Experimental investigation of performance for the novel flat plate solar collector with micro-channel heat pipe array (MHPA-FPC)

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**HIGHLIGHTS**

- A novel flat plate solar collector with micro-channel heat pipe array is proposed.
- MHPA has excellent thermal respond speed and isothermal ability.
- The experimental value of $F_{\text{RD}}(t_0)$ and $F_{\text{dUR}}$ are 0.80 and 4.72, respectively.
- Instantaneous efficiency of MHPA-FPC is compared to other collectors.
- Experiments and comparisons show that MHPA-FPC has excellent thermal performance.

**ABSTRACT**

A novel flat plate solar collector with micro-channel heat pipe array (MHPA-FPC) is presented in this paper. Firstly, a preliminary test was conducted to investigate the thermal performance of the MHPA. It has been found that the surface temperature along the length of MHPA can get stable within 2 min. The temperature difference between the evaporator and condenser sections was less than 1°C, which indicates that the MHPA has excellent isothermal ability and quick thermal respond speed. Based on these advantages, the MHPA was applied to the development of a novel solar collector. The performance test was conducted following the Chinese standard GB/T4271-2007, and a linear correlation between the instantaneous efficiency $\eta$ and the reduced temperature parameter $(T_{\text{sw}}-T_0)/T_0$ was established. The maximum instantaneous efficiency was found to be 80%, and the slope was –4.72. These values are 11.4% and 21.3% superior to the technical required values of the Chinese national standard. Test results were further compared with 6 groups of 15 samples coming either from either open literature or commercial products. The comparisons indicated that the maximum instantaneous efficiency of the MHPA-FPC surpassed 25% over the average level of those selected samples and better thermal insulation ability was presented by the MHPA-FPC. These results from this study demonstrate that the novel MHPA-FPC is one of the top level solar collectors among the current products.

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1. Introduction

Solar energy is a widely used renewable energy for the human beings. The earth receives around 1 x 1018 kWh of solar energy every year [1]. Currently, one of the most accepted ways of utilizing solar energy is solar water heating (SWH), and its key component is solar collectors.

Nowadays, among different types of solar collectors, flat plate solar collectors (FPC) and evacuated tube solar collectors (ETC) are popularly applied in real applications. These two typical types of solar collectors could be further classified into different styles. In Table 1, the advantages and disadvantages of the current FPC and the ETC are listed. The ETC performs better than the FPC in high-temperature operation, because the vacuum envelope around the absorber surface reduces convection heat loss. However, it also has some shortcomings, such as glass tube explosions, scaling, low compressive strength, difficulty in integrating with buildings and so on. On the other hand, conventional FPC has higher efficiency in low-and-medium temperature operation due to higher ratio of absorber area to aperture area. In addition, there are also some problems, such as freezing, water corrosion, high requirement for
welding. Therefore, a novel solar collector should be developed to keep the good performances and overcome the deficiencies of existing solar collectors.

Heat pipe (HP) is an excellent heat transfer component, and it has been applied to solar collectors. The first study of the HP-FPC was reported by Bienert and Wolf [2]. Since then, numerous studies have been carried out. Some studies focused on the heat pipe heat transfer characteristics while applying in the FPC. Lu et al. [3] investigated the fundamental thermal performance of the HP in the FPC, and the optimum liquid filling ratio was found to be 25%. Chun et al. [4] developed a domestic SHW using heat pipes. The presence of a wick, working fluids, and some other major design parameters were examined. By experiments, Samuel and Sergio [5] analyzed the effects of evaporator length, filling ratio, cooling temperature and slope on the performance of two-phase closed thermosyphons SHW systems. Esen, M. and Esen, H [6]. investigated the effects of different refrigerants on the thermal performance of a two-phase closed thermosyphons. Some studies have shown great interest in improving the thermal performance of various geometries of the HP-FPC. Emmanouil and Vassilis [8] investigated the performance of a new SHW system with an integrated wickless gravity assisted loop HP solar collector. The wickless HP-FPC has been studied through theoretical analysis and experiment [9—12]. Optimal studies have also been carried out to improve the collector efficiency. Rittidech and Wannapakne [13] investigated the performance of a solar collector with closed-end oscillating HP by experiment, and the results showed that the collector’s maximum efficiency was about 62%. Azad [14] developed a theoretical model based on the effectiveness-NTU method for evaluating the thermal efficiency of the gravity assisted HP-FPC and the modeling predictions were validated by experimental data. Azad [15] tested three different types of HP-FPC, and compared their instantaneous efficiency. Lan et al. [16] put forward a theoretical model to analyze and discuss the influences of relevant parameters on the thermal performance of HP-FPC.

