Thermal Performance Test for Centralized Domestic Solar Water Heating System

Jiayu Guo  
School of Environment and Energy Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, Beijing, China

Bin Hao  
Shenzhen Institute of Building Research Co. Ltd, Shenzhen 518049, Shenzhen, China

Chen Peng, Shanshan Wang  
Center of Energy Efficiency in Buildings, Beijing 100835, Beijing, China

Abstract
This article conducted an investigation on centralized domestic solar water heating systems and test data during operation, thereby analyzing the shortcomings in the existing test methods such as incomplete description of the system’s heat quantities, lack of comprehensive consideration of thermal performances, and inconsistencies between test results and actual results. To address these problems, a novel testing method for centralized solar water heating systems was proposed, which was oriented towards the system’s actual operating performances and identified specific testing parameters and methods for two different types of systems. Finally, a case study was performed to verify the effectiveness of the proposed method, which aims to provide reference for further engineering tests and evaluations.

Key words: Domestic Solar Water Heating System, Performance Test Method, Thermal Performances; Energy Consumption in Operation, System Evaluation

1. INTRODUCTION

Owing to advantages, such as energy conservation and environmental friendliness, domestic solar water heating systems are widely used throughout China. In order to evaluate the practical effects of their application, more data should be acquired based on certain testing methods. Currently, the engineering test standards for solar water heating systems include Technical Code for Solar Water Heating System of Civil Buildings (GB50364-2005), Evaluation Standards for Application of Renewable Energy in Buildings (GB/T50801-2013), and Evaluation Standards for Application of Solar Water Systems in Civil Buildings (GB50604-2010). Testing standards regarding the system’s critical components include All-Glass Evacuated Solar Collector Tube (GB/T17049-2005), Evacuated Tube Solar Collectors (GB/T17581-2007), and Test Methods for Thermal Performances of Domestic Solar Water Heating Systems (GB/T18708-2002), and Assessment Code for Performances of Solar Water Heating Systems (GB/T 20095-2006). As stipulated in Assessment Code for Performances of Solar Water Heating Systems (GB/T 20095-2006), the system test should include assessments of thermal performances, safety performances, critical components, system appearance, etc.

A great deal of research has been conducted on the engineering of solar water heating system tests. An investigation on different systems in several regions, and concluded that different test methods should be adopted according to specific locational conditions, i.e., the test methods should be refined according to their usage patterns (Chen et al., 2015). Some researchers tested the thermal performances of split-type solar water heating systems in Hangzhou, China, and found that some systems, although exhibiting high heat collecting efficiency, were lacking in solar fractions (Liao, Wang and Cui, 2011).

Solar water heating systems are an engineering application in the solar photo-thermal domain in which heat collection, supply, and storage are involved. As such, its thermal performance can be regarded as the system’s essential factor. This article focused on testing of centralized solar water heating systems’ thermal performances. In order to further identify the systems, they can be classified according to the positions of the heat collectors and the auxiliary heat sources, i.e., the systems can be classified into the following two types: centralized-collector/centralized-auxiliary-heating (CCCAH) systems, and centralized-collector/distributed-auxiliary-heating (CCDAH) systems.
2. Existing problems in current testing methods

2.1. Incomplete Description of the System

A typical solar water heating system mainly includes a solar collecting system, heating supply system, and control system. However, according to the testing contents specified in Evaluation Standards for Application of Renewable Energy in Buildings, only the heat gain of the solar collecting system is used as the index for tests and evaluations. However, this index cannot give a full description of the system, as shown in Table 1.

