Experimental study of the wickless loop thermosyphon solar water heating system under passive and active cycle mode

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Abstract

Wickless loop thermosyphon solar water heating (LT-SWH) systems, which working under the passive and active cycle modes, were designed and experimental setup, systems’ performance were comparative studied. The results showed that pump made the active cycle system overcharged, a small hydraulic head was observed most of time; because of that, there was a worse photothermal performance under the active cycle mode, no matter in the comparison of the instantaneous photothermal efficiency or the collector and system performance linear fitting; at the same time, there was also a worse isothermality of the solar evaporator under the active cycle mode.

Keywords: solar water heating; passive; active; photothermal performance; isothermality

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1 INTRODUCTION

Solar water heating (SWH) systems are grouped into two broad categories as passive and active SWH systems. The passive SWH systems generally transfer heat by natural circulation; hence they do not prescribe pumps to operate. However, the water tank must be located above the solar collector. Active SWH systems have electric pumps, valves and controllers to circulate water through the collectors; hence the collector in the active system does not need to as close to the water tank, the water tank also has no location limited [1].

Currently, the most common SWHs are the thermosyphon, according to Soin et al. [2], problems like corrosion, fouling and freezing presented in this kind of system. However, it can be eliminated in two-phase systems. Loop thermosyphon (LT) [3–6] is a two-phase (liquid/vapor) heat transfer device allowing a high thermal flux to be transported over a distance of up to several tens of meters. LTs have the separate evaporator and condenser, thus it is suitable for use in SWHs, owing to its unique features such as a highly effective thermal conductance and flexible design embodiment and installation. A number of studies [7–9] have been previously conducted in which LTs were used in SWHs.

LTs use wicks or gravity to provide the force needed to return the condensed liquid to the heated end of the device. Thewick in a porous structure, which needs a complex and expensive manufacturing process, is usually located in the evaporator [10]. It produces the capillary force to drive the liquid back to the evaporator and ensures the heat transfer liquid is evenly distributed over the evaporator surface. However, it is costly to set up wicks in the copper tubes behind a flat plate solar collector. At the same time, consider that the solar collectors are usually inclined installed, a wickless gravity assisted LT is more preferred. Simpler wickless LTs will be modest cost and are conceptually simpler to study. Nevertheless, the wickless LT-SWH cannot be used when the water tank lower than the solar collector, which made it hard to integrate with buildings and not suitable for household using.

Copy the way of water-based SWHs, a pump can be introduced to wickless LT-SWHs. To show the pump effect and the performance comparison under different cycle mode, passive and active wickless LT-SWH systems were designed and...
constructed individually in this paper. Outdoor tests were both carried out in the same volume-filling ratio to offer data for comparison and future optimization.

2 SYSTEM DESIGN AND EXPERIMENTAL SETUP

Figure 1a and b show the schematic of the passive and active wickless LT-SWH system. The passive LT-SWH system contains a solar evaporation collector, a water tank with an inner spiral coil pipe, a vapor rising pipe, a liquid return pipe, four inspection mirrors and R600a as the working fluid. The solar evaporation collector is located in the LT evaporation section and the spiral coil pipe in the condensation section of the passive system. And the water tank is higher located than the solar evaporation collector.

The active LT-SWH system has a solar evaporation collector, evaporation and condensation liquid storage tanks, a water tank with an inner spiral coil pipe, a reflux pump, four inspection mirrors and R600a as the working fluid too. Reflux pump supplies fluid from the condensation liquid storage tank to the evaporation liquid storage tank. The condensation liquid storage tank separates the vapor and fluid from the coil pipe to ensure that the pump is properly functioning. The evaporation liquid storage tank supplies fluid to the solar collector. The pump makes the location of the water tank flexible, such that the easy integration of the system into the building is facilitated. The check valve prevents the reverse flow of the fluid when the pump stops.

Solar collectors and water tanks used in this paper are all provided by the same manufacturer. More information on the parts and dimensions of the copper tube used in this paper is presented in Table 1.

The experiments were conducted in Hefei (31.52°N, 117.17°E), a central Chinese city that belongs to the subtropical zone with a humid monsoon climate. The collectors were installed facing south with a tilt angle of 40° in the two systems, which were a little higher than the latitude of the city because the working tilt angle of the LT was considered. The heights of condensation fluid storage tank and evaporation storage tank in the active system were 500 and 900 mm, respectively. The heights of the water tank under the passive and active system were 1390 and 150 mm, respectively. The inspection mirrors and the pyranometer were parallel to the collector. The distances between the inspection mirrors and the bottom of the collector were 350, 750, 1150 and 1550 mm, respectively. Seven thermal T-type thermocouples were set in the water tank to monitor temperature variation.

