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The effect of measurement uncertainty and environment on domestic solar water heating systems' energy efficiency grades

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Abstract

In China, two important national standards were implemented on Aug 1st, 2012, one is 'Specification of domestic solar water heating systems' (GB/T 19141-2011), the other is 'Minimum allowable values of energy efficiency and energy efficiency grades for domestic solar water heating systems' (GB 26969-2011). According to these two standards, the energy efficiency grades indicator CTP (coefficient of thermal performance) should be tested and calculated by daily useful energy and average heat loss factor of domestic solar heating system. Through experiment and calculation, the effect of measurement uncertainty and daily average ambient temperature on the migration of domestic solar water heating systems' (DSWHS) energy efficiency grades was discussed. The calculation and analysis methods may be helpful for data consistency co-verfication between different inspection organizations.

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Keywords: Daily mean ambient temperature; Measurement uncertainty; DSWHS' energy efficiency grades

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1. Introduction

In China, two important national standards were issued on September 29, 2011 and implemented on August 1, 2012 by General Administration of Quality Supervision, Inspection and Quarantine of the People' Republic of China and Standardization Administration of the People' Republic of China. One is 'Specification of domestic solar water heating systems' (GB/T 19141-2011) [1], the other is 'Minimum allowable values of energy efficiency and energy efficiency grades for domestic solar water heating systems' (GB 26969-2011) [2] which is the first compulsory standard in domestic solar water heaters' industry. These standards are very important and affect the future of solar manufacturers.

In traditional, measurement error is common to indicate the difference between the result and actual value of the measurand. The actual value is unknown in fact. In metrology, measurement error is a primarily a theoretical concept. In recent years, the measurement uncertainty is more popular to describe the measurement result. The measurement uncertainty is a parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand. A measured value without some indication of its uncertainty is useless [3] [4] .

Nomenclature

A_c	contour aperture area, m^2
a$_1$, a$_2$, a$_3$	coefficient derived by experiment results using least squares fitting method
C_{pw}	specific heat of water, J/(kg• °C)
H	amount of solar radiation, MJ/m^2
m_w	quality of water in water storage tank, kg
Q_s	heat energy gain of DSWHS, MJ
t_{ad}	daily average ambient temperature during experiment, °C
$t_{\mathrm{as(av)}}$	average ambient temperature during experiment, °C
t_{b}	temperature of water in water storage tank before experiment, °C
t_{e}	temperature of water in water storage tank after experiment, °C
Δt	temperature difference of water in water storage tank during experiment, $\Delta t=t_{\mathrm{e}}-t_{\mathrm{b}}$, °C
t_{i}	temperature of water in water storage tank before experiment, °C
t_{f}	temperature of water in water storage tank after experiment, °C
ρ_W	density of water, kg / m^3
$\Delta\tau$	time of experiment, s

According to GB/T 19141-2011 and GB 26969-2011, the energy efficiency grades indicator *CTP* (coefficient of thermal performance of solar water heating systems) should be tested and calculated with daily useful energy q_{17} and average heat loss factor U_{SL} of domestic solar heating system, as follows:

$$CTP = \frac{q_{17}(e)}{q_{17}(m)} - \alpha \cdot \frac{U_{SL}(e)}{U_{SL}(M)} \tag{1}$$

where $q_{17}(e)$ is daily useful energy per unit contour aperture area when the amount of solar radiation is 17 MJ/m^2; $q_{17}(m)$ is the minimum of daily useful energy per unit contour aperture area and is a constant, 7.7 MJ/m^2 in this paper; U_{SL} (e) is average heat loss factor under experiments; U_{SL} (M) is the maximum of average heat loss factor and is a constant, 16 W/(m^{3}K) in this paper; α is a weight coefficient of average heat loss factor in *CTP*, α=0.9.

Daily useful energy $q_{17}(e)$ is calculated as follows:

$$q_{17}(e) = \frac{C_{\mathrm{pw}} \mathrm{m}_{\mathrm{w}} \Delta t}{A_{\mathrm{c}}} \cdot \frac{17}{H} \tag{2}$$

Average heat loss factor $U_{SL}(e)$ is calculated as follows:

$$U_{SL}(e)=\frac{\rho_W C_{\mathrm{pw}}}{\Delta\tau}\cdot\ln\frac{t_{\mathrm{i}}-t_{as(av)}}{t_f-t_{as(av)}} \tag{3}$$

2. CTP and energy efficiency grades

There are 3 energy efficiency grades for domestic solar water heating systems (DSWHS), grade 1 is the best. The values of CTP for compact type DSWHS are specified as Table 1. If the values of CTP are lower than grade 3, the products cannot be sold in the market in China [5].