Table 1. Summary of testing contents of solar water heating systems

<table>
<thead>
<tr>
<th>Calculation indexes</th>
<th>Test indexes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat gain of the solar collecting system</td>
<td>Temperature at the inlet of the solar heating system</td>
</tr>
<tr>
<td>Conventional energy consumption by the system</td>
<td>Temperature at the outlet of the solar heating system</td>
</tr>
<tr>
<td>Heat loss coefficient of the hot water storage tank</td>
<td>Flow of the solar heating system</td>
</tr>
<tr>
<td>Efficiency of the solar collecting system</td>
<td>Environment temperature</td>
</tr>
<tr>
<td>Solar fraction</td>
<td>Environment air velocity</td>
</tr>
<tr>
<td>Substitution amount of conventional energy (converted by a ton of standard coals)</td>
<td></td>
</tr>
<tr>
<td>Project’s cost-benefit ratio</td>
<td></td>
</tr>
</tbody>
</table>

According to the requirements of thermal performance testing in Assessment Code for Performance of Solar Water Heating Systems (GB/T20095-2006), the heat storage effect of the hot water storage tank is generally measured using a drainage method that ensures heat gain of the solar collector. During the test, the water storage tank is firstly filled with cold water in daylight. The large-temperature-difference heat transfer leads to an increase of the heat collector’s heat exchange. Using the drainage method means that the contribution of the solar collecting system on energy input is overestimated. (Yao et al. 2015; Cao , Gao and Wang, 2015; Ding, Dai and Li, 2015)

2.2. Lack of Comprehensive Consideration of the Quantity Of Heat

For a system, the quantity of heat includes the heat gain of the solar collecting system, the heat consumption by the auxiliary heat source, the heat consumption by users, and the system’s heat dissipation. Nevertheless, only the first item is tested in most systems, while the contributions of the latter three factors are usually ignored.

- Heat consumption by the auxiliary heat source

Since a solar heating supply is generally not stable, conventional heat sources should be provided for supplementary water heating. The auxiliary heat sources greatly affect a system’s energy conservation performance strongly (Yu et al. 2016). Other studies have demonstrated that, during the night or on rainy days that do not have solar radiation, solar energy should be combined with an auxiliary heat source. In these cases, the type and contribution ratio of the supplementary heat source are important factors that directly affect a solar system’s energy consumption (He et al, 2009).

However, full attention is not given to auxiliary heat sources in the existing testing methods. The saved conventional energy is generally calculated based on the heat gain of the solar collecting system, leading to an overestimation of the substitution amount of conventional energy. This means that the heat gain of the solar collecting system is greater when more solar energy collection panels are used, and accordingly, the substitution amount of conventional energy is larger.

- Heat consumption by users

Heat consumption by users is affected by multiple factors. The heat consumption by users is not fixed, and inconsistencies are common between heat supply requirements and the design value (Wang, 2003). They also investigated water usage characteristics in many regions and concluded that seasonal factors induce variations of water load within the same region, as shown in Figure1 (Wang et al. 2015)
In most water heating systems, the design and practical operation settings were set based on the data provided by the manufacturer rather than the region the heat collectors were installed. The setting of these parameters relied only on experience and thus lacked scientific support (Lu, 2008). Figure 2 shows the variations of hot water loads used in a day.

Additionally, the existing tests are always conducted during the period of four hours before high noon to four hours after high noon. As shown in Figure 2 (Wang et al. 2015), the test periods are inconsistent with the users’ water consumption periods, i.e., the effects of the users’ actual water consumption periods on the system’s operation are not taken into account, and thus the acquired heat consumption by the users is not very accurate.

System’s heat dissipation

To facilitate the study on domestic water heating systems’ operating energy consumption, this article used heat consumption by the end users as the standard, and conducted standardization on the four tested parts of energy quantities including those from three CCCAH systems and one CCDAH system. During the standardization, the heat consumption by the end users was set as 100, and the results after standardization are shown in Table 2.

Table 2. Results of different water heating systems’ operating energy consumptions

<table>
<thead>
<tr>
<th>Project</th>
<th>Heat gain of the solar collecting system</th>
<th>Energy consumption by the auxiliary energy source</th>
<th>Heat consumption by the end users</th>
<th>System’s heat dissipation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCCAH system</td>
<td>Fengtai</td>
<td>100</td>
<td>112</td>
<td>100</td>
</tr>
<tr>
<td>Xizhimen</td>
<td>295</td>
<td>82</td>
<td>100</td>
<td>277</td>
</tr>
<tr>
<td>Chifeng</td>
<td>100</td>
<td>79</td>
<td>100</td>
<td>79</td>
</tr>
<tr>
<td>CCDAH system</td>
<td>Tianjin</td>
<td>41</td>
<td>71</td>
<td>100</td>
</tr>
</tbody>
</table>

