"The advantage lies in the serviceability of covered or diffused sky conditions for outdoor collector testing."

Outdoor Test Facility for Solar Flat-Plate Collectors

by

Henry J. Ramos and Edgardo S. Reyes*

Abstract

An outdoor test facility based on the open-loop design has been developed for determining the efficiency of solar flat-plate collectors. The applicability and adoption of the various published standards on collector testing like the ASHRAE, AFNOR, DIN/BSE, EIR and CSIRO under actual Philippine climatological conditions are discussed. Features of the developed test facility are described and results obtained using one of the published standards are presented.

Introduction

Flat-plate collector testing has not been pursued with much vigor in the Philippines in the past. With the growing solar thermal energy utilization, however, as indicated by the increasing number of solar flat-plate collectors for domestic, commercial and industrial hot water requirements, the need for collector testing becomes desirable.

There are three objectives of solar flat-plate collector testing, namely:

1. to improve collector designs;
2. to determine the collector's technical data for system design; and
3. to compare commercially available collector types for consumer protection.

Collector testing makes use of recommended and well-known test procedures such as the American Society of Heating, Refrigerating and Airconditioning Engineers (ASHRAE), USA standard (1); Bundesverband Solarenergie (BSE), Germany standard (2); AFNOR, France standard (3); Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia standard (4); and Eidg. Institut für Reaktorforshung (EIR), Switzerland standard (5) among others. The testing could also be done by means of comparative methods and integrated methods which feature an intercomparison of collectors using known standards or using any other procedure which suits the local conditions. A test collector can be compared, for example, with a well-known reference collector under the same conditions. If energy measurements were to be used, the integrated method applies for collector testing under fluctuating environmental or transient conditions.

---

*Energy Research and Development Center, PNOC, Don Mariano Marcos Avenue, Diliman, Q.C.

In this paper, the differences of the various standards and the problems associated to their adoption in collector testing in the Philippines will be described in addition to the experimental set-up and loop design. Finally, results and recommendations for further work are discussed.

Theoretical Considerations

It is first necessary to summarize the governing equations. The primary considerations are the measurement of thermal performance (or efficiency), thermal capacity and pressure drop of collectors.

The procedures to be considered are all based on the investigation of the steady-state efficiency: the rate of energy extracted from the collector balances the rate of radiative energy absorbed and of heat loss to the environment. This steady-state efficiency η – also called the instantaneous efficiency – is the most suitable item to characterize the thermal performance of collectors.

$$\eta = \frac{\int_{T_1}^{T_2} m_f C_p (T_o - T_i)\, dt}{\int_{T_1}^{T_2} G\, dt} \tag{1}$$

where:

T_i = inlet temperature of the fluid (°C)
T = outlet temperature of the fluid (°C)
A = area of the collector (m^2)
G = solar irradiance, in the plane of the collector per unit area (W/m^2)
m_f = mass flow rate of the fluid (g/s)
and C_p = specific heat of the transfer fluid (J/g. °C) (See Table 1)

The integration and averaging over the period of measurements is to exclude time dependencies. What is actually to be investigated is a rather quasi-steady state since, even for clear sky conditions, changes in solar irradiance are inevitable. This could be gauged, for example, in Figure 1 which typifies a quasi-steady state.

Three first-order parameters govern the thermal performance, hence instantaneous efficiency, of a collector:

- solar irradiance (global and diffuse)
- operating temperatures
- flow rate and direction

Environmental parameters like the ambient air temperature, wind speed and direction, the sky condition and the radiation properties of the surroundings viewed by the collector have to be either monitored during the testing or subjected to certain restrictions defined by the procedure.

The analysis and description of flat plate collector performance are based on papers by Hottel and Woertz (6); Whillier (7) and Bliss (8).

