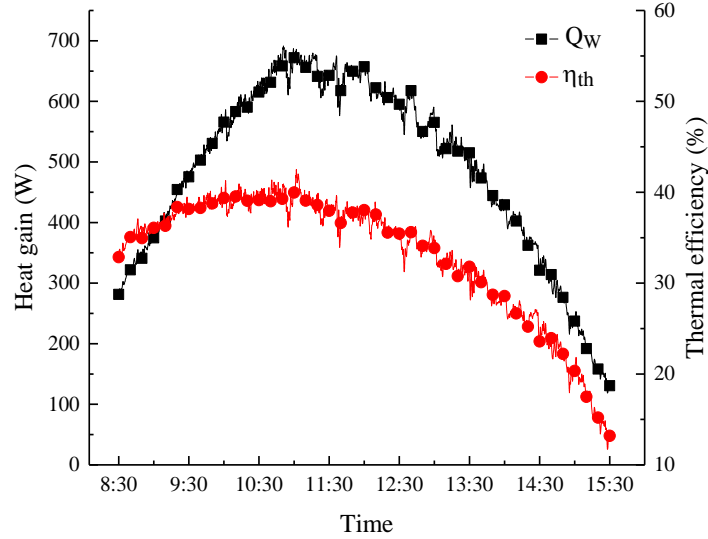
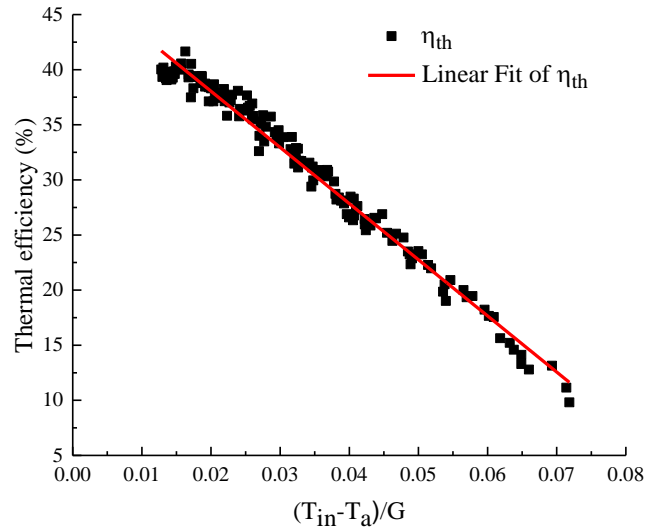


Fig. 11. Variations of heat gain and thermal efficiency on April 2

During the experiment, the system could be considered to operate on quasi-steady conditions in regard to the slow rise in the temperature of water-storage tank. Therefore the thermal efficiency of a-Si PV/T collectors was obtained by the inlet and outlet temperature difference as shown in Fig. 12. The thermal efficiency can be expressed by the regression formula:

$$\eta_{th} = 0.4823 - 5.096 \frac{T_{in} - T_a}{G} \quad (27)$$

It is a function of $(T_{in} - T_a)/G$. According to the regression line, the intercept thermal efficiency is 48.23% when the inlet temperature was equal to the ambient temperature, and the coefficient of heat loss is 5.096 W/(m²·°C). The electrical efficiency of the a-Si PV/T collectors is around 5.58%. Thus the overall intercept efficiency i.e., optical efficiency is 59.3%.



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Fig. 12. Plot of instantaneous electrical efficiency of a-Si PV/T collector on April 2

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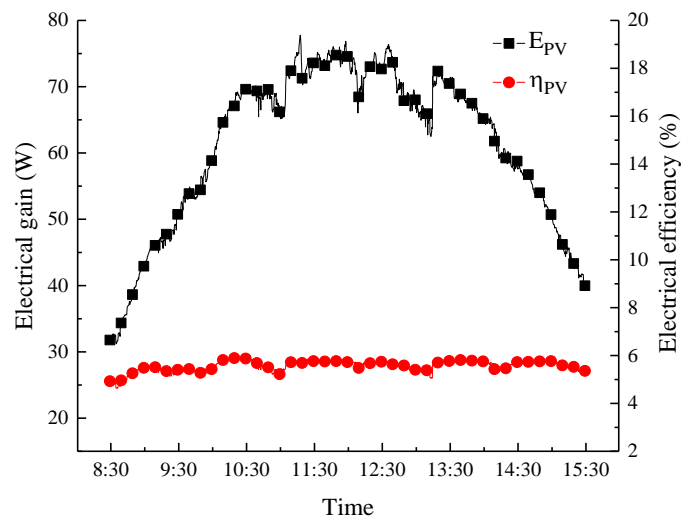
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The variations of electrical gain and electrical efficiency are presented in the Fig. 13. There was a significant correlation between electrical gain and solar irradiation. The electrical gain ranged from 30.6W to 77.8W with a daily total electrical gain of 1.55MJ. The electrical efficiency was between 4.62% and 5.92%, and the daily average electrical efficiency according to Eq.(23) was 5.58%.