According to the test data listed in Table 2, the following conclusions were reached. The heat dissipation from the CCCAH system could not be ignored. Among the three CCCAH systems tested, the heat dissipation from two systems exceeded the heat consumption by the end users, yielding serious heat losses. Taking a system in Xizhimen District, Beijing, China, as an example, the heat dissipation induced by circulating a day’s hot water supply for 24 hours used 73.5% of the total heat gain, which far exceeded the users’ effective heat gain. In regards to a system in Chifeng, Inner Mongolia, China, owing to the adoption of a regular hot water supply, the
system’s heat dissipation equaled 44.1% of the total heat gain, meaning nearly half of the heat losses were not utilized. Accordingly, although the heat gain of the solar collecting system can satisfy the heat consumption by the end users, a great amount of heat should be provided by the supplementary heat sources to ensure a hot water supply. For the CCDAH system, which generally adopts the strategy of a regular hot water supply, the heat loss by dissipation equaled 11% of the produced heat. On this system, the auxiliary heating devices are installed in indoor water tanks, which the user can open in accordance with their requirements; this promotes effective utilization of the auxiliary heat system.

Thus, heat loss induced by the dissipation of a CCDAH system is smaller than that of a CCCAH system. Differences in system configurations lead to differences in the system’s heat dissipation performances. Therefore, different testing methods should be designated for different systems.

2.3. Poor Performances in Practical Applications

In China, 84% of photo-thermal demonstration projects are now used for the supply of domestic hot water, and the solar fractions of the projects in various provinces can reach approximately 60%. These demonstration projects have gained beneficial achievements in energy conservation; however, these are still many problems in the practical application of solar hot water systems.

The power consumption during the practical application of the projects whose solar fractions were all over 75% was quite high, with the average daily power consumption for each house in the range of 2-4 kWh (Chen et al. 2015). Some users also reported a series of problems such as low water temperature, poor stability, and high water prices. Property management companies also reported difficulties in system maintenance, charging, and management. Some property developers even installed the solar water heating systems by means of lease to fraudulently obtain the governmental subsidies (Deng et al. 2014).

Conclusively, the current testing methods cannot accurately reflect the thermal performances of solar water heating systems. Some corrections should be made to propose a novel testing method for providing guidance for engineering testing to solve these problems.

3. Brief introduction of testing method for system thermal performances

3.1. Theoretical Basis

The proposed testing method focused on the system’s practical operating performances and used three evaluation indexes. As shown in Eq. (1), this method adopted the thermal balance of two input and two output as the theoretical basis and thus fully described and accurately reflected the system’s thermal performances for testing.

![Figure 3. Illustration of system configuration](image)

For a centralized domestic solar water heating system, the following expression was constructed to ensure the system’s energy balance:

\[ Q_e + Q_{aux} = Q_u + Q_{hl} \]  

(1)

where \( Q_e \) denotes the heat gain of the collecting system, \( Q_{aux} \) denotes the energy consumption by the auxiliary energy supply, \( Q_u \) denotes the system’s heat dissipation in operation, and \( Q_{hl} \) denotes the heat consumption by the end users.

It should be noted that the heat dissipated from the heat collectors, heat circulation pipelines, and water tanks. In other words, the heat losses in the solar collecting systems only equaled 10%-25% of the total heat dissipation, which was less than the ratio of heat dissipated from the circulation pipelines in the heating supply system. This indicated that the heat that dissipated from the circulation pipelines should be afforded great
importance in testing. The utilization ratio of solar energy, the effective substitution ratio of conventional energy, and the system’s heat dissipation ratio were used as evaluation indexes in the proposed test (Liu et al. 2015). Equations (2)-(4) were the calculation formulas of these three indexes, in which the heat gain of the collecting system, the heat dissipation from the circulation pipelines, and the actual heat gain of the users were associated. Accordingly, the proposed tests focused on these three heat indexes, as follow:

\[
A_1 = \frac{(B_1-B_2)}{B_1} \quad (2) \\
A_2 = \frac{(B_1-B_2)}{B_2} \quad (3) \\
A_3 = \frac{B_3}{B_2} \quad (4)
\]

where A1, A2, and A3 denote the utilization ratio of solar energy, the effective substitution ratio of conventional energy, and the system’s heat dissipation ratio, respectively; B1, B2, and B3 denote the heat gain of the collecting system, the heat dissipation from the circulation pipelines, and the actual heat gain of the users, respectively.

