Thermal modeling optimization and experimental validation for a single concentrator solar cell system with a heat sink*

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A single concentrator solar cell model with a heat sink is established to simulate the thermal performance of the system by varying the number, height, and thickness of fins, the base thickness and thermal resistance of the thermal conductive adhesive. Influence disciplines of those parameters on temperatures of the solar cell and heat sink are obtained. With optimized number, height and thickness of fins, and the thickness values of base of 8, 1.4 cm, 1.5 mm, and 2 mm, the lowest temperatures of the solar cell and heat sink are 41.7 °C and 36.3 °C respectively. A concentrator solar cell prototype with a heat sink fabricated based on the simulation optimized structure is built. Outdoor temperatures of the prototype are tested. Temperatures of the solar cell and heat sink are stabilized with time continuing at about 37 °C–38 °C and 35 °C–36 °C respectively, slightly lower than the simulation results because of effects of the wind and cloud. Thus the simulation model enables to predict the thermal performance of the system, and the simulation results can be a reference for designing heat sinks in the field of single concentrator solar cells.

Keywords: heat sink, concentrator solar cell, thermal model, cooling

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1. Introduction

Concentrator photovoltaic (CPV) systems can lower cost by concentrating sunlight onto photovoltaic cells and replacing expensive photovoltaic areas with less expensive concentrating mirrors or lenses. A solar cell under concentration can obtain a higher conversion efficiency than a flat-plate solar cell (a typical efficiency value for a concentrator cell is 41.6% at 364 suns[1]). However when concentrated sunlight impinges onto a solar cell, only a fraction of solar power can be converted into electrical energy. The other larger fraction is converted into thermal energy which may induce the cells to reach a higher temperature unless the heat is efficiently dissipated to the ambient. The conversion efficiency (η), the open-circuit voltage (V_{oc}), and the fill factor (FF) of the solar cell will decrease with temperature increasing.[2,3] Previous work in our group has shown that the conversion efficiency of GaInP/GaAs/Ge tandem solar cells under one sun decreased from 28% to 22.1% when the solar cell's temperature increased from 30 °C to 130 °C,[4] and under 400X concentration with no cooling aid, the cell temperature could reach up to about 1200 °C,[5] which is deadly for the solar cell systems. Therefore heat rejection from the CPV system is indispensable.

Passive and active coolings are the two competing methods of removing heat from high illumination photovoltaic cells.[2,6] Passive cooling uses metal plates[7,8] or heat sinks[9,10] to dissipate heat from the solar cells to the ambient through radiation and convection. Active cooling[11,12] involves circulating cooling water through a thermally conductive tube on which the cells are mounted. Passive cooling has the advantage in cost efficiency over the active cooling.[2] For a single concentrator solar cell system, passive cooling with heat sink can suffice because of the very small size of the solar cell (just on the order of a few square millimeters).[13]

To design an efficient CPV system based on electrical conversion efficiency, the temperature levels of the CPV system must be estimated and minimized accordingly.[8] In order to do so, a theoretical heat transfer model is usually required for the designed system to investigate the temperature levels and performance of the system.[14] Heat sinks have been used in many CPV systems to dissipate heat,[9,10] however, temperature distribution of the CPV system and optimal designs for the heat sink were seldom reported.[15] In this research, a CPV system with a single solar cell and a multi-finned structure heat sink was simulated by the thermal analysis computational fluid dynamics (CFD) software — Icepak (Fluent Incorporated). Icepak is being increasingly used by many designers to predict the thermal performance of some electronic devices and systems, such as CPUs, etc.,[16–18] but seldom used in CPV systems. Such a tool can simplify and quickly resolve the thermal management problem of CPV solar cells and allow the designer to integrate thermal analysis into the design process.

