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Evaluation of Solar Hot Water System Based on Temperature Monitoring Data in Hot Summer and Cold Winter Area in China

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ABSTRACT

Solar hot water systems have developed rapidly in recent years. There are lots of problems in the long term monitoring data onto solar hot water systems, which is difficult to learn the realistic effect of solar hot water systems. This paper studies the temperature monitoring data onto the related projects of solar hot water systems, and set up a set of evaluation system for solar hot water systems in order to evaluate the performance of solar hot water systems in realistic operation. Through comprehensive assessment of annual operation efficiency of solar water heating system, the annual COP_s is about 1.5, the COP_s of some projects is less than 1.35.

Keywords: solar hot water, evaluation indicator, hot summer and cold winter area, measured data

NONMENCLATURE

Abbreviations	
COP_s	Solar hot water using coefficient of performance
Symbols	
S	Instantaneous solar radiation intensity, W m^{-2}
t_i	Test interval between twice test of solar radiation intensity, s
T_1	Water temperature of storage tank at the beginning of the test, °C
T_2	Water temperature of storage tank at the end of the test, °C
V_s	Volume of storage tank, m^3
C_{pw}	Specific heat at constant pressure of water, 4.187kJ kg^{-1} m^{-3}
ρ_w	Density of water, 1000kg m^{-3}
T_3	Hot water temperature set by solar heating system, °C
$\Delta\tau$	Cooling time, s
T_4	Water temperature of storage tank at 8 p.m. in that day, °C
T_5	Water temperature of storage tank at 6 a.m. in next day, °C
$T_{as(av)}$	Average environment temperature between cooling time, °C
A	Daylighting area of solar thermal collector, m^2
Q_z	Total energy of solar heating system, MJ
Q_y	Using heat of solar collecting system, MJ
Q_b	Energy consumption of supplementary heat source, MJ

1. INTRODUCTION

Solar energy is recognized as the most important part in renewable energy. The efficiency of solar heating systems can reach 30%~50%, which is several times better than solar photovoltaic systems. So more and more related researches of solar hot water systems are carried all over the world.

To better to evaluate the solar hot water systems and to normalize testing process, a number of standards (e.g., AS 4324-2008; ASHRAE 95-1987; BS 5918-1989;

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CNS 12558-B7277, 1989; GB/T 50801-2013; IS 13129 (parts 1 and 2)-1991; ISO 9459 (parts 1–3 and 5); JIS A 4111- 1997) have been developed for testing a complete system. The test standards can be split into two principal groups based on their approaches. One is stationary methods specifying that the test should be carried out for a number of hours which satisfy certain basic weather conditions. The other is dynamic methods which have been developed in order to minimize test duration and carry out tests of any weather conditions[1].

People also made a great deal of studies to evaluate the solar hot water systems. Norhafana et al. used a solar simulator to evaluate the performance of the solar collectors and showed that at the angle of 45 degrees the maximum values of useful heat and temperature difference are achieved[2]. Chow et al. evaluated the performance of the two common types of evacuated tube solar water heaters for domestic hot-water applications based on experimental and numerical works, which shows that the daily and annual thermal performance of the two-phase closed thermosyphon solar collector is slightly better than the single-phase open thermosyphon design[3]. Yoo evaluated three-year operation of solar hot water heating system installed in multi-family housing complex about 1179 households in 14 units and provided feedbacks on the conventional design baseline[4].

The research of realistic operation of solar water systems is very limited. People made some researches about solar hot water systems based on the monitoring data. Li et al. showed the parameter variances in solar hot water system application and analyzed the differences between theoretical calculation and real data, which would offer practical references from the solar hot water system designs[5]. Julia et al. find the right indicators to guarantee the performance of solar heating and Domestic Hot Water systems through calculation and analysis of monitoring data[6]. Hu et al. evaluated nine solar hot water projects in Wuhan in three main aspects: the initial cost comparison and analysis, calculation and analysis of energy consumption and economic contrast and analysis[7].

