

# 1     **Experimental Investigation of a Solar Collector Integrated with a Pulsating Heat Pipe and a** 2                                    **Compound Parabolic Concentrator**

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8  
9     **Abstract:** The paper reports an experimental investigation of a newly proposed solar collector that  
10 integrates a closed-end pulsating heat pipe (PHP) and a compound parabolic concentrator (CPC).  
11 The PHP is used as an absorber due to its simple structure and high heat transfer capacity. The CPC  
12 has a concentration ratio of 3.4 and can be readily manufactured by three-dimensional printing. The  
13 CPC can significantly increase the incident solar irradiation intensity to the PHP absorber and also  
14 reduce the heat loss due to the decrease in the area of the hot surface. A prototype of the solar  
15 collector has been built, consisting of a PHP absorber bent by 4 mm diameter copper tube, CPC  
16 arrayed by 10×2 CPC units with the collection area of 300×427.6 mm<sup>2</sup>, a hot water tank and a glass  
17 cover. HFE7100 was utilized as the working fluid at a filling ratio of 40%. The operating  
18 characteristics and thermal efficiency of the solar collector were experimentally studied. The steady  
19 and periodic temperature fluctuations of the evaporation and condensation sections of the PHP  
20 absorber indicate that the absorber works well with a thermal resistance of about 0.26 °C/W. It is  
21 also found that, as the main factor, the thermal performance of the collector decreases with  
22 increasing evaporation temperature. The collector apparently shows start-up, operational and  
23 shutdown stages at the starting and ending temperatures of 75 °C. When the direct normal  
24 irradiance is 800 W/m<sup>2</sup>, the instantaneous thermal efficiency of the solar collector can reach up to  
25 50%.

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26 **Keywords:** Solar collector; Pulsating heat pipe; Compound parabolic concentrator; Solar intensity.

## 27 **1 Introduction**

28 Solar energy is one among the most abundant, inexpensive, environment-friendly energies  
29 that can potentially meet the world's growing energy demand. The efficient mean to utilize solar  
30 energy is to convert solar energy into heat stored in water by solar thermal collectors [1]. Evacuated  
31 tube collectors and flat-plate solar collectors are the most commonly and widely used stationary  
32 solar collectors [2]. High-efficient heat transfer absorber and solar radiation concentration are the  
33 main methods to improve the performance of the solar thermal collector. Pandey and Chaurasiya [3]  
34 presented an overview on the different techniques to enhance the efficiency of flat plate collectors.  
35 The application of nanofluids as heat transfer fluid can improve the thermal efficiency of the  
36 collectors. Verma et al [4]. experimentally investigated the effect of a wide variety of nanofluids on  
37 the performance of flat plate solar collector. The thermal efficiency was improved by 23.5% using  
38 multiwalled carbon nanotubes/water instead of water up to 72.5%. In vacuum tube collectors, the  
39 efficiency was improved by 71.8% up to 93.4% due to the improved thermal properties of single  
40 walled carbon nanotubes nanofluid [5]. The combination of heat pipe and evacuated tube is an  
41 efficient way of solar collector due to its high heat transfer capacity. However, the thermal  
42 resistance between the absorber face of the vacuumed tube and the heat pipe determined the  
43 efficiency of the collector. The desalination efficiency was improved from 21.7% to 65.2% by using  
44 oil as the added fluid to the space between heat pipe and evacuated tube collector in a new  
45 desalination system, a combination of heat pipe and parabolic trough collector [6].

46 Pulsating heat pipe (PHP), which was proposed by Akachi [7] in the early 1990s as a new  
47 member of heat pipe, is one of the highly efficient absorber with simple structure and low-cost. At a  
48 steady state working stage, a self-sustained thermal-driven oscillating flow inside the tube is  
49 achieved, leading to higher heat transfer rate. Different from a traditional heat pipe, the sensible  
50 heat of the working fluid plays a major role in heat transfer [8]. Furthermore, complicated  
51 two-phase heat transfer occurs at a capillary scale. Previous efforts have mainly been focused on

52 explaining the working principle of PHPs. Heat flux has a significant effect on the thermal  
53 performance of PHP[9]. There are three working states of PHP, start-up, steady state and dry-out as  
54 the heat input increases. There exists a threshold heat flux at which PHPs start to operate. The  
55 thermal resistance of the PHPs decreases as the heat flux increases at steady state [10]. The  
56 operational regimes, including the start-up and dry-out under different heat inputs, were discussed  
57 in detail [11]. Kim and Lee [12] experimentally investigated the effect of channel geometry on the  
58 operating limit of microchannel pulsating heat pipes. The results showed that the square  
59 microchannel PHP can offer approximately 70% higher maximum allowable heat flux than the  
60 circular microchannel PHP at the same hydraulic diameter. Asymmetric channels decreased the  
61 thermal resistance of PHP under certain heat inputs[13].

62 Over the last decades, an increasing attention has been paid to the applications of PHPs,  
63 especially in the field of space, electronic cooling, heat recovery and solar thermal applications. A  
64 PHP air-preheater was designed and tested in a dryer and played a role of energy recovery and  
65 dehumidification [14]. PHP was also applied in a wire-on-tube heat exchanger as an extended  
66 surface and the heat transfer rate of the heat exchanger increased under different conditions [15, 16].  
67 An unlooped PHP has been developed and tested in an electronic thermal management field with  
68 hybrid vehicle applications and the PHP functioned with high reliability and reproducibility and  
69 without any failure during the start-up or working stage [17]. A simplified theoretical model of PHP  
70 employed as the condenser in a vapor compression refrigeration system has been developed. The  
71 performance of the system was improved [18]. PHP had also been used as heat sink of a high power  
72 LED street light [19] and defrosting plate [20].

73 In the field of solar energy collection, the use of PHP as the heat receiver has presented an  
74 efficient performance that is comparable to that of the traditional heat pipe receiver. PHPs possess  
75 the advantages of simple structure, low cost, and high efficiency. Rittidech and Wannapakne [21]  
76 built a PHP flat-plate solar collector in 2007. The collector was placed on a sheet of black zinc and  
77 had a collection area of  $2.00 \times 0.97 \text{ m}^2$ . An efficiency of approximately 62% was achieved. Choi et al.

78 [22] investigated the effect of the working fluid filling ratio and the cooling water flow rate on the  
79 top heat loss and performance of a PHP flat-plate solar collector. The radiation intensity was  
80 realized by using a halogen lamp solar simulator. The effect of evaporator length on the efficiency  
81 of a PHP flat-plate solar collector has also been investigated [23] and a multilayer perceptron neural  
82 network was trained and used to predict the behavior of the solar collector [24]. The maximum  
83 predicted thermal efficiency of the collector is 61.4%. An extra-long PHP was designed, constructed,  
84 and installed in a thermosiphon solar water heater, and the operating characteristic was investigated.  
85 Several sets of PHPs were placed in glass tubes to create a solar collector, another form of PHP  
86 receiver [25, 26]. An efficiency of approximately 76% was achieved [25], and the heat loss was  
87 reduced by the addition of the glass tube.

