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A CRITERION STUDY OF SOLAR IRRADIATION PATTERNS FOR THE PERFORMANCE TESTING OF THERMOSYPHON SOLAR WATER HEATERS

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Abstract—A Taiwan test standard was established in 1989 using outdoor daily efficiency test methods. This test standard has been implemented for 12 years with satisfactory results. However, it was also found from field applications that the pattern of solar irradiation would affect the result of the performance test. In the present study, we used a distribution factor R_i defined as the ratio of the total irradiation in the morning to that in the afternoon to characterize this effect. R_i reflects the asymmetry of solar irradiation distribution in the morning and afternoon. A field study was carried out. The data collected from the daily efficiency tests were screened using the criterion of $0.5 \leq R_i \leq 1.6$, in addition to the conditions defined in the Taiwan test standard. Two commercial products separately located in latitude 23° N and 25° N were tested. Data scattering occurs without using the R_i criterion. If we adopt test data using R_i, the results turn out to have a much better data correlation coefficient, from 0.915 to 0.969. The system characteristic efficiency η_s^* changes significantly, from 0.479 to 0.514. There is a regulation that the commercial product should have a value of η_s^* exceeding 0.5 in order to obtain a subsidy from the government in Taiwan. The performance test using the old standard is shown to result in a significant error, suggesting modification of the former test standard.

1. INTRODUCTION

The performance of solar hot water heaters is affected by design parameters, climatic conditions, and hot water load patterns. Many researchers (Beale, 1987; Fanny, 1984; Green, 1988; Kubler *et al*., 1988) have studied the test method for thermal performance of solar hot water heaters under various operating conditions. As far as the performance affected by hot water load patterns, the daily efficiency at no hot water load during the energy collecting phase can be treated as the lower bound of the performance (Huang and Du, 1991). Hence, in order to simplify the performance test in this study, it is assumed that no hot water load will be imposed during the energy-collecting phase. The present study focuses on the effect of daily incident solar radiation variation during the performance test concerning climatic conditions.

A Taiwan test standard was established in 1989 using an outdoor daily efficiency test method and a semi-empirical system efficiency model (CNS, 1989; Huang and Du, 1991). It defined some necessary conditions for taking data, including a fixed time period for testing, wind speed limit, minimum daily total irradiation, and minimum number of data points. Huang (1993) further developed a performance rating method in order to create a system characteristic efficiency η_s^* which results in a performance test result independent of system capacity, M/A_c. The CNS test standard has been implemented for 12 years with satisfactory results.

However, it was also found from field applications that the pattern of daily solar irradiation would affect the performance test results. There is a regulation in Taiwan that the commercial product should have a value of η_s^* exceeding 0.5 in order to obtain a subsidy from the government. The performance test using the old standard can result in a significant error.

In the present study, we used a distribution factor R_i that is defined as the ratio of the total irradiation in the morning to that in the afternoon to characterize this effect. R_i reflects the asymmetry of solar irradiation distribution in the morning and afternoon. A field study was carried out. The data collected from the daily efficiency test results were screened using the R_i criterion, in addition to the conditions defined in the CNS test standard.

2. MODIFICATION OF TEST STANDARD

A distribution factor R_i is defined as the ratio of the total irradiation in the morning to that in the

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Table 1. Two systems are used to find a criterion of R_i from solar irradiation pattern

System	M/A_c (kg/m^2)	α_0	U_o (MJ/m^2 °C day)	η_s^*	Correlation coefficient Z_{xy}	System location (latitude)
A	78.088	0.519	0.148	0.516 (29 data pts.)	0.945	23° N
B	71.754	0.511	0.136	0.514 (51 data pts.)	0.905	25° N

afternoon, as shown in Eq. (1). We carried out R_i calculations using 1-year local meteorological data from two systems in latitude 25° N and 23° N, respectively, as shown in Table 1. The distribution of R_i data is shown in Figs. 1 and 2. It is seen that 80% of R_i data, on average, is in the interval $0.5 \leq R_i \leq 1.6$. Therefore, we first chose the criterion $0.5 \leq R_i \leq 1.6$ in order to avoid the effect of asymmetry of solar irradiation. Figs. 3 and 4 represent an example of asymmetry of solar irradiation at $R_i = 2.6$ on the day 07/05/2000. The distribution of solar irradiation intensity is shown in Fig. 3. Fig. 4 is a time integration of the data in Fig. 3.