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379

Fig. 13. Variations of electrical gain and electrical efficiency on April 2

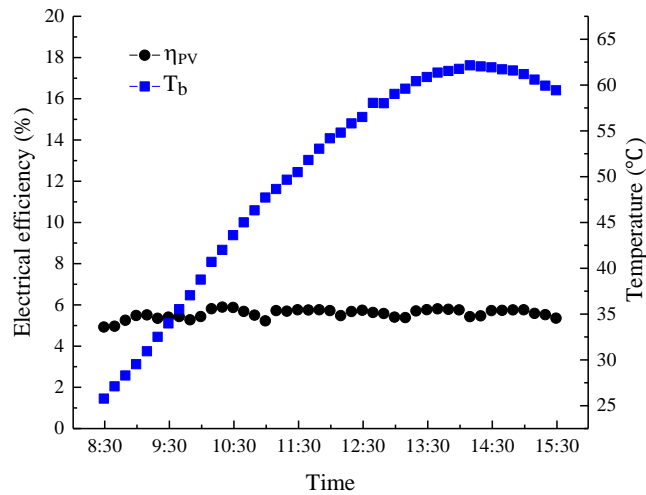
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In order to clarify the relationship between PV efficiency and the operating temperature, the variations of electrical efficiency and aluminum temperature are compared in Fig. 14. The average temperature of aluminum plate climbed in most of the time, and the maximum could

383 reach 62 °C. While the daily electrical efficiency didn't seem to be influenced by the increment
 384 in the operating temperature. The reason may be that the PV/T modules had not been fully
 385 exposed to sunlight and were at early-stage degradation. According to predecessors' work, it
 386 might take hundreds of hours of exposure for the a-Si cells to reach DSS [20, 25]. In the test,
 387 the power generation was expected to be linked with both S-W and thermal annealing effects.



388
 389 Fig. 14. Variations of electrical efficiency and aluminum plate temperature on April 2

390 Fig. 15 depicts the I-V characteristic curve of two a-Si PV/T collectors in series. It was
 391 measured under the solar irradiation of 880 W/m² and the aluminum plate temperature of 47.0
 392 °C at 11:00. The short circuit current, the open circuit voltage and the maximum power were
 393 4.21A, 28.8V and 66.7W, respectively. The experimental results showed that the FF of the a-
 394 Si cells was 56%, which is lower than the FF of 61.25% in standard test condition. There could
 395 be several factors for this reduction. The operating temperature of the cells was higher than 25
 396 °C. FF generally fell down as the temperature went up due to the change in open circuit voltage
 397 and short circuit current [45]. Meanwhile, the cells had been exposed to sunlight before April
 398 2. Some preliminary tests had been conducted in the end of March to ensure that the system
 399 can operate properly. Degradation in the cell performance should have taken place, causing a
 400 lower FF.

