Study on the hysteresis characteristic of solar thermal storage system

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Abstract. The thermal storage efficiency is one of the important indicators for evaluating the operation of solar thermal storage system. Affected by the thermal inertia of the system, the analysis of the relationship between the thermal storage efficiency and solar radiation, which is inadequate at the smaller time scale. This paper measured the operation of a flat plate solar collector system, studied the hysteresis characteristics of the system's collector efficiency changes with solar radiation, took a numerical solution method for the actual lag time of the system and finally obtained the actual influence rule of solar radiation on the collection efficiency per minute. The results show that the solar collector's efficiency change lags behind the solar radiation by 27 min; combined the lag time, the relationship between the modified thermal storage efficiency and solar radiation also were analysed; initially the modified storage efficiency per minute increases with the solar radiation, then gradually decrease after reach a certain value, due to the overall system temperature is higher and the system temperature rise is smaller when the solar radiation is large enough; the varying curve conforms to quadratic function. It provides theoretical support and practical reference for contrasting and evaluating the thermal storage efficiency changes with solar radiation in a smaller time scale.

Keywords: thermal storage efficiency; solar radiation; hysteresis characteristic; flat plate collector

1. Introduction
With the energy crisis become serious, the heat-collecting system that solar energy and other renewable energy sources as heat sources will take the main body for development and utilization [1] under the urgent need of social operation. The effective increase and accurate determination of the actual thermal storage efficiency of the solar system is a key factor to ensure the maximization of solar thermal conversion.

In recent years, various scholars have conducted extensive in-depth research on the collection efficiency by optimizing various components within the heat collection system. Such as Cheng W P [2] and other scholars enhanced the collection efficiency of the system by change the heat transfer area and the distribution of the heat pipe; Zhao J [3] of Tianjin University analysed the effects of the collector area-tank volume ratio (A/V) variation on the thermal storage efficiency; Ji Y M, Duan M L [4] studied a solar-assisted buried pipe compound system in the transition season, the two operating modes with heat storage and the thermal storage efficiency of the system is evaluated. Li X G [5] and other scholars designed a solar thermal system with a ground-source heat pump, stored abundant solar energy in underground soil and improved the system thermal storage efficiency and realized the transfer and utilization of solar energy finally. Lin Y [6], Han Z W [7] added a phase change thermal storage device based on the original solar-soil source heat pump, which increased the system's thermal storage efficiency up to 60% and the average heating COP reached to 6.5.

Influenced by the thermal inertia of the heat-collecting system, the whole temperature rise of the system will change lags behind the solar radiation for a certain period of time, all the above researches
use the thermal storage efficiency of the large time scale to evaluate the solar heat collection system, which cannot accurately reflect the actual influence of the solar radiation on the thermal storage efficiency.

In order to research the quantitative effect of the solar radiation on the thermal storage efficiency at a small time scale, this paper established a planar solar collector-thermal storage system, measured the solar radiation, outdoor temperature and system water temperature during the operation of the system, took advantage of the numerical solution to accurately calculate the lag time of the system's heat gain and combined with the lag time, obtained the actual rule of the modified collector efficiency (min) change with the solar radiation finally.

2. Experimental system and methods

2.1. Experimental system

In combination with the meteorological conditions, a flat-plate solar collector-thermal storage system has been designed and installed. The system consists of 2 plate-type heat collector (FPC-1-CTL), 1 booster pump, 1 heat storage tank, some pipeline, 1 flow meter, 1 intelligent solar radiation recorder (JR-08) and 1 multi-channel temperature data acquisition system (JTDL-80).

During the operation of the system, clean water is adopted as the system heat storage medium for those large specific heat capacity relatively, heated up rapidly in the plate heat collector by the solar radiation and transported to the hot water storage tank through the pipe network, then send into the inlet of a plate collector after uniformly mixed in the tank. The experimental system and temperature measurement point layout are shown in Figure 1.

![Figure 1. The experimental system and the arrangement of temperature testing points](image)

The heat collector and the heat storage tank are connected through the distribution networks of the PVC pipe of 20 mm diameter and all the transmission pipes are covered with a 35mm-thick rubber sponge to prevent excessive loss of heat. The temperature measurement data is recorded by multi-channel temperature data acquisition system (JTDL-80) matched with the thermocouple, to record the water temperature and ambient temperature of the system meanwhile. Intelligent solar radiation recorder (JR-08) is applied to the solar radiation record, which installed at an inclination of 40° to the south as same as that of the solar radiation panel. The specific parameters of the system components are shown in Table 1.