88         The PHP exhibits a great potential for use as a heat collector because of its high heat transfer  
89 capacity. However, the heat flux of the evaporation section of PHP should be sufficiently high to  
90 meet the demand of its steady and high-efficient work, which has a significant effect on the thermal  
91 performance of PHP [9]. Several experimental studies of PHP with similar structure to the PHP  
92 collector are listed and compared in Table 1. We can find in the application of PHP as solar heat  
93 collector or absorber the heat flux of the evaporation section is much lower than those in the  
94 experimental studies, which can be increased to improve the thermal performance of PHP. To this  
95 end, a solar concentrator is necessary. Compound parabolic concentrator (CPC), which is frequently  
96 utilized in low-temperature applications as a concentrating non-imaging concentrator [27], is  
97 introduced to concentrate solar radiation to the PHP absorber. Therefore, a novel solar collector  
98 integrated with a PHP and a CPC is proposed. The introduction of CPC with a proper concentration  
99 ratio can increase the heat flux of the PHP absorber so that the efficient heat transfer capacity of  
100 PHP is fully utilized. In the new collector, solar energy is concentrated by CPC instead of the absorb  
101 plate of the plate solar collector. The heat loss of the new collector will be reduced by decreasing  
102 the hot surface area. From another point of view, the disadvantage of CPC is the size, which  
103 depends on the size of the absorber, affecting the combination of the CPC collector and buildings.

104 The diameter of PHP is usually not more than 4mm that is much smaller than the traditional heat  
 105 pipe absorber. When PHP is used as absorber, the size of CPC can be the same as that of the plate  
 106 solar collector. This makes it easy to combine the new collector to buildings.

107 In this work, the detailed design of the collector is presented. The operating characteristics and  
 108 thermal performance of the collector are tested under different weather conditions, and the features  
 109 of the collector are also discussed.

110 Table 1 Summary of dimensions, working fluid and heat flux of PHPs in literature

Authors	Parameters of evaporation section				$Q$ (W)	$q_{rad}$ (W/cm <sup>2</sup> )	Working fluid	Solar collector
	ID(mm)	OD(mm)	n	$A_{rad}$ (cm <sup>2</sup> )				
Rittidech et al. [21]	3	4	14	7033.60	300~900	0.082~0.248	R-134a	Y
Rittidech et al. [25]	3	4	20	7536	600~1350	0.046~0.115	R-134a	Y
Yang et al. [26]	3	5	12	3015.93	20~90 50~350	0.0067~0.030 0.017~0.117	water	Y
Nguyen et al. [22]	2	4	8	492.35	66.766 79.013 87.955 101.063	0.1356 0.1605 0.1786 0.2053		Y
Kargarsharifabad et al. [23]	2	4	21	10857 8218 5579	860~1440 645~1080 430~720	0.092~0.133 0.079~0.131 0.077~0.129	water	Y
Yoon et al. [28]	2	3.2	19	267.28	100~600	0.374~2.245	water	N
Zhang et al. [29]	1.18	2	3	20.99	8~30 10~30 20~50	0.381~1.429 0.476~1.429 0.953~2.382	FC72 ethanol water	N
Borgmeyer et al. [30]	1.59	2.69*	28	46.78	50~160	1.069~3.420	water ethanol flutec PP2	N
Dmitrin et al. [31]	2	4*	8	180.86	30~100	0.166~0.553	water	N
Yang et al. [32]	1 2	2 3	40	12.38 22.79	50~380	4.038~30.687 2.194~16.675	R123	N
Sarangi et al. [33]	1	2	16	200.96	20~56 12.5~96	0.10~0.28 0.062~0.478	water ethanol	N
Naik et al. [34]	1.95	3	1	17.44	9~15	0.516~0.860	acetone methanol ethanol	N
Mameli et al. [35]	2	4	2	15.42	0~30 40~100	1.945 2.593~6.484	ethanol	N
Cui et al. [36]	2	4	5	285.36	5~15	0.018~0.053	water	N

					20 35~50 65~100	0.07 0.122~0.175 0.228~0.350	methanol ethanol acetone	
Karthikeyan et al. [37]	2.3	3.3	5	41.47	50~180 50~240 50~240	1.206~4.341 1.206~5.875 1.206~5.875	water Ag colloidal Cu nanofluids	N
Hao et al. [38]	2	4*	4 6	13.44 20.16	30~105 30~280	2.232~7.813 1.488~13.889	water	N
Mohammadi et al. [39]	2.2	3.2	4	65.95	25~85	0.379~1.289	water	N
Karthikeyan et al. [40]	2	3	8	90.48	30~500	0.332~5.526	water	N
Tseng et al. [41]	2.4	3	4	72.38	20~140	0.276~1.934	water methanol HFE-7100	N
Mohammadi et al. [42]	1.75	3	5	74.85	20~140	0.267~1.870	water nanofluid	N
Mameli et al. [43]	1.1	2	16	15.51	10~100	0.645~6.449	FC-72	N
Xian [44]	2	6	5	118.20	40~110	0.338~0.931	water	N
Pachghare et al. [45]	2	3.6	2	21.57	8~80	0.371~3.709	water ethanol methanol	N
Xian et al. [46]	2	6	5	118.20	30~40 40~100 100~110	0.254~0.338 0.338~0.846 0.846~0.931	water	N

111 \* The thickness of the tube was not given and is taken to be 0.5 mm here.

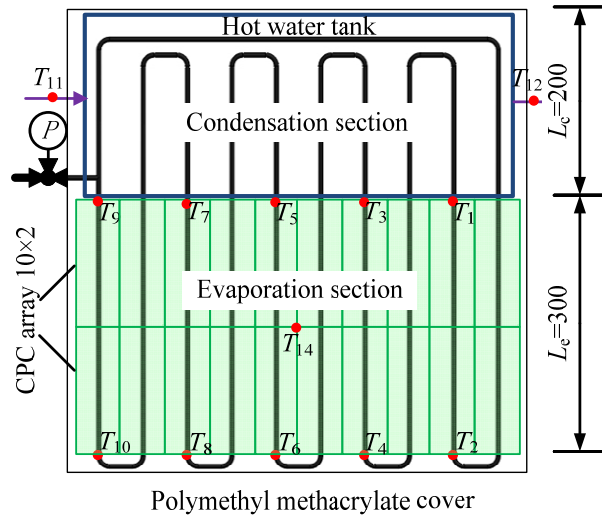
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## 113 2 Design of the PHP solar collector with CPC

### 114 2.1 Solar collector and PHP absorber

115 Figure 1 shows the configuration and dimensions of the solar collector which consists of a PHP  
116 absorber, CPC, a hot water tank and a glass cover. The PHP absorber is made of copper tubes  
117 having an outer diameter of 4 mm and an inside diameter of 2 mm. The bending radius depends on  
118 the capture width of the CPC (see section below). The evaporation section is 300 mm long and is  
119 painted black with absorption rate of 0.85. The evaporation section of the PHP absorber is fixed at  
120 the focus of the CPC and the outer diameter of the absorber is the original cycle of the CPC so that  
121 all solar radiation can be reflected to the PHP. The condensation section is 200 mm long and is  
122 sealed inside the hot water tank. The hot water tank is made of stainless steel plate with dimensions

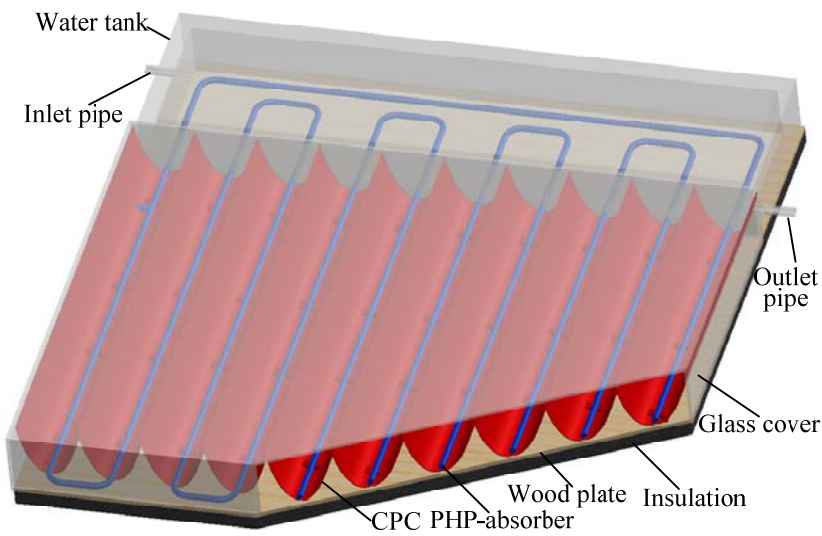
123 of 500 mm × 250 mm × 25 mm and 1 mm wall thickness. The outer surface is insulated by  
 124 polyurethane. No adiabatic section exists between the evaporator and condenser sections. The PHP  
 125 absorber, CPC, and hot water tank are fixed on a wood plate. The solar collector is insulated by  
 126 polymethyl methacrylate to minimize heat loss to ambient.