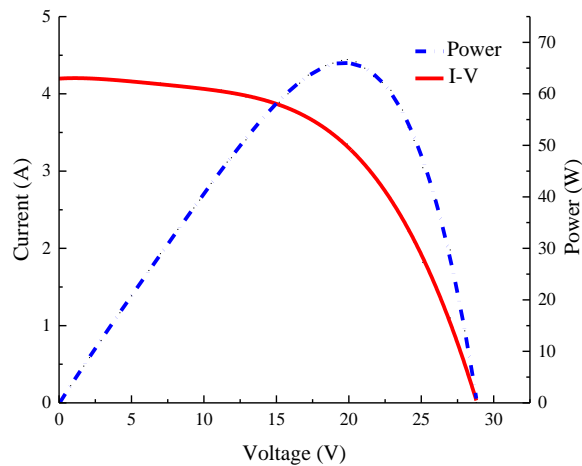
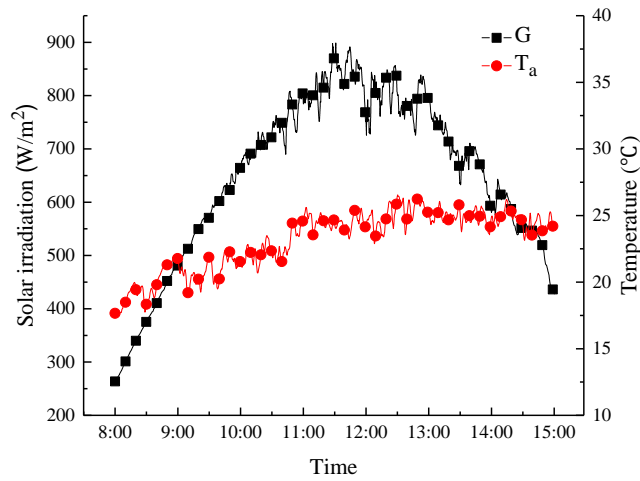


Fig. 15. I-V characteristic curve of the a-Si PV/T collectors on April 2

$G=880\text{W/m}^2$ $FF=56\%$ $V_{oc}=28.8\text{V}$ $I_{sc}=4.21\text{A}$ $V_{mp}=19.9\text{V}$ $I_{mp}=3.35\text{A}$

5.2 Test on October 27, 2017

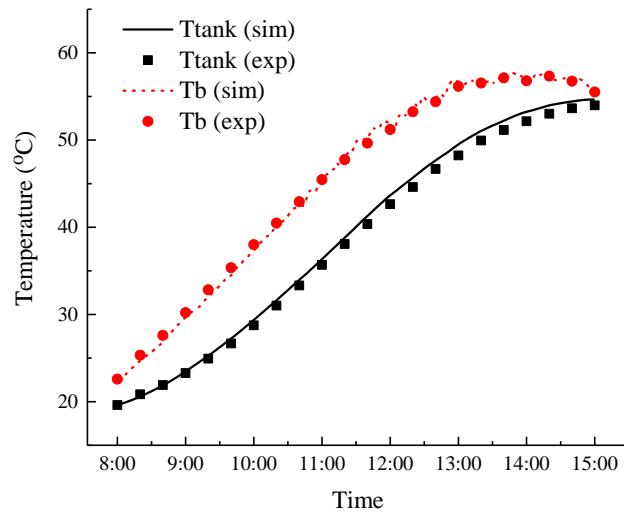
After more than half a year operation, a daily performance of the a-Si PV/T system from 8:00 to 15:00 on October 27, 2017 was summarized and investigated in this section. The mass flow rate was the same as that on April 2. Fig. 16 shows the variation of solar irradiation and ambient temperature during the day. The irradiation intensity ranged from 264.6 W/m² to 899.0 W/m². The daily total solar irradiation was 16.43 MJ/m². The ambient temperature fluctuated from 17.5 °C to 26.6 °C and the daily average ambient temperature was 23.2 °C. Fig. 17 and Fig. 18 present simulated and tested temperatures of the aluminum plate, water in the storage tank and at the inlet and outlet of the PV/T system. The final temperatures of water in tank were 54.0 °C and 54.6 °C in experiment and simulation, respectively. The maximum temperature of aluminum plate was about 58.0 and 57.7 °C.



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416

Fig. 16. Variations of solar irradiation intensity and ambient temperature on October 27

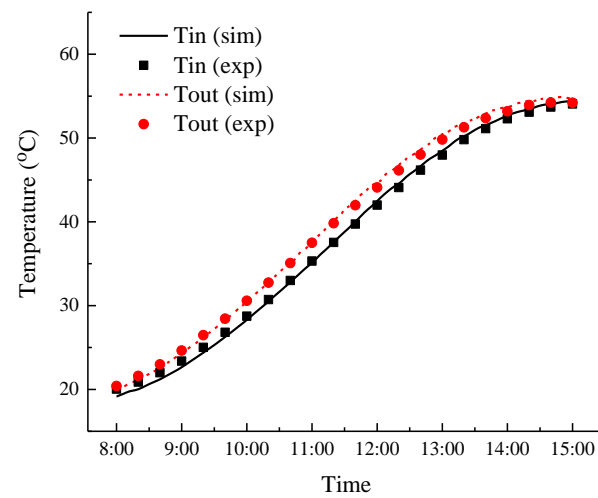


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Fig. 17. Simulation and experiment results of the temperatures of the aluminum plate and water in the tank on October 27