In the present paper, a model of a single concentrator so-

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lar cell system is established and the Icepak software is used to simulate the temperature profiles by varying the number of fins, base thickness, fin height, fin thickness, and thermal resistance of the thermal conductive adhesive. According to the simulation results, an optimized structure of the heat sink is obtained. The heat sink is made in terms of the optimized structure, and a CPV prototype with the heat sink is fabricated. Temperatures of the cell and the heat sink are both simulated by Icepak and tested outdoors.

2. Thermal modeling

A single CPV model with a heat sink is built as shown in Fig. 1. In the model, a lens is designed to concentrate the sunlight onto the solar cell to increase the light density. The solar cell and the metal shell (Cu plate with radius of 1 cm and height of 1 mm) are adhered by highly thermally conductive and good electric conductive material. A heat sink made of aluminum (Al) with black paint on the surface is used for dissipating heat from the solar cell to the atmosphere.

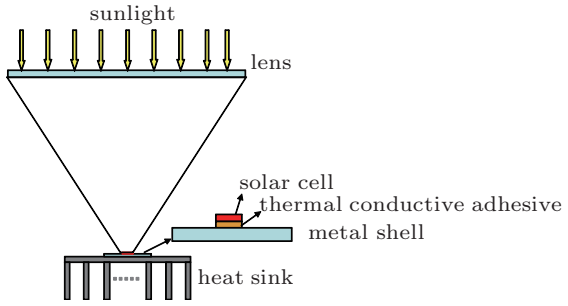


Fig. 1. (color online) Model illustration for single concentrator solar cell system with heat sinks.

Table 1. Initial parameters in the model.

Parameters	Parameters description	Value
C	geometric concentration ratio of lens	400
τ	transmissivity of lens	0.85
α	surface absorptivity of solar cells	0.85
q	energy density (AM1.5)	100 mW/cm^2
η	conversion efficiency of the solar cell (GaInP/GaAs/Ge triple solar cell)	28%
A_0	size of the solar cell	3 mm×3 mm×0.2 mm
	size of the metal shell	radius of 1 cm and height of 1 mm
k	heat conductivity	Cu 401 W/(mK)[19] Al 237 W/(mK)[19]
ε	surface emissivity of the metal plate	0.9 (black paint)[19]
h	natural convective transfer coefficient	5 W/(m^{2}K)
R	heat resistance of thermal conductive adhesive	10 °C/W
T_0	ambient temperature	30 °C

Icepak is used to predict the temperature profile of the CPV system. Initial parameters are shown in Table 1. The acceleration of gravity is set to simulate natural heat dissipation. The six surfaces of the cabinet are set as openings as shown in Fig. 2(a). On the basis of energy conservation law, a fraction of the concentrated sunlight absorbed by the cells is converted into electrical energy, and the other fraction is turned into the thermal energy which will be transported to the metal shell and the heat sink. Heat energy is simulated through the source which is mounted on the place of the solar cell with the same size. Considering scattering and absorbing by lens and solar cells, the energy Q in the source can be described as

$$Q = (1-\eta)C\tau\alpha q A_0, \tag{1}$$

where η is the conversion efficiency of the solar cell, C the geometric concentration ratio of concentrator lens, τ the transmissivity of lens, α the surface absorptivity of the cell, q the sun energy density (AM1.5), and A_0 the area of solar cell.

In the model, a coarse mesh is built in the cabinet, and a refined mesh is built in some important units such as the solar cell, metal shell, and base and fins of the heat sink. A grid-independent study is carried out and the optimum mesh size of the geometry is obtained with 65 thousands of hexahedral unstructured nodes. Figure 2(b) shows the mesh in a vertical plane cut passing through the middle of the central chip. The energy residual error is obtained with a convergence criterion of 10^{-7}. Temperatures of the solar cell and heat sink can be obtained through solving mass, momentum, and energy equations.

