

An Automation of Collector Testing and Modification of ANSI/ASHRAE 93-1986 Standard

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The steady-state performance test of solar collectors using ANSI/ASHRAE 93-1986 Standard was revised and an automation for the testing was carried out in the present study in order that the test can be easily performed outdoors in areas with variable weather conditions. It was shown that the 95 percent settling time of the collector τ_{95} can be adopted as the time basis in the selection of steady-state period for the test. To make the best use of the time available for the testing, the steady-state period defined by ANSI/ASHRAE 93-1986 Standard was changed to the τ_{95} plus five minutes, or ten minutes, whichever is larger. To reduce scatter uncertainty in the test results, the test period for the efficiency calculation was chosen as the segment of the last five minutes in the steady-state period and a steadiness condition defined statistically was adopted. To shorten the time for each test run a PC-based expert testing system, which is completely automatic and requires no operator, was developed in the present study. Using this expert system associated with the modified ANSI/ASHRAE 93-1986 Standard, we can effectively carry out the collector test at variable weather conditions with small scatter uncertainty and can substantially shorten the duration of a test.

I Introduction

ASHRAE 93-77 Standard (1977) and its revised version ANSI/ASHRAE 93-1986 Standard (1986) for the performance test of solar collectors is basically a steady or quasi-steady testing method and has been adopted worldwide as a reliable method for the rating of collectors. However, it has been noted that several problems may arise for testing outdoors in use with this standard and by manual operation. In many parts of the world, e.g., southeastern Asia and northern Europe, where the weather is usually not at clear sky conditions for most of the time in a year, the maximum time suitable for the steady-state testing is thus quite limited. If manual operation for the testing is employed in these areas, it might take a very long time (sometimes it takes a month, for example, in Taiwan) to complete a test.

To cope with this steady-state testing problem, different transient testing methods have been proposed recently (Gillett et al. 1983; Emery and Rogers, 1984; Oreszczyn and Jones, 1987; Wang et al., 1987). Two different testing standards have even been established by U.K. (1987) and China (1984). However, implementation of the Chinese transient testing method (Wang et al. 1987) requires a prior test of the collector to determine the impulse response or weighting function of the collector and needs a presumed second-order quasi-dynamic model of the collector for the filtering manipulation of the

measured dynamic data. Thus, it will be subject to errors in the final results due to the uncertainty in the determination of the impulse response function and in the use of the quasi-dynamic model.

The British transient testing method basically employs the deconvolution approach (an off-line nonparametric system identification technique) to identify the collector impulse response function first and then proceed to evaluate the collector parameters through some mathematical manipulations. It has been known that system identification using the off-line deconvolution method involves tedious computation and hence probably needs a mainframe computer with large storage capacity. Besides, the identified results will be biased if the system input (e.g., solar irradiation) is not persistently exciting or the measured output signals are corrupted by non-Gaussian random disturbances or noises (Hsia, 1977). It is conceivable that non-Gaussian external disturbances such as variations of ambient temperature, wind speed/direction, etc., could be introduced during the collector testing period (one hour for each testing point required by the British standard). Thus, the impulse response function identified may be seriously biased.

The steady or quasi-steady testing dictated by ASHRAE 93-77 or ANSI/ASHRAE 93-1986 Standards is thus superior to the transient testing from the points of view described above. However, several problems may arise if the steady-state testing was performed not under the conditions of "clear sky" (i.e., substantially free of clouds). ANSI/ASHRAE 93-1986 Standard is a revised version of ASHRAE 93-77 Standard by adding the "steadiness" requirement for solar irradiance, collector

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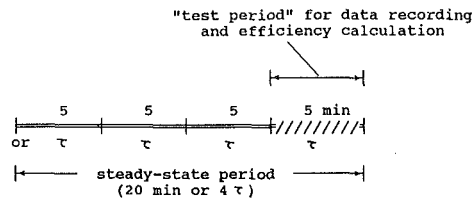


Fig. 1 Steady-state period and test period given by ANSI/ASHRAE 93-1986 Standard

inlet fluid temperature and mass flow rate prior to and during the period when the data are taken.

It is required by ANSI/ASHRAE 93-1986 Standard that: (1) the test should be performed during periods when the sky is clear such that the solar irradiance incident upon the collector aperture plane does not vary more than $\pm 32 \text{ W/m}^2$ for durations of ten minutes or 2 time constants, whichever is greater, both prior to and during the period when the data are taken; (2) the fluid inlet temperature T_i and the flow rate should remain constant within ± 2 percent (or $\pm 1.0^\circ\text{C}$) and $.000315 \text{ l/s}$ whichever is greater, respectively, for 15 min prior to each period in which data will be taken to calculate the efficiency values; and (3) the ambient temperature shall vary by no more than $\pm 1.5^\circ\text{C}$ during the same interval. The efficiency values are determined by integrating the data over a time period equal to the time constant or five min, whichever is larger. That is, the test should remain at a steady or quasi-steady condition for a continuous 20 min or 4 time constants, whichever is larger (Fig. 1). Though the above testing conditions would result in small scatter uncertainty, it could become time-consuming when performed in areas with variable weather condition, for example in Taiwan. It will be examined in the present study to see whether it is possible to shorten the required steady-state period.

The efficiency calculation is based on the data recorded in the test period as shown in Fig. 1. This revision given in ANSI/ASHRAE 93-1986 Standard can reduce the error due to the effect of collector transient response induced before the steady-state period, which was also found by many researchers (e.g., Exell et al., 1988; Edwards and Rhee, 1981; Proctor, 1984).

Edwards and Rhee (1981) first noted the effect of collector dynamics on steady-state testing results and derived a correction method based on a first-order or one-node dynamic model of the collector. Proctor (1984) has also noted this problem

and defined the "steady state" as the condition when the variation of the mean fluid temperature inside the collector is less than 0.75°C over the testing period. Furthermore, the minimum length of the testing period shall be three residence times of fluid in the collector or two residence times plus five min if the residence time is longer than five min. The data at the middle residence time or the five-min segment of the testing period is to be recorded and used for the efficiency evaluation. The purpose of taking an additional two residence times or the five-min segment is to ensure that the dynamic effect before the testing period will not pass to the recorded data. The use of residence time, however, is questionable. From the point of view of system dynamics, the collector transient response is well related to the time constant, instead of the residence time which is usually smaller than the time constant (Prapas et al. 1988). Furthermore, the "settling time" is more precise and appropriate for estimating the time period in which the transient effect is present and thus was used in the present study as the time criterion for selection of the steady-state period.

The time constant defined by ANSI/ASHRAE 93-1986 Standard is based on a first-order or one-node model of collectors which has been proved to be unable to accurately predict the dynamic responses (Smith, 1986). Hence, a modification using the second-order time constant based on a two-node model was made and from which the settling time was used as the time base in the selection of steady-state period for the test. The steadiness of the testing conditions as well as some other requirements given by ANSI/ASHRAE 93-1986 Standard were also modified in the present study such that the test can be easily performed in areas with variable weather conditions. In the meantime, to make the best use of the available time suitable for steady-state testing, an expert testing system was also developed.