### Table 1. System equipment parameter table.

| System equipment   | model    | size (mm)       | amount | power (w) | range  |
|--------------------|----------|-----------------|--------|-----------|--------|
| Flat Solar Collector| FPC-1-CTL| 2000×1000×70    | 4      |           | >0℃    |
| Pump               | PB-H090  | 300×150×200     | 1      | 60        |        |
2.2. Experimental contents
In order to investigate the actual heat storage characteristics of the flat plate solar collector-thermal storage system, the experimental measured the solar radiation, outdoor temperature and system water temperature during 4.20 to 4.23. The specific experimental process and the starting and ending conditions are shown in Table 2.

Table 2. Specific conditions of the experiment

| Date | Test time | Average outdoor temperature(℃) | Total solar radiation (W) | System temperature (℃) |
|------|-----------|---------------------------------|---------------------------|-------------------------|
| 4.20 | 10: 35-17: 50 | 18.9 | 23751.2 | 32.9-55.9 |
| 4.21 | 10: 50-16: 30 | 20.1 | 31577.4 | 26.1-41.3 |
| 4.22 | 10: 50-17: 35 | 24.9 | 79453.2 | 47.5-64.8 |
| 4.23 | 10: 41-18: 29 | 25.1 | 77748 | 47.1-65.7 |

3. Calculation method

3.1. Calculation of heat collecting efficiency
According to the US ASHRAE Standard: Testing and analysis on thermal property has been widely used in solar collectors evaluating and the instantaneous efficiency of collectors is a decisive factor for the thermal characteristics of collectors[8].

The following setup steps assume that the system is fully filled with clean water; the specific heat capacity of water is constant; and the quality of water storage in the system remains stable, which could be converted to the total volume of the system directly. In this experiment, the useful energy gain of the collector can be expressed as the system heat storage, which is calculated by formula (3.1). The calculation formula of the system average thermal storage efficiency per unit time[9] is shown in formula (3.2).

\[ Q_A = C_w \rho_w V_s (t_{i+1} - t_i) \]  \hspace{1cm} (3.1) \hspace{1cm} \omega_A = \frac{Q_A}{I_T} = \frac{C_w \rho_w V_s (t_{i+1} - t_i)}{I_T} \times 100\% \hspace{1cm} (3.2)

\( Q_A \): heat storage in the system per unit time, \( J \); \( C_w \): the specific heat capacity of water, \( 4.2 \times 10^3 \text{ J/(kg.℃)} \); \( \rho_w \): the density of water, \( 1 \text{ kg/m}^3 \); \( V_s \): the volume of the system, \( \text{m}^3 \); \( t_{i+1} \), \( t_i \): the average water temperature of the system before and after the unit time, \( ^\circ \text{C} \); \( \omega_A \): collecting efficiency in the system per unit time, \( \% \); \( I_T \): in the unit time, whole solar radiation energy received on the collector theoretically, \( J \).

3.2. Calculation of lag time
Affected the system's thermal inertia and other reasons, the system water temperature fluctuations would change lag behind the solar radiation during testing, causing that the thermal storage efficiency of a small time scale inaccurately reflect the relationship between solar radiation and the system heat gain.

Heat storage tank
600×600×1750 1 0~414.27L
Solar-recording instrument
JR-08 50×2000×30 1 20
Temperature-recording instrument
JTDL—80 400×300×200 1 35 0~800℃
Thermocouple
WRNT 9 0~800℃
Pipe flow meter
LDG03 20 1 15 0.1~11.3m3/h
In the experimental operation, it is assumed that a mass point moves with the heat storage medium in the system, the time required for a complete circulation of the mass point and the overall of the system evenly heating up is the essence of the lag time.

The time needed for a complete cycle of the mass point can be computed by formula (3.3), which is the ratio of the total volume of the system to the flow rate of the pipeline per unit time[10].

\[ T_1 = \frac{V_a}{v_Q} = \frac{V_p + V_b + V_l}{s_t \times A_s} \]  

(3.3)

\( T_1 \): the time needed for a complete cycle of the mass point in the system, \( V_p \), \( V_b \), \( V_l \): the volume of the Plate collector, storage tank and pipeline, \( m^3 \); \( v_Q \): the volume of flow in the pipe per unit time, \( m^3/h \); \( s_t \): the distance of flow in the pipe per unit time, \( m/s \); \( A_s \): Section area of the pipe, \( m^2 \).

4. Discussion

In this paper, the typical experimental results during one day (April 21st) are taken as an example to deeply study the relationship between the thermal storage efficiency and the solar radiation.

