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Test method for evaluating and predicting thermal performance of thermosyphon solar domestic hot water system

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Abstract

A test method for evaluating and predicting the thermal performance of thermosyphon Solar Domestic Hot Water (SDHW) system was proposed. The evaluating mathematical model of SDHW system was developed based on the two-node theory - a SDHW system was divided into the solid part and the fluid part. By combining the dynamic energy conservation equations of the solid part and the fluid part, the evaluating mathematical model of SDHW system was derived. The model parameters have clear physical meaning which can be used to evaluate the SDHW systems. The evaluating mathematical model was further processed by using the Laplace transformation technique and the predicting mathematical model was then derived. The predicting model can be used to predict the thermal performance of SDHW system for short and long term period with flexible draw off load conditions. The experimental method was designed and experiments were carried out to validate the test method. The measured mean fluid temperature in the storage tank was compared to the predicted mean fluid temperature. The annual thermal performance prediction of the system with two draw off load conditions at different daily hot water consumptions was also carried out.

Key words: solar domestic hot water system; thermal performance prediction; Laplace transformation method; thermosyphon solar water heater

26 Nomenclature

27	A_a	Aperture area of solar collector (m^2)
28	A_t	Heat transfer area from absorber part to fluid part (m^2)
29	A_u	Heat transmitting surface area of solar collector (m^2)
30	c	Specific heat capacity ($J / (kg \cdot K)$)
31	F	Draw off mass fluid rate per collector aperture area ($kg/(s \cdot m^2)$)
32	F'	Collector efficiency factor (-)
33	U_L	Collector overall loss coefficient ($W/(m^2 \cdot K)$)
34	G	Total solar irradiance (W/m^2)
35	G_b	Beam irradiance (W/m^2)
36	G_d	Diffuse solar irradiance (W/m^2)
37	h	Heat convection coefficient $W/(m^2 \cdot K)$
38	K_b	Incidence angle modifier for beam irradiance (-)
39	K_d	Incidence angle modifier for diffuse radiation (-)
40	M	Mass(kg)
41	m	Mass per square meters (kg / m^2)
42	n	Number of times
43	P	Probability that the distribution of $F_{(1,n-2)}$ is greater than F
44	t	Time (s)

45	q_u	Heat flux per square meter (W/m^2)
46	Q	SDHW storage energy change (J)
47	Q_u	Heat flux (W)
48	T	Temperature (K)
49	Greek symbols	
50	Δ	Interval
51	τ	Time (s)
52	η	Efficiency (-)
53	$(\tau\alpha)_{en}$	Transmittance-absorptance product at normal incidence (-)
54	θ	Angle of incidence (degree)
55	Subscripts	
56	a	Ambient
57	avg	Average
58	b	Solid part of SDHW system
59	day	Average value of a day
60	f	Fluid part of SDHW system
61	main	cold water supply
62	max	Maximum value
63		
64		
65		

1 Introduction

Solar domestic hot water (SDHW) systems [1,2] are now widely used in various aspects of civil area throughout the world. Therefore quality certification and thermal performance evaluation are important both for manufacturers and consumers. Testing is the most important and credible method to rate and evaluate different SDHW systems. Many scholars have developed various testing theories/methods and each of them has its own focus [3–7]. Some methods are used as standards in different countries. Among these different theories/methods, there are two categories of methods that are most commonly used. One category is based on the linear relation between the effective heat gain Q and daily accumulated solar irradiation H , such as the International standard ISO 9459-2 [8], the Taiwan standard CNS B7277 [9], Swedish Council Report Document D11 [10], etc. The other category is the dynamic system test (DST) method mainly used in the international standard ISO 9459-5 [11].

1.1 The Q-H method

The standard ISO 9459-2 [12,13] is a typical testing method based on the linear relation assumption of the system heat gain Q and the 12 hours solar irradiation H . This method considers the SDHW as a black box system which can be seen as a whole heat transfer process. The test requires at least 6 days' one-day test, a short time mixing test and an overnight heat loss test. The one-day test is done independently starting with a tank filled with water at a specific temperature (T_{main}). The test should be operated for 12 hours: 6h before solar noon and 6h after, with the weather conditions recorded. Afterwards hot water draw-off with a volume corresponding to at least 3 times of the tank volume is taken with a specific flow rate and a cold water temperature of T_{main} . The effective heat gain of the whole day can be determined by the draw-off process. The one-day test is very strict. Results should be obtained for at least four different days with approximately the same values of $(T_{a(day)} - T_{main})$ and with solar irradiation evenly spread in the range 8 MJ/m² to 25 MJ/m². Furthermore two additional days should be tested with $(T_{a(day)} - T_{main})$ at least 9K above or below the values of $(T_{a(day)} - T_{main})$ obtained for the first four days. The value of $(T_{a(day)} - T_{main})$ should be in the range from -5K to +20K for each test

day. Results of the one-day tests are used to obtain the parameters of the Q - H model (a_1 a_2 a_3) and the parameters of the T - H model (b_1 b_2 b_3), see Eqs. (1) and (2).

$$Q = a_1 H + a_2 (T_{a(day)} - T_{main}) + a_3 \quad (1)$$

$$(T_{max} - T_{main}) = b_1 H + b_2 (T_{a(day)} - T_{main}) + b_3 \quad (2)$$

The model parameters a_1 a_2 a_3 and b_1 b_2 b_3 in Eq. (1) and Eq. (2) do not have clear physical meaning. To some extent, the parameters can be explained as follows: a_1 represents the ability of SDHW system to gain heat from daily irradiation, similar to the maximum efficiency of solar collector panel; a_2 reflects the system's ability to unify the initial water temperature and the ambient temperature, similar to the heat loss coefficient of solar collector; a_3 represents the heat capacity of the system's solid part. The model parameters b_1 b_2 b_3 also have similar meaning. Clearly, these model parameters can't rate different SDHW systems in an explicit way.