Table 1
Characteristics of different kinds of solar collectors.

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC</td>
<td>Higher efficiency in low-and-medium temperature operation; Reliable; Cost-effective; Easy integrated with the building.</td>
<td>Frozen; Scaling; Technical complexity in welding.</td>
</tr>
<tr>
<td>ETC All-glass</td>
<td>Anti-frozen; Easy integrated with the building; Quick start-up.</td>
<td>Scaling; High cost; Technical complexity in manufacturing.</td>
</tr>
<tr>
<td>HP-ETC</td>
<td>Anti-frozen; Less heat loss; Quick start-up.</td>
<td>High cost; Low efficiency; Difficult integrated with the building.</td>
</tr>
<tr>
<td>U-shaped ETC</td>
<td>Higher bearing pressure; Reliable; Less heat loss.</td>
<td>Scaling; Difficult integrated with the building.</td>
</tr>
</tbody>
</table>

Greek symbols

\[ \eta \] instantaneous solar collector efficiency
\[ \tau \] transmittance of glass cover
\[ \alpha \] absorbance of absorber plate
\[ \Delta \] test uncertainty

Abbreviations

MHPA micro-channel heat pipe array
FPC flat plate solar collector
MHPA-FPC flat plate solar collector with micro-channel heat pipe array
ETC evacuated tube solar collector
SWH solar water heating
HP Heat pipe
SHU single honeycomb unit
DHU double honeycomb unit

1) As it uses circular copper heat pipes, higher cost and technical complexity in manufacturing could be expected.
2) As circular shape heat pipe has smaller contract area, its contract thermal resistance is larger.
3) As it consists of circular heat pipes and aluminum fins, the heat transfer is affect by the fin efficiency.
4) As the condenser section of heat pipes is directly in contact with the water, scaling is inevitable.

To overcome these problems, a novel type of flat plate heat pipe, referred as micro-channel heat pipe array (MHPA), was developed by Zhao et al. [17], and this product has been applied in the FPC. In this paper, the results of both preliminary tests and performance tests are introduced. The preliminary test is used to verify the thermal performance of the novel MHPA, and the purpose of the performance test is to establish the linear relation between the instantaneous efficiency \( \eta \) and the reduced temperature parameter \( (T_{hi}-T_{o})/I \). The tested performance of the MHPA-FPC is further compared with 6 groups of 15 samples, chosen from either open literature or commercial products.

2. MHPA

2.1. Characteristics

The MHPA is a high efficiency heat transfer unit, relying on a phase transition of the working liquid to transport large amount
of heat. The MHPA looks like a thin aluminum plate, which contains many independent micro-channel heat pipes. In each micro-channel heat pipe, there are many inner micro-grooves (or micro-fins) to enhance the heat transfer. For each MHPA, there are two parts: evaporator section and condenser section. As the MHPA proposed in this paper is made of aluminum, it is easily manufactured and can be bent into different shape. The images of the MHPA are shown in Fig. 1a. In Fig. 1b, the physical structure of MHPA is shown. The typical size of an MHPA is 3 mm in thickness and 60 mm in width. The length can be determined according to the demand of particular applications.