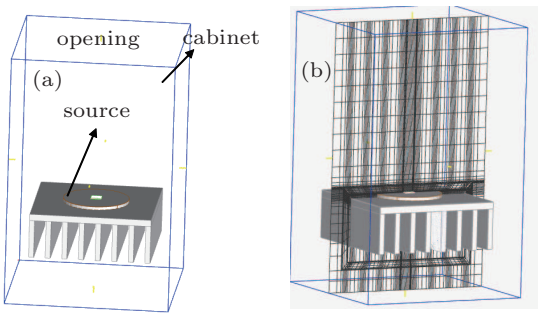


Fig. 2. Model illustrations in Icepak (a) and mesh (b) in a vertical plane cut.

3. Simulation results and discussion

In order to improve the heat dissipation from the solar cell, the structure of the heat sink should be optimally designed. To investigate the effects of the fin number on the heat spreading, the fin numbers are 2, 4, 6, 8, 10, and 12. Considering the cost and volume capacity of the system, the base thickness, height, and thickness of fins are designed to be 2 mm, 1.4 cm, and 1.5 mm, respectively. Figure 3 shows the temperature profiles of the solar cell and heat sink with the fin number of 8. The temperature of solar cell is 41.7 °C which can satisfy the requirements of the regular work. The difference between the highest and lowest temperature of the heat sink is about 0.4 °C which is lower than 1 °C, thus the average temperature is set as the temperature of the heat sink during the simulation.

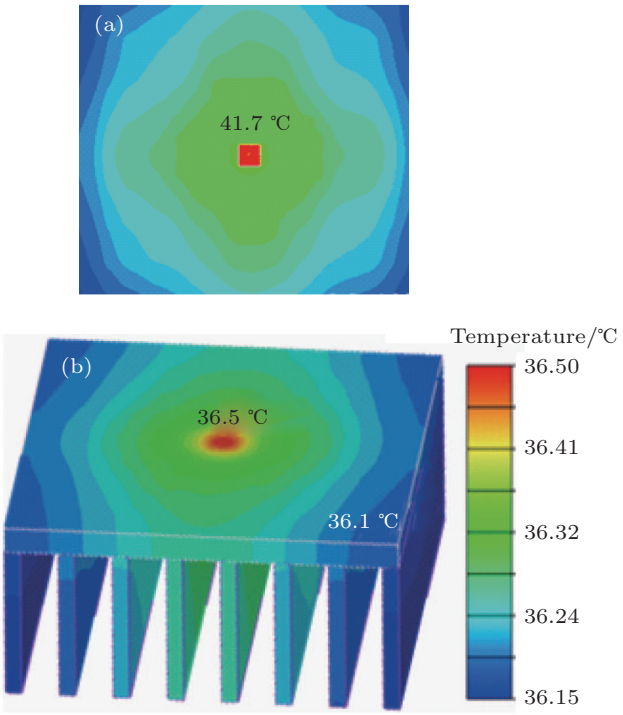


Fig. 3. (color online) Temperature profiles of solar cell (a) and heat sink (b).

Effects of the fin number on temperatures of the solar cell and heat sink are shown in Fig. 4(a). With fin number increasing from 2 to 8, temperatures of the solar cell and heat sink decrease gradually, and when the fin number is more than 8, their temperatures both increase instead. It indicates that when the surface of the heat sink does not satisfy the requirements for heat dissipation, it will worsen the heat performance, but overmuch on the number of fins will lead to smaller space for the air convection in the spacing. Therefore, during the design of the number of fins, the optimal number should be considered. In Fig. 4(a) we can see that the optimal number of fins is 8, which makes the temperatures of the solar cell and heat sink reduced to their lowest values.

In order to study of the influence of the thickness of the heat sink base on the heat dissipation of the CPV system, base thickness is changed into 1.5 mm, 2 mm, 3 mm, and 4 mm separately, with the number, height, and thickness of fins designed to be 8 (the optimal value), 1.4 cm, and 1.5 mm, respectively. Figure 4(b) shows the effects of the base thickness on temperatures of the solar cell and heat sink. We can see that temperatures of the solar cell and heat sink change slightly with base thickness increasing. The heat sink base should be thick enough to bear the component gravity, but too large a thickness will waste the material and impede the heat rejection.