The mixing test requires that the tank should be preconditioned by hot water with temperature above 60°C. The collector should be shielded from the sun. A draw-off test is taken the same as the one-day test. The aim of the mixing test is to obtain a normalized draw-off profile used for calculating the long term performance and to determine a parameter expressing the degree of stratification in the tank.

The overnight test is carried out to determine the heat loss coefficient of the storage tank. The initial water in the storage tank should also be preconditioned to a uniform temperature above 60°C. After cooling period from 12 to 24 hours, the final mean temperature of tank water, the time duration and the average ambient air temperature during the test are recorded and used to determine the overnight heat loss coefficient.

With the model parameters, the draw-off profile of one-day test and the mixing test and the overnight heat loss coefficient determined by the tests, thermal performances of the SDHW system can be calculated day by day based on the weather condition and water load profile. The long term thermal performance of the SDHW system can be estimated by considering the daily energy gain, the overnight heat loss and the previous day's condition.

The aim of the Taiwan standard CNS B7277 [13,14] is to provide a rating method for thermal performance of thermosyphon SDHW system. The mathematical model uses the efficiency equation of a solar collector for reference, see Eq. (3). Eq. (1) is same as Eq. (3), if a_3 in Eq. (1) is set to zero for system operating under a steady state condition. η_0 is related to the solar energy absorption efficiency of the collector and U_s stands for the heat loss from the system to the ambient. It was found that U_s may have larger uncertainty and η_0 , U_s can be varied by changing the system designs with various M/A_c ratios. M is total mass of water in thermosyphon SDHW system and A_c is the collector area. Hung [14] proposed an improved method by solely selecting η_0 for performance rating and its value would not depend on M/A_c ratio. Then a heat loss test is carried out to obtain a cooling time constant instead of U_s .

$$\eta = \eta_0 - U_s(T_{main} - T_{a(day)}) / H \quad (3)$$

The ISO 9459-2 method can be used for long term performance prediction. But the test condition is very strict and the test period is expected to be very long. In addition, the method cannot be used to evaluate different SDHW systems based on the model parameters. The mathematical model is simple which does not describe the complicated heat transfer process in the system during test. The normalized draw-off profile is also roughly divided into two conditions. One is used for daily irradiation in the range of 9MJ/m²-16 MJ/m² and the other for a solar irradiation in the range 16 MJ/m²- 25 MJ/m². This may cause large errors in predicting system thermal performance both on daily and long term basis.

The CNS B7277 method can only rate SDHW system with two system parameters. It can't be used to predict daily or long term thermal performance of SDHW system.

1.2 The dynamic system method

The standard ISO 9459-5 describes a SDHW system by a plug flow store model in conjunction with the dynamic system testing method to predict its long term thermal performance. The operation of the SDHW system can be modeled by a partial differential equation [6]. Each term of the equation characteristically represents a certain sub-process of

the system. The aim of this dynamic method is to obtain these characteristic parameters in short time test which are used to predict the system's long term thermal performance.

The daily test contains two specific operation conditions: namely Test A and Test B. Test A needs at least three valid days to perform and is designed to keep the water at the collector inlet cold and test the system performance at high efficiencies while another three valid days are needed for Test B with the condition of hot inlet water temperature aiming to test the system performance at low efficiencies. Another test sequence is needed to determine the system's overall heat loss. The test should be carried out after two consecutive valid Test B days' operation. Afterwards the system is left to cool down naturally with the collector shielded for 36-48 hours.

After the required tests are finished and enough test data are collected, the model parameters can be identified by software using a unique Dynamic Fitting Procedure [15]. The long term thermal performance of SDHW system can be predicted by the model with the specific weather data and load profile as inputs.

The mathematical model of ISO 9459- 5 is a differential equation considering detailed heat transfer sub-processes in SDHW system. It is a precise equation to describe the system and the test requires fewer days. But the mathematical model is very complicated and the commercial program used to determine the model parameters is not open source. Therefore it is not clear how accurately the program can predict the thermal performance of SDHW system.

1.3 Comparison of the two standard test methods

Kaloudis [12] reported a quantitative comparison of the Q-H test method and the dynamic test method for a SDHW system. A relative error of 21% between the two results for the specific SDHW system was derived by experiments which showed a large uncertainty of using the two test methods. It is also further concluded that the Q-H test method is more beneficial to the manufacturers but needs long time testing while the dynamic test method is more flexible but the needs more demanding in terms of calculation.

The proposed test method is a preliminary research aiming to develop a simple but accurate mathematical model for evaluating and predicting SDHW system. The thermosyphon SDHW system was theoretically modeled and experimentally verified in this study. The designed experimental method and the calculation process are easily implemented and the results comparison shows satisfactory accuracy.