As shown in Fig. 2, the working principle of MHPA is as follows,

1) When the outer surface of evaporator section is heated, the aluminum clapboards between the micro-channel heat pipes perform good thermal conduction and transfer a part of heat from the heating surface to the opposite inner surface with micro grooves and fins, so the phase transition takes place at peripheral surface throughout the micro-channel heat pipe. As shown in Fig. 3a, the working fluid inside the micro groove of evaporator section forms meniscus under capillary force. The evaporating meniscus, which can be classified into an equilibrium thin-film, an evaporating thin-film, and an intrinsic meniscus, are formed as a liquid wets a heater wall. The low thermal resistance across the evaporating thin-film makes high heat flux possible even at lower degree of wall superheat [18]. Hence, evaporation mainly occurs in the evaporating thin-film region at menisci.

2) The working fluid within evaporator section evaporates to saturated vapor at the liquid–vapor interface, and then flows upward from evaporator section to the condenser section under the pressure difference.

3) In the condenser section, the vapor condenses and forms liquid film on the inner surface of the condenser section. As shown in Fig. 3b, the condensate flows from the micro fin top to the micro groove by surface tension, which makes condensing liquid film on the micro fin top spread out to the larger surface, thus the heat transfer through condensing liquid film is enhanced with decreasing of the liquid film thickness. The condensing liquid film at the micro grooves is composed of the vapor condensing at the micro grooves and the condensate flowing from the micro fins. Finally, heat transfers through vapor–liquid interface, condensing liquid film, internal surface of condenser section, and then the outer surface of condenser section to the cold source by heat conduction.

4) The condensing liquid film at the micro grooves returns to the evaporator section liquid pool timely by gravity and capillary force. The cycle makes heat transfer from evaporator section to the condenser section of the MHPA.

![Fig. 1. The schematic of the MHPA.](image)

![Fig. 2. The schematic diagram of working principle for the MHPA.](image)

Owing to the special structure, the MHPA has the following advantages,

1) **High heat transfer performance.** The micro grooves and micro fins inside each micro-channel heat pipe could increase heat exchange areas, which enhance the heat transfer ability. More importantly, as there are a large number of thin-films in the micro grooves, the phase-change heat transfer performance is greatly improved for both evaporation and condensation.

2) **High reliability.** As each micro-channel heat pipe works independently, the failure of a single micro-channel heat pipe has little influence on the whole MHPA.

3) **High compressive strength.** The clapboards between two adjacent micro-channel heat pipes work as a support for the MHPA and the hydraulic diameter of each micro-channel heat pipe is only 0.4—1.0 mm. Therefore, the MHPA has an acceptable compressive strength, which can be up to 10.0 MPa.

4) **Low cost.** MHPA is made of aluminum, which is much cheaper than copper. And the processing technique can be easily achieved. Therefore, the initial cost of the MHPA is quite acceptable.

5) **Small contact thermal resistance.** MHPA is a thin metal plate, whose outer surface can contact easily with the heat exchanger area. Therefore, it can reduce largely the contact thermal resistance at two interfaces due to larger contact area compared with the circular heat pipes.
2.2. Preliminary tests of the MHPA

To verify the thermal performance of the proposed MHPA, a preliminary test was conducted. The testing system and the testing results are shown in Fig. 4. The dimensions of the tested MHPA are $930 \times 60 \times 3$ mm ($L \times W \times T$). According to the practical range of operating temperature for a solar collector, acetone is selected as the working fluid inside the MHPA, with a filling ratio of 20%. The vacuum degree is kept at $10^{-04}$ Pa. In the experiment, the evaporator section was inserted into a thermostatic water bath, and the working conditions were maintained at $60 \degreeC$ and $90 \degreeC$, respectively. The condenser section was cooled by natural convection in the indoor environment ($T_a$ is $20 \degreeC$). Five T-type thermocouples (accuracy of $\pm 0.15 \degreeC$) were installed along the MHPA with a space of 150 mm from the bottom to the top. A data logger was used to collect the testing data.

