Experimental study of a novel photovoltaic solar-assisted heat pump /loop heat-pipe (PV-SAHP/LHP) system

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Abstract. A prototype of a photovoltaic solar-assisted heat-pump/loop heat-pipe system (PV-SAHP/LHP) was constructed in this paper. The system was a combination of photovoltaic solar-assisted heat pump system (PV-SAHP) and loop heat pipe photovoltaic/thermal (LHP-PV/T) system. The combined system can carry out with two modes but using the same working fluid, and the two modes can switch operation freely. R600a was employed as the working fluid, and system performance under different working mode was presented in this paper. The results show that the day average photothermal efficiency & photovoltaic efficiency can reach to 43.6% & 11.3% under LHP-PV/T working mode compared with that of 57.5% & 12.1% under PV-SAHP working mode. Besides that, a day average COP of 3.66 was obtained under PV-SAHP working mode.

1. Introduction

A photovoltaic/thermal hybrid solar system (or PVT system for simplicity) is a combination of photovoltaic (PV) and solar thermal components/systems, which produce both electricity and heat from one integrated component or system. In other words, PV is used as (part of) the thermal absorber [1]. In order to get more power and heat from PV/T system, it is necessary to cool the PV cell and decrease its temperature. The liquid based photovoltaic thermal collector systems are practically more desirable and effective than air based systems. Temperature fluctuation in liquid based PV/T is much less than the air based PV/T collector which subjected to variation in solar radiation levels [2]. However, there are freezing problem when the normal water-based PV/T systems working in winter. Loop heat pipe (LHP) PV/T systems, which using low-boiling refrigerants as the working fluid, proposed a promising prospect to solve the problem above [3].

Photovoltaic solar-assisted heat pump (PV-SAHP) is a combination of solar energy and heat pump that can improve the quality of the energy available and shows potential for different applications [4]. The evaporator-collector used in such system can absorb both solar and ambient energy [5]. Abou-Ziyani [6] conducted series of experiments with R22 and 134a to identify appropriate refrigerant for solar applications. Hawlader et al. [7], Lu et al. [8] and Chyng [9] used solar assisted heat pump (SAHP) to produce hot water. Besides, the PV performance can be improved because of the low evaporating temperature [10].

A novel photovoltaic solar-assisted heat pump/loop heat pipe system (PV-SAHP/LHP), which is a combination of PV-SAHP system and LHP-PV/T system, was conducted in this paper. The combined system can work with two modes, i.e. PV-SAHP independent operation or LHP-PV/T independent
operation, but employing the same working fluid. Iso-butane (R600a), one of the natural fluids that with appropriate thermodynamic and physical properties, well energy performance and negligible ozone depletion potential (ODP) and global warming potential (GWP) is suitable as the working fluid [11] and [12]. R600a is widely used in the domestic refrigerator/freezers and residential heat pump (notably in Europe) [13]. The system can switch operation freely according to different climate or temperature need. The photothermal and photovoltaic performance under different operation mode were presented this paper.

2. System design and experiment set up

2.1. System design and setup

System’s schematic diagram is shown in Figure 1. It comprise two PV/T solar evaporator collectors employing a vacuum magnetron cermet as selective absorbing coating, a water tank with an inner spiral coil pipe, six inspection mirrors, one compressor, one capillary, one gas-liquid separator, one PV control equipment, and the connect pipes. The R600a is employing as the working fluid, and the refrigerant volume-charge is 36.6% of whole system. Detailed information of the system components are listed in table 1.

![Figure 1. Schematic diagram of PV-SAHP/LHP system](image)

**Table 1. Detailed information of the system components**

| Device & copper tube           | Parameter | Remarks   |
|-------------------------------|-----------|-----------|
| water tank                    | Ø450×1570mm | 150±1L    |
| evaporator solar collector    | Ø1270×780×1.16mm | PV coverage rate=0.56 |
| vapor rising pipe             | Ø28×1000×1mm | /         |
| liquid return pipe            | Ø16×1400×1 | /         |
| condensation spiral coil pipe | Ø12×18000×1 | /         |
| inspection mirror             | /         | Emerson   |
| compressor                    | 1/4P      |           |
| battery                       | 150AH     |           |
| Other pipes                   | Ø9.52     |           |
| Gas-liquid separator          |           | 5.9L      |
2.2. Experimental procedure