2 Theory and mathematical model

The theoretical model of thermosyphon SDHW system was specified in this section. The evaluating and predicting mathematical models were developed respectively. The parameters in the evaluating mathematical model can be determined by experiments which are used to evaluate the SDHW system. The predicting mathematical model is used to predict the thermal performance of SDHW system together with evaluating model parameters and weather data. The experimental method was designed and specified in section 4.

2.1 Theory and assumption

A typical evacuated all glass solar hot water system is investigated. It is usually composed of solar collector, storage tank, insulation, frame etc. An example of market product can be seen in Fig. 4 and the working principle of the natural heat convection is simply illustrated in Fig. 1. Therefore a SDHW system is more complex than a single solar collector. However, if the heat transfer of a SDHW system is considered - solar energy is absorbed by solar collector and then transferred to heat storage tank, it is obvious that the heat transfer mechanism of the SDHW system is similar as a single solar collector. Therefore the main assumption is assumed that a thermosyphon SDHW system can be simply seen as a solar collector with large thermal capacity. The large thermal capacity is mainly contributed by the water in the storage tank. Based on the main assumption, the two-node theory [16–19] which is widely used in solar collector testing area can be implemented to analyze the heat transfer process of the SDHW system. According to the two-node theory, a SDHW system is divided into the solid part and the fluid part. The solid part includes the solid components which directly contact the fluid (water in this case) like the solar collector and the storage tank and the solid components which have no direct contact

with the fluid but are influenced by the heat conduction like the insulation and part of the frame. The thermal capacity of the solid part is lumped and referenced to an assumed collector absorber temperature T_b . The fluid part is the water in the storage tank and in the solar collector. The mean fluid temperature is defined as T_f .

Fig. 1. Working principle of heat transfer in all glass evacuated tubular solar water heater

2.2 The evaluating mathematical model

The dynamic energy conservation equation for the solid part of the SDHW system is shown as Eq. (4). The left hand side is the dynamic term which is the instantaneous heat reserved by the solid part. The right hand side of the equation is the heat absorbed from solar irradiance, the heat loss and the heat transferred from the solid part to the fluid part respectively.

$$M_b c_b \frac{dT_b}{dt} = F'(\tau\alpha)_{en} K_{\theta} A_a G - F' U_L A_u (T_f - T_a) - h A_t (T_b - T_f) \quad (4)$$

The dynamic energy conservation equation for the fluid part of the SDHW system is described as Eq. (5) where Q_u is the heat flux obtained by the storage tank.

$$M_f c_f \frac{dT_f}{dt} = h A_t (T_b - T_f) = Q_u \quad (5)$$

By substituting Eq. (5) into Eq. (4), Eq. (6) was easily obtained. For the simplicity's sake, the areas used in Eq. (4) and (5) are all set to the collector aperture area A_a . The error caused by this simplification will be compensated by the model parameters.

$$m_f c_f \frac{dT_f}{dt} = Qu / A_a = F'(\tau\alpha)_{en} K_\theta G - F'U_L(T_f - T_a) - m_b c_b \frac{dT_b}{dt} \quad (6)$$

The absorber temperature T_b cannot be easily measured. Therefore the first order differential term dT_b/dt is implicit to some extent. But it needs to be known in the calculation. It is found that dT_b/dt only plays an important role in the period when the beam irradiance changes rapidly because the absorber is directly heated by the solar irradiance. The influencing period happens in the early morning or at the beginning of experiment, in the late afternoon or at the end of experiments and in the cloudy weather conditions. Therefore the main assumption of the evaluating mathematical model is that by using a model parameter C_b convert the unmeasurable term dT_b/dt to the measurable term dG_b/dt . The parameter C_b can be determined by experiments. C_b is a parameter related to the solid heat capacity and it behaves as the thermal capacity of the system solid part.

$$m_b c_b \frac{dT_b}{dt} = C_b \frac{dG_b}{dt} \quad (7)$$

The final evaluating model is described in Eq. (8). The total solar irradiance should be separated into the beam and diffuse irradiance together with their incident angle modifier.

$$m_f c_f \frac{dT_f}{dt} = F'(\tau\alpha)_{en} K_b G_b + F'(\tau\alpha)_{en} K_d G_d - F'U_L(T_f - T_a) - C_b \frac{dG_b}{dt} \quad (8)$$

SDHW systems with evacuated tubular collector (ETC) are more sensitive to sun light incidence angle. In order to get higher precision results for SDHW system with ETC, the beam irradiance was further divided according to the transversal incidence angle with a resolution of for example 10 degree. This treatment was called “dummy variables” in the Multi Linear Regression (MLR) method, also called “extended MLR” method [20]. The final evaluating equation of extended MLR method is shown as follows:

$$m_f c_f \frac{dT_f}{dt} = F'(\tau\alpha)_{en} K_b(5)G_b(0^\circ - 10^\circ) + F'(\tau\alpha)_{en} K_b(15)G_b(10^\circ - 20^\circ) + \dots \dots$$

$$F'(\tau\alpha)_{en} K_b(85)G_b(80^\circ - 90^\circ) + F'(\tau\alpha)_{en} K_d G_d - F'U_L(T_f - T_a) - C_b \frac{dG_b}{dt}$$

The model parameters which will be determined by test are $F'(\tau\alpha)_{en} K_b(5) \dots \dots F'(\tau\alpha)_{en} K_b(85)$, $F'(\tau\alpha)_{en} K_d$, $F'U_L$, and C_b . These model parameters can be used to evaluate the thermal performance of SDHW systems.