The testing results are shown in Fig. 4b. It demonstrates the instant temperature variations along the MHPA. It could be found that the response time of the MHPA is less than 2 min in different testing positions. These results reflect that the MHPA has a very quick thermal respond speed. In addition, the temperature difference from the evaporator section to the condenser section along a 930 mm long heat pipe is found to be only $1 \degreeC$. This means the isothermal characteristic of MHPA is satisfied. These testing results provide a strong support to verify the agreeable thermal performance of the MHPA. Therefore, the MHPA is a high performance heat transfer unit, and it can be widely applied in the heat transfer process.

3. MHPA-FPC

Owing to the distinctive advantages, the MHPA acts as a basic heat transfer unit for the novel type of FPC, which is called flat plate solar collector with micro-channel heat pipe array, MHPA-FPC. The structure of the novel MHPA-FPC is shown in Fig. 5. The MHPA-FPC is typically installed at a tilt angle (local latitude $\pm 5 \degree$) to achieve maximum annual solar irradiance. This arrangement also ensures the condenser section of MHPA is always located over the evaporator section. So the condensate can easily return to the liquid pool in the evaporator section by gravity and capillary force. The dimension of this collector is $2000 \times 1000 \times 90$ mm ($L \times W \times T$). The top of the collector is covered by the tempered glass with a thickness of 3.2 mm. The transmittance for solar energy is 92% and the absorbability is 5%. Below the tempered glass, there is a 30 mm air
The absorber plate is made of aluminum with a thickness of 0.4 mm, and covered by a highly selective energy absorbing film. The film absorbs 95% of incident solar radiation and converts it into heat, losing only 5% of the captured solar energy as heat radiation. Under the absorber plate, 17 MHPAs are arranged in a line. For each MHPA, the evaporator section is 830 mm in length, and the condenser section is 100 mm in length. The condenser section of MHPA is contacted with a heat exchanger, which is specially designed. To reduce the contact thermal resistance, one of the surfaces of the heat exchanger is made in a flat plate shape. In the center of the heat exchanger, there is a water tube with an inner diameter of 24.5 mm. As the water tube is smooth and straight, it has the minimal hydraulic resistance. A 50 mm polyurethane insulator is attached underneath the MHPAs and the heat exchanger. When the solar collector is in use, the MHPAs are used to transfer the heat absorbed by the absorber plate to the water inside the heat exchanger through the phase change of the working fluid inside the MHPA.

In this MHPA-FPC, the MHPA is able to provide higher effective heat transfer due to larger contact area with absorber plate than that of circular heat pipes. The use of aluminum instead of copper helps to reduce the cost of the system significantly. Additionally, conductive silicone is used for the combination of MHPA and absorber plate without welding. Moreover, the condenser section of the MHPA is connected closely to the heat exchanger with dry type. The heat pipes will not in contact with the water, thus precluding scaling. Therefore, compared with the conventional HP-FPC, great improvements can be achieved by the novel developed MHPA-FPC, such as high reliability, high compressive strength, low hydraulic resistance, low cost, ease of assembling and no-scaling.

4. Experimental study

4.1. Experimental system

The experimental system is shown in Fig. 6. The tested MHPA-FPC was installed and tested under the actual meteorological conditions of Beijing (latitude 39.9° N; longitude 116.46° E), China. It was installed at a 45° tilt angle facing south. The information about the instruments applied in this study is presented in Table 2. All testing instruments have been calibrated before the test. The most concerned parameters included inlet and outlet water temperatures \( T_{\text{i}} \), \( T_{\text{o}} \), water flow rate \( m_{\text{w}} \), solar irradiance \( I \), ambient air temperature \( T_{\text{a}} \), and wind velocity \( v \). Two Pt 100 thermal resistors were utilized to measure \( T_{\text{i}}, T_{\text{o}} \). Another thermal resistor was used to measure \( T_{\text{a}} \). The global pyranometer together with the anemometer were mounted beside the MHPA-FPC, and parallel to the collector. A turbine flow meter was used to measure \( m_{\text{w}} \). The thermostatic tank was used as a cooling source to supply stable
water temperature to the MHPA-FPC. The cooling water temperature could be automatically controlled with an accuracy of \( \pm 0.1 \, ^\circ C \) in the range of 5–95 ℃. The required water temperature could be achieved within 10 min. All testing data were automatically monitored and collected by a data logger.