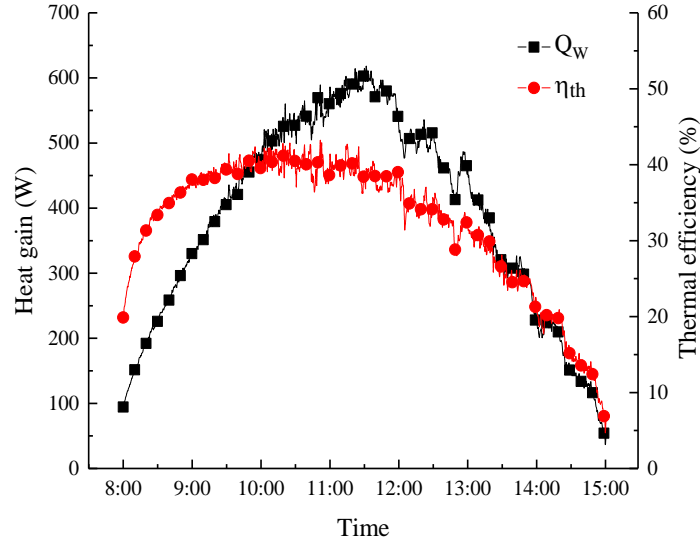
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Fig.18. Simulation and experiment results of water temperatures at the inlet and outlet of the PV/T system on October 27

423 Fig. 19 shows the variation of heat gain and thermal efficiency in the experiment. The
424 maximum heat gain and thermal efficiency were 618.6W and 43.47%. The daily total heat gain
425 of water-storage tank and the daily average thermal efficiency of the a-Si PV/T system were
426 11.46MJ and 38.65%, respectively. Compared to the results in April 2, the PV/T system had a
427 higher daily thermal efficiency on October 27. This phenomenon can be explained as follows.
428 In both days water temperature in the tank stagnated eventually, when the balance between heat
429 input from solar energy and that lost in the ambient was reached. It means in the end of the test,
430 thermal efficiency of PV/T declined to 0, although solar irradiation may still exceed 450 W/m².
431 The final water temperature in the tank over one-day operation was close, which was about 56
432 °C and 54 °C. The daily heat gain in the two days was similar, with a difference of about 0.5
433 MJ. Nevertheless, the total solar irradiation on April 2 was much stronger. For instance, the
434 duration of solar irradiation above 800 W/m² on April 2 was about 4.5 hours (10:00 to 14:30),
435 while it was only 2 hours (11:00-13:00) on October 27. According to Eq.(22), the ratio of the
436 heat gain to the available solar irradiation was higher on October 27. The other reason is that
437 there was more heat loss from the collectors and the connecting tubes to the ambient. As shown
438 in Figs.11 and 19, the instantaneous thermal efficiencies on April 2 and October 27 were close.
439 The average ambient temperature was 19.4 °C and 23.2 °C on April 2 and October 27. A lower
440 ambient temperature increased the heat dissipation.



441

442

Fig. 19. Variations of heat gain and thermal efficiency on October 27

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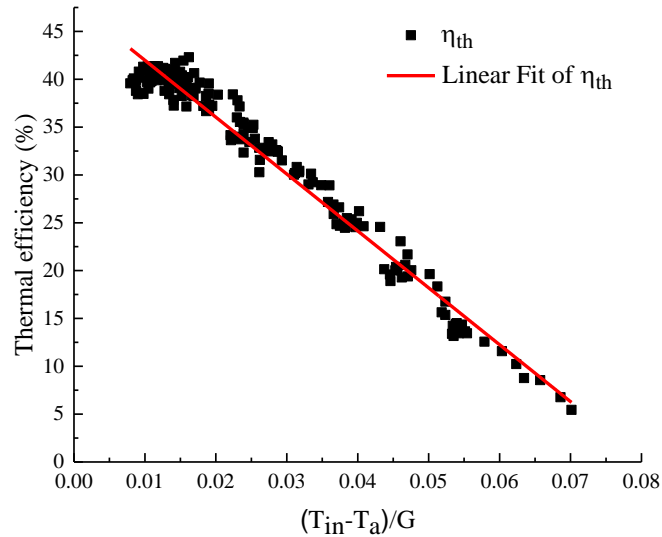
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The thermal efficiency η_{th} against $(T_{in} - T_a)/G$ is shown in the Fig. 20, and it can be determined by Eq.(28). The interception efficiency was close to that in Eq.(27), suggesting that optical efficiencies of PV/T on both days were similar. The coefficient of heat loss was 5.946 W/(m²·°C). It was higher than that in Eq.(27). For accurate regression, thermal efficiency of the collector should be an approximate quadratic function of $(T_{in} - T_a)/G$, rather than a linear function as denoted by Eq.(27) or Eq.(28). The efficiency curve should have a parabola shape since it dropped more dramatically at higher operating temperature. The slope of the linear fit of thermal efficiency would be steeper when data points at higher $(T_{in} - T_a)/G$ were included, resulting in larger first coefficient of heat loss.