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(a)



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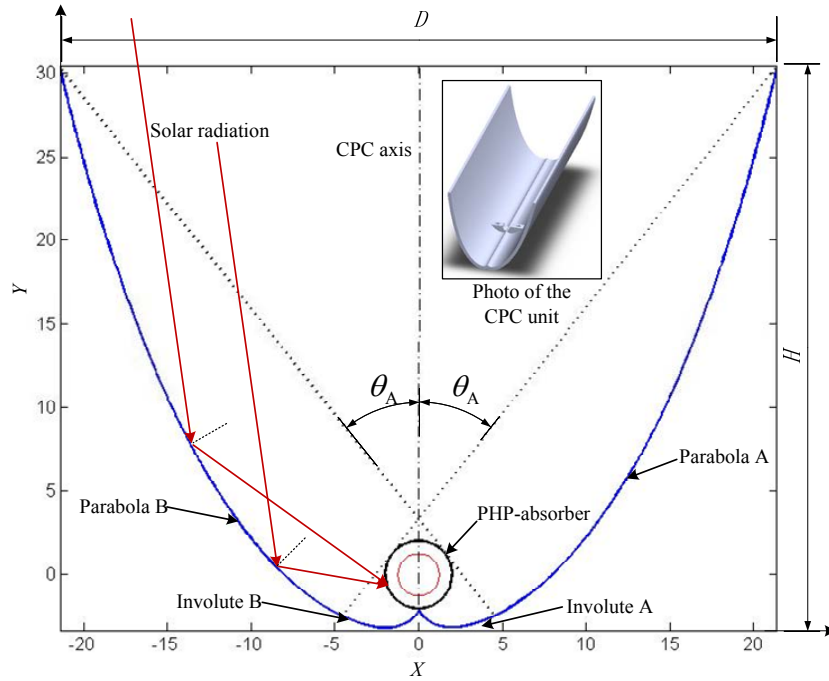
(b)

Fig. 1. Schematic of solar collector integrated with CPC and PHP. (a) top view; (b) model

## 2.2 Design of the CPC

CPC is introduced to increase the solar irradiation intensity to the PHP absorber and hence its heat flux. The CPC consists of two parabolas with compound rotation, and most of the beam and

136 diffuse radiation can be collected and reflected on the absorber surface without a complicated solar  
 137 tracking system (see Fig. 2).



138

139 Fig. 2. Geometry and dimension of CPC and PHP absorber and coordinator

139

140 The CPC involute is defined by Eq. (1) as

140

141

$$\begin{cases} X = \frac{d}{2}(\sin \varphi - \varphi \cos \varphi) \\ Y = -\frac{d}{2}(\varphi \sin \varphi + \cos \varphi) \end{cases} \quad (1)$$

142

for  $0 \leq \varphi \leq 90^\circ + \theta_A$ .

143 The parabola line is defined by Eq. (2) as

143

$$\begin{cases} X = \frac{d}{2}(\sin \varphi - A^* \cos \varphi) \\ Y = -\frac{d}{2}(A^* \sin \varphi + \cos \varphi) \end{cases} \quad (2)$$

144

145 for  $90^\circ + \theta_A \leq \varphi \leq 270^\circ + \theta_A$

146 where

146

$$A^* = \frac{\frac{\pi}{2} + \theta_A + \varphi - \cos(\varphi - \theta_A)}{1 + \sin(\varphi - \theta_A)} \quad (3)$$

147

148  $\varphi$  is the angle between the incident ray and the X-axis.  $\theta_A$  is the aperture angle of the CPC given



149 by Eq. (4)

$$150 \quad \theta_A = \arcsin\left(\frac{1}{CR}\right) \quad (4)$$

151 The concentration ratio ( $CR$ ) is defined by Eq. (5) as

$$152 \quad CR = \frac{D}{\pi \times d} \quad (5)$$

153 where  $D$  is the aperture width and  $d$  is the outer diameter of the PHP absorber. The average heat flux  
154 of evaporation section of the PHP absorber can be calculated by Eq. (6)

$$155 \quad q = \frac{D \times I}{\pi \times d} = CR \times I \quad (6)$$

156 where  $I$  is the solar irradiation intensity measured using a pyranometer.

157 Two key aspects are considered in the design of the CPC. One is to ensure the existence of  
158 sufficient heat flux of the evaporation section of the PHP, and the other is to check that the ratio of  
159 height to width is not too large. The geometric shape of the CPC depends on the outer diameter of  
160 the PHP absorber, and the size of the CPC depends on the concentration ratio  $CR$  or opening width  
161  $D$ . In the present work, the outer diameter of the PHP absorber is 4 mm. According to the values of  
162 heat flux in literature [36, 40, 42, 44, 46] which is 0.166W/cm<sup>2</sup>~5.526 W/cm<sup>2</sup>, a preliminary  $CR = 5$   
163 was selected, and the interception ratio of the CPC is 4/5. Thus, the actual  $CR$  is 3.40 and the  
164 aperture width  $D$  is 42.76 mm. The newly designed solar collector can reach an average heat flux of  
165 0.17~0.34 W/cm<sup>2</sup> under the solar irradiation density of 500~1000 W/m<sup>2</sup>. This level of heat flux  
166 ensures that the PHP can work steadily as in literature [36, 40, 42, 44, 46]. The introduction of CPC  
167 to the PHP solar collector is thus reasonable and necessary.

168 Once the CPC size was finally determined, the model line was drawn using Eqs. (1) to (5) in  
169 Malab and then exported into Solidworks to build a 3D model. To attach a reflective sheet with  
170 0.1 mm thickness onto the inner surface of the CPC, the inner surface was cut off by 0.1 mm depth.  
171 A fastener was designed to fix the pipe of the PHP. The CPC was manufactured using a  
172 three-dimensional printer with an accuracy of 0.02 mm. The limitation of the three-dimensional

173 printer in terms of size required the utilization of CPC units to assemble the entire CPC (see Fig. 2).  
174 The length of one CPC unit is 150 mm. Two units are lined for one pipe of the PHP evaporation  
175 section, and  $10 \times 2$  array CPC units are arranged for the entire PHP absorber. The total area of the  
176 CPC is  $0.12828 \text{ m}^2$  for solar energy collection. The aluminum reflective sheet with a reflective ratio  
177 of 0.80–0.90 was attached to the inside surface of the CPC.