### 4.2. Test conditions and procedures

In this study, performance tests were conducted following the Chinese standard GB/T4271-2007 [19]. As it is normally conducted on-site, the test conditions cannot be controlled. The test conditions and permitted deviations for the steady-state tests are listed in Table 3. Because of the weather change in a day, experiments were performed in several days and the experimental data conformed to the requirements were chosen for the analysis.

The required testing procedures are listed as follows,

1) Start experiment, set the thermostatic tank temperature with a required temperature value.
2) Record testing data when the parameters meet the requirement of steady-state conditions. The test period for a steady state data shall include a pre-conditioning period of at least 12 min and the test period for a steady state data point shall be at least 3 min.
3) Change the thermostatic tank temperature for the next testing round when one inlet water temperature data is completed.

### 4.3. Data reduction

Based on the measured values for the \( T_{wo} \), \( T_{wi} \) and \( m_{iw} \) the useful energy gain of the MHPA-FPC from the water side could be calculated:

\[
Q_{u} = m_{iw}C_w(T_{wo} - T_{wi})
\]  

(1)

The useful energy gain of the MHPA-FPC could also be obtained from the solar collector side:

\[
Q_{u} = A_C F_R [I(\tau a)_e - U_L(T_{wi} - T_a)]
\]  

(2)

The instantaneous solar collector efficiency is defined as:

\[
\eta = \frac{Q_u}{A_C} = \frac{m_{iw}C_w(T_{wo} - T_{wi})}{A_C} \]  

(3)

By Eq. (2), the instantaneous solar collector efficiency under steady-state conditions can be written as [20]:

\[
\eta = \frac{Q_u}{A_C} = \frac{A_C F_R [I(\tau a)_e - U_L(T_{wi} - T_a)]}{A_C} = F_R(\tau a)_e - F_R U_L(T_{wi} - T_a) \]

(4)

where \( m_{iw} \) is the flow rate of water, \( \text{kg s}^{-1} \); \( C_w \) is the specific heat of water, \( \text{J kg}^{-1} \text{K}^{-1} \); \( T_{wo} \) is the temperature of water at the collector outlet, °C; \( T_{wi} \) is the temperature of the water at the collector inlet, °C; \( I \) is the solar radiation intensity, \( \text{W m}^{-2} \); \( A_C \) is the aperture area, \( \text{m}^2 \); \( (\tau a)_e \) is the collector effective transmittance-absorptance product; \( F_R \) is the heat removal factor; \( U_L \) is the heat loss coefficient, \( \text{W (m}^2 \text{K})^{-1} \).

If the tests are performed at near the normal incidence conditions, the \( F_R(\tau a)_e \) and \( U_L \) are constant within the range of testing temperatures. Under this condition, Eq. (4) indicates that \( \eta \) can be represented by a linear relation with the measuring parameters