The experiments were begun at 7:30–8:00, and end at 16:00–16:30. A frequency modulator was utilized to adjust the pump flow rate, and a power sensor was employed to measure the pump and modulator power consumption.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) Schematic of the passive LT-SWH system. (b) Schematic of the active LT-SWH system (1. Water tank, 2. Condensation spiral coil pipe, 3. Condensation liquid storage tank, 4. Check valve, 5. Reflux pump, 6. Evaporation liquid storage tank, 7. Inspection mirrors (four), 8. Evaporation solar collector, 9. Pressure balance pipe and 10. Thermocouples).

| Device and the copper tube                      | Dimension (mm) | Remarks          |
|------------------------------------------------|----------------|-----------------|
| Water tank (both)                               | Φ 450 × 1570   | 150 ± 11        |
| Condensation fluid storage tank (active)        | Φ 58 × 440     | 5.91            |
| Evaporation fluid storage tank (active)         | Φ 58 × 440     | 5.91            |
| Reflux pump (active)                            | /              | 60 W (rated power) |
| Evaporation solar collector (both)              | 1000 × 2000 × 95 | $\eta_{\text{abs}} = 0.751 - 4.20 \times 10^{-5}$ |
| Absorbing plate (both)                          | 950 × 1960 × 0.4 | Absorption rate ≥ 0.96 |
| Emissivity                                     |                | Emissivity ≤ 0.05 |
| Vapor rising pipe (both)                        | Φ 28 × 1000 × 1 | /               |
| Liquid return pipe (passive)                    | Φ 16 × 1000 × 1 | /               |
| Pressure balance pipe (active)                  | Φ 4            | /               |
| Other connection pipes (active)                 | Φ 9.52 × 0.7   | /               |
| Condensation spiral coil pipe (both)            | Φ 12 × 18 000 × 1 | /               |
| Inspection mirrors (both)                       | /              | Emerson         |
The photothermal performance of the water heating system is evaluated with the photothermal efficiency, which is expressed as
\[
\eta = \frac{\left( T_f - T_i \right)}{C_p M H A} \tag{1a}
\]
and
\[
\eta_{sys} = \frac{C_p M (T_f - T_i) - W_PT}{HA}, \tag{1b}
\]
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; \( T_i \) and \( T_f \) are the initial and final temperatures of water in the water tank, respectively. The \( T_i \) and \( T_f \) here are the average value of the seven thermocouples in the water tank. \( A \) is the aperture area of the collector. \( W_p \) is the pump power. \( t \) is the pump working time. System daily average photothermal performance can also be evaluated according to Equation (1), where the \( H \) is the accumulation of solar irradiation of the whole day.

Thermal performance of a thermosiphon system is affected by many factors that involve system design parameters, solar irradiation, ambient temperature, wind conditions, initial temperature and so on. A method to evaluate the natural circulation performance of a water system was proposed by Yanze et al. [12]. It is expressed as
\[
\eta^* = \alpha - \frac{U T_a - T_T}{H}, \tag{2}
\]
where \( T_a \) is the ambient daily average temperature, \( \alpha \) is the daily average thermal efficiency when the initial water temperature equals the ambient daily average temperature, and \( U \) is the heat loss coefficient of the system. The \( \alpha \) and \( U \) values of the system can be determined by linear fitting based on several day experiment data.

The same method as that used in Equation (2) is applied to evaluate the collector performance \( \eta_{col}^* \), where \( T_i \) is the initial fluid inlet temperature of the collector and \( H \) is the instantaneous solar irradiation during the test.
4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Daily Performance Comparison
To present the details of the daily performance of the two systems, a typical day is selected. The ambient environment, including the ambient temperature and solar irradiation on the day, is shown in Figure 3. The details of initial and final water temperature in the water tank, average ambient temperature, and overall solar irradiation on per area of that day are presented in Table 3.

The flow rate of the pump was set at 571.2 ml/min (theoretical, the same followed) from 7:30 to 9:30, 952 ml/min from 9:30 to 14:30, 571.2 ml/min from 14:30 to 16:00 and 380.8 ml/min from 16:00 to 16:30 in that day.