3.2 A brief introduction of testing content

To make a test scheme, clear knowledge of the system’s configuration should be present, i.e., different test parameters and methods should be chosen for CCCAH and CCDAH systems. Figure 4 illustrates the specific procedure of the test.

![Figure 4. Illustration of the test’s procedure](image)

- Test for CCCAH system

<table>
<thead>
<tr>
<th>Table 3. Testing contents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat gain quantity</strong></td>
</tr>
<tr>
<td>Heat gain of the collecting system</td>
</tr>
<tr>
<td>Heat consumption by the users</td>
</tr>
</tbody>
</table>

a) Heat gain of the solar collecting system

In the present study, it was assumed that the heat collectors operated at the rated efficiency. Based on the typical annual meteorological parameters, the heat gain of the collecting system was calculated by the following:

\[
Q_i = \left( \sum \phi \right) \cdot A \cdot \eta_c \cdot T = \sum \left( \phi + \phi_s \cdot \cos \frac{\pi}{4} \right) \cdot A \cdot \eta_s \cdot T 
\]

where \( A \) denotes the total area of the heat collectors (m2); \( \phi \) denotes the overall radiation intensity of the solar panels (W/m2); \( \phi_s \) denotes the scattered solar radiation (W/m2); \( \phi_d \) denotes the direct solar radiation (W/m2); \( \eta_c \) denotes the annual mean heat collecting efficiency of the heat collectors; and \( T \) denotes the heat
collecting duration (s). Generally, $\eta_{cd}$ was set according to the heat collector’s rated heat collection efficiency and ranged from 0.25 to 0.5.

b) Energy consumption by the auxiliary power source

In this study, the energy consumption by the conventional power source was calculated by the data listed on the gas or electricity bills.

c) Heat consumption by the users

The heat consumption by the users was calculated by the heat dissipation by the domestic hot water, which was calculated by the domestic water consumption as shown on the water meter. The specific formula was as follows:

$$Q = C \cdot m \cdot \Delta t \quad (6)$$

where $c$ denotes the hot water’s specific heat capacity ($\text{kJ/(kg \cdot °C)}$); $m$ denotes the amount of cold water (L); and $\Delta t$ denotes the temperature difference between the domestic hot water and cold water (°C). According to the specifications in Code for Design of Building Water Supply and Drainage (GB 50015-2003), the local minimum monthly average water temperature was set as the cold water temperature.

d) Heat dissipation from the circulation pipelines

The heat dissipation from the circulation pipelines was calculated according to the principle of energy balance, or verified by the following cylindrical-wall heat dissipation model of the CCDAH system.

- **Test for the CCDAH system (direct or indirect water intake)**

<table>
<thead>
<tr>
<th>Calculated heat quantity</th>
<th>Test heat quantity</th>
<th>Test period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat gain of the collecting system</td>
<td>Heat dissipation from the circulation pipelines</td>
<td>Test period should be continuous and no less than 24 hours. The step size in test was set as 5 minutes.</td>
</tr>
<tr>
<td>Heat consumption by the auxiliary power source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat consumption by the users</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) Heat gain of the collecting system

For the CCDAH system, the calculation method of the heat gain of the collecting system was the same as that for the CCCAH system.

b) Heat consumption by the users

Based on the investigation results of the user’s hot water consumption, the domestic hot water consumption was estimated by 32 (L/day*(number of people)). The heat consumption of the users ($Q_k$) was calculated by the following:

$$Q_k = c \rho V \Delta t \quad (7)$$

where $V$ denotes the hot water consumption by each person every day (L) and $\Delta t$ denotes the temperature difference between the domestic hot water and cold water (°C). As stated above, the local minimum monthly average water temperature was set as the cold water temperature.