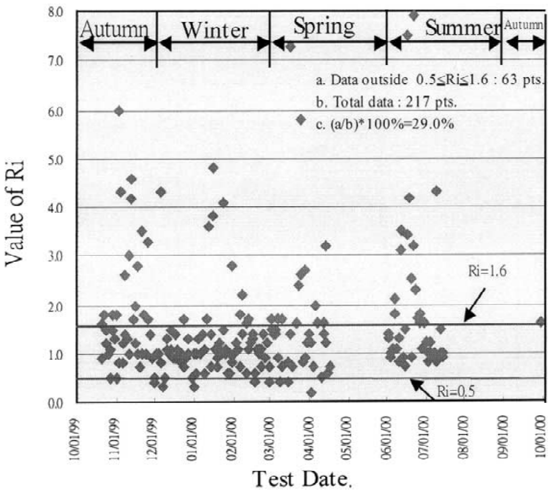

Fig. 1. Data distribution of R_i in latitude 25° N (test date: 10/01/1999–9/30/2000).

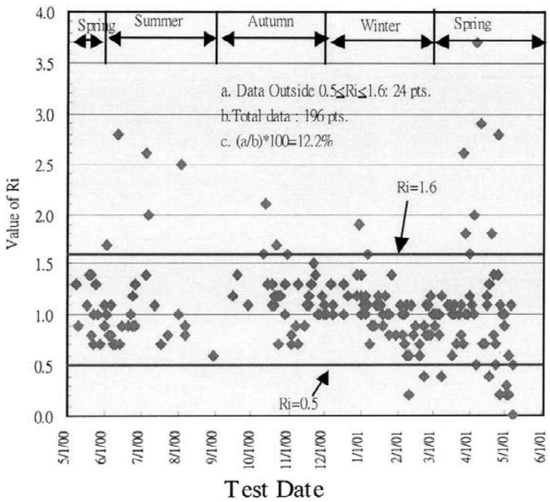

Fig. 2. Data distribution of R_i in latitude 23° N (test date: 5/08/2000–5/08/2001).

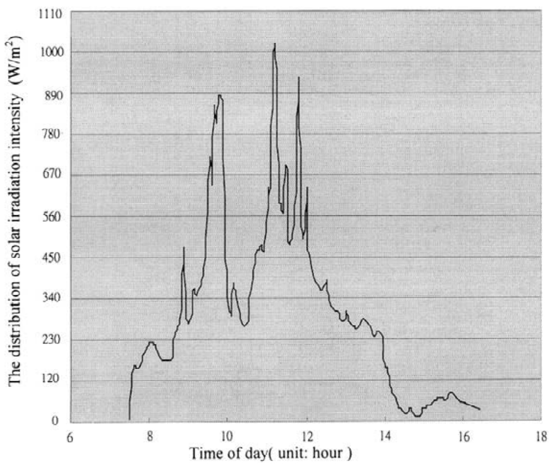

Fig. 3. Pattern of solar irradiation at $R_i = 2.6$ on the day 07/05/2000.

In the study, we follow CNS Standard B7277 (1989) and the additional criterion $0.5 \leq R_i \leq 1.6$ for the performance test. The major parameters are as follows.