There are lots of problems in the long term monitoring data onto solar hot water systems, which is difficult to learn the realistic effect of solar hot water systems. So the objective of this paper was to study the long term monitoring data onto the related projects of solar hot water systems, finally to summarize some evaluation indicators and set up a set of evaluation system for solar hot water systems in order to evaluate the performance of solar hot water systems in realistic operation.

2. DATA SUMMARIZATION

2.1 Basic situation of Jiangsu solar energy

In this paper, we do some relevant analysis on the solar radiation of Jiangsu province. Through the field actual measurement of six typical projects, we get the following results: the annual solar radiation distribution of Jiangsu province is shown in Table 1, and solar radiation is divided into four seasons, as shown in Fig. 1.

Table. 1. Solar radiation intensity in different areas of JiangSu

Solar radiation intensity	<8 MJ/m^2		8~13 MJ/m^2		13~18 MJ/m^2		>18 MJ/m^2		Total
	Days	Mean	Days	Mean	Days	Mean	Days	Mean	
NanJing	129	3.12	76	10.48	87	15.53	73	20.74	11.11
WuXi	107	5.22	78	10.63	115	15.54	65	19.83	12.22
YangZhou	102	4.28	96	10.76	89	15.38	78	20.50	12.16
HuaiAn	105	3.58	83	10.67	124	15.58	53	19.47	11.57
JiangSu	113	4.00	81	10.61	103	15.53	68	20.18	11.74

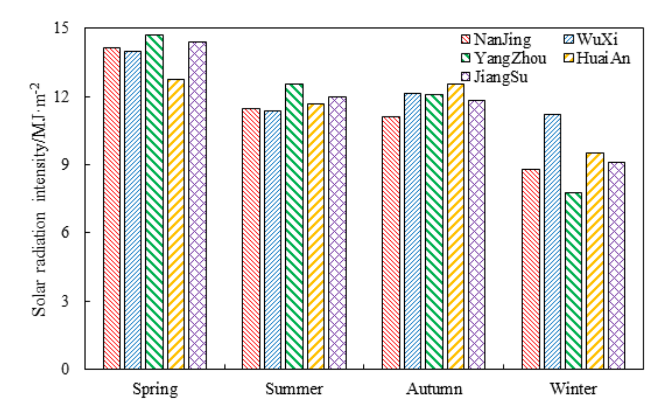


Fig. 1. Variation trend of JiangSu solar radiation intensity in the four seasons

From Table 1, we know in a whole year, the days that daily solar radiation intensity is less than 8 MJ/m^2 are the most, the days that daily solar radiation intensity is more than 18 MJ/m^2 are the least, and the annual daily solar radiation intensity is 11.74MJ/m^2, the totally annual solar radiation intensity is 4285MJ/m^2. So Jiangsu belongs to the fourth category. The solar radiation condition of Jiangsu is connected with local climatic characteristics. As Figure 1 shows, in a whole year, the solar radiation of spring is the greatest and winter is the smallest. The solar radiation appears a decreasing trend from spring to winter, not logical thinks that the solar radiation of summer is the greatest. Since summer plum rain season is long in the hot summer and cold winter area and the solar radiation of summer is worse than spring. The solar radiation of winter is relative low, so it is not suitable for solar energy in winter. The key of improving annual solar power system efficiency is how to maintain a high temperature of solar water heating system and keep it efficient when the solar radiation is low.

2.2 Measurement methodology

2.2.1 Typical system

Contents of investigation contain basic information about architecture, major equipment, system principle diagram, operation strategy and so on. Contents of field test to contain test time, outdoor temperature, solar radiation intensity, inlet temperature of solar collecting system, outlet temperature of solar collecting system, water temperature of heat collection tank and so on.

The solar water heating system chart is shown in Fig. 2, major measuring points are marked in the figure.