II Automation of Collector Testing

To shorten the duration of steady-state collector testing, a PC-based intelligent automatic testing system or expert system was developed in the present study. The hardware of the expert system consists of: (1) a test stand; (2) a constant level and constant temperature bath for supplying a steady flow to the collector; (3) a flow control valve for flow rate regulation; (4) a PC-based numerical controller for temperature and flow rate

Nomenclature

A_c = collector aperture area, m^2	q_u = rate of energy delivered by collector, W	τ_d = time delay in the second-order model, sec
C_p = heat capacity of fluid, kJ/kgK	s = sample standard deviations	τ_e = effective second-order time constant, sec
$F_R(\tau\alpha)_n$ = thermal performance parameter of collector at solar noon, dimensionless	T_a = ambient temperature, $^\circ\text{C}$	τ_{95} = 95 percent settling time, sec
$F_R U_L$ = thermal performance parameter of collector, $\text{W/m}^2\text{C}$	T_{bath} = fluid temperature in the constant-level bath, $^\circ\text{C}$	ζ = damping ratio of the collector, dimensionless
I_T = irradiation on the collector slope, W/m^2	T_e = fluid temperature at the exit of the collector, $^\circ\text{C}$	Δt = time period of steady-state data recording, sec
\bar{I}_T = average irradiation on the collector slope, W/m^2	T_i = fluid temperature at the inlet of the collector, $^\circ\text{C}$	ΔT_{ei} = temperature rise across the collector ($= T_e - T_i$), $^\circ\text{C}$
\dot{m} = mass flow rate through collector, kg/s	$T_{i,\text{max}}$ = maximum fluid temperature at the inlet of the collector given by the manufacturer, $^\circ\text{C}$	$\overline{\Delta T_{ei}}$ = average temperature rise across the collector ($= \overline{T_e - T_i}$), $^\circ\text{C}$
\bar{m} = average mass flow rate through collector, kg/s	V = volumetric flow rate, cc/min	ΔT_{ia} = $T_i - T_a$, $^\circ\text{C}$
Q = heater power in the bath, kW	η_n = solar-noon efficiency	$\overline{\Delta T_{ia}}$ = $\overline{T_i - T_a}$, $^\circ\text{C}$
	τ = first-order time constant, sec	

adjustment; (5) a cover-up actuated by an air hydraulic cylinder through the PC for the shading of sunshine during the time constant test; (6) a data acquisition system for the measurement of irradiation, temperatures, flow rate, wind speed, etc.; and (7) an electronic timer to automatically turn the whole test system on in the morning and off at night. (See Fig. 2 for the testing system configuration and Fig. 3 for the schematic of operation.) The whole test system can be divided into two categories according to its function: the automatic measurement and the automatic control systems. An IBM-PC was used for data acquisition, decision making on the steadiness of testing conditions and the data recording action, computation in the temperature and flow rate control, data analysis and results plotting, sequential control of the whole testing procedures, etc.

1 Automatic Measurement System Design. The automatic measurement system consists of a YOKOGAWA 3880 hybrid recorder, an IEEE488 GPIB interface, and several sensors and their signal conversion circuits. A PSP pyranometer was used to measure the incident radiation upon the collector slope I_T with ± 2.5 percent uncertainty (including span error due to temperature dependence, linearity error, and cosine response error, all given by the manufacturer). A three-cup windmeter was used to measure instantaneous wind speed. T-type thermocouples were used to measure the temperatures at the collector inlet, the ambient, and the bath. To reduce the uncertainty in the measurement of temperature differences across the collector inlet and outlet, ΔT_{ei} ($\equiv T_e - T_i$), and across the ambient air and the collector inlet, i.e., $T_i - T_a$, two thermopiles made of five pairs of T-type thermocouples were used. The thermopiles were calibrated against a HP 2804 high

precision quartz thermometer to give an uncertainty $\leq \pm 0.07^\circ\text{C}$ (Huang, 1988). A turbine-type flowmeter MK508 with analog signal output was used to measure the mass flow rate through the collector and was calibrated with an uncertainty of $< \pm 2$ percent. The automatic measurement is actually a data acquisition process which was controlled by a subroutine written in C language. The maximum uncertainty obtained in the present study in determining the collector efficiency η is around 6.3 percent (including both measurement and scatter uncertainties) in which the scatter uncertainty due to random fluctuation of the process contributes a greater part. (See the Appendix.)

2 Automatic Control System Design. The hardware of the automatic control system essentially consists of a control valve for flow rate regulation; an electrical heater with SCR circuit to regulate the temperature in the constant level bath; a solenoidal valve to flush tap water into the bath if cooling is required during temperature control; an air hydraulic actuator to move the cover-up during the test of time constant; and an AD/DA interface to send control signals to control valve, SCR, and air actuator of the cover-up.

(i) *Control of Temperature in Constant-Level Bath.* To maintain a constant water temperature at the collector inlet and avoid flow fluctuations due to blockage of water vapor bubbles, the electrical heater was installed inside the bath. So, there is a large transportation time delay in temperature wave front from the bath to the inlet of the collector (about 6 m apart). Since the desired temperature to be controlled is at the collector inlet and the temperature set point is inside the bath, an empirical relation, which was derived and determined experimentally, was used to set the bath temperature T_{bath} for a desired inlet temperature T_i :

$$T_{\text{bath}} = \frac{T_i - (C/V)T_a}{1 - C/V}, \quad (1)$$

where V is the volumetric flow rate in cc/min and C is a constant determined experimentally to be $135.2 \text{ min}^\circ\text{C/cc}$.

The water temperature in the bath was controlled digitally. The control signal generated from a control algorithm was first converted into a standard $0 \sim 10 \text{ V}$ output through an 8-bit D/A interface. The analog signal was then used to trigger the SCR so that the heating rate of the electric heater inside the bath can be adjusted within the range $0 \sim 7 \text{ kW}$.

PI, P, and ON/OFF control algorithms were used interchangeably in the temperature control of the bath. The controller switches into PI algorithm when the bath temperature reaches $\pm 2^\circ\text{C}$ of the setting value. P-control algorithm was used when cooling is required. ON/OFF control associated with the maximum heating rate was used during the switching phase in order to accelerate the response. It takes about 15 min for each inlet temperature regulation and T_i can be controlled to within $\pm 1^\circ\text{C}$ (Fig. 4).