The products tested in this paper are all compact domestic solar water heating system with vacuum tubes collector and non-pressurized heat storage tank, which are the most type in China. According to GB 26969-2011, there are other products types including remote-storage single-loop, remote-storage double-loop and integral collector storage domestic solar water heating system.

Table 1 Energy efficiency grades of compact domestic solar water heating system

Energy efficiency grades	Grade 1	Grade 2	Grade 3
CTP	CTP⩾0.50	0.32⩽CTP⩽0.50	0.10⩽CTP⩽0.32

3. Measurement of CTP

Experimental conditions are as Table 2 according to GB/T 18708-2002[6].

Table 2 Experimental Conditions

Experimental Conditions of Daily Useful Energy		Experimental Conditions of average heat loss factor	
Ambient temperature	(8~35) ℃	Ambient temperature	(8~39) ℃
Outdoor wind speed	u⩽4m/s	Outdoor wind speed	u⩽4m/s
Daily amount of solar radiation	17MJ/m^2		
Water temperature in storage tank	(20±1)℃	Water temperature in storage tank	(50±1)℃
Daytime		Night	
Time of experiment	$\Delta\tau$=8 h	Time of experiment	$\Delta\tau$=8 h

Experiments were carried by the test equipments of solar laboratory in SDQI as shown in Fig.1.

Fig.1 (a) Photo of the control room (b) Photo of the experiment outdoor

Main facilities are as follows:

Table 3 Facilities

Name of Facilities	Type	Measurement Range
Platinum resistance thermometer	HL-A10S	(-40~150)℃
Pyranometer	TBQ-2	(0 ~1400)W/m^2
Electronic platform scale	TC300KA	(0~300)kg
Steel tape	5m	(0~5)m

From the DSWHS samples of product quality supervision and inspection implemented by SDQI in 2014, a DSWHS sample (DSWHS-01) with vacuum tubes collector and non-pressurized heat storage tank is randomly selected as subject. Data of experiments are as follows, and energy efficiency grades indicator *CTP* is calculated as 0.51.

Table 4 Data of Daily Useful Energy

$q_{17}(e)$/(MJ/m^2)	t_e/(℃)	t_b/(℃)	A_c/(m^2)	H/(MJ/m^2)	m_w /(kg)
8.3	20.7	52.6	1.65m×1.33m	18.21	148.1

Table 5 Data of Average Heat Loss Factor

$U_{SL}(e)$/(W/(m^3·K))	t_i/(℃)	t_f/(℃)	$t_{\mathrm{as(av)}}$ /(℃)
10	50.5	48.1	16.19

4. Measurement uncertainty analysis

As described in the reference[7], consider a process that has an output, y, based on N input quantities, x_i. For the generic basis equation:

$$y = f(x_1, x_2, \ldots, x_N) \tag{4}$$

The standard uncertainties are combined by root-sumsquare (RSS):

$$u_C(y) = \sqrt{\sum_{i=1}^{N} (\frac{\partial y}{\partial x_i})^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=1}^{N} \frac{\partial y}{\partial x_i}\frac{\partial y}{\partial x_j} u(x_i)u(x_j)r(x_i, x_j)} \tag{5}$$

where $u(x_\mathrm{i})$ is the standard uncertainty for each of the inputs, $u_c(y)$ is the combined standard uncertainty of the measurand, and $r(x_\mathrm{i}\ x_\mathrm{j})$ is the correlation coefficient, ranging from –1 to 1, and equaling zero if the two components are uncorrelated. The partial derivatives in Eq. (5) represent the sensitivity of the measurand to the uncertainty of each input quantity.