When the rate of energy extracted from the collector balances the rate of radiative energy absorbed and of heat lost to a uniform environment, this results in a state which may be expressed as:

$$\frac{\mathring{Q}_u}{A} = G.(\zeta\alpha)_e - U_L \cdot (T_p - T_a) \tag{2}$$

where:

$\mathring{Q}_u$ = rate of useful energy extracted (W)
A = area of collector (m^2)
G = solar irradiance, in the plane of the collector per unit area (W/m^2)
$(\zeta\alpha)$ = effective transmittance – absorption product of the cover-absorber system
U_L = heat transfer loss coefficient for the collector (W/m^2 °C)
T_p = average temperature of the absorber surface of the collector (°C)
and T_a = ambient air temperature (°C).

It is difficult to measure directly the plate temperature, T_p, without resulting to destructive techniques, hence it is convenient to relate the performance to the temperature of the fluid. Duffie and Beckman (9) has shown that either the inlet temperature or a mean temperature can be an appropriate reference temperature. This results in an essentially linear efficiency characteristic represented by the two equations:

$$\frac{\mathring{Q}_u}{A} = F' \cdot G(\zeta\alpha)_e - F'U_L \cdot (T_m - T_a) \tag{3}$$

and

$$\frac{\mathring{Q}_u}{A} = F_R \cdot G(\zeta\alpha)_e - F_R \cdot U_L \cdot (T_i - T_a) \tag{4}$$

where:

F' = collector efficiency factor
F_R = collector heat removal factor
T_m = average temperature of fluid in the collector (arithmetic mean of inlet and outlet temperature)
T_i = inlet temperature of the fluid
and T_o = outlet temperature of the fluid.

Equation 4 is a feature of the ASHRAE method (1), while Equation 3 was adopted in the NBS method (10). Hottel and Woertz (6) correlated these two equations as follows:

$$F_R = F' \frac{(1 - 3^{-n})}{n}, \; n = \frac{U_L \cdot F'A}{\mathring{m} f \, Cp} \tag{5}$$

The collector efficiency η is the quotient of two energy rates:

$$= \frac{Q_u}{A.G.} = F'(\zeta\alpha)_e - F'U_L \frac{(T_m - T_a)}{G} \tag{6}$$

$$\text{or} \quad \eta_o = \eta - U \frac{(T_m - T_a)}{G} \tag{7}$$

where:

U_o = $F'(\zeta\alpha)_e$, efficiency for $T_m = T_a$

and

U = $F' U_L$, global heat transfer coefficient (W/m^2 °C).

If values of η are plotted against corresponding values of $T^* = (T_m - T_a)/G$, this will result in a curve with negative slope U and intercept n_o (Figure 2). Equations 6 and 7 form the basis of the test procedures.

The different standard procedures mentioned previously are characterized by the following features (11).

ASHRAE-method: the instantaneous efficiency is obtained by pure outdoor testing under quasi-steady state conditions and other specified climatic conditions (typical desert conditions). A minimum irradiance of 630 W/m^2 is required. Moreover, the air velocity across the collector should be less than 4.5 m/s and the ambient air temperature less than 30 °C during the test period. The test is conducted by monitoring a number of steady-state conditions. The flowrate is standardized at a value of 0.02 kg/(s.m^2), if the transfer fluid is liquid. At least four data points for inlet temperature well distributed over the range of operating temperatures (determined by the stagnation temperature or the maximum temperature the assembly can withstand), should be determined. To evaluate Equations 1 and 7, the solar irradiance (direct/diffuse), the temperature rise of the fluid over the collector, the inlet temperature, and the ambient air temperature are measured. The efficiency is then presented as a line or a curve obtained by least-squares fit of η against the parameter T* (See Figure 2).

BSE-method: This method involves a mixed indoor-outdoor test under described outdoor and laboratory conditions typical of Middle Europe. Here, Equations 6 and 7 are rewritten thus:

$$\frac{Q}{A} = \eta_o \cdot \overset{o}{G} - U \cdot (T_m - T_a) \tag{8}$$

with the term $U_o \cdot (T_m - T_a)$ interpreted as a heat loss rate.

