PERFORMANCE RATING METHOD OF THERMOSYPHON SOLAR WATER HEATERS

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Abstract—A rating method for the thermal performance of thermosyphon solar water heaters was developed. Except that the outdoor test procedure still follows the Taiwan Standard CNS B7277, a system characteristic efficiency η_s^* which is defined as the α_o value corrected at $M/A_c = 75$ kg/m^2, was derived so that η_s^* is independent of the M/A_c ratio. Here, η_s^* can be evaluated by linear regression analysis of the test data. It is found from a series of tests for 31 systems that η_s^* is independent of M/A_c indeed, and thus can be used to rate the thermal performance of different thermosyphon solar water heaters during the energy-collecting period. The cooling loss during the no-radiation period is rated by the system cooling time constant τ_c. The present rating method associated with the Taiwan Standard CNS B7277 has been implemented for more than three years and is accepted by the Taiwan solar industry.

1. INTRODUCTION

Commercialization of thermosyphon solar water heaters is very successful in Taiwan. The number of units installed is around 25,000 per year, mostly for domestic applications. The market will be expanded several folds in the near future. The rapid growth of the solar market is mainly a result of the subsidy program provided by the Energy Commission, Ministry of Economic Affairs, Taiwan, which was started in 1986 and ended at the end of 1991. To improve the quality, the subsidy program requires that all the qualified products should pass a performance test with results exceeding certain criteria. Therefore, a method for the performance rating of the different solar water heaters on a commonly trusted basis was required.

Through a series of research programs, the Taiwanese Testing Standard (CNS B7277) was established in 1989 for the thermal performance test of thermosyphon solar water heaters[1,2]. This standard has been implemented in an expert system, which was developed and has been continuously running for about three years since early 1989 (see[1]). More than 30 commercial solar water heaters have been tested so far and the results are collected and analyzed. The semiempirical efficiency model: $\eta_s = \alpha_o - U_s(T_i - \bar{T}_a)/H_t$, which was derived to correlate the daily efficiency test results[1], was carefully examined and no serious defect has yet been found.

It has been shown that the parameters α_o and U_s, defined in the above equation, can be used to rate the thermal performance of thermosyphon solar water heaters during energy-collecting periods[1]. Above, α_o is related to the solar energy absorption efficiency of the collector; while U_s stands for the capability of the system heat loss to ambient during the energy-collecting periods. However, two problems may arise by this rating method.

First, the testing result of U_s may have a larger uncertainty, sometimes $> \pm 20\%$, which is caused by the scattering of the field test data due to inevitable disturbances of the testing environment[1]. Therefore, the performance rating based on the results of U_s may be deviated and cause serious controversy in obtaining the subsidy. Second, α_o and U_s can be varied by changing the system designs with various M/A_c ratios, so that the rating may become unfair. For example, filling more water in the tank during the test will increase the M/A_c ratio as well as the testing result on α_o. This can easily be done during the test for thermosyphon solar water heaters of the nonpressurized type (with a float valve in the tank to control the makeup water flow to the tank). A larger M/A_c value can also be achieved by designing a larger tank size in order to pass the performance test, though the hot water will be supplied at a lower temperature which may not meet the load requirement.

Therefore, it is realized that the performance rating based purely on the values of α_o and U_s may be unfair. To overcome this problem, we have to seek a rating method that is independent of the M/A_c ratio.

In practice, the daily initial temperature of the thermosyphon systems, T_i, is relatively low since the hot water collected during daytime is completely used at night and cold make-up water is refilled again. Therefore, the performance rating using U_s is not always necessary since T_i approaches $\bar{T}_a$, i.e., $(T_i - \bar{T}_a)/H_t \approx 0$. This means that the rating method can be simplified. Therefore, we solely select the value of α_o for the performance rating of different thermosyphon solar water heaters during energy-collecting periods, but redefine it so that it will not depend on the M/A_c ratio. The modified α_o (called *system characteristic efficiency* denoted by η_s^*) will then be used in the rating.

The system cooling loss during the no-radiation period (particularly at night) basically includes the insulation loss and the reverseflow loss. The cooling loss test can be performed to determine the cooling time constant τ_c by the testing method presented in Huang and Du's article[1]. The effect of reverse flow can also be analyzed by comparing the cooling time constant, τ_c, of the individual tank loss and the system loss[1].