4.1.1 Comparison of instantaneous photothermal efficiency
Figure 4 shows two systems’ instantaneous photothermal efficiency. Overall trend in photothermal efficiency under the two cycle modes was both increased at first and then decreased. It was because in the beginning of the test, 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. Based on the test data, the average daily photothermal efficiency of the passive system was 57.22%, while the value of the active system was 51.32%; the final water temperature of the two systems was 59.9 and 56.2°C, respectively.

From the Figure 4, one can easily observe that system had a better performance under the passive cycle condition. Expect the reasons of solar incident angle change and heat loss change, the influence of evaporation liquid level and pump should also be concerned. To show the detail reasons for the photothermal performance difference, the variations of the evaporation liquid level were presented in Figure 5.

Figure 5 qualitatively described the liquid level of the evaporator under different cycle mode. It only presented the

| Type   | \( T_i (^\circ \text{C}) \) | \( T_f (^\circ \text{C}) \) | \( Ta (^\circ \text{C}) \) | \( H (\text{MJ/m}^2) \) |
|--------|-----------------|-----------------|-----------------|-----------------|
| Passive| 24.9            | 59.9            | 30.7            | 21.29           |
| Active | 24.8            | 56.2            | 30.7            | 21.29           |

Table 3. Details of the ambient environment of the 2 days.
location of the liquid level, not the concrete values. From the Figure 5, under the passive convection, one can see that in the beginning of the test, the liquid level was between 750 and 1150 mm, i.e. between the second and third inspection mirror (the bottom one was set as the first one here); then the liquid level dropped gradually with the solar irradiation increase, and will be stay between the first and the second inspection mirror for a long time; finally, the liquid level will raise with the solar irradiation decreasing at the end of the test. When under the active convection, the initial liquid level was usually low, because the R600a liquid will be evaporate slowly after the test yesterday and before the test start today, at which times the pump were not work and the solar irradiation was although weak; the absorbed solar energy was stored by R600a vapor; the liquid level will raise gradually when the pump start to work, and then stay nearby the second inspection mirror for ~2 h; after that, the liquid level began to raise and continued to raise although the pump had turned down two times; the liquid level under the active convection finally reach to a height higher than the forth inspection mirror, it means that the evaporation liquid storage tank was full of R600a liquid at the end of the test.

Although the two cycle conditions had the same volume-filling ratio, the exist of pump, condensation liquid storage tank, evaporation liquid storage tank made the actual evaporation liquid level under the active convection was higher than the passive convection most of time, as shown in Figure 5. According to Aung and Li [9], the driving force for circulation of working fluid in a LT system is mainly related to hydraulic head between highest liquid level in the liquid return pipe and evaporation liquid level in the solar collector (see Figure 2). From Figure 5 and the location of the evaporation liquid storage tank, it can be concluding that the hydraulic head of the active system was smaller than the passive system most of the time, and it was the reason why it had a worse thermal performance most of time. Therefore, high position of the evaporation liquid storage tank will be helpful; besides that, the pump volume flow rate and the control principle should also be optimized.

Summing up the above, a better performance was achieved by the passive cycle; the pump in the active LT-SWH liberated the location of the water tank with the cost of efficiency reduction and power consumption (the daily average value was 29.64W). Active LT’s small hydraulic head caused by the pump was the main reason for the low photothermal performance.

4.1.2 Comparison of the temperature distribution
Isothermality of the evaporator section is one of the important characteristics of the LT. The temperatures of the points, shown in the right of Figure 2, at the bottom, middle and top of the evaporator section were recorded. In order to show the detailed temperature distribution of the LT solar collector under different working mode during the tests, the average temperature of the points at the bottom, middle and top of the LT evaporator were presented in Figure 6, as well as the temperature of the middle of absorber plate surface facing sun and the glass cover.

From the Figure 6, one can see that the temperatures of the collector at different positions under the passive convection were, most of the time, higher than the corresponding positions under the forced convection. Besides, one can also see that the temperatures at the bottom and the middle of the collector under the active condition had a sharp rise after the test began, and tend to be normal gradually after about an hour. It was because there was weak solar irradiation before the test began at 7:30, the solar energy was absorbed and stored when the R600a liquid change to R600a vapor; the accumulated solar energy caused the R600a vapor temperature rise and then released when the pump start to work, which made a sharp temperature rise at the bottom and the middle of the collector; however, the temperature at the top of the collector was less affected because the solar irradiation before 8:30 was weak, the little vapor generated by the phase change was cooled when flow upwards along the pipe.