In the permission of volume, fin height is usually increased to improve thermal dissipation. Effects of the fin height on the temperatures of the solar cell and heat sink are studied as shown in Fig. 4(c). Fin height is changed into 0.5 cm, 1.0 cm, 1.4 cm, 2 cm, and 3 cm separately. The fin number, fin thickness, and base thickness are designed to be 8 (the optimal value), 1.5 mm, and 2 mm (the optimal value), respectively. As shown in Fig. 4(c), temperatures of the solar cell and heat sink decrease with fin height increasing, and the reduction in rate slows down with the increase of fin height. Higher fins are helpful to increase the area for heat rejection, however, too high fins will need larger space to be held, thereby worsening the convection in the spacing, and causing the fins to fracture easily. Therefore, space holding and stress standing of the fins should be considered synthetically in actual design.

Fin thickness is often increased to improve the heat conducting. We study the effects of fin thickness on the temperatures of the solar cell and heat sink, and the results are shown in Fig. 4(d). The fin thickness is changed into 0.5 mm, 1.0 mm, 1.5 mm, 2 mm, and 4 mm separately. The fin number, fin height, and base thickness are designed to be 8 (the optimal value), 1.4 cm (volume permission), and 2 mm (the optimal value), respectively. In Fig. 4(d), the temperatures of the solar cell and heat sink change smoothly with fin thickness. During the practical design, too thin fins will be hard to fabricate, and too thick fins will increase the cost and weight of the system.

In order to see the simultaneous effects of fin number and fin thickness on the temperatures of the solar cell and the heat sink, simulation is carried out for the system based on both changes of fin number (4, 6, 8, 10, 12) and fin thickness (1, 1.5, 2 mm), and the results are shown in Fig. 5. There is an optimal thickness value of 1.5 mm for different numbers of fins and the most suitable number of fins of 8 for the lowest temperatures of the solar cell (Fig. 5(a)) and the heat sink (Fig. 5(b)), which is consistent with the analyses of Figs. 4(a) and 4(d).