2.3 The predicting mathematical model

Eq. (8) is the governing equation for the model parameter evaluation. Therefore, a whole day testing without draw off is needed. However, in the thermal performance test, draw off operation is necessary no matter with an evening draw off adopted by ISO 9459-2 or several draw offs load profile used by ISO 9459-5. The governing equation with the draw off sub-process is written as Eq.(10).

$$m_f c_f \frac{dT_f}{dt} = F'(\tau\alpha)_{en} K_b G_b + F'(\tau\alpha)_{en} K_d G_d - F'U_L(T_f - T_a) - C_b \frac{dG_b}{dt} - Fc_f(T_f - T_{main})$$

By applying the Laplace transformation process and the reverse process [21] for Eq. (10), the integral equation of the mean fluid temperature in the storage tank can be obtained as Eq. (11). The first order differential term dG_b/dt is rewritten as G_b' . The beam irradiance term is not expanded for the purpose of easy-read equation. But it can be expanded for each incidence angle range for extended MLR method as Eq. (9) for ETC collectors in practical use.

$$T_f(\tau) = T_f(0) \exp(-\frac{F'U_L}{m_f c_f} t) +$$

$$\int_0^\tau [\frac{F'(\tau a)_{en} K_b}{m_f c_f} G_b(\tau - t) - \frac{C_b}{m_f c_f} G_b'(\tau - t) + \frac{F'(\tau a)_{en} K_d}{m_f c_f} G_d(\tau - t) - \frac{F'U_L T_a}{m_f c_f}(\tau - t) - \frac{F}{m_f} T_{main}] \exp(-\frac{F'U_L}{m_f c_f} t) dt$$

The predicting model of Eq. (11) has clear physical meaning. During the time period (0- τ), the mean fluid temperature in the end $T_f(\tau)$ equals to the summation of the initial fluid temperature $T_f(0)$ and the accumulative effect of the environmental influence (irradiance, ambient temperature and draw off) each with an exponential term as the weighting factor. The mean fluid temperature is dependent on the environmental conditions, the initial fluid temperature and the model parameters. The cold water supply temperature during draw off is usually constant. Therefore T_{main} is used.

The integral equation of Eq. (11) has to be discrete for calculation. Assume that in the period from 0 to τ_d . τ_d is divided into n time intervals. Each time interval is Δt . Therefore $\tau_d = n \Delta t$.

The discrete equation is derived as Eq. (12). For simplicity's sake, the beam and diffuse irradiance term were written together. It can be easily separated in practical.

$$T_f(\tau_d) = T_f(0) \exp\left(-\frac{F'U_L}{m_f c_f} \tau_d\right) + \sum_{k=0}^{n-1} \left[\frac{F'(\tau_d)_{en} K_{\theta}}{m_f c_f} G(\tau_d - k\Delta t) - \frac{C_b}{m_f c_f} G_b'(\tau_d - k\Delta t) - \frac{F'U_L T_a}{m_f c_f} (\tau_d - k\Delta t) - \frac{F}{m_f} T_{main} \right] \exp\left(-\frac{F'U_L}{m_f c_f} k\Delta t\right) \Delta t \quad (12)$$

A simple example without draw off process is created for illustrating the calculation method of the discrete equation, see Fig. 2. It shows a typical mean fluid temperature developing profile of a thermosyphon SDHW system in one day. Four points were taken for illustration. Each point represents a mean fluid temperature and the time interval in between is Δt . So the fluid temperature $T_f(3)$ can be calculated as Eq.(13) based on the initial fluid temperature $T_f(0)$, the environmental condition (G_b , G_b' , G_d , T_a) in each time step and the model parameters. Eq. (12) is a progressive equation therefore the mean fluid temperature at one time step can also be calculated in another way based on the previous mean fluid temperatures step by step, see Eq. (14).

Fig. 2. A typical mean fluid temperature developing profile of a thermosyphon SDHW system in one day

$$\begin{aligned}
 T_f(3) = & T_f(0) \exp\left(-\frac{F'U_L}{m_f c_f} 3\Delta t\right) \\
 & + \left[\frac{F'(\tau\alpha)_{en} K_b}{m_f c_f} G_b(1) - \frac{C_b}{m_f c_f} G_b'(1) + \frac{F'(\tau\alpha)_{en} K_d}{m_f c_f} G_d(1) - \frac{F'U_L}{m_f c_f} T_a(1)\right] \exp\left(-\frac{F'U_L}{m_f c_f} 2\Delta t\right) \Delta t \\
 & + \left[\frac{F'(\tau\alpha)_{en} K_b}{m_f c_f} G_b(2) - \frac{C_b}{m_f c_f} G_b'(2) + \frac{F'(\tau\alpha)_{en} K_d}{m_f c_f} G_d(2) - \frac{F'U_L}{m_f c_f} T_a(2)\right] \exp\left(-\frac{F'U_L}{m_f c_f} 1\Delta t\right) \Delta t \\
 & + \left[\frac{F'(\tau\alpha)_{en} K_b}{m_f c_f} G_b(3) - \frac{C_b}{m_f c_f} G_b'(3) + \frac{F'(\tau\alpha)_{en} K_d}{m_f c_f} G_d(3) - \frac{F'U_L}{m_f c_f} T_a(3)\right] \exp\left(-\frac{F'U_L}{m_f c_f} 0\Delta t\right) \Delta t
 \end{aligned} \quad (13)$$