c) Energy consumption by the auxiliary power source

This value was difficult to acquire through direct calculations and needed to be tested. When electricity was used as the auxiliary heat source, the electric quantity was measured by the socket-type electric energy meter with the function of continuous recording. Thus, to acquire the energy consumption of the auxiliary power source, electric energy meters should be installed in each house. However, since the auxiliary power sources were used in each house, large differences in use existed among different households. In addition, the tests were not very convenient. When gas was used as the auxiliary heat source, the auxiliary energy consumption was difficult to acquire accurately without the installation of separate meters. Therefore, it was recommended that priority not be given to the measurement of auxiliary energy consumption.

d) Heat dissipation from the circulation pipelines

Thermographs were installed along the pipelines at the water outlets of the hot water storage tanks and at the tube wells. It was assumed that the temperature of the pipeline near the water outlet of the hot water storage tank approximately equaled the temperature at the water outlet. The thermal insulation materials along the pipelines were first stripped and then the thermocouple was attached closely to the metal pipe walls. Finally, the pipelines were rewrapped with thermal insulation materials and fixed. The temperature variations were continuously recorded for at least 24 hours.

According to the formula for the cylindrical-wall heat dissipation model, the heat dissipation from the unit pipeline ($q_l$, W/m) was calculated by the following:
\[ q_i = \frac{(t_w - t_f) \times \pi}{2hr_1 + \frac{1}{2h_\lambda_1} \times \ln\left(\frac{r}{r_1}\right) + \frac{1}{2h_\lambda_3} \times \ln\left(\frac{r}{r_3}\right) + \frac{1}{2h_\lambda_3} \times \ln\left(\frac{r}{r_3}\right)} \] (8)

Where \( t_w \) denotes the temperature inside the stand pipes (°C); \( t_f \) denotes the air temperature in the tube well (°C); \( h \) denotes the air convective heat transfer coefficient (w/m²·k); \( r \) denotes the pipe radius (m); and \( \lambda \) denotes the thermal insulation material heat conductivity coefficient (W/m·K).

According to the piecewise calculation formula, the heat dissipation from the circulation pipelines \((Q, w)\) was calculated by the following:

\[ Q = q \times l \] (9)

Where \( q \) denotes the heat dissipation from the unit pipeline (w/m) and \( l \) denotes the overall length of the circulation pipeline (m).

### 3.3 Brief Summary

Compared to the existing testing methods, the proposed test method can give a more complete description of the system performances. Specifically, previous testing methods only focused on the measurement of the heat gain of the collecting system, while the proposed test method included the measurements of four parts of heat quantities and thus can more accurately reflect the actual energy consumption. Meanwhile, the acquired heat consumption by the users was closer to the actual results than the previous simulated results. Using the proposed testing method, the actual testing process was simplified and the test parameters were greatly reduced.

Admittedly, the proposed testing method also showed errors. For example, the heat gain of the collecting system was calculated based on the typical year’s meteorological parameters, which were somewhat different from the actual results.

### 4. A CASE STUDY

#### 4.1 Project Overview

The verification testing was conducted in a certain residential quarter of Beijing, in which a forced-circulation CCCAH system installed in each building. Unit 1 of the #15 Building was selected as the test object. This tested system included 19 floors, each of which included 8 houses, i.e., 148 houses used this system, as shown in Figure 5. The flat-plate solar thermal collectors, with a total area of 242 m² and an incline angle of 42°, were used on the roof. A centralized hot water storage tank (with a volume of 25 m³), a wall-mounted gas-fired boiler (with a power of 40 kW), and a fixed-frequency water pump (with a fixed frequency of 700 W) were deployed in the machine room on the roof, which were used for maintaining circulation among the system’s heat collecting side, auxiliary heating side, and heat supply side.