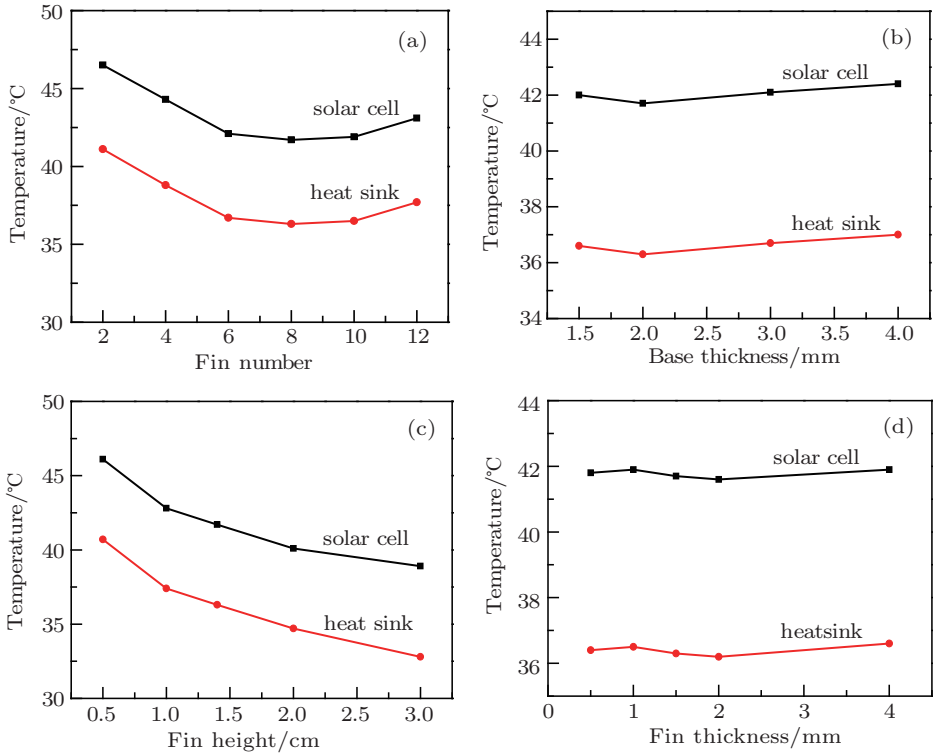


Fig. 4. (color online) Temperatures of the solar cell and heat sink versus (a) fin number, (b) base thickness, (c) fin height, and (d) fin thickness.

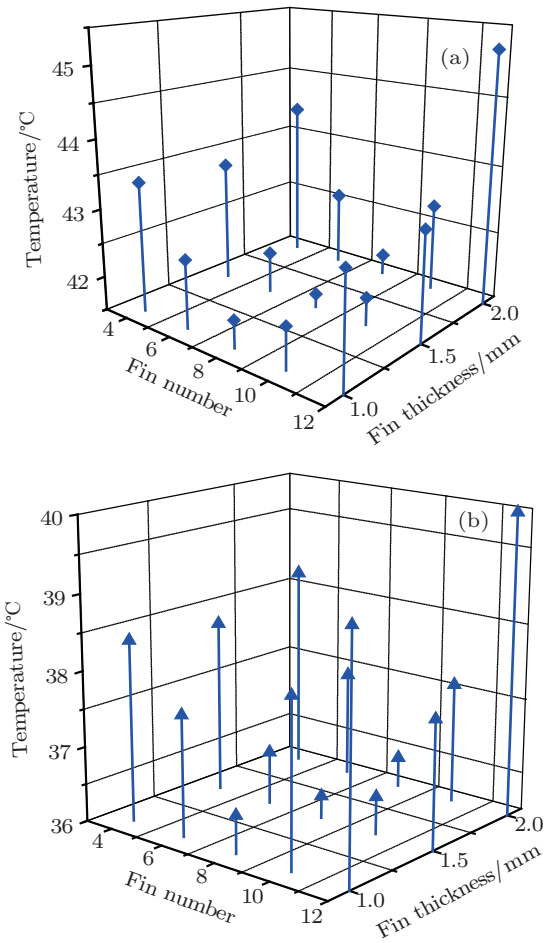


Fig. 5. (color online) Temperatures of the solar cell (a) and heat sink (b) against fin number and fin thickness.

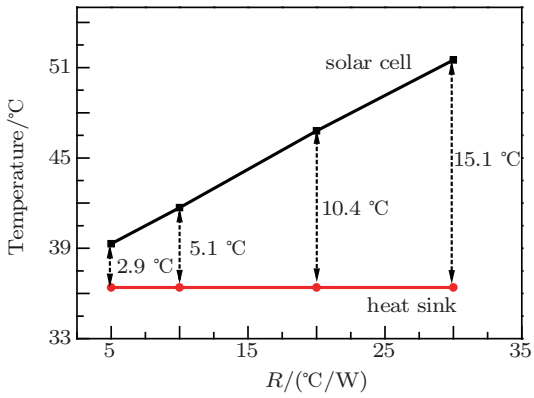


Fig. 6. (color online) Temperatures of the solar cell and heat sink against the heat resistance of thermal conductive adhesive.

The heat resistance of the thermal conductive adhesive between the cell and metal shell plays a big role in the heat dissipation, and the lower heat resistance is beneficial to heat rejection. The heat resistance of the thermal conductive adhesive is changed into 5 °C/W, 10 °C/W, 20 °C/W, and 30 °C/W separately. Structural parameters of the heat sink are set according to the optimal values and the practical volume. The fin number, fin height, and fin thickness, and the base thickness are designed to be 8 (the optimal value), 1.4 cm (volume permission), 1.5 mm (fabrication permission), and 2 mm (the optimal value), respectively. Figure 6 shows the effects of heat resistance of thermal conductive adhesive on the temperatures of the solar cell and heat sink, and the temperature of the solar cell increases linearly with heat resistance increasing. The

temperature of the heat sink is almost constant with the respect to the variation of heat resistance, which implies that the temperature on the heat sink just mainly depends on its structure and the ambient temperature.