Temperature differences between the top and the bottom, middle and the bottom were used to show the details of the isothermality under different operation mode, and the results were presented in Figure 7, in where the first half hour was removed. From Figure 7, one can see that the temperature differences between the middle and the bottom of the collector under the two conditions were very small; the average values were 1.1 and 1.0°C, respectively. The temperature difference between the top and the bottom of the collector under passive convection presented a trend of increased firstly then decreased; the highest value temperature difference was 4.0°C, appeared around 10:00. Note that the R600a vapor at the middle and top was under different dryness, heat resistance between the copper pipe and the R600a vapor at the top was higher than that of the middle. So one can conclude that the collector temperature was almost evenly distributed under the passive cycle mode.

The temperature difference between the top and the bottom of the collector under the active convection was segmented in
four parts. Between 8:00 and 9:00, the influence of the stored solar energy was not entirely eliminated, so the temperature difference raised with time; between 9:00 and 11:30, when the system back to normal, the temperature difference presented an overall trend of increased firstly then decreased; however, because the system was over-charged, the lower photothermal efficiency caused a slower evaporation rate, which caused a bigger superheat of the R600a vapor, so the temperature difference was higher than the passive condition. Between 11:30 and 13:30, with the solar irradiation decrease, the superheat of the R600a vapor began to decrease; the temperature difference began to decrease too. After 13:30, because of the pump, the liquid level of the collector began to increase; when the highest inspection mirror was full of liquid, the temperature difference toward zero.

4.1.3 Collector thermal performance comparison

Based on GB/T 4271-2007 [13], only test data when solar irradiation is bigger than 700 W/m² are chosen for analysis. Inlet temperature (Tᵢ), which is usually used in curves for water-cooled units, is replaced by inlet R600a temperature (Tᵢc, calculated based on the inlet R600a liquid pressure, and saturation state was assumed here). Linear fitting, calculated based on Equation (2), is plotted in Figure 8.

Corresponding to the photothermal efficiency, the LT solar collector achieves a better performance under the free convection, it had a slightly bigger typical efficiency and smaller heat loss coefficient. The typical photothermal efficiencies under the passive and active cycle mode were 0.71 and 0.69, respectively; and heat loss coefficients were 3.84 and 6.20, respectively. However, no matter under which cycle mode, both of them had a worse performance compared to the value manufacturer provided (see Table 1). But both of them achieved better performance than the results presented in [9], in which the solar collector photothermal performance with the approximate size and system structure was numerical simulated.

4.2 System performance comparison

In order to evaluate the two systems’ daily performance under different weather conditions, long-term outdoor tests were carried out. Linear fittings of two systems overall photothermal performance, based on Equation (2), are plotted in Figure 9.

From Figure 9, one can easily observe that under the passive convection, system had an obviously better performance, it had a bigger typical efficiency and smaller heat loss coefficient. System typical photothermal efficiencies under the passive and the active cycle modes were 54.58 and 47.30%, respectively. Because of the instability of solar irradiation, pump flow rate was hard to control, which made the solar collector overcharged.
and unstable most of the time, and it was the reason of the low photothermal efficiency under the active convection.

A comparison between the earlier work [14] with water as the working fluid and the present study is made. The results showed that the passive LT-SWH system had a similar photothermal performance as that of the traditional SWH system; the active LT-SWH had a worse photothermal performance, and an obvious big heat loss. However, the LT-SWH system has no corrosion and freezing problems during winter, and it has low heat loss of heated water at night; In addition to the above, the active LT-SWH can easily integrate with buildings. Both of the two systems were therefore a good substitute for the normal solar collector when they were used in a high-latitude area.

5 CONCLUSION

Passive wickless LT-SWH cannot be used when the water tank lower than the solar collector, which made it hard to integrate with buildings and not suitable for household using. A pump was introduced to a LT-SWH system. Passive and active LT-SWH systems were designed and experimental setup in this paper; system photothermal performance and solar evaporator isothermality were comparatively studied. Based on the outdoors tests, useful information was observed. Summarized as follows:

(1) Passive LT-SWH system had a better transient photothermal performance; the pump in the active LT-SWH liberated the location of the water tank with the cost of efficiency reduction and power consumption; small hydraulic head caused by the pump responsible for the worse performance.

(2) The solar evaporator had a uniform temperature distribution under the passive system; based on linear fitting, the two systems had a similar collector performance, but different system performance.

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