2. DERIVATION OF CHARACTERISTIC SYSTEM EFFICIENCY

We start with the daily system efficiency model derived in the previous study[1]:

$$\eta_s = \alpha_o - U_s \frac{T_i - \bar{T}_a}{H_t} \tag{1}$$

where

$$\alpha_o \equiv \alpha_e - \frac{\beta}{(M/A_c)} ; \quad \beta \equiv \frac{bU_s}{2} . \tag{2}$$

In eqn (2), α_e is the average solar absorption coefficient; b is the proportional constant between $T_f - T_i$ and $H_t A_c/M$, according to Kubler et al.[3] and Adnot et al.[4]. That is,

$$T_f - T_i = b \frac{H_t A_c}{M} . \tag{3}$$

Here, H_t is the daily total solar irradiation upon the collector slope:

$$H_t = \int_{t_i}^{t_f} I_T dt \tag{4}$$

where t_i and t_f are the initial and final time, respectively, during energy collecting period at each test day.

The system efficiency model, eqn (1), has been verified experimentally well in the previous study[1]. The parameter α_o can be interpreted as the daily system efficiency if the initial water temperature T_i is as cold as the mean ambient temperature $\bar{T}_a$. It can also be seen from eqn (2) that the parameter α_o is dependent on the M/A_c ratio. The larger the water mass in the tank, the higher the value of α_o. Thus, the higher value of α_o can be easily obtained by filling more water in the tank during the test. Therefore, a correction of the parameter α_o from an arbitrary M/A_c value to a fixed M/A_c value is necessary in the performance rating of different thermosyphon solar water heaters.

The system parameters α_o and U_s are determined from the linear regression analysis of eqn (1) by using the measured system efficiency η_s (the dependent variable) and $(T_i - \bar{T}_a)/H_t$ (the independent variable). The constant b defined in the second part of eqn (2) is determined separately by linear regression analysis to the model eqn (3) by using the measured $T_f - T_i$ (the dependent variable) and $H_t A_c/M$ (the independent variable). The coefficient β can then be evaluated by using the second part of eqn (2) and α_e can be found from the first part of eqn (2):

$$\alpha_e = \alpha_o + \frac{\beta}{M/A_c} . \tag{5}$$

With known β and α_e, we can extrapolate the test results of α_o to the point with a fixed M/A_c value. Here,

$M/A_c = 75$ kg/m^2 was chosen as the criterion and the corrected α_o, denoted $\alpha_o|_{75}$ or η_s^* becomes:

$$\eta_s^* \equiv \alpha_o|_{75} = \alpha_e - \frac{\beta}{75} . \tag{6}$$

The corrected α_o, denoted η_s^*, is the *system characteristic efficiency* which can be used as the criterion for the performance rating of different thermosyphon solar water heaters in the energy absorption phase.

Substituting eqn (5) into eqn (6), we obtain:

$$\eta_s^* = \alpha_o + \frac{\beta}{M/A_c} - \frac{\beta}{75} = \alpha_o + \left[\frac{1}{(M/A_c)} - \frac{1}{75}\right]\beta. \tag{7}$$

Equation (7) can be written in the form

$$\eta_s^* = C_F \alpha_o \tag{8}$$

where C_F is the correction factor which is defined as

$$C_F = 1 + \left[\frac{1}{(M/A_c)} - \frac{1}{75}\right]\frac{\beta}{\alpha_o} . \tag{9}$$

Since $\beta = bU_s/2$, C_F can be evaluated when the parameters b, U_s, and α_o have been determined. The above derivation of the system characteristic efficiency η_s^* is basically semiempirical and thus needs experimental verifications.