In Eq. (1), $q_{17}(e)$ and $U_{\mathrm{SL}}(e)$, the inputs of *CTP*, are uncorrelated. The combined standard uncertainty of *CTP* is as follows:

$$u_c(CTP) = \sqrt{(\frac{\partial(CTP)}{\partial(q_{17}(e))} \cdot u_c(q_{17}(e)))^2 + (\frac{\partial(CTP)}{\partial(U_{SL}(e))} \cdot u_c(U_{SL}(e)))^2} \tag{6}$$

the sensitivity of the measurand is as follows:

$$\left[\frac{\partial(CTP)}{\partial(q_{17}(e))}\right] = \frac{1}{q_{17}(m)}, \qquad \left[\frac{\partial(CTP)}{\partial(U_{SL}(e))}\right] = \frac{-\alpha}{U_{SL}(M)} \tag{7, 8}$$

In Eq. (2), C_{pw}, m_w, Δt, A_c and H, the inputs of q_{17}(e), are uncorrelated. The combined standard uncertainty of $q_{17}(e)$ is as follows:

$$u_c(q_{17}(e)) = \sqrt{(\frac{\partial(q_{17}(e))}{\partial(C_{pw})} \cdot u(C_{pw}))^2 + (\frac{\partial(q_{17}(e))}{\partial(m_w)} \cdot u(m_w))^2 + (\frac{\partial(q_{17}(e))}{\partial(\Delta t)} \cdot u(\Delta t))^2 + (\frac{\partial(q_{17}(e))}{\partial(A_c)} \cdot u(A_c))^2 + (\frac{\partial(q_{17}(e))}{\partial(H)} \cdot u(H))^2} \tag{9}$$

In Eq. (3), C_{pw}, ρ_W, $\Delta\tau$, t_i, t_f, and $t_{\mathrm{as(av)}}$ the inputs of U_{SL}(e), are uncorrelated. The combined standard uncertainty of $U_{\mathrm{SL}}(e)$ is as follows:

$$u_c(U_{SL}(e)) = \sqrt{(\frac{\partial(U_{SL}(e))}{\partial(C_{pw})}\cdot u(C_{pw}))^2 + (\frac{\partial(U_{SL}(e))}{\partial(\rho_W)}\cdot u(\rho_W))^2 + (\frac{\partial(U_{SL}(e))}{\partial(\Delta\tau)}\cdot u(\Delta\tau))^2 + (\frac{\partial(U_{SL}(e))}{\partial(t_i)}\cdot u(t_i))^2 + (\frac{\partial(U_{SL}(e))}{\partial(t_f)}\cdot u(t_f))^2 + (\frac{\partial(U_{SL}(e))}{\partial(t_{as(av)})}\cdot u(t_{as(av)}))^2} \qquad (10)$$

4.1. Specific heat of water C_{pw}, density of water ρ_W and time of experiment $\Delta\tau$

Specific heat of water C_{pw} and density of water ρ_W are found in Manuals and used as constants. The uncertainties are zero.

Measurements of time $\Delta\tau$ are made with the crystal oscillator in computer. Each experiment lasts 8 hours, and the uncertainty of time is ignored.

4.2. Quality of water (m_w)

Measurements of the quality of water are made with an electronic scale. The resolution of the electronic scale is 0.05kg. The probability distribution of the resolution is uniform (rectangular) distribution. First the quality of empty storage tank is weighed. Then the quality of storage tank full of water is weighed. The difference of two values is the quality of water in storage tank.

$$u(m_w) = \sqrt{2\times(\frac{0.05}{\sqrt{3}})^2} = 0.041\text{kg} \qquad (11)$$

4.3. Temperature (t) *and temperature difference of water* (Δt)

Measurements of the temperature are made with platinum resistance thermometers. An expanded uncertainty of 0.2°C (coverage factor k=2) is given in the calibration certificate [8]. The standard uncertainty of temperature difference is obtained by measuring temperature twice.

$$u(t) = \frac{0.20}{2} = 0.10°\text{C} \qquad (12)$$

$$u(\Delta t) = \sqrt{2\times(0.1)^2} = 0.14°\text{C} \qquad (13)$$

4.4. Average ambient temperature ($t_{\text{as(av)}}$)

Average ambient temperature is measured hourly according to GB/T 18708-2002. During the experiment, nine measurements are made to obtain average ambient temperature $t_{\text{as(av)}}$ in eight hours. Measurement results are as follows:

Table 6 Measurement Result of ambient temperature

Time	20:00	21:00	22:00	23:00	0:00	1:00	2:00	3:00	4:00
Ambient temperature(℃)	16.65	14.95	15.19	15.81	16.09	17.31	16.70	16.59	16.45

Arithmetic mean of ambient temperature ($t_{\text{as(av)}}$) is 16.19 °C. And experimental standard deviation of ambient temperature ($s(t_{\text{as(av)}})$) [9] is 0.76 °C.

$$u(t_{as(av)}) = \sqrt{s^2(t_{as(av)}) + u^2(t)} = 0.77°\text{C} \qquad (14)$$

4.5. Contour aperture area (A_c)

Measurements of the length L and width W are made with a steel tape. The area is calculated by $A_c=L*W$. The discernible value of the steel tape is 1mm. The probability distribution of the resolution is uniform (rectangular) distribution.

$$u(L)=u(W)=\frac{1}{2\sqrt{3}}=0.29\text{mm} \tag{15}$$

$$u(A_\text{c})=\sqrt{(W\cdot u(L))^2+(L\cdot u(W))^2}=\sqrt{(1.65\times 0.289\times 10^{-3})^2+(1.33\times 0.289\times 10^{-3})^2}=0.00061\text{m}^2 \tag{16}$$

4.6. *amount of solar radiation* (*H*)

The time integral of solar radiation intensity *G* is the amount of solar radiation *H*. Measurements of the solar radiation intensity are made with pyranometers. The measurement range of pyranometer is 0 W/m^2 to 1400 W/m^2. For pyranometer, the maximum permissible measurement error is ±5.0%. The probability distributions are uniform (rectangular) distribution [9].

$$u(H)=\frac{H\cdot 5\%}{\sqrt{3}}=\frac{18.21\times 5\%}{\sqrt{3}}=0.53\text{MJ}/\text{m}^2 \tag{17}$$

4.7. *Uncertainty of daily useful energy* ($u_\text{c}(q_{17}(e))$)

Uncertainty of daily useful energy is calculated as Table 7.

Table 7 Uncertainty of Daily Useful Energy

Inputs of $q_{17}(e)/x_i$	$u(x_i)$	$\frac{\partial y}{\partial x_i}$	$\frac{\partial y}{\partial x_i}\cdot u(x_i)$
m_w/(kg)	0.041	$\frac{q_{17}(e)}{\text{m}_w}=0.056$	2.30×10^{-3}
Δt/(℃)	0.14	$\frac{q_{17}(e)}{\Delta t}=0.26$	3.69×10^{-2}
A_c/(m^2)	0.00061	$\frac{-q_{17}(e)}{A_c}=\text{-}3.80$	-2.32×10^{-3}
H/(MJ/m^2)	0.53	$\frac{-q_{17}(e)}{H}=\text{-}0.46$	-0.24
Combined standard uncertainty of daily useful energy: $u_\text{c}(q_{17}(e))$=0.24 MJ/m^2			

4.8. *Uncertainty of average heat loss factor* ($u_\text{c}(U_\text{SL}(e))$)

Uncertainty of average heat loss factor is calculated as Table 8.

Table 8 Uncertainty of daily useful energy

Inputs of $U_{SL}(e)/x_i$	$u(x_i)$	$\frac{\partial y}{\partial x_i}$	$\frac{\partial y}{\partial x_i}\cdot u(x_i)$
t_i/(℃)	0.10	$\frac{\rho_W C_{pw}}{\Delta\tau}\cdot\frac{1}{(t_i-t_{as(av)})}=4.22$	0.42
t_f/(℃)	0.10	$\frac{\rho_W C_{pw}}{\Delta\tau}\cdot\frac{-1}{(t_f-t_{as(av)})}=-4.54$	-0.45
$t_{\text{as(av)}}$/(℃)	0.77	$\frac{\rho_W C_{pw}}{\Delta\tau}\cdot\frac{(t_f-t_i)}{(t_i-t_{as(av)})\cdot(t_f-t_{as(av)})}=\text{-}0.32$	-0.24
Combined standard uncertainty of daily useful energy: $u_\text{c}(U_{SL}(e))$=0.67 W/(m$^3\cdot$K)			

4.9. Uncertainty of energy efficiency grades indicator ($u_c(CTP)$)

Uncertainty of energy efficiency grades indicator is calculated as Table 9.