$$\begin{aligned}
 T_f(1) = & T_f(0) \exp\left(-\frac{F'U_L}{m_f c_f} \Delta t\right) + \left[\frac{F'(\tau\alpha)_{en} K_b}{m_f c_f} G_b(1) - \frac{C_b}{m_f c_f} G_b'(1) + \frac{F'(\tau\alpha)_{en} K_d}{m_f c_f} G_d(1) - \frac{F'U_L}{m_f c_f} T_a(1)\right] \Delta t \\
 T_f(2) = & T_f(1) \exp\left(-\frac{F'U_L}{m_f c_f} \Delta t\right) + \left[\frac{F'(\tau\alpha)_{en} K_b}{m_f c_f} G_b(2) - \frac{C_b}{m_f c_f} G_b'(2) + \frac{F'(\tau\alpha)_{en} K_d}{m_f c_f} G_d(2) - \frac{F'U_L}{m_f c_f} T_a(2)\right] \Delta t \\
 T_f(3) = & T_f(2) \exp\left(-\frac{F'U_L}{m_f c_f} \Delta t\right) + \left[\frac{F'(\tau\alpha)_{en} K_b}{m_f c_f} G_b(3) - \frac{C_b}{m_f c_f} G_b'(3) + \frac{F'(\tau\alpha)_{en} K_d}{m_f c_f} G_d(3) - \frac{F'U_L}{m_f c_f} T_a(3)\right] \Delta t
 \end{aligned} \quad (14)$$

2.4 Overnight heat loss coefficient

In order to have a precise heat loss coefficient during night time, a separate overnight heat loss test is needed. The mathematical model of night heat loss is easy to obtain from Eq. (10) by eliminating the irradiance related terms and the draw off term which is shown as Eq. (15).

$$m_f c_f \frac{dT_f}{dt} = -F' U_L (T_f - T_a) \quad (15)$$

The heat loss coefficient during night time can be calculated by solving Eq. (15) and the expression is shown in Eq. (16). $T_{f-start}$ and T_{f-end} are the storage fluid temperatures at the start and end time of the overnight heat loss test. $T_{a(avg)}$ is the average ambient temperature during the overnight heat loss test.

$$F' U_L = \frac{m_f c_f}{\Delta t} \ln \frac{T_{f-start} - T_{a(avg)}}{T_{f-end} - T_{a(avg)}} \quad (16)$$

2.5 Long term thermal performance prediction

The SDHW storage average temperature can be calculated by Eq. (12), together with the given climate data (G_b , G_d , T_a), the initial storage average temperature $T_f(0)$, the draw off flow rate (F) and the supply cold fluid temperature (T_{main}). Of course, the heat loss coefficient needs to be used separately during the day time and the night time.

The thermal performance can be obtained by calculating the storage energy change Q before and after draw off process, see Eq. (17). T_f and T'_f are the storage average temperatures before and after draw off process.

$$Q = M_f c_f (T'_f - T_f) \quad (17)$$

3 Thermal performance test method

The thermal performance test method is designed based on the evaluating model and the thermal performance predicting model, together with a separate overnight heat loss coefficient test and the draw off load condition.

309 The thermal performance test includes:

310 1. Model parameters tests.

311 The SDHW system is exposed to the sun for 12 hours in daytime - 6 hours before solar
312 noon and 6 hours after solar noon. In the morning before the start of the experiment,
313 the solar collector should be shielded from sunlight. The SDHW system was then filled
314 with cold water or this can be prepared overnight in advance. The measurement starts
315 immediately when the shielding was removed. Then the SDHW system operates
316 normally for the whole day. During the day, the water temperature in the storage tank
317 was measured and recorded every 30 to 60 minutes. This was done by a fully mixing
318 process for the storage tank using a bypass circulation loop. When the temperature
319 difference of the inlet and outlet of the circulation loop was less than 1 K in 10 minutes,
320 the mean temperature of the inlet and outlet can be assumed as the mean water
321 temperature of the storage tank. When a test ends, the solar collector needs to be
322 shielded again from sunlight until the next test starts.

323 The total and diffuse solar irradiance on the collector surface, the ambient temperature,
324 and the storage mean fluid temperatures should be recorded.

325 2. Overnight heat loss coefficient test.

326 The overnight heat loss coefficient test method is similar to the storage tank heat loss
327 test of ISO 9459-2. The storage with a mean fluid temperature over 60 °C should be
328 prepared. After cooling period during night, the storage fluid was mixed and the final
329 mean fluid temperature can be obtained. The ambient temperature during test should
330 also be recorded.

331 3. Draw off load condition

332 The draw off load condition for the new test method is flexible. It could be designed as
333 an evening draw off like ISO 9459-2 or several times draw off per day at any time like

ISO 9459-5. The flow rate of draw off and the cold water supply temperature should be recorded.