3. VERIFICATION BY FIELD TESTS

An experiment with seven thermosyphon solar water heaters, i.e., Systems A, B, C, D, E, F, and G used by Huang and Du[1], were carried out in the present study. The outdoor tests were performed automatically by the expert system developed previously[1]. The testing procedure follows Standard CNS B7277[2] with the following operating conditions:

1. Period of day for daily efficiency test: nine hours with symmetry to the solar noon time.
2. $H_t \geq 7$ MJ/m^2 *day* for each test day.
3. Daily-mean wind speed during tests $\bar{v}_w \leq 3$ m/s for each test day.
4. $-0.5 \leq \dfrac{T_i - \bar{T}_a}{H_t} \leq 2.0°C$ m^2 *day*/MJ.
5. At least ten test points, which satisfy the above testing conditions, have to be taken.

The parameters α_o and U_s, obtained from linear regression analysis of the test data using eqn (1) are listed in Table 1. The correlation coefficients of eqn (1) are well shown and the system efficiency model was validated. The proportional constant, b, the correction factor, C_F, and the characteristic system efficiency η_s^* were further calculated. The results are listed in Table 2. The correlation coefficients presented in Table 2 are very close to 1.0 and thus eqn (3) is shown to be valid.

To further verify the suitability of the correction method for the rating of thermosyphon solar water heaters, a large number of field test data to check

Table 1. Fitting of test results for the system efficiency model, eqn (1)

System	M/A_c (kg/m^2)	α_o	U_s (MJ/m^2 °C day)	Correlation coefficient of eqn (1)
A	73.4	0.397	0.174	-0.944
B	78.6	0.517	0.147	-0.986
C	74.5	0.592	0.162	-0.944
D	81.8	0.506	0.114	-0.895
E	67.8	0.487	0.129	-0.883
F	71.8	0.507	0.190	-0.943
G	77.9	0.566	0.170	-0.955

whether η_s^* is independent of M/A_c, is required. Thirty-one commercially available solar water heaters have been tested and analyzed. The results are summarized in Table 3. Figure 1 shows that α_o increases with increasing M/A_c ratio, as was expected by eqn (2). The effect of M/A_c is not very clear for U_s, as shown in Fig. 2. Figure 3 shows that the system characteristic efficiency η_s^* is independent of the M/A_c ratio indeed. This indicates that the performance rating of solar water heaters by using the η_s^* value will not be biased by the variation of the M/A_c ratio, and thus can be commonly trusted.

Table 3 also presents the test results of the cooling time constant τ_c, which can be used to rate the performance during no-radiation or cooling-loss periods. Here, τ_c is defined as

$$\tau_c = \frac{MC_p}{(UA)_L} \qquad (10)$$

which is derived by a first-order system cooling model[1]:

$$MC_p \frac{dT_t(t)}{dt} = -(UA)_L[T(t) - \bar{T}_a] \qquad (11)$$

where T_t is the bulk temperature of water in the tank; $(UA)_L$ is the total heat loss coefficient of the system (including tank, collector, and connecting pipes); $\bar{T}_a$ is the mean ambient temperature during the no-radiation test period. Therefore, τ_c represents the time at which the difference between the hot water temperature in the tank and the mean ambient temperature drops to 36.8% of its initial temperature difference, i.e., $T_t(0)$

$- \bar{T}_a$. Table 3 shows that τ_c, for most solar water heaters, exceeds 2 $days$.

A criterion of $\eta_s^* \geq 0.5$ during energy-collecting periods has been adopted by the Taiwan Government in early 1989 as a necessary condition for the acceptance of the subsidy program. By this criterion, 7 out of 31 systems tested in the present study were not allowed to accept subsidy. In addition to the performance criterion during energy-collecting periods, $\tau_c \geq 2.0$ $days$ will be suggested in the future as an additional criterion for performance during no-radiation or cooling-loss periods in order to make the rating more complete. If both the criteria of η_s^* and τ_c were obeyed, then eight systems will not pass the test.

4. DISCUSSION AND CONCLUSIONS

In the present study, a method of performance rating for different solar water heaters was derived. The outdoor test procedure basically follows the Taiwanese Standard B7277[1,2]. In addition, a system characteristic efficiency, η_s^*, which is defined as the α_o value corrected at $M/A_c = 75$ kg/m^2, was further derived, so that η_s^* is independent of M/A_c. Then, η_s^* can be evaluated by linear regression analysis of test data using eqn (3) in conjunction with eqns (2) and (7). From the tests of 31 solar water heaters, it was found that η_s^* is indeed independent of M/A_c and thus can be used to rate the thermal performance of different thermosyphon solar water heaters during energy-collecting periods. The present rating method has been used for more than three years during the subsidy program, and is now widely accepted by Taiwanese solar industry.