Table 9 Uncertainty of energy efficiency grades indicator

Inputs of CTP/x_i	$u(x_i)$	$\frac{\partial y}{\partial x_i}$	$\frac{\partial y}{\partial x_i}\cdot u(x_i)$
$q_{17}(e)$/(MJ/m^2)	0.24	$\frac{1}{q_{17}(m)}=0.13$	0.032
$U_{SL}(e)$/(W/(m^3·K))	0.67	$\frac{-\alpha}{U_{SL}(M)}=-0.056$	-0.038
Combined standard uncertainty of energy efficiency grades indicator: $u_c(CTP)$=0.049			

4.10. Expanded uncertainty of energy efficiency grades indicator ($U(CTP)$)

A coverage factor k of 2 will be applied to give expanded uncertainty of energy efficiency grades indicator with an approximate 95% confidence level. As follows:

$$U(CTP)=k\cdot u_c(CTP)=2\times 0.049=0.098 \tag{18}$$

4.11. Energy efficiency grades indicator (CTP)

The energy efficiency grades indicator of the sample DSWHS-01 is: $CTP\pm U(CTP)$=0.51±0.098.

According to above calculation, the sample DSWHS-01's CTP should be 0.412~0.608 with an approximate 95% confidence level. The sample' energy efficiency grades can be evaluated as grade 1 with extend limit criterion, and grade 2 with tight limit criterion. As describe in Fig.2 and Fig.3, respectively. It will result to CTP's migration.

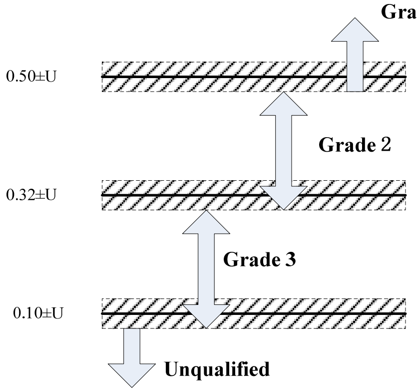

Fig. 2 The extend limit criterion

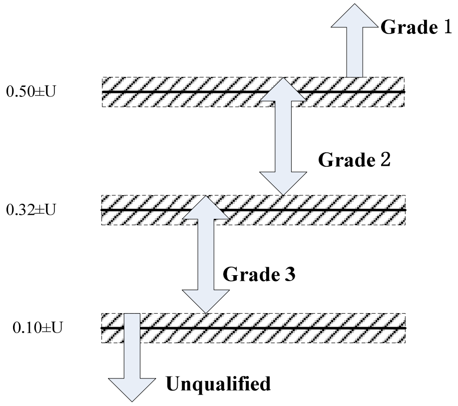

Fig. 3 The tight limit criterion

5. The effect of daily average ambient temperature on CTP

The equation of heat energy gain of DSWHS is as (19) according to GB/T 18708-2002.

$$Q_s=a_1H+a_2(t_{ad}-t_b)+a_3 \tag{19}$$

A formula could be derived by analysis methods of Yin Zhiqiang et al. as [10].

$$\Delta q_{17}(e) = \mathrm{a}_2(t_{ad1} - t_{ad2}) / A_c \tag{20}$$

As mentioned in Table 2, the ambient temperature suiTable for experimental conditions is 8℃≤t_{ad}≤ 35 ℃. The maximum value of(t_{ad1}- t_{ad2})are 27 ℃. As to a DSWHS sample's long time testing data [11], a $\Delta q_{17}(e)$ value 0.52 MJ/m^2 was calculated and $\Delta q_{17}(e) / q_{17}(m) = 0.07$. So, it will also result to the CTP's migration.

6. Conclusions

By means of measurement uncertainty analysis, a sample (DSWHS-01), with vacuum tubes collector and non-pressurized heat storage tank, was confirmed that it have a 0.51±0.098 CTP value with an approximate 95% confidence level.

The different daily average ambient temperatures also have significant effect on CTP. A lower ambient temperature will result to a lower actual CTP than the calculated one.

The 'migration' of the DSWHS' energy efficiency grades is mainly caused by measurement uncertainty and daily average ambient temperature. It should be more focused on data consistency co-verfication between different inspection organizations in the future.

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