The following is the LHP-PV/T’s cycle process. First, the incident solar irradiation is partly absorbed by the liquid R600a in the copper tubes behind the PV/T evaporator, to heat the liquid R600a to R600a vapor. R600a vapor is continuously heated when flowing along the copper tubes. Then the R600a vapor flows into spiral coil pipe in the water tank along the vapor rising pipe, where it is cooled by the water and condensed into fluid or gas-liquid and transfers the heat energy to water. Condensed R600a finally flows to the evaporator section through liquid return pipe under gravity for next heating cycle. While in the PV-SAHP cycle process, the heated R600a vapor is flow into the gas-liquid separator instead, and then be compressed by the compressor; the condensed R600a is flow into the capillary instead, and then return to the PV/T evaporator.

The experiments were carried out in Hefei (31.52°N, 117.17°E), a city located in central China. The collector was installed facing south with a tilt angle of 40°, which was a little higher than the city’s latitude, because the working tilt angle of the heat pipe was considered. The water tank was a little higher than the collector. The inspection mirrors and the pyranometer were parallel with the collector. Seven thermal T type thermocouples were set in the water tank to monitor temperature variation. Ambient temperature and solar irradiation were also recorded. All the measured parameters were recorded using Agilent 34970A every 30 s. Figure 2 presents the experiment setup.

![Figure 2. PV-SAHP/LHP system experiment setup](image)

3. Results and discussion

The daily thermal efficiency of solar water heating system can be evaluated using the daily average efficiency, which is defined as[14]:

\[
\eta_t = \frac{C_p M (T_f - T_i)}{H A} \quad (\text{For LHP-PV/T; 1a})
\]

\[
\eta_t = \frac{[C_p M (T_f - T_i) - W_p]}{H A} \quad (\text{For PV-SAHP; 1b})
\]

Where \( M \) is the mass of water in the water tank; \( C_p \) is the specific heat of water; \( H \) is the total solar irradiation on the collector surface during the experiment; \( W_p \) is the power of compressor; \( T_i \) and \( T_f \) are the initial and final temperatures of water in the water tank, respectively; \( A \) is the aperture area of the collector in this paper.

The daily electric efficiency of a hybrid PV/T system can be evaluated using the daily average efficiency, which is defined as[15]:

\[
\eta_e = \frac{V_{pv} I_{pv}}{H A_{pv}} \quad (2)
\]

Where \( V_{pv} \), \( I_{pv} \) and \( A_{pv} \) are the output voltage, output current and aperture area of the PV module, respectively.

The coefficient of performance (COP) of a heat pump can be evaluated as [16]:

\[
COP = \frac{C_p M (T_f - T_i)}{W_p} \quad (3)
\]
3.1. Performance of LHP-PV/T independent operation mode

In order to show the details of the system daily performance under LHP-PV/T independent operation, a fully representative sample day was chosen. The average solar irradiation, ambient temperature, presented in Figure 3, during the test was 703W/m², 30°C, respectively; test time was from 8:09 to 16:09, and the water temperature rising gradually form 19.1°C to 43.4°C during the test. System instantaneous photothermal efficiency and photovoltaic efficiency of every 30 minutes is shown in Figure 4a and Figure 4b, respectively.

![Figure 3. Variation of solar irradiation, ambient temperature, water temperature under LHP-PV/T independent operation mode](image)

![Figure 4. Variation of photothermal (a) & photovoltaic efficiency (b) under LHP-PV/T independent operation mode](image)