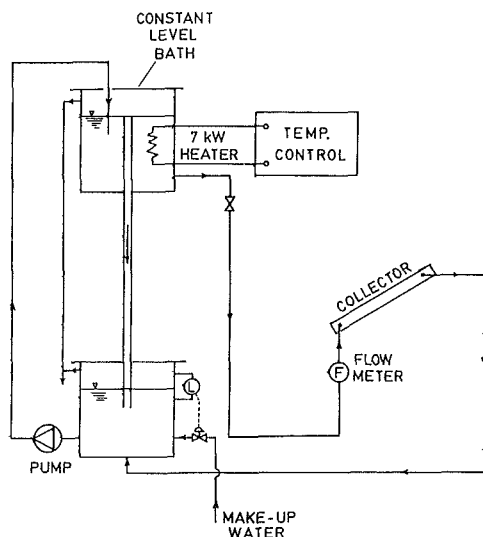


Fig. 2 Configuration of testing system

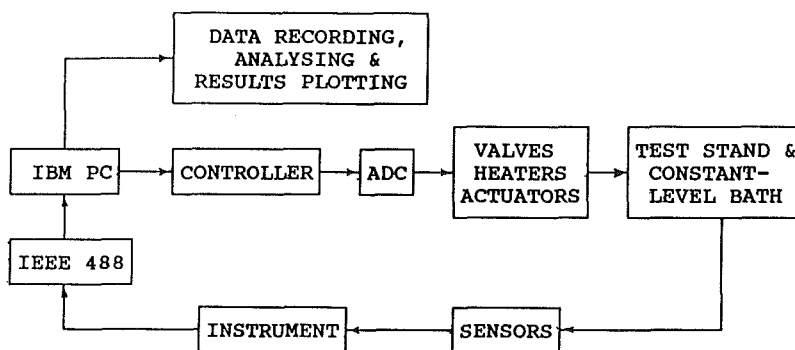


Fig. 3 Schematic of testing system operation

PI CONTROL OF BATH TEMPERATURE

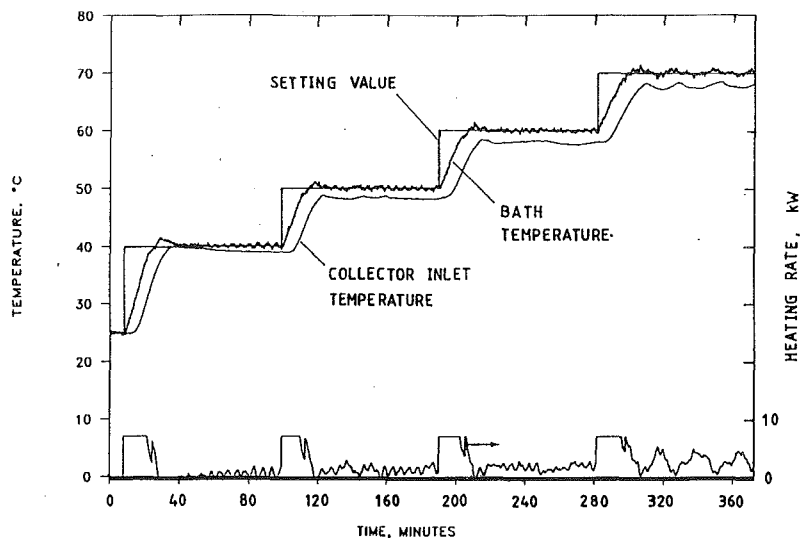


Fig. 4 Responses of temperature controller

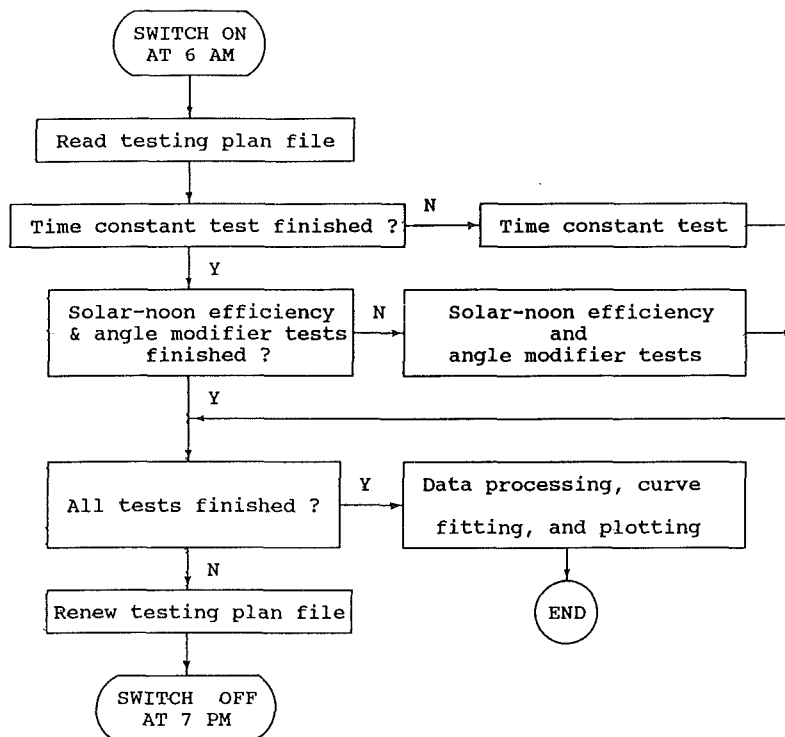


Fig. 5 Flow chart of the automatic testing process

(ii) *Control of Mass Flow Rate.* A digital PI-control algorithm was used for the control of mass flow rate. A compensation for the backlash of the control valve was also employed to overcome the cycling problem. It takes 5 min for a flow rate regulation.

3 System Software for Steady-State Data Recording, Analyzing, and Plotting. The testing task includes sequential tests of time constant, angle modifier, and solar-noon efficiency and is controlled by a main program written in C language. A separate user-written testing plan file, which includes all the items at various testing conditions, will be read in the morning when the test system is first turned on. This testing plan file will be updated everyday to indicate which test items have been

finished and which have not. The system software also includes an intelligent program to make decision on whether the operating conditions have reached a "steady state" (which is to be defined in the next section) and on what period of the steady-state data should be recorded. A curve fitting program using linear regression analysis and a plotting program are also included for data processing and plotting at the end of the test. Figure 5 shows the flowchart of the automatic testing process. Figure 6 presents a typical solar-noon test result. The result of the angle modifier test is shown in Fig. 7.

The operation of the expert system is completely automatic and no operator is required. To improve the accuracy and ensure the repeatability of the test results, some modifications on the ANSI/AHSRAE 93-1986 Standard are necessary.