178

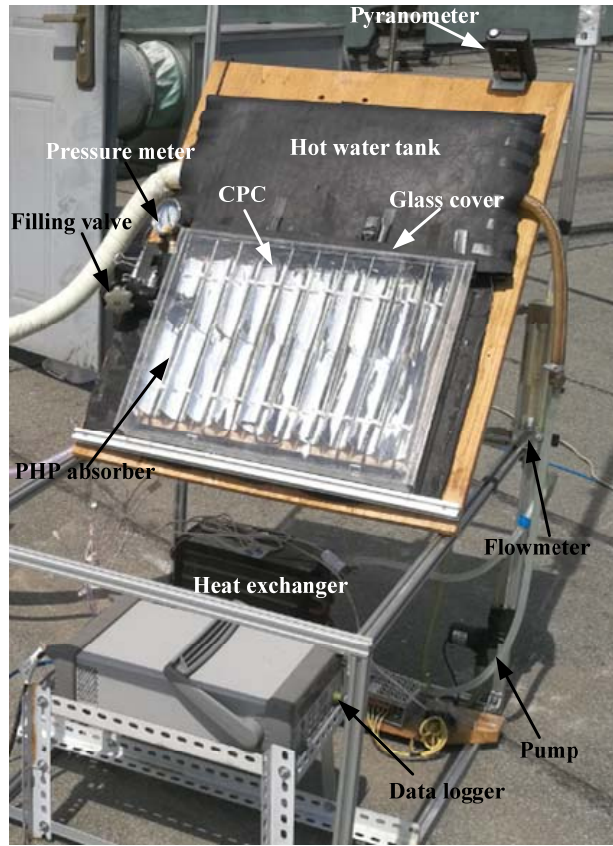
### 179 **3 Experimental setup and procedures**

#### 180 **3.1 Experimental setup**

181 Figure 3 shows the apparatus which consists of the solar PHP absorber, a hot water loop and  
182 data acquisition system. The hot water loop was built to maintain a proper heat-collecting  
183 temperature of the solar collector. The hot water loop includes a hot water tank, pump, fin-tube heat  
184 exchanger and flow meter. The pump drives the circulation of the hot water. The hot water is cooled  
185 in the air-cooled heat exchanger, then circulated back to the hot water tank through the flow meter  
186 with a reduced temperature and finally heated through the condensation section.

187 Figure 3 also shows the data acquisition system and the temperatures, total solar radiation  
188 intensity, and flow rate of the hot water are measured. Ten T-type thermocouples (Omega<sup>®</sup>, bead  
189 dimension of 0.8 mm, accuracy  $\pm 0.1 \text{ K}$  after calibration), numbered  $T_1$  to  $T_{10}$ , were soldered on the  
190 external tube wall of the PHP absorber (see Fig.1). The PHP absorber has five turns and two  
191 thermocouples are used for each turn. One thermocouple is located at the beginning of the  
192 evaporation section and another thermocouple is located at the end where the condensation section  
193 begins. Two thermocouples,  $T_{11}$  and  $T_{12}$ , were used to measure the hot water temperatures at the  
194 inlet and outlet of the hot water tank. The air temperature inside the cover at the center of the  
195 evaporation section of the PHP absorber was also measured using thermocouple  $T_{14}$  and for the  
196 ambient air temperature was measured by thermocouple  $T_{13}$ . A data logger (Agilent34972A Data  
197 Acquisition/Switch Unit, with  $\pm 1 \text{ K}$  accuracy) was utilized to record the temperatures. Solar  
198 radiation intensity was measured and recorded using a solar pyranometer (TES-1333R) with an

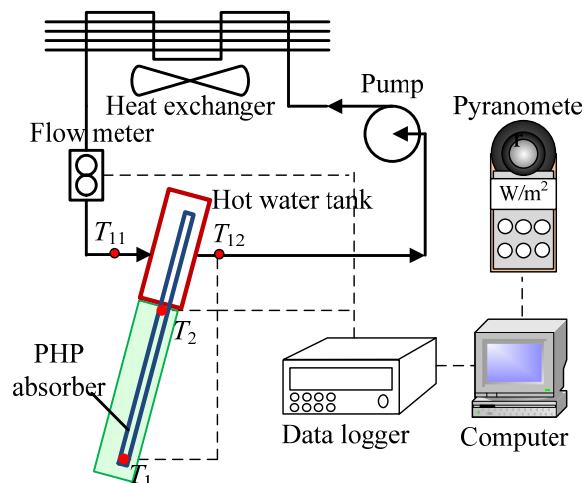
199 accuracy of  $\pm 10 \text{ W/m}^2$ . The frequency of the temperature and solar intensity data acquisition is  
 200 0.5 Hz. A rotameter (Senlod, LZB-6) with an accuracy of 2.5% at a 60 L/ H flow range was utilized  
 201 to measure the flow rate of the hot water.



202

203

(a)



204

205

(b)

206

Fig. 3. Experimental set up. (a) Photograph; (b) Schematic and data acquisition

207

## 208 3.2 Experimental conditions and procedure

209 All experiments were conducted on the top of a building in Beijing, China (latitude: 39°48';  
210 longitude: 116°28'). The daily experiment time was between 9:00 AM and 5:00 PM because  
211 approximately 90% of solar energy is obtained in this period of time. The experiments were  
212 conducted from May 14, 2015 to September 5, 2015.

213 In the present work, a pressure of 0.1 Pa in the tube can be created using a double-stage rotary  
214 vacuum pump and can be maintained for 24 h without increasing. HFC7100 (C4F9OCH3) was  
215 filled at a volume filling ratio of 40%. The inclination angle of the solar collector was adjusted to  
216 45°. The flow rate of the hot water was fixed to 50 L/h, and the pump of the hot water loop was not  
217 turned on until the temperature of the hot water reached 40 °C that was maintained.

218

## 219 3.3 Data processing

220 The temperature fluctuation is another key parameter indicating the operating characteristic of  
221 the solar collector. Apart from the temperature fluctuation, the average temperatures of the  
222 evaporation ( $T_e$ ) and condensation ( $T_c$ ) sections are also considered.

223 The thermal resistance of the PHP absorber is determined by

$$224 R_T = (T_e - T_c) / Q_s = (T_e - T_c) / (IA). \quad (7)$$

225 The instantaneous quantity of heat transferred to water can be calculated by the flow rate,  
226 specific heat and temperature rise between the outlet and inlet of water.

$$227 Q_w = c_w m_w (T_{out} - T_{in}) \quad (8)$$

228 The instantaneous heat collecting efficiency of the solar collector is defined as the ratio of the  
229 heat absorbed by water to the total solar irradiation reached to the solar collector.

$$230 \eta = Q_w / Q_s = c_w m_w (T_{out} - T_{in}) / (IA), \quad (9)$$

231 where  $A$  is the area of the CPC array.

232

### 233 3.4 Uncertainty analysis

234 The maximum uncertainty of temperature is estimated to be  $\pm 1.1$  K depending on the accuracy  
235 of the twelve T-type thermocouples  $\pm 0.1$  K and the accuracy of the data logger  $\pm 1.0$  K. The  
236 uncertainties of the water flow rate and solar irradiation intensity are 2.5% of the measuring range  
237 ( $\pm 1.5$  L/h) and  $\pm 10$  W/m<sup>2</sup>, respectively. The uncertainties of thermal resistance of the PHP-absorber  
238 and thermal efficiency of the solar collector are obtained from Eqs. (7) and (9) using Eq. (10) [47].

$$239 \quad w_R = \sqrt{\sum \left( \frac{\partial R}{\partial x_i} w_i \right)^2} \quad (10)$$

240 where  $w_R$  is the uncertainty of the dependent variable and  $w_i$  are the uncertainties of the independent  
241 variables. A summary of the maximum uncertainties of the main parameters are given in Table 2.