A criterion of $\eta_s^* \geq 0.5$ during energy-collecting periods has been adopted by the Taiwan Government in

Table 2. Fitting of test results for eqn (3)

System	M/A_c (kg/m^2)	b/C_p	Correlation coefficient of eqn (3)	α_o	Correction factor C_F	η_s^*
A	73.4	0.342	0.978	0.397	1.005	0.399
B	78.6	0.517	0.969	0.517	0.991	0.512
C	74.5	0.504	0.938	0.592	1.001	0.593
D	81.8	0.506	0.977	0.506	0.986	0.499
E	67.8	0.467	0.982	0.487	1.021	0.498
F	71.8	0.517	0.980	0.507	1.014	0.514
G	77.9	0.566	0.979	0.566	0.989	0.560

$C_p = 0.004184$ MJ/kg °C; b = dimensionless.

Table 3. Test results for 31 commercially available solar systems

System no.	M (kg)	A_c (m^2)	M/A_c (kg/m^2)	α_o	U_s (MJ/m^2 °C day)	η^*	τ_c (day)
1	272.35	3.71	73.51	0.406 ± 0.029	0.153 ± 0.035	0.41	2.46
2	290.03	3.69	78.69	0.514 ± 0.009	0.140 ± 0.010	0.51	3.32
3	283.23	3.80	74.49	0.585 ± 0.016	0.158 ± 0.019	0.59	2.33
4	305.76	3.74	81.66	0.510 ± 0.017	0.136 ± 0.021	0.50	2.61
5	254.32	3.75	67.75	0.488 ± 0.016	0.126 ± 0.025	0.50	2.81
6	201.63	2.81	71.68	0.510 ± 0.009	0.145 ± 0.012	0.52	2.69
7	300.00	3.85	78.00	0.516 ± 0.008	0.185 ± 0.020	0.51	—
8	290.00	3.61	80.30	0.470 ± 0.018	0.191 ± 0.027	0.46	3.21
9	318.60	3.97	80.20	0.541 ± 0.037	0.187 ± 0.045	0.53	4.00
10	298.00	3.68	81.00	0.575 ± 0.022	0.171 ± 0.030	0.56	3.00
11	397.70	5.52	72.00	0.519 ± 0.010	0.163 ± 0.016	0.52	3.50
12	284.00	3.74	75.90	0.571 ± 0.025	0.142 ± 0.038	0.57	2.97
13	409.30	5.62	72.80	0.562 ± 0.022	0.159 ± 0.026	0.57	3.20
14	176.30	1.87	94.30	0.574 ± 0.020	0.156 ± 0.029	0.55	3.82
15	440.10	7.49	58.80	0.508 ± 0.022	0.114 ± 0.030	0.53	3.26
16	352.20	3.68	95.70	0.550 ± 0.043	0.167 ± 0.054	0.52	3.43
17	435.40	5.52	78.90	0.546 ± 0.016	0.109 ± 0.025	0.54	3.27
18	385.10	3.68	104.60	0.599 ± 0.032	0.179 ± 0.037	0.55	2.21
19	485.50	5.52	88.00	0.535 ± 0.030	0.153 ± 0.037	0.52	3.47
20	246.80	4.29	57.54	0.425 ± 0.042	0.136 ± 0.078	0.45	2.40
21	313.60	5.71	54.90	0.420 ± 0.028	0.117 ± 0.042	0.44	2.80
22	298.80	3.79	78.90	0.555 ± 0.026	0.158 ± 0.042	0.55	2.46
23	489.00	7.37	66.40	0.463 ± 0.061	0.132 ± 0.086	0.47	4.39
24	131.30	1.80	72.95	0.461 ± 0.023	0.156 ± 0.033	0.46	1.02
25	292.70	3.63	80.60	0.476 ± 0.023	0.131 ± 0.031	0.47	2.71
26	488.50	5.44	89.80	0.510 ± 0.027	0.127 ± 0.034	0.50	3.82
27	520.00	5.44	95.60	0.557 ± 0.015	0.136 ± 0.021	0.53	2.99
28	383.70	5.53	69.40	0.539 ± 0.020	0.207 ± 0.040	0.55	4.79
29	306.70	3.69	83.10	0.517 ± 0.017	0.126 ± 0.028	0.51	2.91
30	88.85	1.29	68.85	0.497 ± 0.012	0.177 ± 0.014	0.51	1.52
31	342.1	3.63	94.30	0.571 ± 0.021	0.166 ± 0.026	0.55	2.08