The conversion factor $\eta = \overset{o}{Q}_u / G.A.$ is determined by running the collector in a steady-state condition at a mean fluid temperature which is close to the ambient air temperature. In this case, the heat loss rate $U_o \cdot (T_m - T_a)$ tends to become zero, thus η_o is determined with four data points. Deviations up to 10°C are allowed since it is difficult to satisfy the requirement $T_m = T_a$ exactly. The heat loss coefficient U_o is obtained by testing indoors in a number of steady-state with G = O. U is then determined as a function of the difference temperature $T_m - T_a$ thus:

$$U = \frac{\overset{o}{Q}_u}{A.(T_m - T_a)} \; ; \; \overset{o}{Q}_u = m\,CP \cdot \Delta T \tag{9}$$

A linear best fit reveals a possible dependence of U_o on $(T_m - T_a)$. Further, the coefficients U_1 and U_2 determine U:

$$U_o = U_1 + U_2 (T_m - T_a) \tag{10}$$

Thermal losses are determined for both natural convection (air speed less than 4 m/s) and forced convection of $(T_m - T_a)/G$:

$$= \bar{\eta}_o - U_1 \frac{(T_m - T_a)}{G} - U_2 \frac{(T_m - T_a)^2}{G^2} \cdot G \tag{11}$$

where $\bar{\eta}$ = arithmetic mean of the data points.

The efficiency is then plotted for a number of G values. For a meaningful comparison of this method with the ASHRAE method, a value of G = 800W is appropriate.

AFNOR-method: This is a pure outdoor test under specific reference conditions typical of the Mediterranean. The mass flow rate is set to 0.01 kg/(s.m^2). The surrounding air speed V is between 1.5 m/s and 5 m/s. The ambient air temperature is in the interval $5°C < T_a < 30°C$ and solar irradiance is between 760W and 840W. Quasi-steady state conditions to be investigated are determined by the subsequent requirements $T_i = T_a$, $T_i + 20°K$, $T_i = T_a + 40°K$ and $T_i = T_a + 60°K$.

EIR-method: This method is similar to the BSE method but instead of the indoor test component, covered sky conditions are used. Thermal losses are determined outdoors under covered sky conditions when the radiation is stable and close to 100 percent diffuse.

CSIRO-method: This method is a pure outdoor test and specifies that the efficiency be expressed as a second-order function of $(T_m - T_a)/G$ but T_a, being defined here as the equivalent temperature of the surroundings, is derived by measuring the sky temperature, a rather difficult parameter to measure.

The above standards specify common parameters to be measured in order to obtain the efficiency of a flat-plate collector. It is noted how stringent the requirements are for the climatic conditions if one were to use any of the above methods. Similarly, the requirements about instrumentations and accuracy are very strict. For instance, the following parameters should be measured with an accuracy during the test as follows:

- collector inlet temperature, $T_i \pm 0.1°C$
- temperature difference, $\Delta T \pm 0.01°K = (T_o - T_i) \pm 0.1°K$
- ambient air temperature, $T_a \pm 0.5°C$
- mass flow rate, $\overset{o}{m}_f \pm 1\%$
- global radiation, $G \pm 1\%$
- wind speed, $V \pm 2.5\%$

Experimental Set-Up and Loop Design

The Nonconventional Resources Division (NCRD) of the Bureau of Energy Development in 1977 developed a test facility (Figure 3) based on the open loop design (see Figure 5 of reference 1). With this test facility, a standard absolute testing method was developed for rating solar flat-plate collectors based on thermal performance (12). This set-up enables one to measure collector efficiency at near normal incidence (4). It also allows evaluation of the incident angle modifier accounting for the effects of varying the angle of incidence.