242 Table 2. Uncertainties of the measurements

Quantity	Max uncertainty
Temperature (K)	$\pm 1.1$
Water flow rate	2.50%
Solar irradiation intensity (W/m <sup>2</sup> )	$\pm 10$
Temperatures of evaporation and condensation, (K)	0.64%
Thermal resistance	5.34%
Thermal efficiency	11.01%

243

## 244 4 Results and discussion

### 245 4.1 Operating characteristics of the PHP absorber

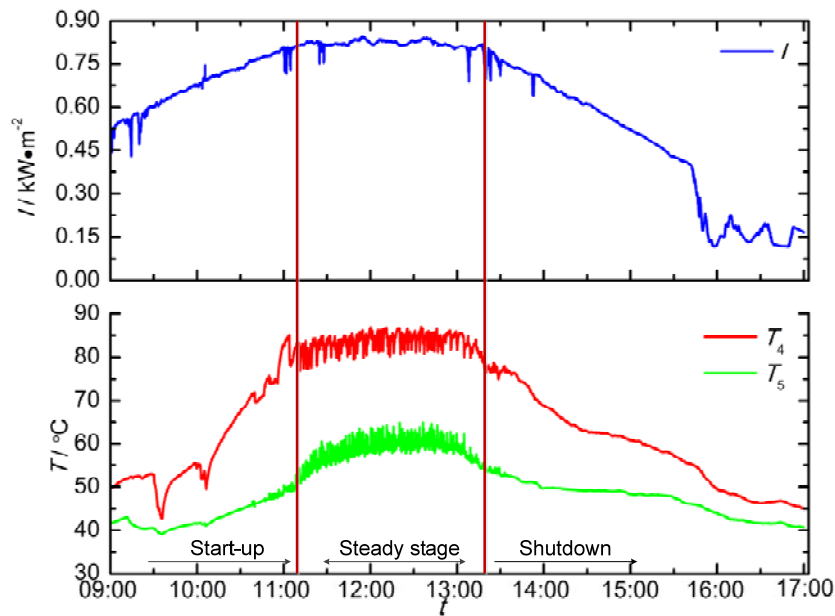
246 In present work, three representative tests were chosen to analyze the system performance. The  
247 first test was conducted on June 12, 2015 named as case I; the second test on June 13, 2015 named

248 as case II; and the third test on June 14, 2015 named as case III. The variations of the solar intensity  
249 during tests on the first two days were similar; whereas that on the third day was different.

250 Evaluation of the pulsating working condition was the first step in the experiments. Two  
251 indicators were adopted to verify whether or not the copper tube functions as a pulsating heat pipe  
252 or not. One indicator is the temperature fluctuation in the evaporation and adiabatic sections, and  
253 the other is the temperature increase in the evaporation section. If the PHP absorber does not work  
254 as a PHP or if dry-out occurs, the temperature of evaporator section will increase rapidly. In other  
255 words, if the temperature of the evaporation section does not increase along with the increase in  
256 solar intensity, the copper tube functions as PHP even without a pulsating temperature. These  
257 conditions are a guide to determine whether or not dry-out occurs, particularly under high solar  
258 intensity conditions. The same approach was used in Nguyen et al. [22].

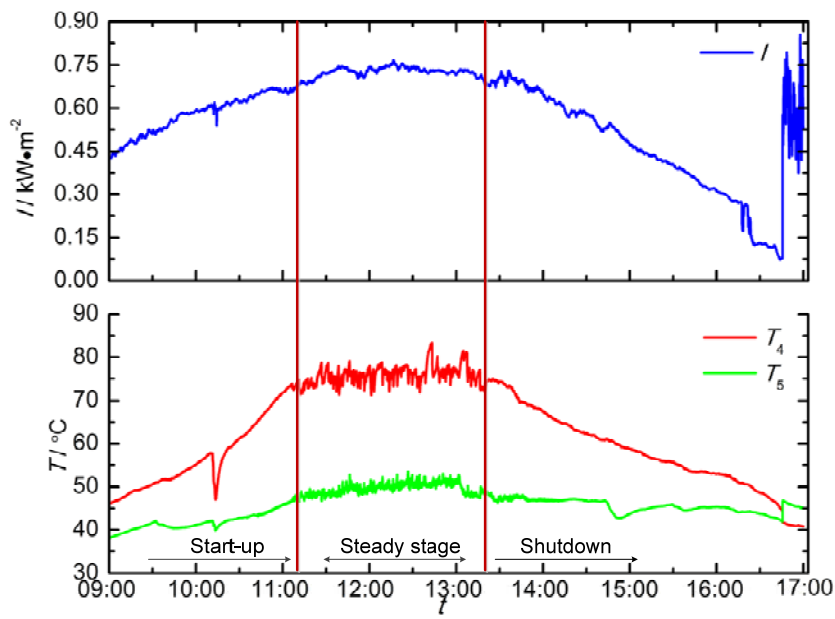
259 Figure 4 shows the variations of the measured solar intensity and temperature ( $T_4$  and  $T_5$ ) of  
260 the PHP solar collector with local time for case I (a) and case II (b). It can be seen that the  
261 temperature fluctuation for case I and case II are similar under the similar solar intensity. The  
262 pulsating temperature pertains to the pulsation of vapor bubbles or liquid slug inside the tube as a  
263 result of different temperatures they have. For the PHP-absorber, there exists a minimum heat flux  
264 that starts up the pulsating flow [10]. Therefore, the operation of the solar collector appears three  
265 working stages, namely, start-up, steady state, and shutdown corresponding to the level of solar  
266 intensity. At the start-up stage, the temperature of the PHP increases rapidly as the solar intensity  
267 increases. It was observed that vapor bubbles does not generate in all of the tubes at the same time  
268 and instead generating small vapor bubbles in one or two tubes at 65 °C. The bubbles can reach the  
269 condensation section and the temperature exhibits a small fluctuation. When the temperature of the  
270 evaporation section reaches 75 °C, a sharp drop and fluctuation in temperature occur with no further  
271 increase. This marks the startup of the pulsating heat pipe. The startup time of the solar collector is  
272 approximately 11:00 AM, with a solar irradiation intensity of 750 W/m<sup>2</sup>. In the next working stage,  
273 the temperature variation in the evaporation and condensation sections are violent and nearly

274 periodic. At this stage, the solar irradiation intensity reaches its highest value of the day and stable.  
 275 With irradiation intensity decreases, the PHP enters the shutdown stage. As the solar irradiation  
 276 intensity decreases, both the temperature fluctuation frequency and amplitude decrease until they  
 277 disappear. The temperature declines rapidly, especially in the evaporation section. The ending time  
 278 of the PHP absorber is approximately 2:00 PM, and the ending temperature of the evaporation  
 279 section is about 75 °C (similar to startup). The first rapid drop in temperature was observed at the  
 280 start-up stage because of the opening of the glass cover to check the thermocouples.



281  
 282

(a)



283  
 284

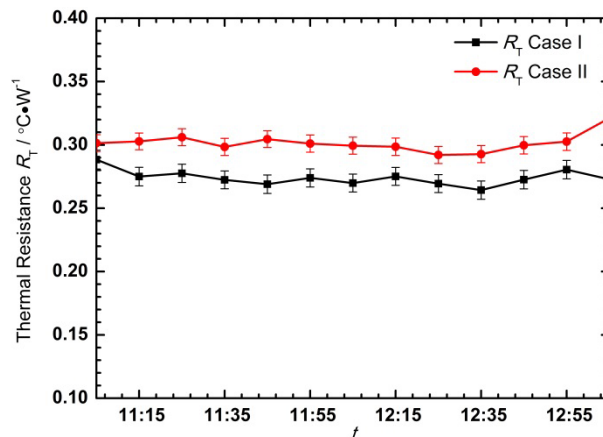
(b)

285 Fig. 4. Variations of solar intensity and measured temperatures at locations in solar collector (see  
286 Fig. 1 (a)) with local time for (a) Case I and (b) Case II.