1. The criterion of $0.5 \leq R_i \leq 1.6$.

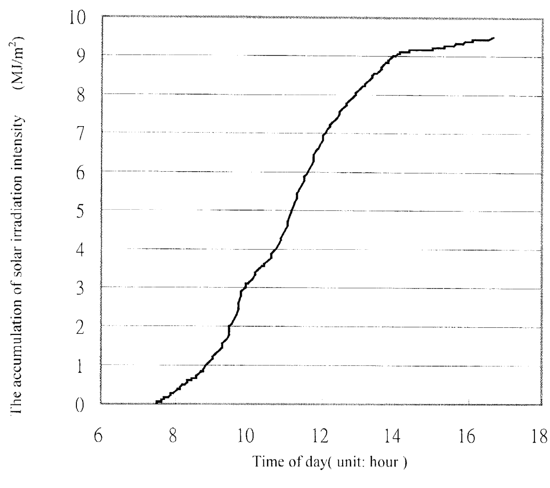

Fig. 4. Accumulation of solar irradiation intensity at $R_i = 2.6$ on the day 07/05/2000.

2. Time period for daily efficiency test: 9 h with symmetry to solar noon.
3. Total daily incident solar irradiation $H_t \geq 7\,MJ/m^2$ day.
4. Daily mean wind speed during test $\bar{v}_w \leq 3$ m/s for each day.
5. $0 \leq (T_i - T_a)/H_t \leq 2.5$.
6. At least 10 test points that satisfy the above testing conditions have to be taken.

$$R_i = H_m/H_a \tag{1}$$

where H_m is the total irradiation in the morning (MJ/m^2) and H_a is the total irradiation in the afternoon (MJ/m^2).

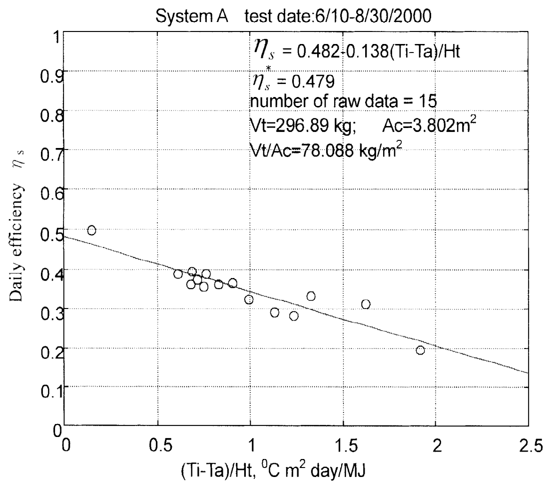

Fig. 5. Daily efficiency test results of system A without data screening using the criterion $0.5 \leq R_i \leq 1.6$ — case 1a in Table 2.

3. VERIFICATION OF THE NEW TEST STANDARD

Huang and Du (1991) developed a daily system efficiency model as shown in Eq. (2), where α_0 can be interpreted as the daily system efficiency under the condition that the initial temperature T_i equals the mean ambient temperature $\bar{T}_a$; U_s is the energy loss coefficient in the energy collecting phase. The parameters α_0 and U_s are determined from the linear regression analysis of Eq. (2) and we can extrapolate the test results of α_0 to the point with a fixed M/A_c value, as shown in Eq. (3). Therefore, η_s^* is defined as the α_0 value corrected at $M/A_c = 75\,kg/m^2$, which is chosen and verified by Huang (1993)

$$\eta_s = \frac{q_{net}}{H_t} = \alpha_0 - U_s \frac{T_i - \bar{T}_a}{H_t} \tag{2}$$

$$\eta_s^* = \alpha_0|_{M/A_c=75}. \tag{3}$$

In order to verify the new test standard including the criterion $0.5 \leq R_i \leq 1.6$, we carried out a field study in which we test two systems in latitude 25° N and 23° N.