The stringent requirements of the well-known test standards has led us to redesign the NCRD test facility. As shown in the schematic diagram in Figure 3, the immersion heater is incorporated within the supply tank of the system. The collector inlet water temperature being held constant throughout the performance test is very important. In Figure 3, as water is pumped continuously into the header tank, there is a great possibility of the inlet water temperature changing due to the changing water temperature from the collector to the supply tank. To eliminate this possibility during a test run, a circulation heater equipped with thermostatic control and several switching mechanisms designed in the laboratory is installed just before the transfer fluid enters the collector. The immersion heater is thus removed from the supply tank. The flowrate per aperture area during the test run is maintained at a standard value of 0.02 kg/m^2s. This would give the circulation heater sufficient reaction time to heat the water at a desired temperature before it enters the collector. The constancy of the inlet water temperature as tested with the developed system is shown in Figure 4.

Figure 5 shows a schematic diagram of the developed test facility and the various instrumentations used. The configuration is based on the open-loop design to determine the overall performance of solar collectors and conforms to the accuracy requirements recommended by the various well-known standards.

The facility is fitted with a weigh tank as an added feature. Water is drawn off automatically into a batch weighing system resting on a load beam. The load beam operate on the strain gauge principle and the amount of strain recorded due to the weight of added water to the weigh tank is converted directly as mass of the water drawn off from the collector. Regular draw-off tests are conducted in this manner and this serves as calibration procedure for the mass flow rate. The transferred fluid weight is measured by the balance over a fixed time interval. Thus the flow meter can be calibrated to read a mean accuracy of ± 1.0%. Contents of the weigh tank are drawn off automatically by solenoid valves from the batch weighing system to the storage tank.

The heat dump cools hot water emanating from the collector before it is deposited back to the supply tank. This eliminates undue rise in water temperature which would adversely change the inlet collector water temperature being supplied to the collector.

The overall check of the calometric accuracy of the test loop was conducted and systematic errors in the facility were determined.

The header tank is equipped with a mechanical level switch which activates the pump thereby ensuring a constant water level.

The collector is supported by an adjustable frame where the angle of tilt (and orientation) can be varied.

Global radiation and diffuse radiation are measured with first class Eppley, PSP pyranometers calibrated to an international standard and recorded as an electrical output directly converted to solar energy during specific times of investigation.

Operating temperatures for the inlet and outlet of the collector and the ambient air temperature are measured with Pt-100 standard resistance bulbs. Two of these are encapsulated in separate special insulated boxes. The special casing developed in the laboratory acts as a mixing device to ensure high turbulence inside the fluid stream to guaranty an accurate average measurement of inlet and outlet operating temperatures. The other resistance bulb is installed in a louvered instrument housing for proper recording of ambient air temperature.

The mass flowrate is measured with a 0.0303 – 0.3029 kg/s (0.48-4.8 gpm) effective range flowmeter with an electrical output in the range of 4 – 20 mA equivalent to 0. – 1090 kg/h output.

Wind speed is measured with a three-cup anemometer provided with a programmable integrator.

The measured parameters are registered in a common KONTRON twelve channel point with two line chart recorders. Absolute temperatures (T_i and T_o), the ambient air temperature (T_a), wind speed (v), mass flow rate (mf) are recorded on any of the twelve point channels. Global radiation and diffuse radiation are recorded continuously on the two line channels.

Development of Appropriate Collector Testing Standard

The outdoor test rig developed under this project conforms to the accuracy requirements of the ASHRAE, AFNOR, EIR and CSIRO standards. These standards, therefore, could be directly adopted as long as the strict requirements on climatic conditions imposed by the standards are met. The assumption of steady-state conditions, however, when adopting any of the well-known standards would pose a problem under Philippine climatic conditions. Additional recommendations and some changes in the test procedures are therefore required.

Typical Philippine climatic conditions are presented in Figures 6, 7 and 8. The environmental scans on global radiation, diffuse radiation, ambient air temperature and wind speed were primarily done to establish which periods during the day would have steady or quasi-steady state conditions during which time outdoor test methods can be applied.