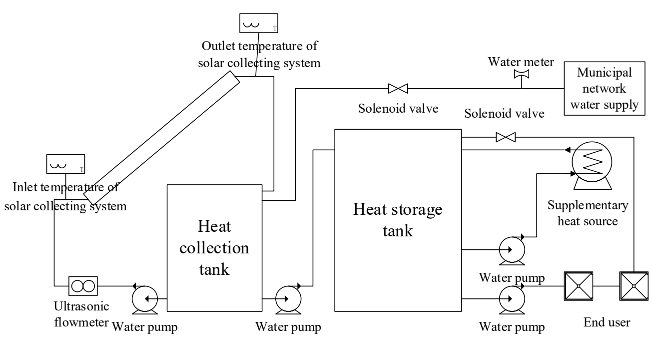


Fig. 2. The typical solar water heating system chart

Since the water flow of solar heating system is small and not constant, the water-flow data onto solar heating system is inaccuracy. Meanwhile the water-flow data onto solar heating system exists a lot of problems with acquisition process. So we could not calculate the accurate parameter of heat-collecting capacity by the water-flow, inlet and outlet temperature of solar collecting system. The measurement of water temperature is relatively simple, stable and accurate. Therefore in this paper, we calculate and analyze the related evaluation indexes based on the water temperature data, and the computing method of major evaluation indexes is as follows.

(1) Daily accumulated solar irradiation

The accumulated solar irradiation on the lighting surface of solar thermal collector during one day:

$$H = \left(\sum S \cdot t_i\right) / 10^6 \tag{1}$$

(2) Heat gain of solar thermal collector

The useful energy supplied by solar thermal collector in solar heating system:

$$Q_j = \left[\left(T_2 - T_1\right) \cdot V_s \cdot C_{pw} \cdot \rho_w\right] / 10^3 \tag{2}$$

(3) Energy consumption of supplementary heat source

The energy consumption of supplementary heat source of solar heating system:

$$Q_b = \left[\left(T_3 - T_2\right) \cdot V_s \cdot C_{pw} \cdot \rho_w\right] / 10^3 \tag{3}$$

(4) Heat loss coefficient of heat storage tank

The representative parameter of thermal insulation properties in heat storage tank:

$$U_{SL} = \frac{\rho_w c_{pw}}{\Delta \tau} \ln\left[\frac{T_4 - T_{as(av)}}{T_5 - T_{as(av)}}\right] \tag{4}$$

(5) Heat collecting efficiency

The ratio of useful heat gain of solar heating system and the daily accumulated solar irradiation during test period:

$$\eta = \frac{Q_j}{A \cdot H} \times 100\% \tag{5}$$

(6) Solar fraction

The ratio of energy supplied by solar energy and system demand energy:.

$$f = \frac{Q_j}{Q_z} = \frac{Q_j}{Q_j + Q_b} \times 100\% \tag{6}$$

2.2.2 Testing data

In this paper, we made the field research and measurement of typical projects of solar hot water in order to know the actual usage of solar water heating system in Jiangsu province. The data contain two types: field tests of typical working conditions and long-term operating data of monitor platform. The location distributions of these solar hot water projects are shown in Fig. 3.

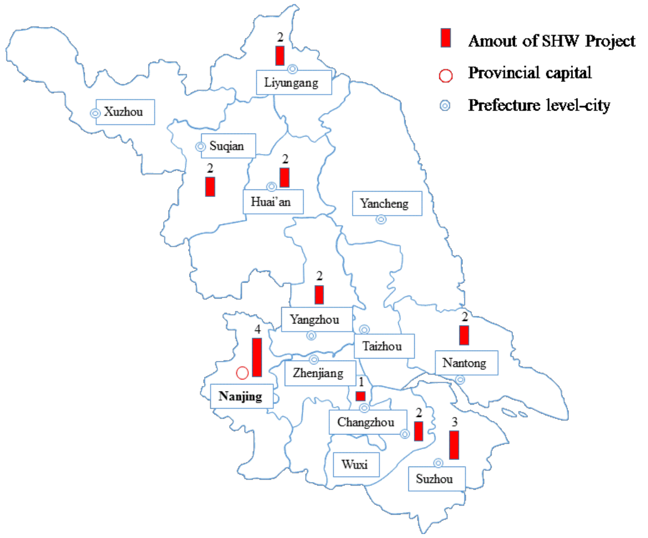


Fig. 3. The location distributions of solar hot water projects

In this paper, we chose 15 projects to make measurement of typical working conditions, of which we made measurement of one typical day about 13 projects and four typical days about 2 projects. And we chose 7 typical projects in monitor platform of Jiangsu renewable energy source to analyze and calculate. These projects run time span is more than one year, which cover three areas of central Jiangsu, South Jiangsu and northern Jiangsu and major building types of hospital, school, residence and so on.