287

288 The temperature fluctuations of the evaporation and condensation sections at the steady stage  
289 are steady and periodic. The temperature of evaporation and condensation sections are differences  
290 (approximately 30 K). The evaporating temperature is around 85 °C and the condensing  
291 temperature is approximately 55 °C for case I. This temperature difference is slightly larger than  
292 that in Case II because the solar irradiation intensity in Case I is higher. Both evaporation and  
293 condensation temperatures at the steady stage slightly decrease.

294 Figure 5 shows the variations of the thermal resistance in the PHP solar absorber at the steady  
295 working stage for Case I and Case II. The thermal resistance in Case I is steady and fluctuates  
296 between 0.26 °C/W and 0.29 °C/W. The working state of the PHP absorber is steady under a good  
297 working condition. The thermal resistance value is more reasonable than those found in literature  
298 [36, 40]. The design of the solar collector with PHP and CPC is thus reasonable.



299

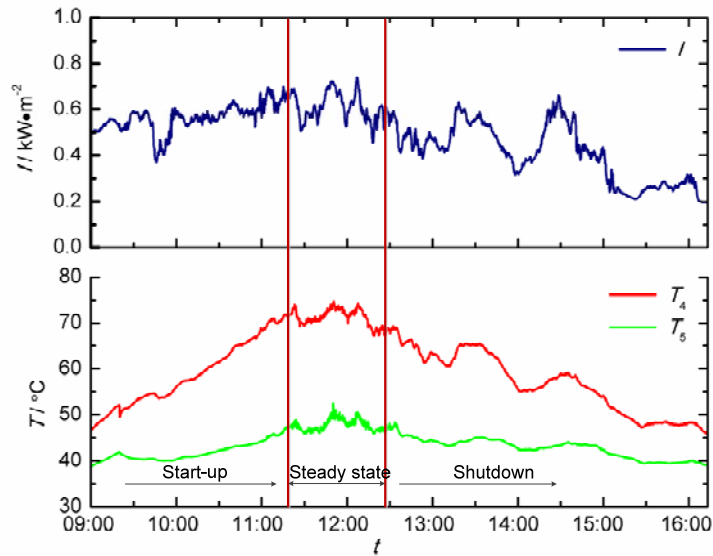
300 Fig. 5. Variations of thermal resistance of solar absorber at the steady working stage for Case I and  
301 Case II

302

303 To compare with the working characteristics of the PHP solar thermal collector, the  
304 temperature variation and thermal performance of the solar collector were tested on different days  
305 with different levels of solar irradiation intensity. Three working stages also exist for different solar  
306 irradiation intensities even on a cloudy day (see Fig. 6). The solar collector can still operate  
307 normally even under cloudy weather. The startup temperature is almost the same (approximately



308 75 °C) on different days. However, the temperature fluctuation appears larger and varies with the  
 309 solar irradiation on cloudy days. The steady working stage is seen to be short, with a lower  
 310 evaporation section temperature of approximately 70 °C and condensation section temperature of  
 311 approximately 50 °C. The amplitude of temperature pulsation caused by the moving of liquid and  
 312 bubble slugs in side PHP is significantly small.



313

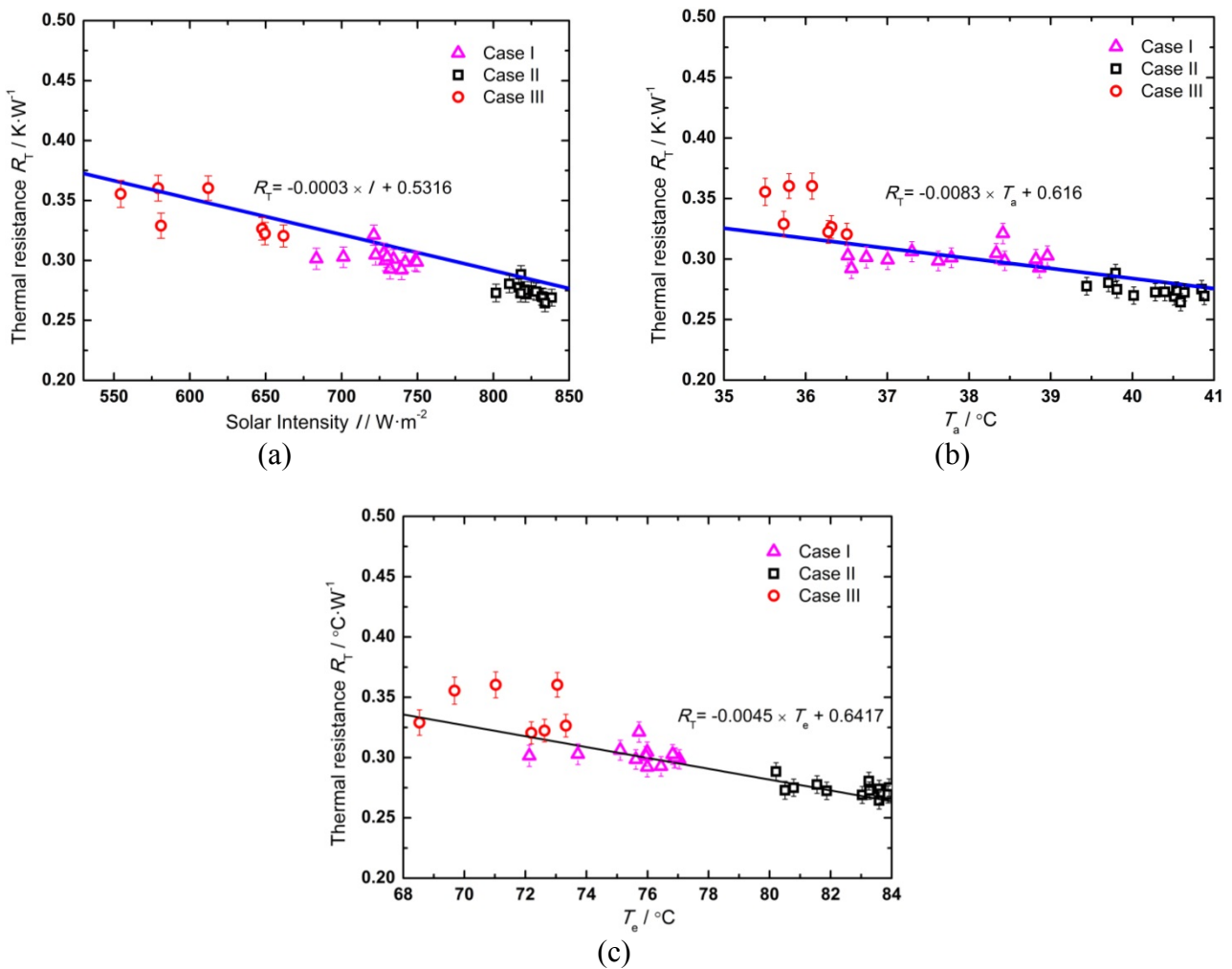
314 Fig. 6. Variations of solar intensity and measured temperatures at locations in solar collector (see  
 315 Fig. 1 (a)) with local time for Case III.

316

317 Thermal resistance is an important indicator of the operation and performance of solar  
 318 collectors. To further investigate the thermal resistance variation and influencing factors, the  
 319 thermal resistance was statistically analyzed based on these three-day experimental data at steady  
 320 state stage.

321 Figure 7 (a) shows the effect of solar irradiation intensity on the thermal resistance of the solar  
 322 collector. The thermal resistance of the PHP absorber decreases with the increase in heat input,  
 323 similar to traditional PHPs. The difference between traditional PHPs and the PHP absorber is in the  
 324 heat flux distribution in the evaporation section. The heat flux distribution of the PHP absorber is  
 325 uneven due to the reflection of solar radiation of the CPC. The thermal resistance decreases from  
 326 0.37 °C/W to 0.25 °C/W with the increase in solar irradiation intensity from 500 W/m<sup>2</sup> to 900 W/m<sup>2</sup>.