early 1989 as a necessary condition for the acceptance of the subsidy program. In addition to the performance criterion during energy-collecting periods, $\tau_c \geq 2.0$ $days$ will be suggested as an additional criterion for perfor-mance during no-radiation or cooling-loss periods, in order to make the rating more complete.

It is noted that System B presented in Tables 1 and 2, and System No. 2 in Table 3 are of a close-type
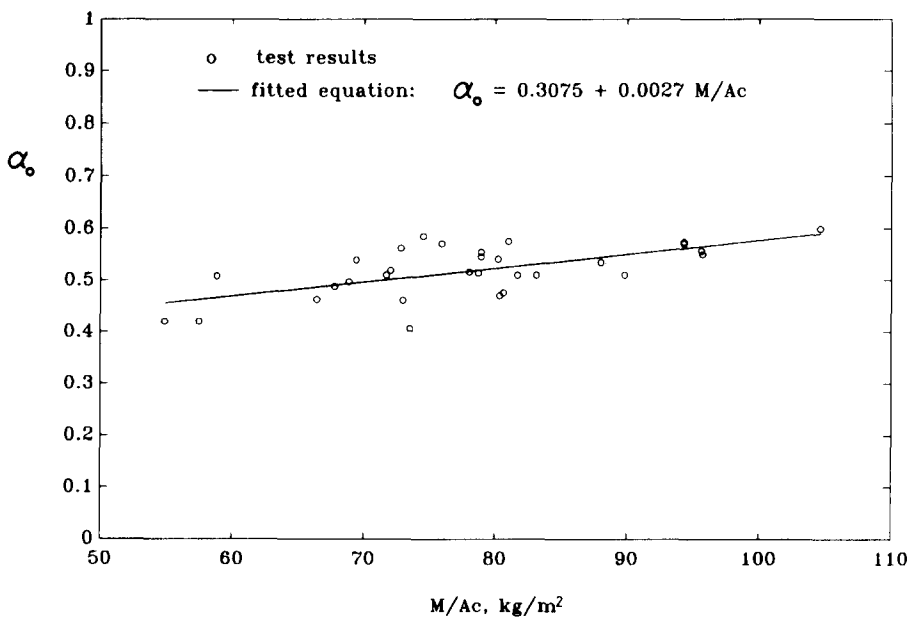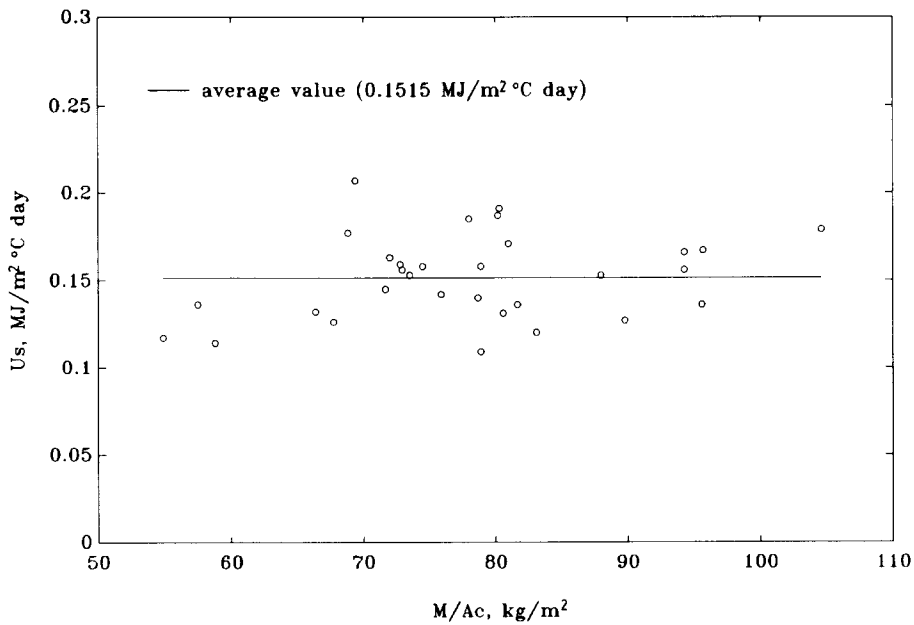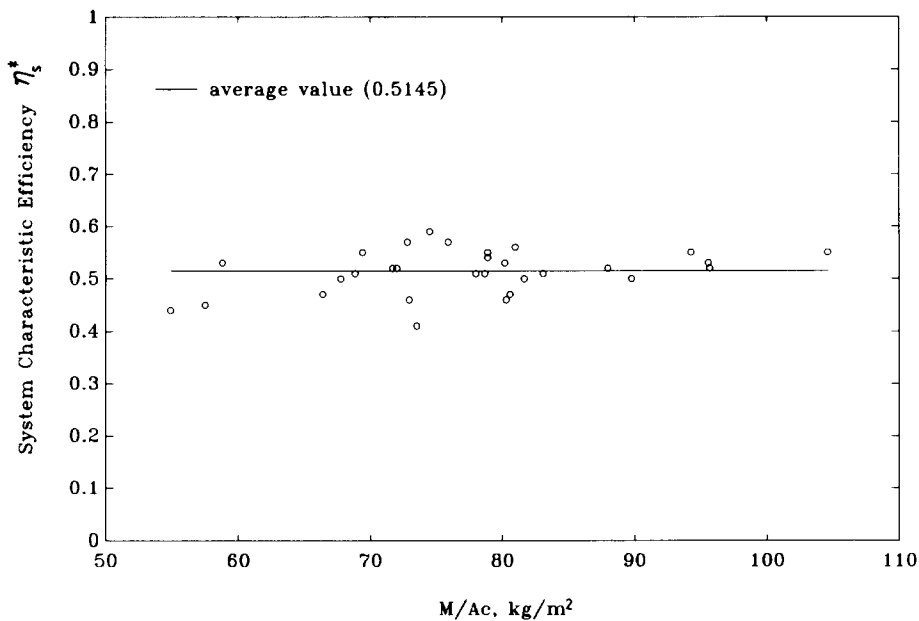