3. PERFORMANCE EVALUATION OF SOLAR HOT WATER

There are two energy balance systems in solar thermal systems, as follows.

Solar collecting system: Solar irradiation = Heat-collecting capacity + Heat-collecting loss

Using heat system: Heat-collecting capacity + Concurrent heating capacity = Using heat capacity + Heat accumulation loss + Circulation heat loss

We can use energy flow diagram to show the process, as shown in Fig. 4.

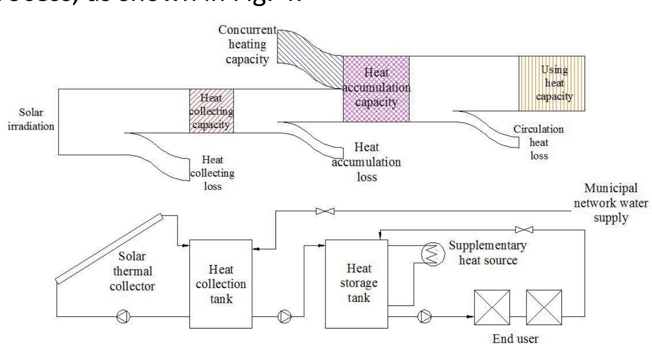


Fig. 4. The solar water heating system energy flow diagram

From Figure 4, we can know the final useful energy is using heat. Modeled after conception of EER (energy efficiency ratio), **we come up with the index of COP_s (solar hot water using coefficient of performance) to evaluate the effect of solar thermal systems,** which definition is as follows: it shows the using coefficient of solar heating system, which is the ratio of using heat of solar collecting system and the energy consumption of supplementary heat source.

$$COP_S = \frac{Q_y}{Q_b} \tag{7}$$

From the energy flow diagram, we can know the determinant of using heat is solar irradiation. So in order to analyze long-term operating data, we use the method that is analyzing the changing situation of COP_s by dividing different intervals of solar irradiation to evaluate the using effect of solar water heating system. According to government standard, the interval division of Jiangsu solar irradiation is adopted in the following four standards:(1) H < 8 MJ/(m^2·d);(2) 8 MJ/(m^2·d) ≤ H < 13 MJ/(m^2·d);(3) 13 MJ/(m^2·d) ≤ H < 18 MJ/(m^2·d);(4) 18 MJ/(m^2·d) ≤ H.

Therefore the post-evaluation method based on energy balance is used to evaluate the using effect of solar water heating system by analyzing COP_s of solar water heating system in different intervals of solar irradiation during a whole year. When the COP_s is high in the interval of 13 MJ/(m^2·d) ≤ H < 18 MJ/(m^2·d) and the other interval of 18 MJ/(m^2·d) ≤ H, the solar water heating system runs well.

4. RESULTS AND DISCUSSION

4.1 Variation rules of heating temperature rise

We obtain the typical annual variation rules of heating temperature rise of long-term projects from A to D by the pooled analysis of heating tank temperature, as shown in Fig. 5.

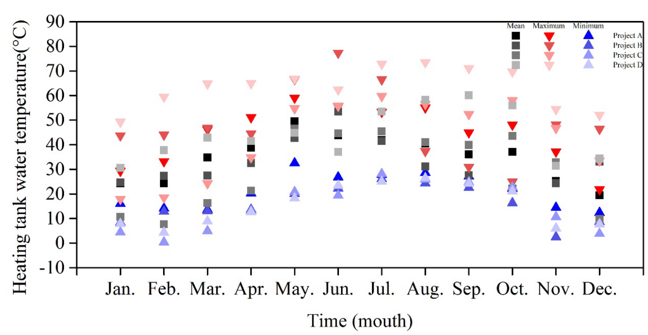


Fig. 5. The heating tank water temperature data of four projects from A to D

From Fig. 5, we can know the average heating tank temperature of different projects is about 30°C, which the temperature of summer is high than the other seasons. The variation range of heating tank temperature is between 15°C and 45°C, and the heating tank temperature in summer is 60°C, which means the heating tank temperature maintains a high level, but cannot satisfy the needs of using water temperature in a whole year.