327 The results demonstrate that the PHP absorber can work well at a proper heat flux under solar  
 328 radiation intensity. Figure 7 (b) and (c) show the influence of ambient and evaporation temperatures  
 329 on the thermal resistance of the PHP absorber. The thermal resistance decreases with the increase in  
 330 ambient temperature. The ambient temperature is the main factor that influences the heat loss of the  
 331 solar collector. When the ambient temperature increases, the heat loss decreases leading more heat  
 332 transferred by the PHP absorber to the condensation section. It can be seen that the thermal  
 333 resistance of the PHP absorber decreases with the increase in evaporation temperature. This result is  
 334 encouraging because it shows that the combination of CPC and PHP can be effectively utilized in  
 335 high-temperature solar thermal collectors.



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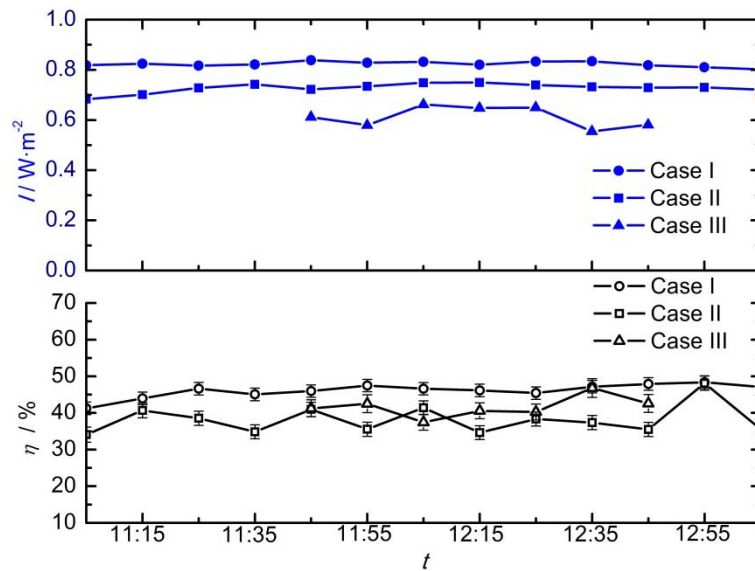
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341 Fig. 7. Effects on thermal resistance of PHP absorber. (a) solar intensity; (b) ambient temperature; (c)  
342 evaporation temperature

343

344 **4.2 Thermal efficiency of the solar collector**

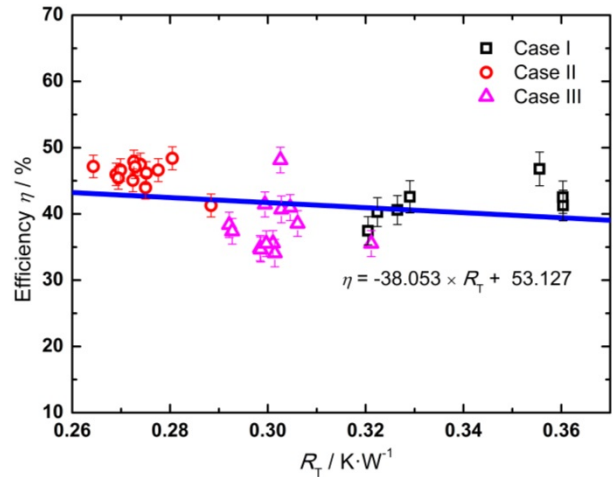
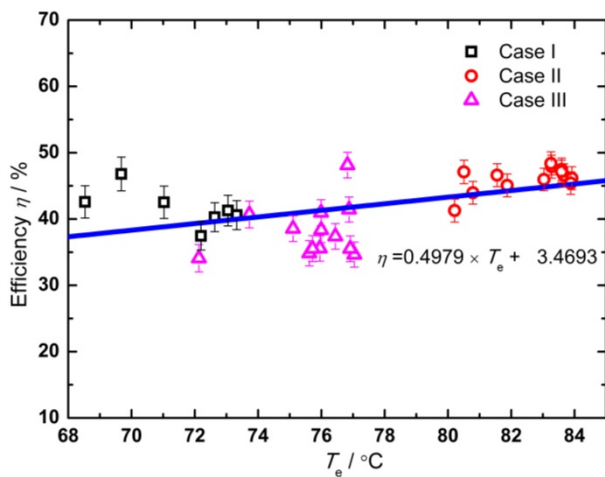
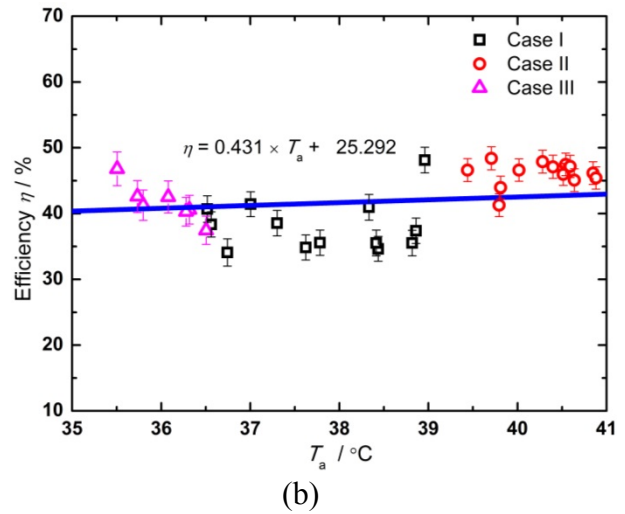
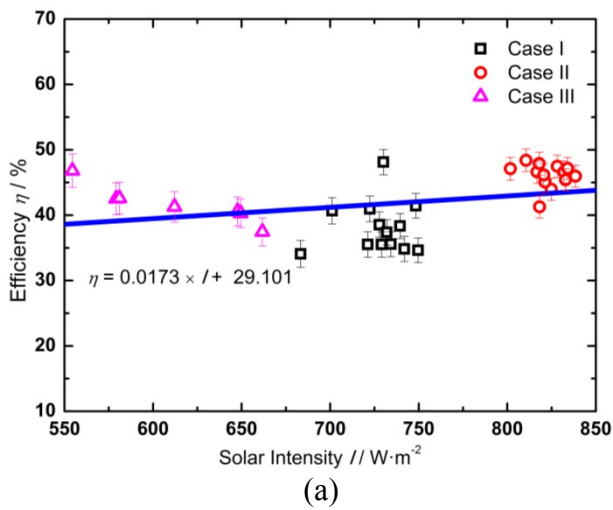
345 The the performance of the solar collector at the steady working stage is shown in Fig. 8. The  
 346 instantaneous heat collecting efficiency is stable. The efficiencies are approximately 50% with a  
 347 solar intensity of  $800 \text{ W/m}^2$ , and 40% with a solar intensity of  $730 \text{ W/m}^2$ . Respectively the value of  
 348 efficiency is comparable to those in literature [36, 40, 43]. The performance of the solar collector on  
 349 a cloudy day is shown in Fig. 8. It can be found that the fluctuation of instantaneous efficiency of  
 350 the collector on a cloudy day is larger but it still achieves an overall efficiency of approximately  
 351 50%. Although large fluctuations in solar irradiation occur, the collector can still work and achieve  
 352 highly satisfactory collection efficiency, thereby indicating the reliability of its operation.  
 353 Furthermore, the thermal performance of the collector can be improved by increasing the reflective  
 354 ratio of the reflective film and absorption coating efficiency and reducing the heat loss of the glass  
 355 cover.