4. Outdoor experimental results

A single cell CPV prototype based on Fig. 1 is fabricated. The solar cell (3 mm×3 mm) with the structure of GaInP/GaAs/Ge is grown on p-type Ge substrate using the metal–organic chemical vapor deposition (MOCVD) technique. The main precursors used to form the lattice layers for the solar cells are trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), arsine (AsH_3), and phosphine (PH_3) with growth temperatures typically ranging from 600 °C to 700 °C. The bottom Ge cell is formed by a thin layer diffused from p-Ge substrate. The middle GaAs cell (4 μm) connected to both the bottom Ge cell and the top GaInP cell (0.7 μm) with the tunnel junctions. A highly doped GaAs cap layer is fabricated on the top cell. For electrical evaluation purposes, Au/Ti is deposited on the GaAs cap layer using the photolithography technique. A conversion efficiency of 28% is obtained by the solar cell as shown in Fig. 7. Designs for the lens, thermal conductive adhesive, and metal shell are based on Table 1. The heat sink is carefully designed according to the simulation results (see Fig. 8). The fin number, fin height, fin thickness, and the base thickness are set to be 8 (the optimal value), 1.4 cm (volume permission), 1.5 mm (fabrication permission), and 2 mm (the optimal value), respectively. The heat sink is black, painted with a high-temperature durable paint.

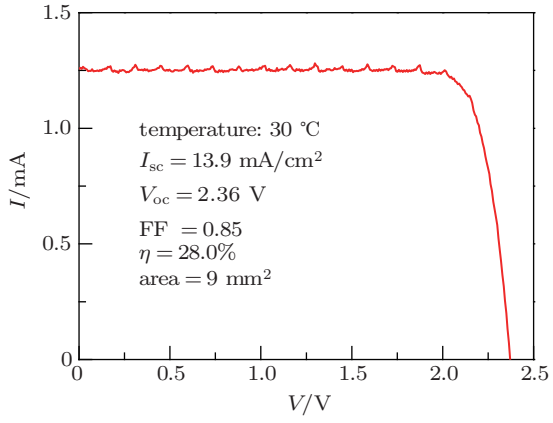


Fig. 7. (color online) *I*–*V* curves for the GaInP/GaAs/Ge solar cell.

The temperatures on the solar cell and heat sink of CPV prototype were tested outside in summer at noon with thin clouds and weak winds. Temperatures were monitored using two sheet temperature sensors (Pt100) each with an accuracy of 1 °C. The two sensors were mounted on the upper surfaces of the solar cell and heat sink respectively. The CPV prototype was tracked with the sun during the test course. Figure 9 shows the temperature test results of the solar cell with 37 °C–38 °C and heat sink with 35 °C–36 °C, respectively. A comparison between the simulation results of 41.7 °C (heat sink) and 36.3 °C (solar cell) shows that there is a very smaller difference in heat sink temperature between the simulation and the test result but there is a slightly bigger difference in solar cell temperature, which can be explained to be due to the outdoor test conditions. Firstly, thin clouds cannot be ignored when temperature test is carried out outdoors, which can make the density of sun energy falling onto the solar cell lower than the simulated one of 100 mW/cm^2 (AM1.5), therefore outdoor tested temperatures of the solar cell and the heat sink will be lower than the simulated ones. Secondly, wind in the air cannot be neglected which can accelerate heat dissipation to the air through forced convection. According to the Newton's law, the heat energy transferred by convection is proportional to the temperature difference,[20] which can be described in detail as

$$\phi_s = h \cdot \mathrm{d}s \cdot (T - T_0), \tag{2}$$

where ϕ_s is the heat energy dissipated through convection per unit area, h the convective transfer coefficient, ds the heat convection per unit area, T the temperature of the warmer body, T_0 the ambient temperature, and T–T_0 the temperature difference. Temperature difference of the solar cell is larger than that of heat sink, so more heat energy of the solar cell can be dissipated by winds,[8] which can account for the slightly bigger temperature difference between the simulated and the test result for the case of solar cell.