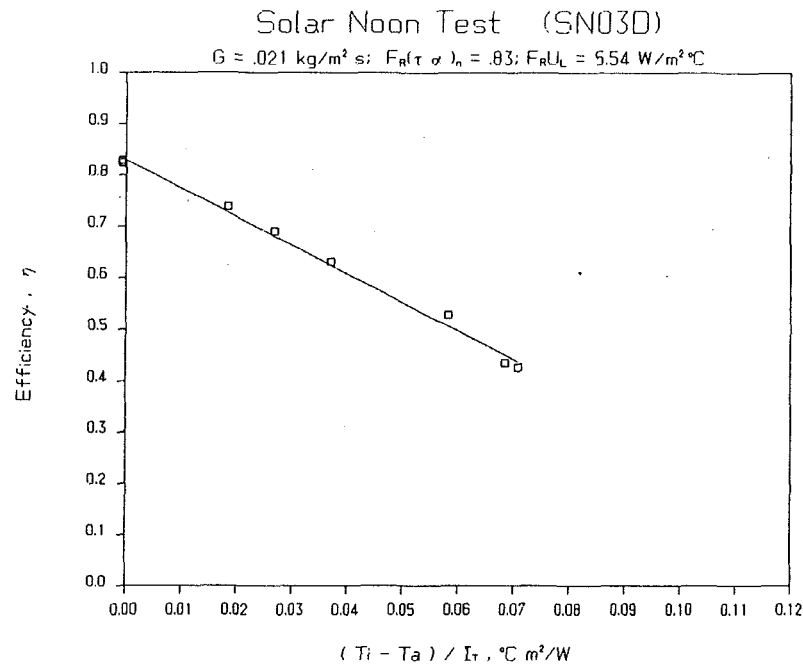


Fig. 6 Output of solar-noon efficiency test result

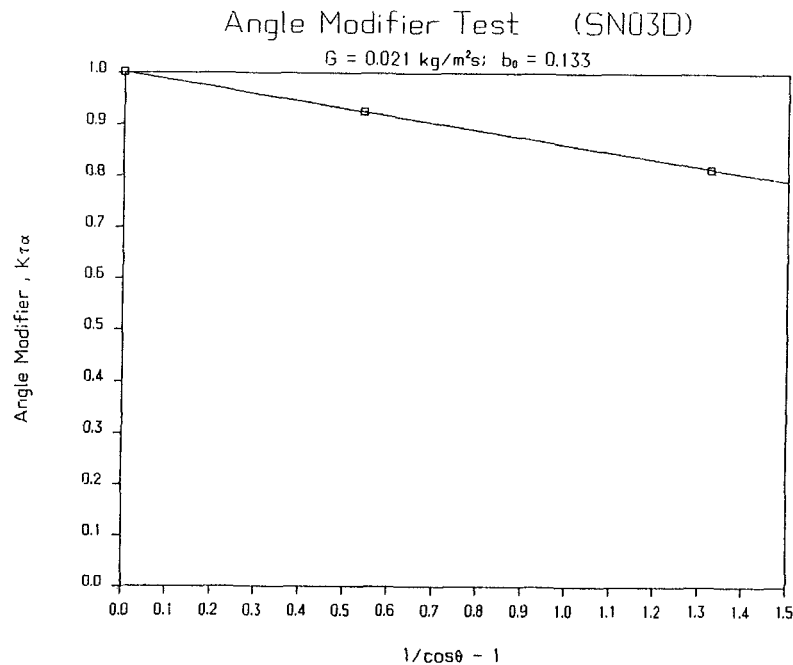


Fig. 7 Output of angle modifier test result

III Revisions of Steady-State and Test Periods

In ANSI/ASHRAE 93-1986 Standard, the definition of collector time constant is based on the one-node model derived by Klein et al. (1974) which is then used as the time base for the definition of steady-state period (ASHRAE, 1986). It has been noted recently by many researchers that the first-order or one-node model of solar collectors does not describe the dynamic behavior accurately. Smith (1986) found that the first-order or one-node collector dynamics cannot accurately predict the collector transient response. Similar conclusion was also obtained by Wang et al. (1988). That is, the one-node model as used in ANSI/ASHRAE 93-1986 Standard needs to be re-examined. As a result, a modification using a higher-order model is necessary. A second-order dynamic model which de-

fines two collector time constants was derived recently based on a two-node or two-phase (solid and fluid) physical model by Huang and Wang (1989). The following semi-empirical model was obtained:

$$W(s) = \frac{\bar{T}_e(s)}{\bar{I}_T(s)} = \frac{K e^{-\tau_d s}}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (2)$$

where $\bar{T}_e(s)$ is the Laplace transform of the perturbed collector outlet temperature from the steady-state value, i.e., $\bar{T}_e(t) = \Delta T_{el}(t) - \Delta \bar{T}_{el}$; τ_d is the collector time delay; $\bar{I}_T(s)$ is the Laplace transform of the perturbed irradiation from a steady-state value, i.e., $\bar{I}_T(t) = I_T(t) - \bar{I}_T$; τ_1 and τ_2 are the time constants related to the dynamic responses of the solid and liquid parts of the collector, respectively. τ_1 , τ_2 , K , τ_d were

Table 1 Collector time constants based on first and second-order models

Flowrate $\text{kg/m}^2\text{s}$	Time Constant, sec							
	1st-order		2nd-order					
	τ	τ_1	τ_2	τ_d	K^\dagger	τ_e	ζ	τ_{95}
.020	152	80	22	16.0	.00767	42	1.214	282
.015	142	86	29	14.8	.00875	50	1.150	308
.010	288	95	58	18.7	.01420	74	1.034	370
.005	273	128	128	24.0	.02230	128	1.000	632

$^\dagger K$ is the gain in $^\circ\text{Cm}^2/\text{W}$.

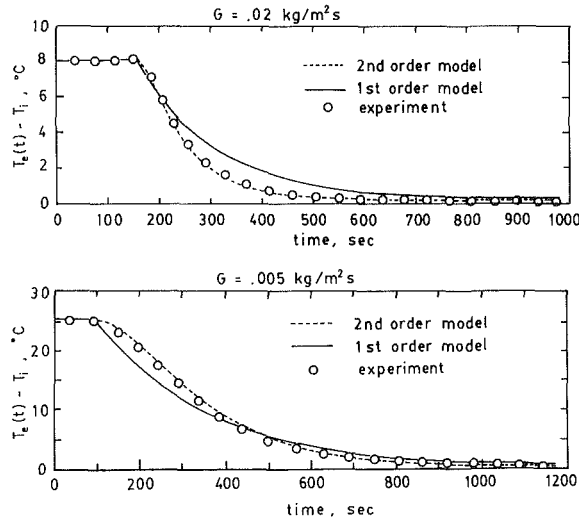


Fig. 8 Step responses of a flat-plate collector

identified by a least-squares estimation method using step response test results (Huang and Wang, 1989). Results of the step response test and the model fitting of equation (2) for a flat-plate collector are presented in Fig. 8. It can be seen that the prediction based on the first-order model does not agree with the experimental results.