452

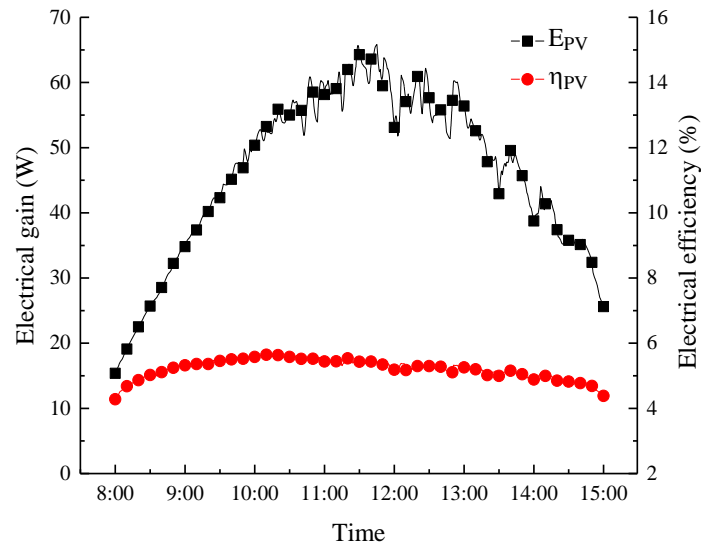
$$\eta_{th} = 0.4793 - 5.946 \frac{T_{in} - T_a}{G} \quad (28)$$



453

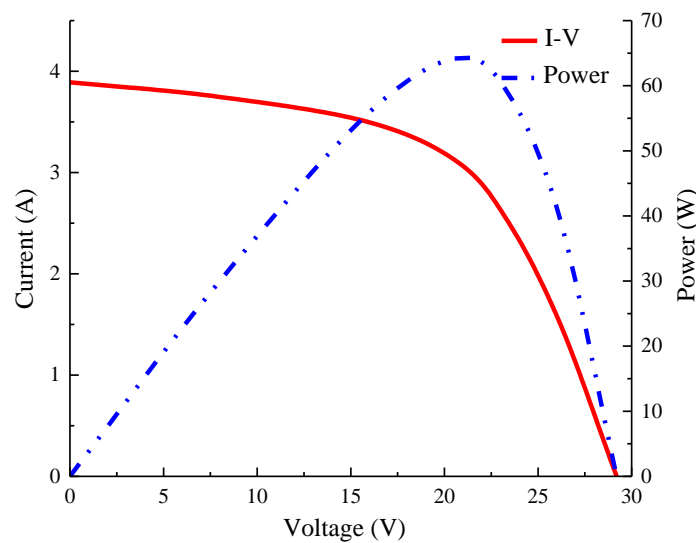
454 Fig. 20. Plot of instantaneous electrical efficiency of the a-Si PV/T collector on October 27

455 The variations of electrical gain and electrical efficiency are presented in the Fig. 21. The
 456 instantaneous electrical gain ranged from 15.85W to 66.73W with the daily total electrical gain
 457 of 1.18MJ. The electrical efficiency was between 4.35% and 5.69%. The lower efficiency
 458 generally appeared when the solar irradiation was relatively weak. The daily average electrical
 459 efficiency was 5.22%, which was slightly below that on April 2. Differing from the electrical
 460 efficiency in Fig.13, there was a more appreciable decrement in efficiency with time in Fig.21.
 461 Over half a year outdoor exposure, the cells were supposed to reach the DSS. The operating
 462 temperature should play a dominant role in the power generation. Therefore as the water
 463 temperature increased, the electricity efficiency was reduced. During 10:00 to 13:20 the
 464 irradiation stayed above 650 W/m², the water temperature was elevated from about 25 to 50 °C
 465 and the electricity efficiency changed from about 5.5% to 5.2%. The power temperature
 466 coefficient of the PV/T was thus estimated to be about -0.22%/°C in the daily, short-time scale
 467 test.