### Table 3

<table>
<thead>
<tr>
<th>Test parameters</th>
<th>Required conditions</th>
<th>Permitted deviations</th>
<th>Average test conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar irradiance</td>
<td>( &gt; 700 \text{ W m}^{-2} )</td>
<td>( \pm 50 \text{ W m}^{-2} )</td>
<td>800 W m(^{-2})</td>
</tr>
<tr>
<td>Ambient air temperature</td>
<td>–</td>
<td>( \pm 1 , ^\circ C )</td>
<td>34.1–35.1 ℃</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>( 0.02 \text{ kg (m}^2 \text{s})^{-1} )</td>
<td>( \pm 1% )</td>
<td>0.137–0.138 kg s(^{-1})</td>
</tr>
<tr>
<td>Inlet water temperature</td>
<td>At least four ( T_{wi} ) points spaced evenly over the operating temperature range</td>
<td>( \pm 0.1% )</td>
<td>Six points in the range of 36–62 ℃</td>
</tr>
<tr>
<td>Ambient air velocity</td>
<td>( 2–4 \text{ m s}^{-1} )</td>
<td>–</td>
<td>( 2–4 \text{ m s}^{-1} )</td>
</tr>
</tbody>
</table>

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**Table 2** Information about the experiment instruments.

<table>
<thead>
<tr>
<th>Device</th>
<th>Number</th>
<th>Accuracy</th>
<th>Full scale</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermostatic tank</td>
<td>1</td>
<td>( \pm 0.1 , ^\circ C )</td>
<td>(-10 \text{ to } 99 , ^\circ C )</td>
<td>DTY-30A</td>
</tr>
<tr>
<td>Inlet temperature sensor</td>
<td>1</td>
<td>( \pm 0.1 , ^\circ C )</td>
<td>(0 \text{ to } 400 , ^\circ C )</td>
<td>P1100</td>
</tr>
<tr>
<td>Outlet temperature sensor</td>
<td>1</td>
<td>( \pm 0.1 , ^\circ C )</td>
<td>(-20 \text{ to } 80 , ^\circ C )</td>
<td>P1100</td>
</tr>
<tr>
<td>Ambient air temperature sensor</td>
<td>1</td>
<td>( \pm 2% )</td>
<td>(0 \text{ to } 2000 \text{ m}^2 \text{ h}^{-1} )</td>
<td>TRT-2</td>
</tr>
<tr>
<td>Global pyranometer</td>
<td>1</td>
<td>( \pm 0.5% )</td>
<td>(0 \text{ to } 9 \text{ m}^3 \text{ h}^{-1} )</td>
<td>LWGY–20C</td>
</tr>
<tr>
<td>Flow meter</td>
<td>1</td>
<td>( \pm 0.3 \text{ m s}^{-1} )</td>
<td>(0.05 \text{ to } 30 \text{ m s}^{-1} )</td>
<td>WS–95</td>
</tr>
<tr>
<td>Anemometer</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The intercept of the efficiency line with the y-axis represent the product \(F_0(\alpha)\), which is the maximal efficiency for the solar collector. The slope of the efficiency line represents \(-F_0U_s\), which indicates the total heat loss factor for the solar collector. High intercept and small slope mean that the collector has good thermal efficiency in the practical conditions.

### 4.4. Uncertainty analysis

The direct testing parameters include \(m_w\), \(T_{wo}\), \(T_{wi}\) and \(I\). The testing accuracies of these parameters are listed in Table 2. The uncertainty of \(\eta\) can be determined by Eq. (5).

\[
(\Delta\eta)_{\text{overall}} = \sqrt{\left(\frac{\partial\eta}{\partial m_w} \Delta m_w\right)^2 + \left(\frac{\partial\eta}{\partial T_{wo}} \Delta T_{wo}\right)^2 + \left(\frac{\partial\eta}{\partial T_{wi}} \Delta T_{wi}\right)^2 + \left(\frac{\partial\eta}{\partial I} \Delta I\right)^2}
\]

where \(\Delta\eta\), \(\Delta m_w\), \(\Delta T_{wo}\), \(\Delta T_{wi}\), and \(\Delta I\) are the uncertainty of \(\eta\), \(m_w\), \(T_{wo}\), \(T_{wi}\) and \(I\) respectively.