4. Long term thermal performance prediction

The long term thermal performance prediction can be calculated by knowing the SDHW's model parameters, the overnight heat loss coefficient, the climate data, the initial SDHW storage temperature, the draw off load profile and the cold water supply temperature. Then the storage temperature can be calculated at any time or time step by time step for the whole period. Usually, when the calculated storage temperature T_f is over 100 °C, the solar collector should be shielded ($G_b=0$ and $G_d=0$) to avoid boiling water or when T_f is lower than the cold water supply temperature T_{main} , the draw off flow should stop to avoid useless thermal output. If there is a temperature limit for draw off, the draw off flow rate should also stop when T_f is lower than the temperature limit to avoid unwanted low temperature draw off.

4 Experimental verification

4.1 Test facilities

The experimental verification for the evaluating and predicting model of a thermosyphon SDHW system was carried out in Beijing during a period from October to November 2012. The test platform was built according to ISO 9459-2. A schematic diagram of the test rig was shown in Fig. 3 while the main equipment was listed in Table 1. The thermosyphon solar water heater contains 18 evacuated tubes at 50° tilted angle. The aperture area of the evacuated tubes is 2.61 m². The volume of the storage tank is 190 Liter. The photograph of solar water heater was shown in Fig. 4.

Fig. 3. Schematic diagram of the test platform

Fig. 4. Photograph of the solar water heater

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Table 1 Test rig facilities

No.	Facility	No.	Facility
1	Solar water heater	7	Ambient temperature sensor
2	Pyranometer	8	Charging pump
3	Pyranometer with shadow band	9	Electrically operated valve
4	Anemometer	10	Constant temperature tank
5	Temperature sensor	11	Feeding pump
6	Mixing pump	12	Water storage tank

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362 The constant temperature tank was well insulated and used for preparing water with a
363 certain temperature. Water was pumped to the SDHW system by the charging pump. After test,
364 the water in the SDHW system drained back to the water storage tank or can be pumped out by
365 the charging pump. There was a bypass circulating loop between the inlet and outlet of the
366 SDHW system which was used for mixing the water inside the storage tank. The PLC control
367 system was implemented to start and stop each electronic device in order to achieve different
368 control strategies.

369 ***4.2 Model parameters regression***

370 The experimental data of four days (2012-10-25, 10-28, 10-31, 11-07) were used to
371 determine the model parameters. All the data processing, multi-linear regression [20] and
372 statistical analysis were carried out by R-tool software [22]. The evaluating mathematical model
373 of the SDHW system is Eq. (9). The results were shown in Table 2.

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Table 2 Model parameters regression results with statistics

Coefficients	Estimate	Standard error	t value	P(> t)
$F'(\tau\alpha)_{en} (0^\circ - 10^\circ)$	4.52×10^{-1}	2.33×10^{-2}	19.39	$< 2 \times 10^{-16}$
$F'(\tau\alpha)_{en} (10^\circ - 20^\circ)$	5.10×10^{-1}	2.45×10^{-2}	20.83	$< 2 \times 10^{-16}$
$F'(\tau\alpha)_{en} (20^\circ - 30^\circ)$	4.41×10^{-1}	2.82×10^{-2}	15.68	$< 2 \times 10^{-16}$
$F'(\tau\alpha)_{en} (30^\circ - 40^\circ)$	5.35×10^{-1}	2.96×10^{-2}	18.08	$< 2 \times 10^{-16}$
$F'(\tau\alpha)_{en} (40^\circ - 50^\circ)$	5.86×10^{-1}	3.75×10^{-2}	15.64	$< 2 \times 10^{-16}$
$F'(\tau\alpha)_{en} (50^\circ - 60^\circ)$	5.13×10^{-1}	7.15×10^{-2}	7.17	3.26×10^{-9}
$F'(\tau\alpha)_{en} (60^\circ - 70^\circ)$	7.37×10^{-1}	1.54×10^{-1}	4.80	1.48×10^{-5}
$F'(\tau\alpha)_{en} (70^\circ - 80^\circ)$	7.06×10^{-1}	6.08×10^{-1}	1.16	2.51×10^{-1}
$F'(\tau\alpha)_{en} K_d$	3.25×10^{-1}	9.30×10^{-2}	3.49	1.01×10^{-3}
$F'U_L$	9.54×10^{-1}	4.63×10^{-1}	2.06	4.43×10^{-2}
C_b	4.30×10^2	94.7	4.54	3.56×10^{-5}

380 The R^2 statistic value of the regression is 0.9771 indicating a satisfactory fitting of the
 381 measured data by the model. From the results in Table 2 it can be seen that all the model
 382 parameters are significant ($|t \text{ value}| > 2$). Only the efficiency under the transversal angle
 383 between 70 and 80 degree is not significant which was caused by the low irradiance value and
 384 limited data in that angle range.

385 **4.3 Predicting model verification**

386 Additional tests of the SDHW system were carried out in order to validate the predicting
 387 model. According to the model parameters in Table 2 and the predicting model of Eq. (11), the
 388 water temperatures in the storage at different time steps were calculated and compared with
 389 the measured values for the test days of 2012-10-30, 11-1 (half day) and 11-8. Table 3 to Table
 390 5 listed the measured and predicted mean water temperature of the storage tank and the

temperature difference together with other weather conditions. Fig. 5 to Fig. 7 show the measured and predicted mean water temperature developing profile during one day as plot. T_p is the predicted water temperature and T_{diff} is the difference between the measured and predicted values.