Table 1 presents the time constants obtained from the first and second-order models for the same flat-plate collector. For the second-order model, the "effective time constant, τ_e ", and the damping ratio, ζ , can be defined and determined:

$$\tau_e \equiv \sqrt{\tau_1 \tau_2} = \frac{1}{\omega_n}, \quad (3)$$

$$\zeta \equiv \frac{\tau_1 + \tau_2}{2\tau_e}, \quad (4)$$

where ω_n is the natural frequency. It can be seen from Table 1 that the dynamics of solar collector usually belongs to an overdamped system ($\zeta > 1$). The symbol τ_{95} appearing in Table 1 is the "95 percent settling time" defined as the time that the collector outlet temperature response reaches 95 percent of the steady value. τ_{95} can be evaluated analytically by using the well-derived step response functions presented in some textbooks, e.g., by Van de Vegte (1986). Another straightforward method of determining τ_{95} is by graphical approach using the step response results from the time constant test. The latter approach was used in the present study.

The 95 percent settling time, τ_{95} , represents the time period during which the effect of collector dynamics is significant. Thus, this is the time period in which the "steady-state" efficiency calculation should be avoided. Hence, the steady-state test period and the time segment used for the steady-state data recording and efficiency calculation should be carefully chosen based on τ_{95} in order to eliminate the error due to the dynamic effect imposed before the steady-state period.

Figures 9 and 10 present the test results using ASHRAE 93-77 Standard (1977) in which the periods of steady-state test and data recording are the same and taken as five min or one time constant, whichever is larger. Thus, large scattering due to the dynamic effect can be seen. Though ANSI/ASHRAE 93-1986 Standard uses a longer steady-state period (20 min or four first-order time constant, whichever is larger) to cope with this problem, it would take a longer time for tests performed outdoors in areas with variable weather conditions.

From the point of view of system dynamics, it is reasonable to redefine the steady-state period as $\tau_{95} + 5$ min or 10 min, whichever is larger. (See Fig. 11.) Thus, the steady-state period can be reduced by one half on ANSI/ASHRAE 93-1986 Standard and the test can be easily performed in areas with variable weather conditions. The time segment of the last five minutes is the test period on which the steady-state data are to be recorded and used to calculate the efficiency values.

IV Definition of Steadiness for Steady-State Period

A definition of "steadiness" for the test period is necessary in the tests of collector time constant, solar-noon efficiency, and angle modifier in order to reduce the scattering or bias of the test results due to the variation of solar irradiance. Since the time variations of testing conditions are inevitable and always observed in practice, the steadiness will have to be defined on a statistical basis. From the point of view of system dynamics, the solar irradiance, mass flow rate, and inlet temperature act as the system inputs. The time variation of these variables results in a transient response of the output (collector exit temperature or useful energy gain). Thus, in order to achieve a steady-state or quasi-steady condition, the system input signals (i.e., irradiance, mass flow rate and inlet temperature) have to be monitored and maintained constant as much as possible during the testing.

The time-variant input signals during the steady-state period always appear random and can be treated as a stationary random process. The condition of "steadiness" thus can be defined statistically with respect to the input signals. In the present study, we define the "steady-state" or "quasi-steady" testing condition as follows:

If the standard deviation s_x of the sampled signal in the testing period is smaller than a value β which is chosen as $\alpha\bar{x}$, i.e., $s_x \leq \beta$ ($= \alpha\bar{x}$), then the signal is said to be at a "steady-state" condition. That is, more than 100 $(1 - 2\alpha)$ percent of the number of sampled data will lie within the interval between $\bar{x} - z_{\alpha}\beta$ and $\bar{x} + z_{\alpha}\beta$ for a "steady-state," i.e., within $[(1 - \alpha z_{\alpha})\bar{x}, (1 + \alpha z_{\alpha})\bar{x}]$, where z_{α} is the 100 α percent significance point of the standard normal distribution. In other words, at most (2α) 100 percent of the sampled data are allowed to lie outside the interval $[(1 - \alpha z_{\alpha})\bar{x}, (1 + \alpha z_{\alpha})\bar{x}]$.

In the present study, the steadiness for the solar irradiance incident upon the collector aperture is defined according to the above criterion with $\alpha = 0.025$. For sampled solar irra-

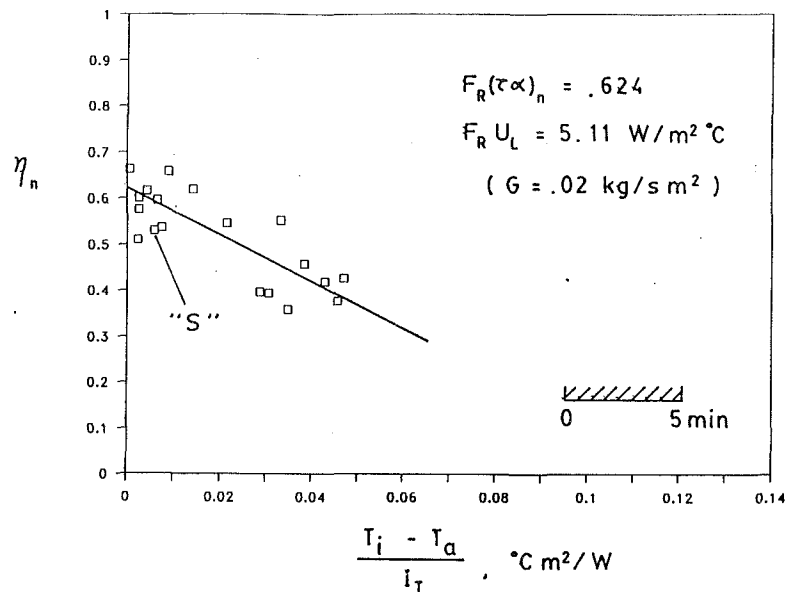


Fig. 9 Scattering of test results using ASHRAE 93-77 Standard for $\dot{m} = 2400 \text{ cc/min}$ ($0.02 \text{ kg/m}^2\text{s}$)