Fig. 1. Variation of α_o with M/A_c.

Fig. 2. Variation of U_s with M/A_c.

Fig. 3. Variation of η_s^* with M/A_c.

design (with a heat exchanger in the tank), and no abnormal test results were found. The testing method presented in [1] and Standard CNS B7277[2] are thus shown to be applicable to close-type thermosyphon water heaters with a heat exchanger in the tank. The results obtained from a recent test for a storage-collector type solar water heater (similar to thermosyphonic water heaters in design principle) also reveals that the Standard CNS B7277 is applicable too.

NOMENCLATURE

A_c collector area, m^2
b empirical constant defined in eqn (3)
C_p heat capacity of water, 0.004184 MJ/kg °C
H_t daily total solar irradiation upon collector slope, J/m^2 day
I_T solar irradiation incident upon collector slope, W/m^2
M total mass of water in the thermosyphon system, kg
T_a ambient temperature, °C
$\bar{T}_a$ daily average ambient temperature, °C
T_i daily initial tank temperature, °C
T_f daily final tank temperature, °C
T_t water temperature in tank, °C
t_i initial time, s
t_f final time, s

U_s overall system loss coefficient during energy-collecting periods, MJ/m^2 °C *day*
$(UA)_L$ overall system loss coefficient during no-radiation periods, MJ/m^2 °C
α_e effective solar absorptance, dimensionless
α_o overall solar absorptance defined in eqn (1), dimensionless
η_s daily system efficiency, dimensionless
η_s^* system characteristic efficiency, dimensionless
τ_c cooling time constant during no-radiation periods, *day*

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