Table 3 Comparison of the measured and predicted results 2012-10-30

2012/10/30	Δt (s)	G_b (W/m ²)	G_b' (W/m ² ·s)	G_d (W/m ²)	T_a (°C)	T_f (°C)	T_p (°C)	T_{diff} (°C)
7:30	0	0	0	0	0	22.4	22.4	0
8:30	3620	412.2	0.113866	29.0	4.9	24.4	24.1	0.28
9:03	1980	597.7	0.093683	41.4	7.5	26.3	26.0	0.30
9:43	2380	742.1	0.06069	48.3	8.5	29.1	28.7	0.36
10:15	1920	858.4	0.060534	54.6	9.0	31.6	30.8	0.70
10:48	1990	943.8	0.042911	60.8	9.5	34.0	33.3	0.68
11:24	2150	999.0	0.025687	64.1	10.0	36.9	36.7	0.14
11:58	2040	1054.1	0.027005	61.4	10.5	40.1	39.6	0.46
12:30	1940	1034.9	-0.0099	69.0	10.9	42.9	42.5	0.42
13:36	3952	889.2	-0.03686	89.0	11.5	48.2	48.3	-0.09
14:09	2010	614.0	-0.13689	112.3	12.1	50.6	50.3	0.27
14:49	2380	386.9	-0.09544	130.4	12.1	52.5	52.1	0.33
15:31	2500	419.4	0.013007	91.9	12.5	54.5	53.8	0.60
16:05	2050	282.6	-0.06673	55.9	12.3	55.7	54.7	0.94
16:37	1910	126.5	-0.08172	35.2	11.8	56.2	55.2	0.96
17:04	1620	23.5	-0.06362	13.9	11.3	56.1	55.1	0.98

Fig. 5. Comparison of the measured and predicted water temperature 2012-10-30

Table 4 Comparison of the measured and predicted results 2012-11-1

2012/11/01	Δt (s)	G_b (W/m ²)	G_b' (W/m ² ·s)	G_d (W/m ²)	T_a (°C)	T_f (°C)	T_p (°C)	T_{diff} (°C)
08:11	0	285.1	0	41.2	3.0	40.6	40.6	0
08:50	2340	359.4	0.031767	45.8	4.0	41.7	41.6	0.06
09:20	1810	588.5	0.126547	57.3	7.2	43.3	43.2	0.08
09:53	1990	720.3	0.066264	62.9	8.5	45.4	45.3	0.05
10:23	1790	807.4	0.04863	69.8	9.9	47.6	47.1	0.46
10:53	1820	870.9	0.034882	73.8	11.2	49.9	49.5	0.33
11:29	2150	917.6	0.021743	78.4	12.3	52.8	52.5	0.22
12:10	2430	942.2	0.010113	79.2	13.5	56.3	55.6	0.66

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Fig. 6. Comparison of the measured and predicted water temperature 2012-11-1

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Table 5 Comparison of the measured and predicted results 2012-11-8

2012/11/08	Δt (s)	G_b (W/m ²)	G_b' (W/m ² ·s)	G_d (W/m ²)	T_a (°C)	T_f (°C)	T_p (°C)	T_{diff} (°C)
07:32	0	0	0	0	0	52.7	52.7	0
08:12	2450	244.6	0.099857	39.7	3.0	52.3	53.0	-0.74
08:51	2300	435.2	0.082852	55.2	5.0	52.8	54.4	-1.63
09:22	1890	591.0	0.082422	65.4	7.1	54.25	55.9	-1.67
09:59	2220	728.8	0.062086	71.5	9.1	56.65	58.3	-1.62
10:40	2450	822.1	0.038074	83.3	10.7	59.8	60.7	-0.94
11:16	2160	841.9	0.009151	102.6	11.5	62.55	63.5	-0.96
11:59	2550	851.6	0.003818	113.4	12.5	65.35	66.4	-1.07
12:40	2500	822.1	-0.0118	120.5	13.2	69	69.2	-0.20

13:32	3090	749.4	-0.02352	117.0	13.7	72.85	72.8	0.08
14:09	2209	637.3	-0.05076	107.9	13.7	75.3	74.6	0.68
14:51	2560	520.0	-0.0458	97.4	13.7	77.7	76.7	1.03
15:34	2570	361.7	-0.06161	74.1	13.8	79.45	77.9	1.52
16:27	3180	166.4	-0.0614	43.0	13.4	80.1	78.7	1.36

Fig. 7. Comparison of the measured and predicted water temperature 2012-11-8

The measured and predicted energy gain of the thermosyphon solar water heater for the three days was also calculated and plotted in Fig. 8 together with the relative error. It can be seen from the figure that all the relative error of three days energy gain was less than or equal to 5% which shows a satisfactory accuracy of the predicting method.

Fig. 8. Comparison of the measured and predicted energy gain in four days

4.4 Overnight heat loss coefficient

The overnight heat loss coefficient test was carried out during the night from 2012-11-7 to 2012-11-8. The calculated heat loss coefficient is 1.83 W/K.