For system A tested in latitude 23° N, Fig. 5 shows that data scattering occurs. If we adopt the test data using the criterion $0.5 \leq R_i \leq 1.6$, the result is Fig. 6 and reveals a much better correlation. The correlation coefficient of data based on linear regression analysis, as shown in Eq. (4) and Fig. 6, is improved from 0.915 to 0.969. It is also seen from the results in Figs. 5 and 6 that the system characteristic efficiency η_s^* changes significantly, from 0.479 to 0.514. The related information of Figs. 5 and 6 is also shown in the case 1a and 1b of system A in Table 2, respectively. From Fig. 7 in case 2a and Fig. 8 in case 2b of system A in Table 2, Fig. 7 also shows that data scattering occurs, and Fig. 8 in which test data are screened by the criterion $0.5 \leq R_i \leq 1.6$ has a much better correlation. The correlation coefficient of data between Figs. 7 and 8 is improved from 0.932 to 0.976. It is also seen from these results in Figs. 7 and 8 that the system characteristic efficiency η_s^* changes from 0.483 to 0.501.

For system B tested in latitude 25° N, Fig. 9 shows that data scattering occurs. If we adopt the test data using the criterion of $0.5 \leq R_i \leq 1.6$, the result turns out to be Fig. 10 that reveals a much better correlation. The correlation coefficient of data is improved from 0.936 to 0.976. It is also seen from these results in Figs. 9 and 10 that the

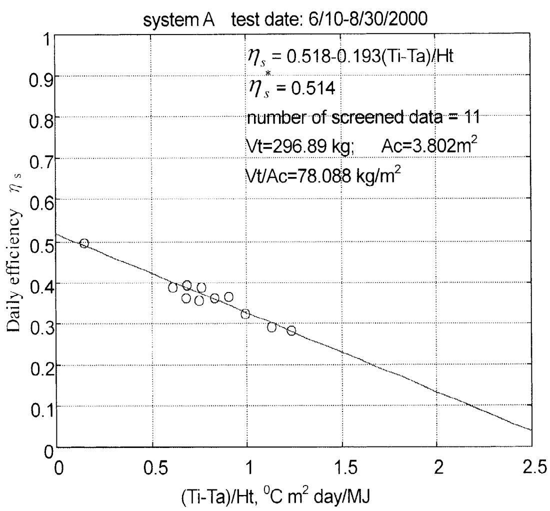

Fig. 6. Daily efficiency test results of system A with data screening using the criterion $0.5 \leq R_i \leq 1.6$ — case 1b in Table 2.

Table 2. Data in the five cases of system A were screened and not screened by $0.5 \leq R_i \leq 1.6$ in latitude 23° N

No. of case	Date of test (in 2000)	Number of data	Number of data after being screened by $0.5 \leq R_i \leq 1.6$	Error screened out by $0.5 \leq R_i \leq 1.6$	η_s^*	Correlation coefficient Z_{xy}
1a	0611–0830	15	Non-screened		0.479	0.915
1b	0611–0830	15	11	6.8%	0.514	0.969
2a	0608–0830	16	Non-screened		0.483	0.932
2b	0608–0830	16	12	3.5%	0.501	0.976
3a	0531–0830	20	Non-screened		0.475	0.928
3b	0531–0830	20	15	3.4%	0.493	0.967
4a	0524–0830	22	Non-screened		0.478	0.931
4b	0524–0830	22	17	3.1%	0.494	0.971
5a	0519–0830	26	Non-screened		0.481	0.964
5b	0519–0830	26	21	0.2%	0.482	0.982

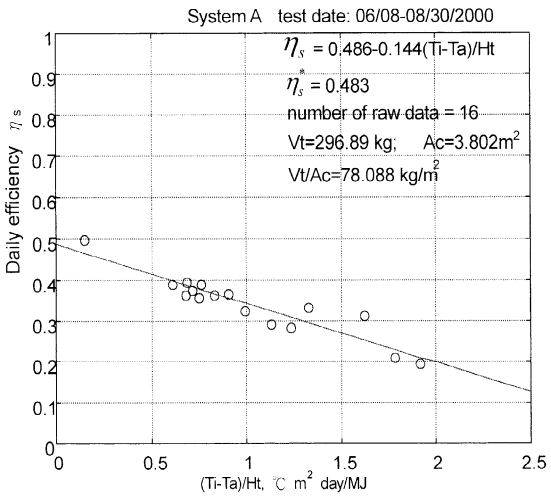

Fig. 7. Daily efficiency test results of system A without data screening using the criterion $0.5 \leq R_i \leq 1.6$ — case 2a in Table 2.