468
469 Fig.21. Variations of electrical gain and electrical efficiency on October 27

470 The I-V characteristic of a-Si PV/T collectors at 11:30 is shown in the Fig. 22. The solar
471 irradiation intensity, FF, open circuit voltage, short circuit current, maximum power point
472 voltage and current are also provided. The aluminum plate temperature was 38 °C at the
473 moment. The FF of about 57% was slightly higher than that on April 2. The main cause was
474 the lower aluminum plate temperature. Another cause could be the spectrum. Spectral
475 irradiance effects were significant on the seasonal performance of PV cells, especially on a-Si
476 cells [45, 46]. Solar irradiation and short circuit current were lower on October 27.



477
478 Fig. 22. I-V characteristic curve of the a-Si PV/T collectors on October 27

479 $G=870\text{W/m}^2$ $FF=57\%$ $V_{oc}=29.2\text{V}$ $I_{sc}=3.89\text{A}$ $V_{mp}=20.73\text{V}$ $I_{mp}=3.1\text{A}$

480 As summarized in Table 3, the daily simulation and experiment results of a-Si PV/T system
 481 on April 2 and October 27 are compared. The relative deviations of the experimental data from
 482 the simulated values are generally less than 2.11%. The daily average electrical efficiency of
 483 the simulation is slightly higher than the experiment. The reason may be that the frame shadow
 484 is not considered in the simulation. After a half year of operation, there was minor performance
 485 degradation of the a-Si cells. No technical problems had occurred during the operating period.

486 Table 3 Comparison of daily simulation and experiment results of the a-Si PV/T system

Date	4.2			10.27		
	Experiment	Simulation	RE	Experiment	Simulation	RE
$\bar{T}_a(^{\circ}\text{C})$	19.4			23.2		
H(MJ/m ²)	20.33			16.43		
$T_{w,i}(^{\circ}\text{C})$	20.2			19.9		
$T_{w,f}(^{\circ}\text{C})$	56.0	56.5		54.0	54.6	
$\eta_{th,a}(\%)$	32.80	33.28	-1.48%	38.65	39.37%	-1.86%
$\eta_{PV,a}(\%)$	5.58	5.66	-1.51%	5.22%	5.33%	-2.11%
$\eta_{PVT,a}(\%)$	43.87	44.51	-1.46%	49.01	49.94%	-1.90%

487
 488 **5.3 Uncertainty Analysis**

489 The operating temperature, solar irradiation, water flow rate and PV/T module output could
 490 be measured directly by the thermocouple, thermal resistance, radiator, flowmeter and power
 491 sensor. Their accuracies are shown in Table 2.

492 The instantaneous heat gain is related to the water temperature increment through the
 493 collectors and the mass flow rate. The accuracies of thermal resistance (Pt 100) and flowmeter
 494 are $\pm 0.1^{\circ}\text{C}$ and $\pm 5\%$. With minimum increment of about 1°C , the relative error in the
 495 instantaneous heat gain is $\pm 15\%$.

496 The total heat gain by the storage tank is associated with the temperature increment over the
 497 day. The ultimate increment is around 35°C on both April 2 and October 27. Given an accuracy
 498 of T-type thermocouple of $\pm 0.5^{\circ}\text{C}$, the relative error in the total heat gain is $\pm 1.4\%$.

499 The instantaneous and daily average thermal efficiencies are determined by Eqs.(19) and (22)
 500 respectively. The derivatives of the efficiencies with respect to the irradiation, temperature
 501 increment and flowrate could be deduced accordingly. Therefore, given radiator accuracy of
 502 $\pm 2\%$, the relative error in the instantaneous and daily average thermal efficiencies are $\pm 17\%$
 503 and $\pm 3.4\%$, respectively. In view of its high accuracy, the daily average thermal efficiency is a
 504 better criterion for the thermal performance estimation.

505 The instantaneous electrical efficiency is expressed by Eq.(21). The relative error is about
 506 $\pm 2.1\%$ on the condition of current sensor and radiator accuracies of $\pm 0.1\%$ and $\pm 2\%$. The daily
 507 average electrical efficiency is calculated on the basis of integral of the instantaneous efficiency
 508 with time, so the error should be similar.