Figure 4a shows that system instantaneous photothermal efficiency presents a trend of increasing first and then decreased. It is because in the beginning of the tests, temperature difference between water and the ambient temperature, positive or negative was small. The incident angle decreased with time, thereby increasing photothermal efficiency. In the middle of the tests, temperature difference between water and the ambient temperature was bigger, making the heat loss bigger. However, there was also a bigger irradiation density and a smaller incident angle, so efficiency decreased slowly. At the end of the tests, the temperature difference between the water and the ambient was big, and also there was big incident angle, so the efficiency decreased sharply. The highest photothermal efficiency during the test was 55.1%, while the average was 43.6%. Figure 4b presents the fluctuation of photovoltaic efficiency during the test; it also has a trend of increasing first and then decreased. The fluctuation reason was similar to the photothermal efficiency, but with different range. The highest photovoltaic efficiency during the test was 12.1%, while the average was 11.3%.
Obtained results indicate that the LHP-PVT system manage to achieve the performance no less than the water based PV/T systems [17-19], and the daily average primary efficiency can reach 71.9%, which offers a promising prospect. Therefore, the results indicate that the LHP-SWH can ensure a satisfactory performance of the LHP-PV/T. Moreover, it must be underlined that the diode characteristic of the LHP can ensure a smaller heat loss at night compared to the conventional water based PV/T systems.

3.2. Performance of PV-SAHP independent operation mode

System performance under PV-SAHP independent operation mode was also studied. Ambient environment, including ambient temperature, solar irradiation, and the water temperature fluctuation of one of the typical day, are shown in Figure 5. The average solar irradiation during the test was 765W/m², and the average ambient temperature was 27.1°C, test time was from 8:30 to 14:00. Figure 6 shows the trend of temperature rising and variation of compressor power. The results show that the water temperature is linear rising from 20.5°C to 53.6°C, and the compressor power is rising gradually from 195W to 372W. The condensing pressure rising with the temperature rising, so as the compressor power.

Figure 5. Variation of solar irradiation, ambient temperature, water temperature under PV-SAHP independent operation mode

Figure 6. Variation of water temperature and compressor power under PV-SAHP independent operation mode

Figure 7 shows the system instantaneous photothermal efficiency and COP every 30mins under PV-SAHP independent operation mode. It can be seen that the overall trend of COP is increasing first
and then decreased, while the photothermal efficiency is declining most of time. The highest and lowest COP during the test was 4.37 and 3.03, respectively. The daily average COP and photothermal efficiency were 3.66 and 57.5%, respectively, which present a satisfactory performance compared with the works in a review [20]. Considering that, the compressor rated power used here is only 184W, the PV/T collector area is small too, and it can be conclude that the hybrid PV-SAHP system can achieve a better performance if the system is bigger.

Figure 8 presents the instantaneous photovoltaic efficiency every 30mins; it has a similar trend with LHP-PV/T working mode. The results show that the highest instantaneous photovoltaic efficiency during the test can reach to 12.8%, while the lowest is 10.9%. System average photovoltaic efficiency can reach to 12.1%, which is higher than that of LHP-PV/T also. The absorb plate always under a low temperature because of the refrigerants evaporation benefits the PV performance compared with the LHP-PV/T system.

Satisfactory COP, photothermal efficiency and photovoltaic efficiency, one can conclude that the system operates well under the PV-SAHP working mode. And it can also be conclude that the hybrid PV-SAHP/LHP system achieves a remarkable performance under the two independent working modes. However, the essence of the proposed hybrid PV-SAHL/LHP system is the working mode switch according to the ambient environment or domestic requirement. The switching strategy should be deeply studied. Therefore, further experiments should be carried out, and full theoretical model should be established. Based on that, the novel hybrid PV-SAHP/LHP system can be more power saving, and can present a more promising application prospect.

4. Conclusion
A novel system (PV-SAHP/LHP, combined the PV-SAHP system and the LHP-PV/T system) was conducted in this paper. The combined system can work with two modes, but employing the same working fluid. System can switch operation freely according to different climate or temperature need. The photothermal and photovoltaic performance under different operation mode were presented this paper. The major conclusions can be summarized as follows:

1) Under the LHP-PV/T working mode, system had a highest instantaneous photothermal efficiency of 55.1%, while the day average was 43.6%. And the highest photovoltaic efficiency can reach to 12.1% with an average value was 11.3%.

2) Under the PV-SAHP working mode, system had a highest COP of 4.37, while the day average value was 3.66. The average photothermal and photovoltaic efficiency during the test was 57.5% and 12.1%, respectively, which were both higher than that of LHP-PV/T operation mode.
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