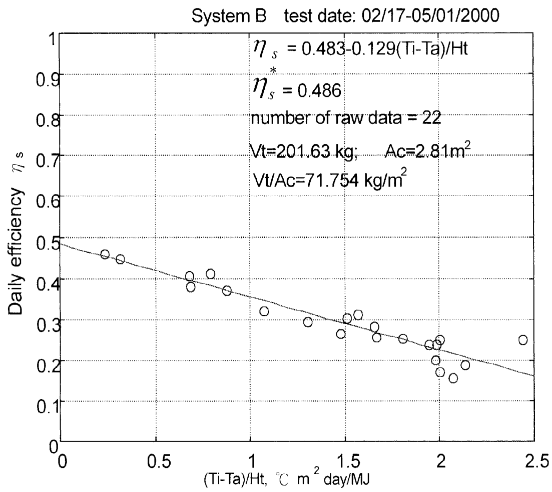

Fig. 9. Daily efficiency test results of system B without data screening using the criterion $0.5 \leq R_i \leq 1.6$ — case 1a.

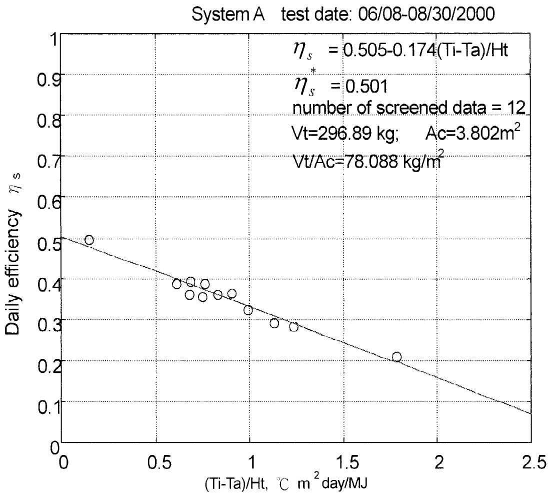

Fig. 8. Daily efficiency test results of system A with data screening using the criterion $0.5 \leq R_i \leq 1.6$ — case 2b in Table 2.

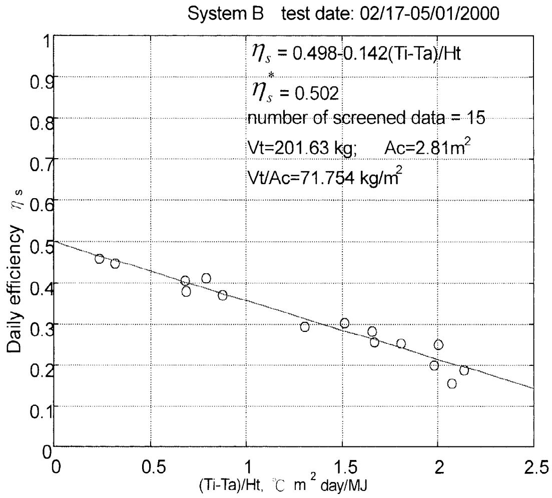

Fig. 10. Daily efficiency test results of system B with data screening using the criterion $0.5 \leq R_i \leq 1.6$ — case 1b.

system characteristic efficiency η_s^* changes from 0.486 to 0.502.

There is a regulation that the commercial product should have a value of η_s^* exceeding 0.5 in order to obtain a subsidy from the government. The performance test using the old standard can result in a significant error, according to the results above. The old test standard should be modified by incorporating the criterion of $0.5 \le R_i \le 1.6$

$$\eta_s = 0.518 - 0.193(T_i - T_a)/H_t. \quad (4)$$

4. DISCUSSION

There are five cases of system A tested in latitude 23° N, as shown in Table 2 and Fig. 11. They show the criterion $0.5 \le R_i \le 1.6$ is effective when the number of test data is less than 25 points. Under this condition, the criterion can be used and eliminate 6.8% error from the heat performance test of system A. For most test standards in the world, the number of test data must be at least six points, such as test standard ISO 9459-2 (1995) and BSEN 12976-2 (2001). Therefore, the criterion $0.5 \le R_i \le 1.6$ is effective when the number of test data is from six points to 25 points, and the criterion is at least useful to the thermosyphon solar hot water systems located at places with the same latitudes as Taiwan.