Figure 6 represents a typical profile of the above-mentioned environmental parameters during a relatively bright sunny day. Curve a represents the measured global radiation. Curve b indicates the changes of the surrounding air temperature. Curve c is for the diffused radiation. Curve d shows the histograms for the average wind speed. For the ASHRAE and other outdoor test methods to be applicable, a minimum irradiance of 630 W/m^2 under quasi-steady state conditions is required. These conditions normally occur during solar noon and the quasi-steady nature is typified in Figure 1.

Also, in accordance with the ASHRAE method, the air velocity across the collector should be less than 4.5 m/s. This condition is easily satisfied and can be controlled by three interconnected 0.36 m diameter electric fans which collectively act as a blower in front of the collector being tested. The ambient air temperature being less than 30°C when the condition is quasi-steady and the insolation above 630 W/m^2 on the other hand, is difficult to obtain. Normally, as shown in Figure 6, bright sunny days in the Philippines correspondingly entail temperatures of the surrounding air above 30°C. This deviation, however, should not discount the adoption of the ASHRAE standard for collector testing during bright sunny days. And the number of such days throughout the year, particularly in Metro Manila is very limited. Based on insolation data gathered at the Energy Research and Development Center (ERDC) and on PAGASA data on the number of bright sunshine hours on a monthly duration, reasonable outdoor testing could only be conducted during the period from February to May. The frequency of occurrence of bright sunny days during other periods in the year are highly unpredictable and more often improbable for outdoor collector testing. This is so, because of the highly-diffused nature of radiation in the Philippines being in the order of about 50 percent. Under these circumstances, quasi-steady state conditions occur only during small time intervals or are non-existent at all. Such transient phenomena resemble more closely the conditions specified by the EIR-standard.

For transient conditions, the collector is tested using the heat balance based on the following relation:

Total power collected = Useful power extracted + rate of heat gained in the collector

Let $\overset{o}{Q}_t$ = total power collected
$\overset{o}{Q}_u$ = useful power extracted

and $C_e \dfrac{d\,(T_m)}{d_t}$ = rate of heat gain in the collector.

Then
$$\overset{o}{Q}_t = \overset{o}{Q}_u + C_e \frac{d\,(T_m)}{d_t} \qquad (12)$$

where C_e = effective thermal capacity of the collector
T_m = average temperature of fluid in the collector.

If the fluid goes from state 1 to state 2, the transient behavior of the collector is represented thus:

$$C_e \frac{d\,(T_m)}{dt} = -\overset{o}{m}_f\, C_p\, \Delta T - A_e U_m (T_m - T_a) \qquad (13)$$

Here, $\overset{o}{m}_f$ = mass flow rate
C_p = specific heat of the fluid
ΔT = outlet temperature of the fluid – inlet temperature of the fluid
= $T_o - T_i$
A_e = effective collector area
U_m = collector heat loss coefficient
and T_a = ambient air temperature.

In Equation 13 the specific heat, C_p, of the fluid is taken at a mean fluid temperature. Table 1 gives values of C_p for use in Equations 9 and 13.

Integrating Equation 13 over the time period between the two states:

$$C_e\ (T_{m2} - T_{m1}) = -\int_1^2 \overset{o}{m}_f\ C_p\ T\, dt - A_e U_m \int_1^2 (T_m - T_a)\ dt \qquad (14)$$

But,

$$T_m = T_i + \frac{\Delta T}{2}$$

and

$$T_m - T_a = (T_i - T_a) + \frac{T}{2} \qquad (15)$$

Combining Equations 13 and 15 and simplifying, the collector thermal capacity, C_e becomes:

$$C_e = \frac{m_f C_p \int_1^2 T dt - A_e U_m \left| \int_1^2 (T_i - T_a) dt + \frac{1}{2} \int_1^2 T dt \right|}{(T_{m_2} - T_{m_1})} \qquad (16)$$

The useful power collected is determined from

$$Q_u = \overset{o}{m}_f C_p \Delta T$$

Substituting this into Equation 13 and with the value of $C_e \frac{d(Tm)}{dt}$ determined from Equation 13, the total power collection of the collector is determined. This is then used to solve the corresponding efficiency

$$\eta = \frac{\overset{o}{Q}T}{A\,G} \qquad (17)$$

where, G = solar irradiance at the plane of the collector.