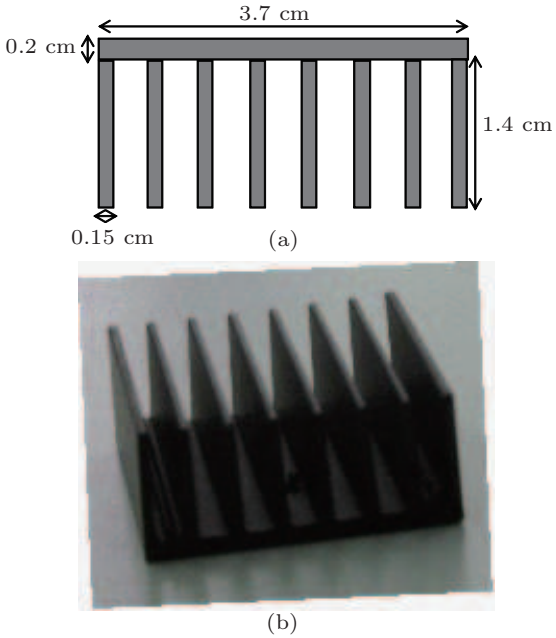


Fig. 8. (a) Schematic diagram of optimal structure and (b) photo of the heat sink.

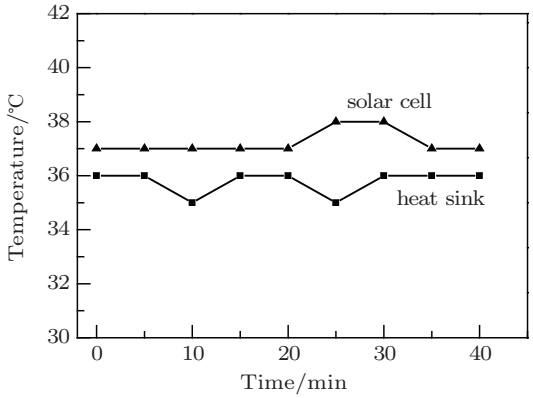


Fig. 9. Temperature test results of the solar cell and heat sink.

5. Conclusions

A single concentrator solar cell model with a heat sink is established to simulate the cooling performance for the system by varying the fin number, fin height, fin thickness, base thickness, and thermal resistance of the thermal conductive adhesive. With fin number and base thickness increasing, the temperatures of the solar cell and heat sink first decrease and then increase, with an optimal fin number and a base thickness being for the lowest temperature. Temperatures of the solar cell and heat sink decrease with fin height increasing and change smoothly with fin thickness increasing. Meanwhile, with the increase of heat resistance of the thermal conductive adhesive between the solar cell and metal shell, temperature of the solar cell increases linearly, and the temperature of the heat sink is almost constant with heat resistance increasing. According to influence disciplines of those parameters an optimized structure of the heat sink is obtained, in which the solar cell and heat sink can reach their lowest temperatures of 41.7 °C and 36.3 °C, respectively.

A CPV prototype with the optimized structural heat sink is built. Outdoor temperatures for the CPV prototype are tested. With time continuing, temperatures on the solar cell and heat sink are stabilized at about 37 °C–38 °C and 35 °C–36 °C, slightly lower than the simulation results because of the wind and cloud, showing that the measured temperature is well predicted by our model. The results of this work are significant for designing the heat sinks in the field of single concentrator solar cells.

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