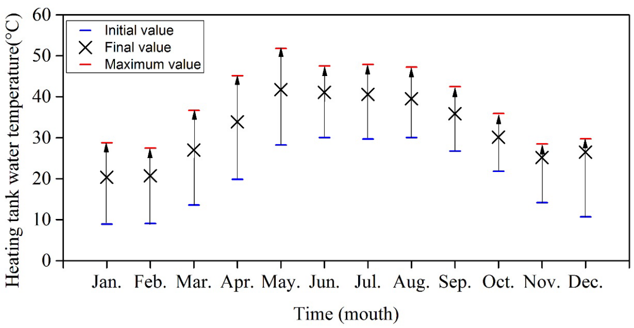


Fig. 6. The variation rules of monthly heating temperature rise of projects from A to G in a typical year

We obtain the variation rules of monthly heating temperature rise of projects from A to G in a typical year by the pooled analysis of variation on heating tank temperature in daytime, as shown in Fig. 6. In summer, the initial heating tank temperature is about 30°C, which is relatively high. In winter, the initial heating tank temperature is about 10°C, which is relatively low. In spring and summer, the maximum heating tank temperature rise is about 25~30°C, and in autumn and winter, which is about 15~20°C. The finishing heating tank temperature is high in summer, which is about 45°C and it can satisfy the needs of most users. The finishing heating tank temperature is low in autumn and winter, which is about 30°C and it needs to use supplementary heat source for concurrent heating. In general, the heating tank heat collecting capacity of most projects is relatively good at spring and summer, which is relatively bad at autumn and winter in whole year operation.

We obtain the variation rules of yearly heating temperature rise of projects from A to G by the pooled analysis of long-term data onto existing test years, as shown in Fig. 7. The average maximum heating temperature rise of different projects is about 20°C, and which of project G is more than 30°C. The average finishing heating temperature of different projects is about 30~40°C. The average finishing heating temperature of project A, B, E and F is close to the maximum heating tank temperature, which means the heat preservation effect of heating tank is better. The average finishing heating temperature of project C, and G have relatively large difference to the maximum heating tank temperature, which means the heat

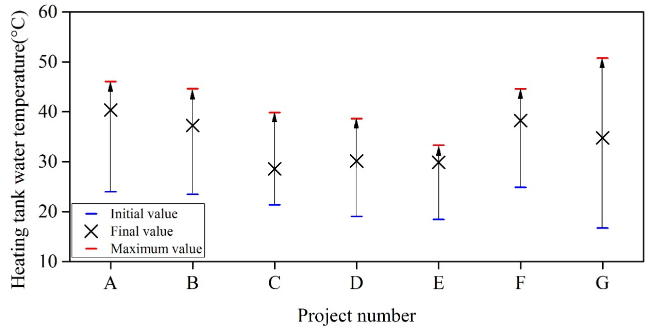


Fig. 7. The variation rules of heating temperature rise of projects from A to G

preservation effect of heating tank is worse.