With this method the performance characteristic of a collector no longer requires sufficiently long sunny days. The advantage lies in the serviceability of covered or diffused sky conditions for outdoor collector testing. This can be combined with the well-known outdoor testing methods whereby the conversion factor

$$\eta_o = \frac{\overset{o}{Q}_u}{A\,G} \qquad (18)$$

is determined under clear sky conditions. Thermal losses are then determined outdoors under sudden radiation changes when the sky is covered by clouds. Under these conditions, radiation is stable and approximately 100 percent diffused. Low values of radiation (10-300 W/m^2) normally prevail and ambient air temperature varies slowly with a cloud cover. Further development of this method would lead to long-term collector testing under actual Philippine conditions. This deviates from the BSE-method in the sense that the thermal losses are determined during the occurrence of a cloud cover and not placing the collectors indoors.

One disadvantage would be the tedious data processing routine involved considering the enormous recorded profiles to be gathered and doing a step-by-step reading of the profiles.

Results and Discussions

Figure 9 shows a typical test run showing the quasi-steady condition for G. The other lines indicate the constant values of outlet temperature T_o, inlet temperature T_i and the surrounding ambient air temperature T_a. This set of curves gives one value of instantaneous efficiency as a function of T*. Similar sets of curves are obtained for other constant values of T_i. The instantaneous efficiency for these points are then plotted against T*. A computer program has been developed for least-squares curve fitting of the experimental data points.

A description of the solar collector tested is shown in Table II. The efficiency curves for this collector using the ASHRAE-standard and for both natural and forced convections are shown in Figure 10.

Tests for other collectors which are available in the Philippine market are presently being conducted. Results of these tests will be subsequently reported.

It should be noted that the results presented in this report give only an indication of the performance of the collector during the specific conditions mentioned. It is planned that the performance of the collector be determined also at other conditions, particularly those specified by climatological conditions represented in Figures7 and 8.The facility developed is also intended for the long-term performance testing of solar collectors.

References

ASHRAE Standard 77-93, "Methods of Testing to Determine the Thermal Performance of Solar Collectors," ASHRAE, 354 East 47th Street, New York, N.Y. 10017,1977.

AFNOR 50 – 501, Mesure des Performances Thermique-Capteurs Solaires, France, 1977.

BLISS, R.W., "The Derivations of Several Plate Efficiency Factors Useful in the Design of Flat-Plate Solar-Heat Collectors," Solar Energy, 3,55, No. 4; 1959.

BSE – Guidelines, "Guidelines and Directions for Determining the Usability of Solar Collectors," Technical Report, Bunderverband and Solarenergie, Essen, Germany, 1979.

DUFFIE, I.A., and BECKMAN, W.A., "Solar Energy Thermal Processes," John Wiley and Sons, New York, 1980.

HILL, J.E.; KUSUDA, T., "Method of Testing for Rating Solar Collectors Based on Thermal Performance," NBSIR 74-635, Washington D.C.; 1974.

HOTTEL, H.C. and WOERTZ, B.B., "Performance of Flat-Plate Solar-Heat Collectors," Trans. ASME 64, 91; 1942.

MAHILUM, D.M., Private Communication, PNOC-ERDD, Diliman, Quezon City,1982.

SUTER, J.M.,; Widder, F.; Kesselring, P. "Wärmetrager und Kenngrössen von Sonnenkollektoren," Eidg. Institut für Reaktorforshung, Würenlingen, Switzerland, 1979.