### 5. Results and discussion

#### 5.1. Experimental results and discussions of MHPA-FPC

The experimental instantaneous efficiency curves are presented in Fig. 7. On the basis of uncertainty analysis, the maximum uncertainty of experimental result is found to be 5.7%. The linear relation between \(\eta\) and \((T_{wi} - T_o)I^{-1}\) is achieved as below,

\[
\eta = 0.80 - 4.72\left(\frac{T_{wi} - T_o}{I}\right)
\]

The experimental value of \(F_0(\alpha)\) is 0.80, and the value of \(F_0U_s\) is 4.72. According to the Chinese standard GB/T6424-2007 [21], the value of \(F_0(\alpha)\) should be no less than 0.72 and the values of \(F_0U_s\) shall be no more than 6.0. The testing results in this study indicate that the \(F_0(\alpha)\) is 11.4% higher, and the \(F_0U_s\) is 21.3% lower than the required value. This agreeable performance can be attributed to excellent MHPA characteristics, including agreeable isothermal ability and quick thermal response speed. Due to the excellent isothermal characteristic of the MHPA, the absorber plate has uniform temperature field so that the heat loss by natural convection is reduced, thus the MHPA-FPC has relatively low heat loss factor. In addition, high transmittance of the glass cover, good absorption and low emissivity of the absorber film also help to improve the efficiency.

#### 5.2. Performance comparison

The performance of the tested MHPA-FPC is further compared with 6 groups of totally 15 samples coming from either open literature or commercial products. These 6 groups respectively represent different types of collectors, including the HP-FPC (G-1, G-2), U-tube ETC (G-3), HP-ETC (G-4), and conventional FPC (G-5, G-6). Specifications of the contrasted groups are listed in Table 4.

![Fig. 7. Experimental instantaneous efficiency curve of the MHPA-FPC.](image)

**Table 4** Specifications of contrasted samples.

<table>
<thead>
<tr>
<th>Group</th>
<th>Type</th>
<th>Author</th>
<th>Source</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-1</td>
<td>HP-FPC</td>
<td>E. Azad</td>
<td>Renewable and Sustainable</td>
<td>1) FPC with circular heat pipes \</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3) Three different condenser designs FPC with \</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>circular copper heat pipes \</td>
</tr>
<tr>
<td>G-2</td>
<td>HP-FPC</td>
<td>Hussein et al.</td>
<td>Energy Conversion and</td>
<td>1) Copper fin between absorber and U-tube. \</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Management 48 [12]</td>
<td>2) Filling layer inside absorber \</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heat pipes inside evacuated tube \</td>
</tr>
<tr>
<td>G-3</td>
<td>ETC</td>
<td>Liang Ruobing</td>
<td>Solar Energy 85 [22]</td>
<td>1) Copper fin between absorber and U-tube. \</td>
</tr>
<tr>
<td></td>
<td></td>
<td>et al.</td>
<td></td>
<td>2) Filling layer inside absorber \</td>
</tr>
<tr>
<td>G-4</td>
<td>HP-ETC</td>
<td>Farzad and</td>
<td>Journal of Renewable and</td>
<td>1) Filling layer inside absorber \</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hossein</td>
<td>Sustainable Energy 4 [23]</td>
<td>Heat pipes inside evacuated tube \</td>
</tr>
<tr>
<td>G-5</td>
<td>FPC</td>
<td>Abdullah et al.</td>
<td>Energy Conversion and</td>
<td>Different honeycomb arrangements in air gap \</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Management 44 [24]</td>
<td></td>
</tr>
<tr>
<td>G-6</td>
<td>FPC</td>
<td>-</td>
<td>Commercial products from</td>
<td>Sheet-tube collectors with copper absorber \</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>three different companies</td>
<td></td>
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Group 3 is ETC type of collectors. Two products are developed and tested for group 3. In the first one, copper fins between absorber and U-tube are applied. In the second one, graphite component with the thermal conductivity of 100 W m K$^{-1}$ is filled inside the absorber. From Fig. 8c), the FR$^{(sa)}$ values of these two products are 0.69 and 0.77, respectively. The average value is 0.73, which is 9.0% lower than MHPA-FPC. The FRUL values are found to be 1.92, and 1.38. The average value is 1.65, which is superior to MHPA-FPC. It is found that when the value of \((T_{\text{a}} - T_{\text{b}}) I^{-1}\) is higher than 0.01 K m$^2$ W$^{-1}$, the instantaneous efficiency of group 3 with filled graphite component exceeds the value of MHPA-FPC, while the \((T_{\text{a}} - T_{\text{b}}) I^{-1}\) reaches 0.04 K m$^2$ W$^{-1}$, the instantaneous efficiency of group 3 with copper fins exceeds the value of MHPA-FPC.