The varying curve of solar radiation and the water temperature of each measuring point as shown in the Figure 2.a): Analysed the water temperature at each measuring point, the order is flat water outlet, water tank upper, water tank inlet, flat water inlet, water tank middle, the water tank outlet and water tank lower, were 41.7°C, 36.77°C, 36.75°C, 36.72°C, 35.8°C, 35.3°C and 35.1°C respectively. The temperature at the outlet of the flat plate is highest, partly because the water flows through the flat plate and converts the heat of solar radiation into internal temperature rise. The temperature in the lower part of the water tank is lowest due to the delamination phenomenon of the water tank, Hot water floats on the top of the tank and the lower water is not heated sufficiently. Considering the influence of system thermal inertia, the overall temperature of the system will change lag behind that of solar radiation and the calculation of the collection efficiency per minute is inaccurate. As a result, the time scale of 0.25h and 0.5h is often used as a unit time to calculate the system thermal storage efficiency, as shown in Figure 2.b). When 0.5h is selected as the unit time, the range of efficiency varies from 18% to 81% and the average heat storage efficiency is 47.4%. When 0.25h is selected as the unit time, the range of efficiency varies from 11% to 89% and the average heat storage efficiency is 49.2%.

Figure 2. a) Solar radiation and water temperature   b) The system thermal storage efficiency

From the above analysis, it can be seen that the variation of heat storage efficiency and solar radiation with time is more consistent at smaller time scales. Taking 1min as a unit time, the calculated results of total heat gain, solar radiation and thermal storage efficiency of the system are shown in Figure 3.a). The total heat of the system come to 7487.9 KJ, the solar radiation reach 15788 KJ whole day and the average daily thermal storage efficiency is 47.4%, what’s more, the solar radiation reaches the maximum value at 11:55 and 14:07 respectively and the variation range is 15-226KJ. While the collector efficiency (min) of the system reaches the extreme value at 12:29 and 14:34 respectively, with a range of 2% to 109%. This is because the bulk
temperature of the system is lag behind the solar radiation due to the overall thermal inertia, which also has a corresponding effect on the thermal storage efficiency.

The relationship between the thermal storage efficiency (min) and solar radiation can be used to evaluate and compare the thermal storage performance of the system. As shown in Fig. 3.b), the total solar radiation per minute is mainly distributed in the range of 20 to 90 KJ during testing. With the solar radiation gradually increases, the variation of thermal storage efficiency (min) is unpredictable. This is because the effect of the system thermal inertia, the real-time thermal gain of the system does not match the real time solar radiation, the calculated collector efficiency (min) can’t accurately reflect the thermal storage performance of the system.

**Figure 3.** a) Solar radiation, system heat gain and thermal storage efficiency

b) The relationship between the thermal storage efficiency (min) and solar radiation

According to the calculation of formula (3.3), the overall temperature changes of the system lags behind the variation of the solar radiation about 27 min.

Applying this lag time to the correction calculation of the thermal storage efficiency (min), the varying curve of solar radiation, modified system heat gain and modified thermal storage efficiency are shown in Figure 4.a). The modified thermal storage efficiency (min) is consistent with the fluctuation of solar radiation, and concentrated at 10% to 60%.

The relationship between the modified storage efficiency (min) and solar radiation is shown in Figure 4.b). Firstly, with the gradual increase of solar radiation, the system thermal storage efficiency increases rapidly, whose rate of increase is nearly 0.57%/KJ, then gradually decreases after reach to 55%. The varying curve conforms to quadratic function, and the fitting formula is: \( y = -0.004x^2 + 0.0113x - 0.0535, R^2 = 0.7566 \). When the solar radiation reaches a certain intensity, the overall temperature of the system is higher accordingly, and It is more difficult to increase the temperature of the system, causing gradually reduce in the thermal storage efficiency.

**Figure 4.** a) Solar radiation, system heat gain and modified thermal storage efficiency

b) The relationship between the modified storage efficiency (min) and solar radiation
5. Conclusion

(1) During the experiment, the highest and the lowest temperatures of the system appear at the flat outlet and the water tank lower respectively. Selecting 0.25h and 0.5h as the unit time, the variation of heat storage efficiency and solar radiation with time is more consistent at smaller time scales.

(2) Affected by the thermal inertia of the system, the variation of thermal storage efficiency (min) with solar radiation is unpredictable. The time required for a complete circulation of the mass point is the essence of the lag time, which is about 27 minutes.

(3) Applying this lag time to the correction calculation of the thermal storage efficiency (min), the varying curve of the modified thermal storage efficiency (min) and solar radiation conforms to quadratic function.

(4) The modified storage efficiency per minute increases with the solar radiation in the initial stage, then gradually decrease after reach a certain value, due to the overall temperature is higher and the system temperature rise is smaller when the solar radiation is large enough.

6. References

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