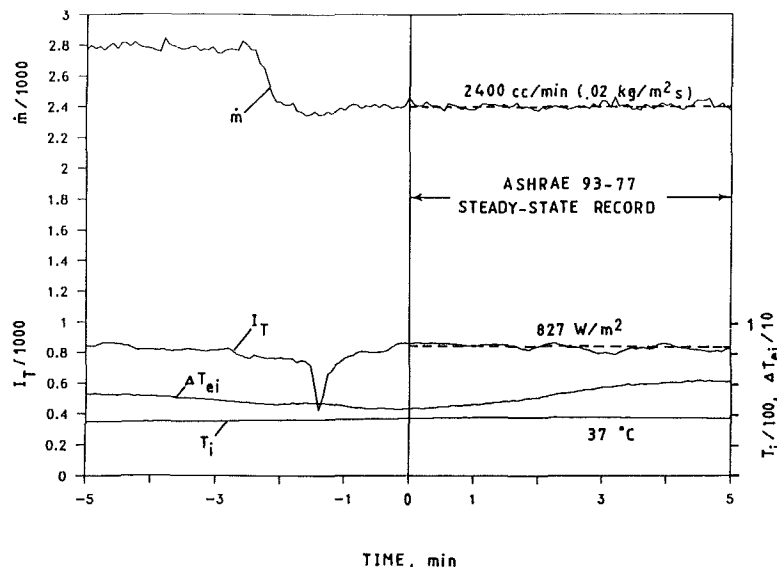


Fig. 10 Operating conditions of the test point "S" in Fig. 9

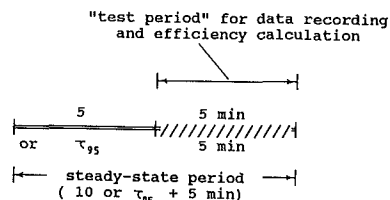


Fig. 11 Modified steady-state period and test period

diance data, it means that more than 95 percent will lie within $[0.951\bar{x}, 1.049\bar{x}]$. In other words, at most 5 percent of the number of sampled data are allowed to lie outside the above interval. The present steadiness requirement for solar irradiance is analogous to that given by ANSI/ASHRAE 93-1986. Thus, small scatter uncertainty on the final test results can be assured.

The steadiness condition was given to the mass flow rate \dot{m} according to the above criterion with $\alpha = 0.01$, which is also analogous to that of ANSI/ASHRAE 93-1986 Standard.

It should be noted that the present steadiness criterion for the inlet temperature still follows the requirement of ANSI/ASHRAE 93-1986 Standard which allows T_i to vary within 1°C . However, to ensure steady-state results, an additional requirement for the steadiness condition was given to the temperature difference ΔT_{ia} with $s_{\Delta T_{ia}} \leq 0.5^\circ\text{C}$. The above selections of steadiness condition for I_T , \dot{m} , ΔT_{ia} in terms of α value and sample standard deviation are based on field experiences.

To fulfill the above steadiness definition, a moderate sampling rate (0.25 Hz or one sampling every four seconds in the present study) is required so that the process can be randomized in the observation. Besides, the number of sampled data should be ≥ 30 so that the statistical inference using Gaussian, instead of Student- t , distribution can be applied and the interpretation of $100(1 - 2\alpha)$ percent chance of occurrence of sampled data in the interval $[(1 - \alpha z_\alpha)\bar{x}, (1 + \alpha z_\alpha)\bar{x}]$, can hold statistically. This requirement can be easily met by using a modern data acquisition system and with a moderate sampling rate.

The use of a moderate sampling rate in the data collecting

will also filter out the high frequency content. Thus, the observed data can only “see” the low pass behavior of the collector which is, however, usually of major interest in practical applications. For example, for a sampling rate of 0.25 Hz, the dynamic behavior beyond 1 Hz cannot be seen from the sampled data. However, the dynamics of most solar collectors possesses essentially a low pass behavior with cutoff frequency at the order of 0.01 Hz or lower. Thus, the dynamic data at frequency ≥ 1 Hz is of no practical use at all and can be ignored or filtered out during the collector testing. This enables us to use a moderate sampling rate ranging from 0.1 to 0.5 Hz or from two to ten sec per sampling.

In addition, nonstationary, low frequency drift in the recorded irradiation data may also appear due to the time variation of solar incident angle during the day. However, the present steadiness definition allows the testing conditions to have five percent variation. This implies that the allowable maximum drift spans ten percent over the test period which will be smaller than that caused by ANSI/ASHRAE 93-1986.

During the testing, the “steadiness” of the testing conditions such as the irradiation incident upon the collector surface, the inlet fluid temperature, and the mass flow rate through the collector were monitored all the time according to the present definition.

V Method of Efficiency Calculation

In the efficiency calculation in both solar-noon efficiency and angle modifier tests, ANSI/ASHRAE 93-1986 Standard requires to take a “steady-state” data record, including $\dot{m}(t)$, $\Delta T_{ei}(t)$ ($\equiv T_e(t) - T_i(t)$) and $I_T(t)$, over the “test period” Δt as shown in Fig. 1 which is then used for the efficiency calculation according to the following integration:

$$\eta = \frac{\int_{3\tau}^{3\tau+\Delta t} q_u(t) dt}{\int_{3\tau}^{3\tau+\Delta t} I_T(t) A_c dt} = \frac{\int_{3\tau}^{3\tau+\Delta t} \dot{m}(t) C_p \Delta T_{ei}(t) dt}{\int_{3\tau}^{3\tau+\Delta t} I_T(t) A_c dt}, \quad (5)$$

where $q_u(t)$ is the instantaneous useful energy delivered by the collector; the test period Δt is chosen as the first-order time constant or five min whichever is larger.

Actually, for a perfectly steady process, we can record only one set of instantaneous data and then proceed to calculate the instantaneous efficiency without integration. The “steady-state” efficiency is defined in integral form because the integration can act as a filter to the time variant signals.

It was found in the present study that the test results may present a great scatter uncertainty as shown in Fig. 9, if ASHRAE 93-77 Standard (original ASHRAE 93 Standard) was followed and the expert testing system was used to acquire the data. This is due to the fact that the recorded temperature difference $\Delta T_{ei}(t)$ (output signal) contains the transient response of the dynamic process imposed before the recording of the steady-state data. (See Fig. 10.) Of course, this kind of scatter error could be eliminated by using ANSI/ASHRAE 93-1986 Standard. But, a much longer steady-state period has to be maintained during the test.

Since the temperature response $\Delta T_{ei}(t)$ can be corrupted by the dynamic effect before the steady-state period, the integration of the energy gain, i.e., the numerator of equation (5), has to skip over at least one settling time of the steady-state period in which the transient effect is still present. Recalling that, we have previously defined the steady-state period of the test as τ_{95} plus 5 min or 10 min whichever is larger, in which the last 5-min segment is the “test period” (Fig. 11). Therefore, we will perform the efficiency calculation by integrating the data recorded over the last 5 min of the test period.

If the testing conditions match the steadiness definition de-

scribed previously, the sampled signals, $I_T(t)$ and $\dot{m}(t)$ and $\Delta T_{ei}(t)$, can then be described by the following relations:

$$I_T(t) = \bar{I}_T + e_I(t) \quad (6)$$

$$\dot{m}(t) = \bar{\dot{m}} + e_m(t) \quad (7)$$

$$\Delta T_{ei}(t) = \overline{\Delta T_{ei}} + e_{Tei}(t) \quad (8)$$

where \bar{I}_T , $\bar{\dot{m}}$ and $\overline{\Delta T_{ei}}$ are the statistically mean or “quasi-steady” values; $e_I(t)$, $e_m(t)$, and $e_{Tei}(t)$ are the random fluctuations.