509 The fill factor (FF) is determined by Eq.(25). With voltage and current accuracies of $\pm 0.5\%$
 510 and $\pm 2.0\%$, the relative error in FF is $\pm 5\%$.

511 For the sake of good encapsulation of the module, the temperature of the cells was not
 512 measured. Instead, the thermocouple was placed at the back of aluminum plate. An evaluation
 513 on the temperature difference between the cell and the plate (ΔT) could be carried out. the EVA
 514 and black TPT were both 0.2mm thick and their thermal conductivities were 0.23 and 0.36
 515 W/(m·K). Given a heat flux up to 450 W/m², ΔT should be less than 1 °C.

516 Table 4 Daily experimental results of a-Si PV/T system on some other days

Date	\bar{T}_a (°C)	H (MJ/m ²)	$T_{w,i}$ (°C)	$T_{w,f}$ (°C)	$\eta_{th,a}$ (%)	$\eta_{PV,a}$ (%)	$\eta_{PVT,a}$ (%)
4.1	15.7	16.12	21.7	48.8	31.31	5.58	42.37
4.14	23.7	19.56	23.2	55.7	30.95	5.51	41.87
10.22	22.1	16.41	20.4	51.2	34.92	5.25	45.34
10.24	20.7	18.29	20.9	53.3	33.12	5.21	43.46

517

518 As mentioned previously, the test results represent the performance of the PV/T system at

519 the early stage of degradation and DSS. Nevertheless, the performance may vary from day to
520 day, as shown in Table 4. Due to the different operation conditions, the daily electrical
521 efficiency and thermal efficiency on other days were not the same as that on April 2 and October
522 27.

523 **5.4. Further discussion**

524 Although a-Si cells have potential in the medium-high temperature PV/T application, some
525 challenges should be noted: (1) a-Si cells are not the mainstream solar cells; (2) The PV
526 modules have an efficiency around 8%, while conventional c-Si modules on the market have
527 an efficiency of about 17%. In particular, c-Si cells have experienced a much more significant
528 decrement in cost than a-Si cells during the past decade. (3) Knowledge on the practical a-Si
529 PV/T system is lacked. The Staebler-Wronski (S-W) effect on the a-Si PV/T system in the long-
530 term operation still needs to be evaluated.

531 **6. Conclusions**

532 A novel PV/T system using a-Si deposited on stainless steel is introduced in this paper. Tests
533 on the outdoor performance of the system have been carried out and the experimental results
534 for two sunny days (April 2, 2017 and October 27, 2017) are summarized as follows:

- 535 1. The peak instantaneous and daily average electricity efficiencies were 5.92% and 5.58%
536 on April 2, and they were 5.69% on 5.22 % on October 27. After more than half a year
537 operation, the daily average electricity efficiency had a 0.36% reduction owing to the S-W
538 effect. The instantaneous electrical efficiency varied slightly with the operating
539 temperature, especially at the early stage of degradation due to the trade-off between the S-
540 W and thermal annealing effects. The power temperature of the PV/T modules after
541 extended exposure was about $-0.22\%/^{\circ}\text{C}$ on the conditions of solar irradiation of $650\text{W}/\text{m}^2$
542 and operating temperature from 25 to 50°C .

- 543 2. The instantaneous thermal efficiency of the PV/T was subject to solar irradiation and
544 operating temperature. In both tests, the water temperature would eventually stagnate
545 around 55 °C even though the irradiation remained available ($>450\text{W/m}^2$), owing to the
546 balance between the collectors and environment. The maximum instantaneous thermal
547 efficiencies on April 2 and October 27 were close and around 43%. However, the daily
548 average thermal efficiency on April 2 was about 6% lower than that on October 27,
549 attributed to more heat loss from the collectors and pipes.
- 550 3. In the more than half a year operation, the electrical and thermal performances of the PV/T
551 have not shown significant degradation. And there was no sign of technical failure. The
552 feasibility of the a-Si PV/T is preliminarily demonstrated by the prototype.
- 553 4. The test and simulation are in good agreement. The maximum relative deviation between
554 the experimental and simulated daily thermal efficiency is 1.86%. It is 2.11% in the case
555 of daily electrical efficiency.

556 **7. Acknowledgement**

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560 Academy of Sciences (211134KYSB20160005).

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