![Figure 5. Realistic picture of selected residential quarter](image)
The temperature-difference circulation strategy was used on the heat collecting side. The 24-hour constant-temperature water supply circulation strategy was employed on the user side. Specifically, the hot water temperature was maintained at 40°C in summer and 42°C in winter. The temperature on the auxiliary heating side was controlled to keep the tank temperature unchanged. The heat collecting side in this system was only used in non-heating seasons, while the wall-mounted gas-fired boiler was used in heating seasons to ensure the supply of domestic hot water.

4.2 Test Scheme

As stated previously, a forced-circulation CCCAH system (direct water intake) was selected for analysis. In addition, gas was selected as the conventional heat source while a wall-mounted gas-fired boiler was installed in the machine room on the roof. Therefore, the auxiliary heat consumption was calculated according to the gas meter reading and water consumption data for no less than one year.

1) Heat gain of the collecting system
By examining the heat collector’s various parameters, the heat gain of the collecting system was calculated to be 406.1 GJ.

2) Energy consumption by the auxiliary power source
Figure 7 shows the daily natural gas consumption of the solar water heating system during the test period of March 25th to November 17th, 2010. The data was provided by the property management company. Through calculation, the daily average natural gas consumption during the test period was determined to be 456 GJ.

2) Heat consumption by the users
According to the total hot water consumption during the test period (same as above) provided by the property management company, as shown in Figure 8, the heat consumption by the users was calculated to be 408 GJ.
4) Heat dissipation from the pipelines
Heat dissipation from the pipelines was calculated based on the heat equilibrium principle or the cylindrical-wall heat dissipation model.

4.3 Results and discussion
According to the above-described testing method, each heat quantity was calculated, as shown in Table 5.

<table>
<thead>
<tr>
<th>Table 5. Calculation results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat gain of the system (GJ)</td>
</tr>
<tr>
<td>Heat gain of the collecting system</td>
</tr>
<tr>
<td>Energy consumption by the auxiliary heat source</td>
</tr>
<tr>
<td>Heat dissipation</td>
</tr>
<tr>
<td>Consumption by the users</td>
</tr>
<tr>
<td>Heat dissipation</td>
</tr>
</tbody>
</table>

Based on the above heat quantities, the evaluation indexes were calculated, as listed in Table 6.

<table>
<thead>
<tr>
<th>Table 6. Calculated results of evaluation indexes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation index</td>
</tr>
<tr>
<td>Utilization ratio of solar energy</td>
</tr>
<tr>
<td>Conventional energy consumption ratio</td>
</tr>
<tr>
<td>system’s heat dissipation ratio</td>
</tr>
</tbody>
</table>

For a solar water heating system, the utilization ratio of solar energy and the effective ratio of the conventional energy should be no greater than 1, while the system’s heat dissipation ratio should be no less than 0. Furthermore, the greater the first two indexes, the better the performance; the smaller the last index, the better the performance. As shown in Table 6, this project shows great heat dissipation and conventional energy consumption, but a not high utilization ratio of solar energy. This deduction can be verified by the feedback from the project’s property management department. Even in the cases when the system did not operate in heating seasons, the price for heating a ton of water was 16 yuan, which far exceeded the cost of heating water using gas or an electric water heater.

5. CONCLUSIONS
To improve evaluation results of system applications, this article firstly analyzed the shortcomings in the existing testing method and thereby proposed a novel testing method for evaluating the performance of centralized domestic solar water heating systems. The primary conclusions are listed below.
1) The proposed testing method was oriented towards the system’s actual operating performances and focused on the energy consumption of the auxiliary power source.
2) Owing to the full consideration of the system’s multiple thermal performances, such as heat collecting, heat supply, and heat dissipation, the proposed testing method expanded the evaluation range of thermal performances.
3) Different test parameters and schemes were proposed for different types of systems.
4) According to the actual test results, the test data using the proposed method were closer to the actual results; additionally, the test parameters were more easily acquired.

This study can provide reference for improving the design of solar water heating systems and further promote the scientific development and application of solar water heating systems.
Acknowledgements

This work was supported by the National Key Technology Support Program (No.2011BAJ05B00).

REFERENCES