Therefore, we can redefine the “steady” or “quasi-steady” efficiency as, in conjunction with equations (5), (6), (7), and (8),

$$\eta = \frac{\int_{\tau_{95}}^{\tau_{95}+\Delta t} q_u(t) dt}{\int_{\tau_{95}}^{\tau_{95}+\Delta t} I_T(t) A_c dt} = \frac{\bar{q}_u}{\bar{I}_T A_c} = \frac{\bar{\dot{m}} C_p \overline{\Delta T_{ei}}}{\bar{I}_T A_c} \quad (9)$$

where \bar{q}_u and \bar{I}_T are the average values of useful energy rates and irradiation intensity, respectively, over Δt in the time interval $[\tau_{95}, \tau_{95} + 5 \text{ min}]$ or $[5, 10 \text{ min}]$. The last two equalities in equation (9) hold if Δt is large enough such that the residues, $e_I(t)$, $e_m(t)$, and $e_{Tei}(t)$, are random and their integrations over Δt are cancelled out. That is,

$$\int_{\tau_{95}}^{\tau_{95}+\Delta t} e_I(t) dt \approx 0 \quad (10)$$

$$\int_{\tau_{95}}^{\tau_{95}+\Delta t} e_m(t) dt \approx 0. \quad (11)$$

$$\int_{\tau_{95}}^{\tau_{95}+\Delta t} e_{Tei}(t) dt \approx 0. \quad (12)$$

Theoretically, the integration time interval or test period Δt also should be chosen long enough to average out the bias due to the transient effect caused by an abrupt variation of irradiation during the period $[0, \tau_{95}]$ or $[0, 5 \text{ min}]$. In the present study, we choose $\Delta t = 5 \text{ min}$ which was shown to be adequate from many field experiences. With this modification, the scattering error was greatly reduced as shown in Fig. 12. The small scattering shown in Fig. 12 was due to the variation of average wind speed during the test which was allowed to vary between 0 and 4.5 m/s as required by ASHRAE 93-77 Standard and this kind of scatter error was inevitable in outdoor tests (Green, 1988).

It should be noted that the low frequency drift of $q_u(t)$ or ΔT_{ei} due to slowly varying irradiation can lead to errors in the efficiency calculation using equation (9). A criterion was introduced by Aranovitch (1977), which accepted the data as a quasi-steady one when

$$\frac{dT_e(t)}{dt} < 12^\circ\text{C/hr}. \quad (13)$$

Another criterion was given by Proctor (1984), which accepted the steady-state data when the collector outlet temperature does not vary by more than 0.75°C . The Aranovitch criterion may give a maximum overall variation of 1°C for the integration period $\Delta t = 5 \text{ min}$. Since the temperature rise across the collector $\Delta T_{ei}(t)$ is usually in the range $5\text{--}10^\circ\text{C}$ depending upon the irradiation intensity and the collector thermal properties, Aranovitch or Proctor’s criterion can easily lead to an uncertainty in efficiency calculation larger than 10 percent for $\Delta t = 5 \text{ min}$. By using the present definitions of steadiness and test period, this error can be greatly reduced.

Since the low frequency drift due to slowly varying irradiation corresponds to a transient response of $q_u(t)$ or $\Delta T_{ei}(t)$ caused by a ramp input $I_T(t)$, the response $q_u(t)$ or $\Delta T_{ei}(t)$

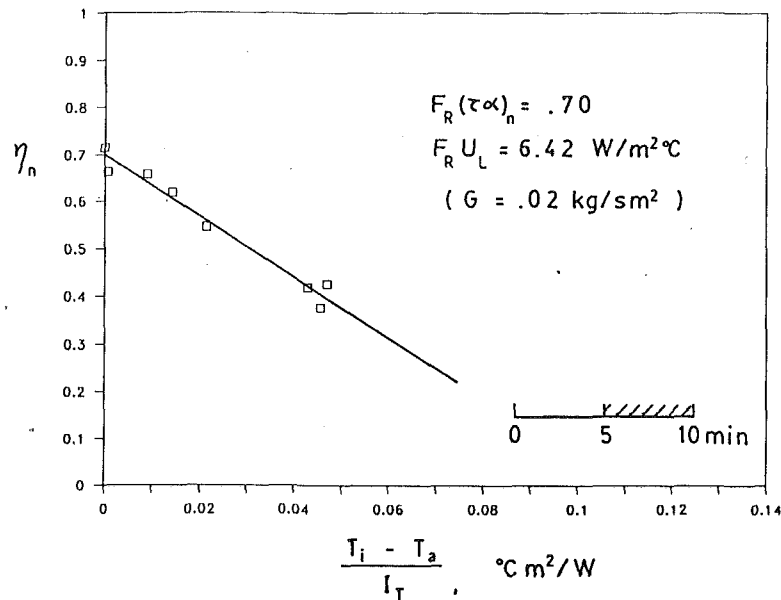


Fig. 12 Test results based on the modified ANSI/ASHRAE 93-1986 Standard for solar-noon efficiency

will also approach to a ramp function at large t . In practice, a ramp response can be reached approximately at time $t > \tau_{95}$. Therefore, a correction with respect to the ramp response can also be made if necessary (Huang and Lu, 1982), though it is usually not required.

VI Some Other Modifications

At this stage, we have modified ANSI/ASHRAE 93-1986 Standard mainly in the selection of test period based upon the collector settling time and the statistical definition of steadiness condition. The following modifications were also made in the present study.

(1) Number of Test Points. ANSI/ASHRAE 93-1986 Standard requires to take at least 16 data points in each solar-noon efficiency test. Among these points, at least four data points shall be taken for each value of T_i ; two of the four data points shall be taken during the time period preceding solar noon and the other two shall be taken in the period following solar noon. The specific period being chosen so that the data points represent times symmetrical to solar noon. This requirement is made so that any low frequency transient effects (with response time in the order of several hours) that may be present will not bias the test results. This low frequency transient effect is mainly due to the long time response of the insulating or constructing material of the collector.

In tropical areas, e.g., Taiwan, there is no collector freezing problem and the collector is usually operated at lower $T_i - T_a$ so that the insulation of the collector can be designed with relatively light weight material as compared to that required in high latitude areas. The low frequency transient response thus can be ignored. In this case, the test points can be chosen based upon the inlet fluid temperature alone. The scatter uncertainty for tests at each T_i is then less important than the variation of T_i . Hence, for simplification, at least eight test points is recommended to be taken according to the evenly distributed inlet fluid temperatures described as follows.

(2) Distribution of Inlet Temperatures. ANSI/ASHRAE 93-1986 Standard requires to take steady-state test points at four different inlet fluid temperatures according to the distribution obtained by setting $T_i - T_a$ to 0, 30, 60, and 90 percent of the value of $T_i - T_a$ at the manufacturer's recommended maximum operating temperature of the collector. The present

modification requires to take the eight steady-state test points evenly distributed for the inlet temperature ranging from ambient temperature T_a to $T_{i,max}$.