4.5 Annual thermal performance prediction

The annual thermal performance prediction was calculated for the tested thermosyphon SDHW system under Beijing climate condition which was exported from TRNSYS 17 [23]. Two draw off load profiles were used. One is the evening draw off and the other is a three times draw off profile per day at 7 am, 12 pm and 18 pm. The total daily hot water consumption was set as 100 liter, 150 liter, 200 liter, 250 liter and 300 liter separately. The cold water supply temperature is 10 °C and the initial storage temperature is 20 °C. The draw off temperature limit is 10 °C.

The SDHW system storage temperature was calculated hour by hour for the whole year. Then the energy output by draw off process was calculated and added together as the annual thermal performance which is shown in Fig. 9. It can be seen from Fig. 9 that the annual thermal performance of the SDHW system is increasing as the increase of the daily hot water

consumption. The evening draw off load condition can obtain higher energy output than the three times draw off load condition. The annual energy output by loading the evening draw off reached the highest at the daily hot water consumption around 250 liter while the annual energy output by loading three time draw off per day was increasing and didn't reach peak as the daily hot water consumption increased to 300 liter.

Fig. 9. Annual thermal performance prediction at Beijing

4.6 Discussion

According to the results comparison in section 4.3 it can be seen that the difference of the measured and predicted mean water temperature in the storage tank was maximum 1.36 °C and minimum 0.66 °C after testing and the relative error of energy gain is within 5%. The deviation was relatively small for the whole day testing which demonstrates that this new method is valid for predicting the thermal performance for thermosyphon SDHW system. However, in theory the accuracy could be further improved if the transversal angle resolution could be even smaller for example 5° or the mixing process could be carried out strictly according to the transversal angle range for example doing the mixing process when the transversal angle changed to 10°, 20°, 30°.....80°. The transversal angle can be calculated in

advance based on the testing date and test facility before experiment. So it is recommended to calculate the exact time of doing the mixing process in advance.

According to the deviation analysis of the temperature increase during one day's test, it is found that the largest error always comes from the beginning period in the morning and the closing period in the late afternoon. The relative large deviation can be explained by the influence of the solid thermal capacitance. It is a common problem when predicting a whole day or some continuous days' temperature, such as a collector field in TRNSYS. The predicted temperature in such period usually had high deviation compared to actual temperature. According to our experiences, the separated solid thermal capacitance method is the best choice compared with other techniques.

The mixing operation was carried out several times during one day. It is needed for the evaluating test but not necessary for the predicting test in practical use. The purpose of doing multi mixing operation is just to show the temperature comparison profile of the mean fluid temperature in the storage tank for the whole day. The mixing experimental method can give accurate measurement of the mean fluid temperature in storage tank. But it needs relatively long time before a uniform tank temperature is achieved. To some extent, the mixing action could break the natural convection process of fluid between the tubular collector tubes and the storage tank by accelerating the fluid velocity and the heat transfer. Therefore if only the final fluid temperature were measured, the predicting accuracy could be better.

Compared to the Q - H test method adopted by ISO 9459-2, the new test method has several advantages. First, the mathematical model of the new test method describes the detailed heating, cooling and draw off processes of thermosyphon SDHW system which is more accurate than the "black box" model of the Q - H test method. Then, the model parameters of the new test method have clear physical meaning. Third, the Q - H test method can only have evening draw off load condition while the new test method can carry out complex draw off load profiles.

Compared to the dynamic system method adopted by ISO 9459-5, the mathematical model of the new test method is simpler and easier to understand. Then, users of the new test

method can easily develop their own calculation based on the equations provided by this paper without buying the calculation software.

5 Conclusions

A test method for evaluating and predicting the thermal performance of thermosyphon SDHW systems was proposed. The evaluating mathematical model was developed based on the two-node theory which is widely used in solar collector testing area. The model parameters derived in the evaluating equation have clear physical meaning and can be obtained by experiments. An analytical expression of the mean fluid temperature in storage tank was derived by using the Laplace transformation treatment for the evaluating mathematical model. The predicting equation of the mean fluid temperature can be used to predict the thermal performance of SDHW system. Thermal performance experimental method was designed for the new test method. The experimental verification for a thermosyphon SDHW system was carried out at a standard test platform in Beijing. Test data of four days were used for determining the evaluating model parameters while the rest of the test data were used to predict the system's storage temperature. The predicted mean fluid temperatures in the storage tank were compared with the measured temperatures. The deviations between the measured and predicted results were analyzed. The results showed that the difference between the measured and the predicted temperature was maximum 1.4 °C at the end of one day test and the relative error of energy gain after whole testing was within 5% which demonstrated that the new method can accurately predict the thermal performance of thermosyphon SDHW system. Possible reasons of the prediction deviation were discussed. Feasible suggestions were recommended for future improvement such as increase transversal angle resolution and carry out the mixing process strictly according to the transversal angles. The annual thermal performance prediction was calculated for the tested SDHW system under Beijing climate condition and two draw off load profiles at different daily hot water consumptions. The proposed test method was compared to the standard test methods ISO 9459-2 and ISO 9459-5.

Future works will focus on the improvement of the test method and the extended application to forced or other SDHW systems.

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