5. CONCLUSIONS

The performance of solar hot water heaters is affected by design parameters, climatic conditions, and hot water load pattern. The data collected from daily efficiency tests were screened by using the criterion $0.5 \le R_i \le 1.6$ in addition to the conditions defined in the CNS test standard.

The present study shows that we should introduce a distribution factor R_i and its criterion into the CNS test standard to provide reliable test results for solar hot water heaters. The modification is very important since there is a regulation that the commercial product should have a value of η_s^* exceeding 0.5 in order to obtain subsidy from the government.

NOMENCLATURE

- A_c collector area, m^2
- H_m the total irradiation in the morning, MJ/m^2
- H_a the total irradiation in the afternoon, MJ/m^2
- H_t daily total irradiation upon collector slope, MJ/m^2
- M total mass of water in the thermosyphon system, kg
- q_{net} daily total net energy absorption, MJ/day
- R_i a distribution factor of solar irradiation, dimensionless
- $\bar{T}_a$ mean ambient temperature, °C
- T_i initial tank temperature, °C
- U_s coefficient of overall system loss rate, MJ/m^2 °C day
- $\bar{v}_w$ daily mean wind speed during test, m/s
- Z_{xy} correlation coefficient of test data based on regression analysis, dimensionless

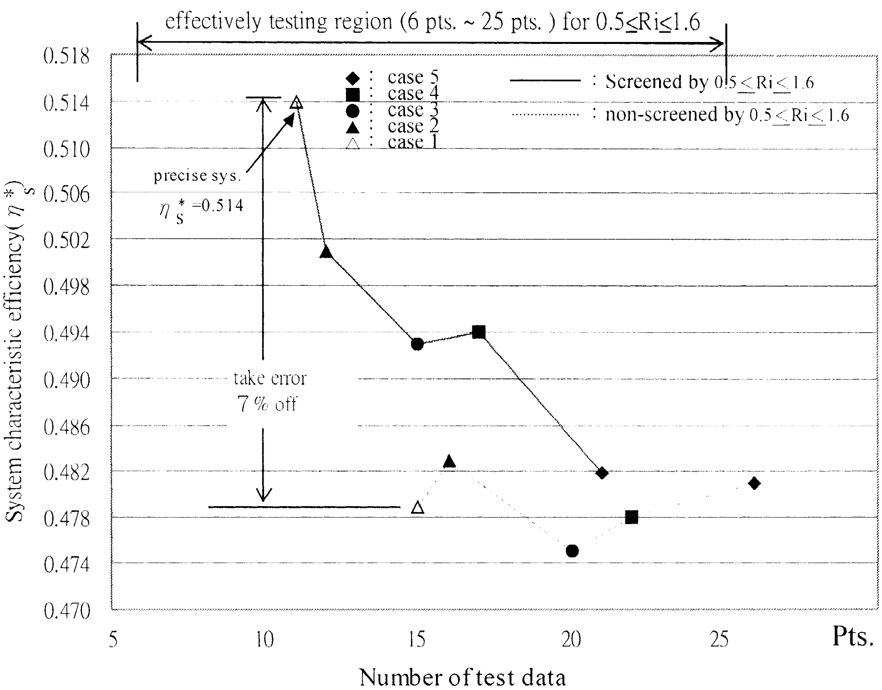

Fig. 11. Five cases of system A screened and non-screened by $0.5 \le R_i \le 1.6$ in latitude 23° N.

η_s daily system efficiency, dimensionless
η_s^* system characteristic efficiency, dimensionless
α_0 overall solar absorptance, dimensionless

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