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This is because ETC type collectors usually have a better thermal insulation characteristic than the FPC.

Group 4 is an HP-ETC type collector, which put heat pipes inside the evacuated tube. From Fig. 8d), the value of FR$^{(sa)}$ is 0.55, which is 31.4% lower than the MHPA-FPC. With the similar reason as group 3, the FRUL value is superior to MHPA-FPC. However, in the typical working range of solar collectors, the instantaneous efficiency of MHPA-FPC is about 50% higher than group 4.

Group 5 is an FPC type collector. Totally, three products, without honeycomb, with single honeycomb unit (SHU) or double honeycomb units (DHU) are tested. From Fig. 8e), FR$^{(sa)}$ values of group 5 are 0.68 for the FPC without honeycomb, 0.57 for SHU and 0.46 for DHU. Correspondingly, FRUL values are 7.75, 3.76 and 3.46.

Fig. 8. Performance comparison with different groups.
MHPA-FPC, especially for the ETC type collectors. However, the totaling 7 samples have better thermal insulation ability than the samples are presented in Fig. 9. It is shown that the merits that surpass the current sheet-tube FPC, such as anti-frozen and no-scale.

The performance of MHPA-FPC has some other advantages in thermal performance, the MHPA-FPC has some other merits that surpass the current sheet-tube FPC, such as anti-frozen and no-scale.

Comprehensive comparisons of MHPA-FPC with 6 groups of 15 samples are presented in Fig. 9. It is shown that the $F_{\alpha}(\alpha)e$ value of MHPA-FPC is the best one among selected samples. A superiority of 25% has been identified. The results indicate that the MHPA-FPC has an agreeable solar energy absorbing ability. For the $F_{\alpha}U_{s}$ value, totaling 7 samples have better thermal insulation ability than the MHPA-FPC, especially for the ETC type collectors. However, the $F_{a}U_{L}$ value of MHPA-FPC is still lower than the average level of 15 samples.

In general, comparison results confirm the fact that the novel MHPA-FPC is one of the top level solar collectors with favorable thermal performance among the current products.

### 6. Conclusions

A novel MHPA-FPC is introduced in this paper. The thermal properties of the MHPA and MHPA-FPC are tested. The results are summarized as follows.

1) The experimental results of the MHPA show that the temperature difference between the evaporator and condenser sections is less than 1 °C, and the start-up time of the MHPA is less than 2 min. It indicates that the MHPA has excellent thermal performance, including quick thermal respond speed and agreeable isothermal ability.

2) A performance test is conducted following the Chinese standard GB/T14271-2007. A linear relation between the instantaneous efficiency and the reduced temperature parameter $(T_{evap} - T_{cond})^{-0.1}$ is established. The maximum instantaneous efficiency is found to be 80%, and the slope is $-4.72$. These values are 11.4% and 21.3% superior to the technical required value in Chinese national standard.

3) Compared with 6 groups of 15 samples from either open literature or commercial companies, it indicates that the maximum instantaneous efficiency of MHPA-FPC surpasses 25% over the average level of those selected samples. Though 7 samples have better thermal insulation ability than MHPA-FPC, comparison results still reflect that the novel MHPA-FPC is one of the top level solar collectors among the current products.

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### References