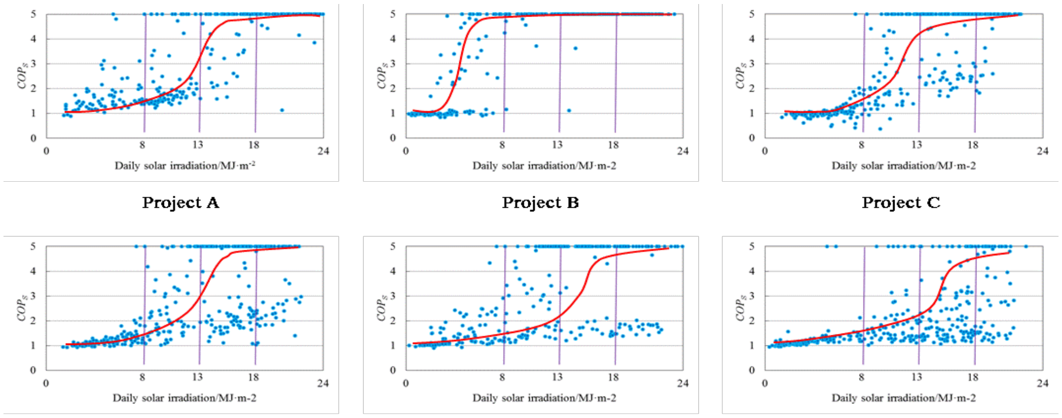
4.2 Year round evaluation based on COP_s

We obtain the changing situation of COP_s based on different solar radiation intensity by the pooled analysis of COP_s of six projects (project F does not have the data of solar radiation intensity), as shown in Fig. 8.

From Fig. 8, we can know when daily solar radiation intensity is less than 8 MJ/m^2, the COP_s is from 1 to 2, when daily solar radiation intensity is more than 8 MJ/m^2, the COP_s shows larger trend, when daily solar radiation intensity is more than 18 MJ/m^2, the COP_s peaks, which means there was a positive correlation between COP_s with daily solar radiation intensity.

If we fit the curve by using the change law of COP_s, we can find the slope of the curve has a point of discontinuity, when the point of discontinuity is in the top and the curve is smooth, the total COP_s is high and the solar energy system using good in a whole year, such as projects B, C, E, which means the use ratio and energy efficiency of solar energy is high, and solar energy systems are suitable for these projects. Otherwise the point of discontinuity of projects A, D, G is in the back and the curve is steep, which shows only the use ratio of solar energy is high when daily solar radiation intensity is high. So the annual energy efficiency of solar energy is not high and solar energy systems are not suitable for these projects.

By means of analyzing long-term data, we can know when heating effective temperature rise is more than 20°C, the finishing heating tank temperature is more than 45°C, and solar energy systems can satisfy the basic operating requirements. When the solar fraction is more than 50% and COP_s is more than 1.5, the solar water heating system has good usage effect. Some projects do not meet these requirements, which reason is that when daily solar radiation intensity is low, the heat-collecting capacity is insufficient and the system heat loss is too much. So we need to use much supplementary heat source of concurrent heating.



Project A Project B Project C
Project D Project E Project G

Fig. 8. The changing situation of COP_s based on different solar radiation intensity of six projects

5. CONCLUSION

According to the measured data onto typical projects, the annual total solar radiation in Jiangsu province is about 4285MJ/m^2, which is at the junction of three types of regions and four types of regions. The solar radiation presents the characteristics of seasonal distribution inequality. In spring, the average daily solar radiation intensity is the best, 13.86 MJ/m^2. In winter, the average daily solar radiation intensity is the least, 9.26 MJ/m^2. The solar radiation intensity is the direct acting factor of heat-collecting capacity. The main reason of low energy efficiency of solar water heating system in autumn and winter is solar radiation seasonal distribution inequality.

Through the analysis of long-term operating data, the finishing heating tank temperature of different seasons is very different. The temperature of most projects is more than 50°C in summer and is less than 30°C in winter. The prevailing problem is summer overheating and winter insufficient.

Through comprehensive assessment of annual operation efficiency of solar water heating system, the annual COP_s is about 1.5, the COP_s of some projects are less than 1.35. According to the analysis of typical working conditions and long-term operating data, the main reasons for low COP_s are as follows: (1) The solar radiation intensity has a significant impact on heat-collecting capacity. When daily solar radiation intensity is less than 8 MJ/ m^2, we need to use supplementary heat source. (2) In autumn and winter, the solar radiation is lower, heat-collecting capacity is insufficient and heat dissipating capacity is big. So the initial heating tank temperature is less than 20°C, the finishing heating tank temperature is less than 30°C and we need to use much supplementary heat source of concurrent heating. (3) The form of heat collection and circulation of the collective solar hot water systems leads to much heat loss.

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