356  
 357 Fig. 8. Variations of thermal efficiency of solar collector with local time  
 358

359 The main factors that influence the thermal performance of the collector include solar intensity,  
 360 ambient temperature, evaporation temperature, and thermal resistance of the PHP absorber. To  
 361 investigate the tendencies among them, several results were analyzed. Figure 9 (a) shows the effect  
 362 of solar intensity on the thermal performance of the collector. The thermal performance of the  
 363 collector depends on solar intensity. The efficiency increases with the increase in solar intensity;

364 however, the rate of the increase is extremely low. The thermal performance of the PHP absorber is  
 365 steady for the entire range of the solar intensity. This finding means that the collector has good  
 366 stability. The same condition can be found in Fig. 9 (b), which shows the effect of ambient  
 367 temperature on the thermal performance of the collector. The ambient temperature is the main  
 368 parameter for the heat loss of the collector. Figure 9 (c) shows that the efficiency of the collector  
 369 increases with the increase in evaporation temperature because the thermal resistance of the PHP  
 370 absorber is lower at a higher evaporation temperature. Furthermore, the water tank obtains  
 371 additional heat from the PHP absorber. Conversely, the heat loss of the collector is high when the  
 372 evaporation temperature is high. In consideration of the solar energy input, heat loss, and heat  
 373 collection, the thermal performance of the collector increases with the increase in evaporation  
 374 temperature and the decrease in the thermal resistance of the PHP absorber is the main factor that  
 375 influences its thermal performance, as shown in Fig. 9 (d).



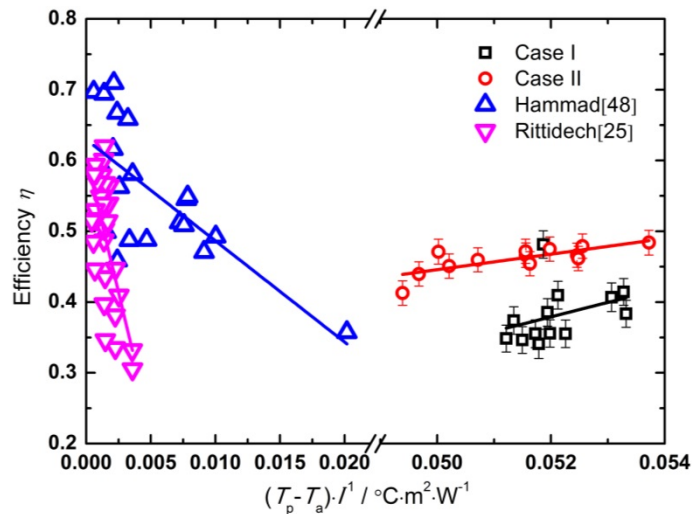
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(c) (d)

Fig. 9. Effects on thermal efficiency of solar collector. (a) solar intensity; (b) ambient temperature; (c) evaporation temperature; (d) thermal resistance of the PHP absorber

384 Figure 10 shows the effect of the  $(T_p-T_a)/I$  on the thermal efficiency of the collector. The  
385 present results are compared with the performance curves of the solar collectors by heat pipe  
386 systems [37] and pulsating heat pipe system [25]. The  $(T_p-T_a)/I$  values of the present work are  
387 higher than those in literatures [25] and [37] due to the solar concentration by CPC. The thermal  
388 efficiency of the present work is slightly lower. The main reason is that no seal exists between the  
389 glass cover and the wood board and also the distance from the glass cover to the wood board. The  
390 thermal efficiency of the new collector increase with the increases of  $(T_p-T_a)/I$  and the trend is  
391 different from those in literatures [25] and [48]. The reason is that the thermal resistance of the  
392 PHP-absorber, which is the main factor influencing the thermal efficiency of the collector, decreases  
393 with the increase in solar irradiation intensity and evaporation temperature (see Fig.7(c)).



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Fig. 10. Effect of the  $(T_p-T_a)/I$  on the collector efficiency,  $T_p=(T_e+T_c)/2$

### 4.3 Discussion on the new solar collector with PHP and CPC

399 To match the heat transfer capacity of the PHP absorber and solar irradiation intensity, a solar  
400 collector equipped with PHP and CPC has been developed. The evaporation section of the PHP  
401 absorber receives proper heat flux that works steadily due to the introduction of CPC. Furthermore,

402 the heat loss to the surrounding air was decreased by reducing the hot surface area of the collector.  
403 From the perspective of the collector of CPC, PHP is a good choice for its small endothermic radius.  
404 In the present work, the total thickness of the collector is less than 50 mm with the CPC at a  
405 concentration ratio of 3.4. Additionally, the new collector also has the advantage of protection from  
406 freezing, which is suitable to the application of low freezing point working fluid. Generally, it  
407 presents a new efficient method of solar thermal collecting at centimeter scale and has great  
408 potential in many applications.

409 The design of the proposed solar collector still has a drawback of short steady working hours.  
410 The CPC aperture angle causes the late startup and the early shutdown. Fortunately, gravity has  
411 minimal effect on the thermal performance of the PHP [9]. The working hours of the collector can  
412 be prolonged by changing the direction of CPC from vertical to horizontal in order to receive more  
413 solar energy and to work for the entire day.

414

## 415 **5 Conclusions**

416 A novel solar collector that integrates a closed-end PHP and a CPC has been proposed, built  
417 and tested. The effects of operating parameters on the operating characteristics of the PHP absorber  
418 and the thermal performance of the solar collector were investigated under different weather  
419 conditions. The following conclusions can be drawn.

- 420 1) The collector apparently shows start-up, operational and shutdown stages at the starting and  
421 ending temperatures of 75 °C. The solar collector can stably operate even in cloudy days.
- 422 2) The thermal resistance of the PHP absorber decreases with the increase in ambient temperature,  
423 solar intensity, and evaporation temperature which is found to be the main factor that affects the  
424 thermal efficiency of the collector and can reach nearly 0.26 °C/W.
- 425 3) The experimental results suggest that the heat flux of the PHP absorber's evaporation section  
426 concentrated by CPC with a concentration ratio of 3.4 is appropriate and the use of CPC is  
427 reasonable.

428 4) The proposed design offers a promising efficiency of 50% when compared with conventional  
429 solar collectors and PHP solar collectors.

430

#### 431 **Acknowledgments**

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435 Engineering and Architecture.

## Nomenclature

$A$	area ( $\text{m}^2$ )
$CR$	concentration ratio of CPC
$c$	specific heat capacity ( $\text{kJ/kg}\cdot\text{K}$ )
$d$	diameter (m)
$D$	aperture width (m)
$H$	height of CPC (mm)
$m$	mass flow rate ( $\text{kg/s}$ )
$n$	number of PHP turns
$I$	solar irradiation density ( $\text{W}/\text{m}^2$ )
ID	inner diameter (mm)
$i$	the number of a thermal couple
OD	outer diameter (mm)
$Q$	Heat transfer rate (W)
$q$	heat flux ( $\text{W}/\text{m}^2$ )
$T$	temperature ( $^{\circ}\text{C}$ )
$R$	thermal resistance ( $^{\circ}\text{C}/\text{W}$ )

## Greek symbols

$\eta$	efficiency of the solar collector
$\sigma$	surface tension of the working fluids ( $\text{N}/\text{m}$ )
$\rho$	density of the working fluids ( $\text{kg}/\text{m}^3$ )
$\varphi$	angle between the incident ray and the X-axis ( $^{\circ}$ )
$\theta_A$	aperture angle of the CPC ( $^{\circ}$ )

## Subscripts

1-13	location of thermal couples
------	-----------------------------



c	condensation section
e	evaporation section
in	inlet of the hot water tank
l	liquid
r/rad	radial direction
out	outlet of the hot water tank
p	plate
s	solar energy
T	temperature
w	water
v	vapor

436

437

438

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