(3) Range of Ambient Temperature. ANSI/ASHRAE 93-1986 requires that the range of ambient temperatures for all reported test points comprising the efficiency curve shall be less than 30°C. If this requirement is obeyed for the tests in tropical areas, then the time available for the test in a year will be greatly reduced. However, it can be seen from the principles of the collector heat transfer that this requirement is not important as compared to the others such as steadiness and selection for test period, etc. Thus, the range of ambient temperature is not given in the present modification.

(4) Wind Speed Range. ANSI/ASHRAE 93-1986 requires that the average wind speed shall be between 2.2 and 4.5 m/s during the test period and a minimum of 20 min or four first-order time constants, whichever is greater, for glazed collector under test just prior to the beginning of the test period. For the cases in which the natural wind conditions do not satisfy the above requirements, the natural wind may be supplemented with artificial wind.

In many tropical areas such as Taiwan, the natural wind varies year around over a wide range. For the test results to be met with the situation of practical applications, it is recommended in the present study that the wind speed range still follow the requirement of ASHRAE 93-77 Standard. That is, the allowable average wind speed in the test is between 0 and 4.5 m/s.

We summarize the modifications of ANSI/ASHRAE 93-1986 Standard in Table 2. The test results presented in Fig. 6 and 12 are based on the test method with this modifications.

VII Discussion and Conclusions

The steady-state performance test of solar collectors using ANSI/ASHRAE 93-1986 Standard was revised and an automation for collector testing was carried out in the present study in order that the test can be easily performed in areas with variable weather conditions. It was found that the time constant derived from the first-order dynamic model is unable to predict the transient response of the collector accurately. A modification using the second-order time constants based on

Table 2 Summary of the present modification on ANSI/ASHRAE 93-1986 Standard

	ANSI/ASHRAE 93-1986	Present Modifications
Time constant	first-order τ	second-order τ_e or τ_{95}
Test period definition	20 minutes or 4 τ	10 minutes or $\tau_{95} + 5$ minutes
Steadiness definition	absolute	statistical
Steadiness for I_T	$\leq \pm 32 \text{ W/m}^2$	$s_{I_T} \leq 0.025 \bar{I}_T$
Steadiness for T_i	$\pm 1^\circ\text{C}$	not changed
Steadiness for \dot{m}	$\leq \pm 0.02 \bar{m}$	$s_m \leq 0.01 \bar{m}$
Steadiness for ΔT_{ia}	not given	$s_{\Delta T_{ia}} \leq 0.5^\circ\text{C}$
Number of test points	at least 16	at least 8
No. of test points at each T_i	at least 4	at least 1
Time-symmetry test	required	not required
Average wind speed range	2.2 ~ 4.5 m/s	0 ~ 4.5 m/s
T_i distribution	by 0, 30, 60, 90% of ($T_{i,max} - T_a$)	evenly-distributed between T_a and $T_{i,max}$
Ambient temperature range	$\leq 30^\circ\text{C}$	not given

a two-node model was made and from which the 95 percent settling time was used as the time basis in the selection of steady-state period of the test.

Though the use of ANSI/ASHRAE 93-1986 Standard can reduce the scatter error due to the dynamic effect of the collector, it takes longer for outdoor tests. To make the best use of the time available for the testing in areas with variable weather conditions, the steady-state period of the test defined in ANSI/ASHRAE 93-1986 Standard was changed to the 95 percent settling time of the collector plus five or ten minutes whichever is larger. The efficiency calculation was then performed by integrating the data recorded over the time segment of the five minutes (i.e., test period) in order to reduce the scatter error resulting from the transient response imposed before the test period. Furthermore, the steadiness condition, which is defined statistically, was adopted.

To shorten each test run, a PC-based expert testing system which is completely automatic and requires no operator was developed in the present study. Using this expert testing system associated with the modified ANSI/ASHRAE 93-1986 Standard, we can carry out the collector test at variable weather conditions with small scatter uncertainty and substantially shorten the time period of a test. No direct comparison of the present test results with those followed ANSI/ASHRAE 93-1986 Standard, however, can be made in the present study, since it is very difficult to perform the test in use with ANSI/ASHRAE 93-1986 Standard under the variable weather conditions in Taipei City, Taiwan, where the present study was carried out. It also should be pointed out that, theoretically, the present modification is not only applicable to the particular climate in Taiwan. It can be applied to other areas with variable weather conditions.

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APPENDIX

Uncertainty Analysis

The combined uncertainty in determining the "steady-state" collector efficiency η consists of both measurement and scatter

uncertainties. The former is caused by uncertainty of the measuring equipments; the latter is caused by data scattering due to random fluctuation of the process.

The combined uncertainty w_η of collector efficiency η based on equation (9) can be evaluated by the following relation, assuming negligible errors in C_p and A_c ,

$$w_\eta = \sqrt{w_m^2 + w_{I_T}^2 + w_{\Delta T_{ei}}^2}, \quad (\text{A1})$$

where w_m , w_{I_T} , and $w_{\Delta T_{ei}}$ are the uncertainties of \dot{m} , I_T , and ΔT_{ei} , respectively, all of which are expressed in percent (i.e., relative error with respect to the average values) and each consists of measurement and scatter uncertainties. That is,

$$w_i = \sqrt{w_{i,s}^2 + w_{i,u}^2} \quad (\text{A2})$$

where $w_{i,s}$ represents the scatter uncertainty of the i th component; $w_{i,u}$ represents the measuring uncertainty of the i th component. It can be seen that the present study gives

$w_{m,s} = 1$ percent; $w_{m,u} = 2$ percent;

$$w_m = \sqrt{0.01^2 + 0.02^2} = 2.24 \text{ percent}$$

$$w_{I_T,s} = 2.5 \text{ percent; } w_{I_T,u} = 2.5 \text{ percent; } w_{I_T} = \sqrt{0.025^2 + 0.025^2} = 3.54 \text{ percent.}$$

For ΔT_{ei} , the maximum scattering was found to be around 0.2°C and the maximum scatter uncertainty is thus $w_{\Delta T_{ei},s} = 0.2/4.5 = 0.044$ for a minimum $\Delta T_{ei} = 4.5^\circ\text{C}$ observed in the tests. The maximum measurement uncertainty is $w_{\Delta T_{ei},u} = 0.07/4.5 = 0.016$. Therefore, from equation (A2),

$$w_{\Delta T_{ei}} = \sqrt{0.044^2 + 0.016^2} = 4.7 \text{ percent.}$$

Hence, the maximum combined uncertainty w_η in the present experiments can be estimated by equation (A1),

$$w_\eta = \sqrt{w_m^2 + w_{I_T}^2 + w_{\Delta T_{ei}}^2} = \sqrt{0.0224^2 + 0.0354^2 + 0.047^2} = 6.3 \text{ percent.}$$

By following the statistical definition of the steadiness and assuming that all the measurement uncertainties are at 20:1 odds, this uncertainty can be considered to be at 20:1 odds (or 95 percent confidence).