SYMONS, J.G., "An Outdoor Test Facility for Solar Flat-Plate Collectors," CSIRO Division of Mechanical Engineering Technical Report No. TR9, Commonwealth Scientific and Industrial Research Organization, Highett, Victoria, Australia, 1977.

TALAREK, H.D., "Testing of Liquid-Heating Flat-Plate Collectors Based on Standard Procedures," International Report No. KFA-IKP-IB-4/79, Institute für Kernphysik, Jülich, 1979.

WHILLIER, A.and Saluja, G., "Effects of Material and Construction Details on the Thermal Performance of Solar Water Heaters," Solar Energy, 9, 21; 1965.

Table 1. Properties of Water for Analysis of Collector Testing Results.

Temperature Tm (°C)	Specific Heat Cp (J/g °C)
5	4.204
10	4.193
15	4.186
20	4.183
25	4.181
30	4.179
35	4.178
40	4.179
45	4.181
50	4.182
55	4.183
60	4.185
65	4.188
70	4.191
75	4.194
80	4.198
85	4.203
90	4.208
95	4.213

Table 2. Description of Solar Collector Tested.

1. Transparent covers
    - number *1*
    - material *tempered glass, clear*
    - thickness *3 mm*
    - aperture dimensions *1.91 m*^{2}
2. Absorber plate
    - material *ultra low carbon ferretic stainless steel* (18 Cr-2 Mo)
    - surface treatment *selective surface*
    - manufacturing process *tube insheet*
    - water content *2.5 l*
3. Thermal insulations and casing
    - thermal insulation: Thicknes *5 cm (back), 1.5 cm (side)*
    - material *fiberglass and teflon sheet*
    - casing: material *galvanized steel*
    - total collector weight with water *48 kg.*
    - gross dimensions *2.01 m*^{2}
4. Limitations
    - maximum pressure *300 KPa*
    - acceptable heat transfer fluid *water*

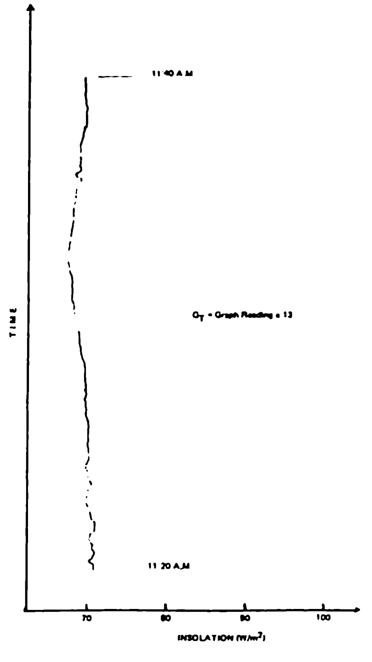


Figure 1. Quasi-steady state condition near solar noon for latitude 14°36′N and longitude 121°4′ E.

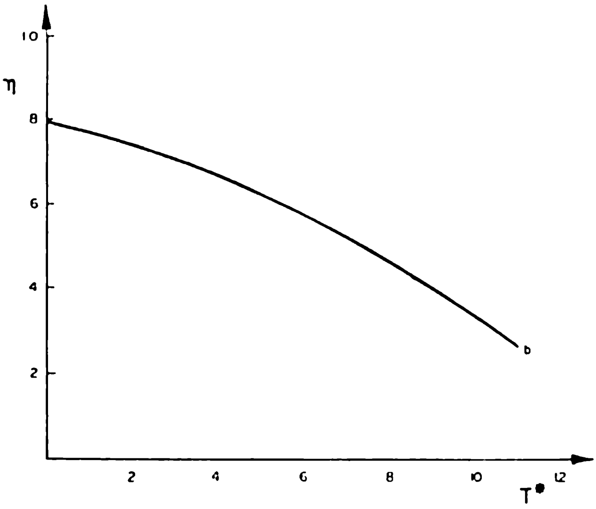


Figure 2. Efficiency η plotted against the parameter $T^* = (Tm - Ta)/G$.

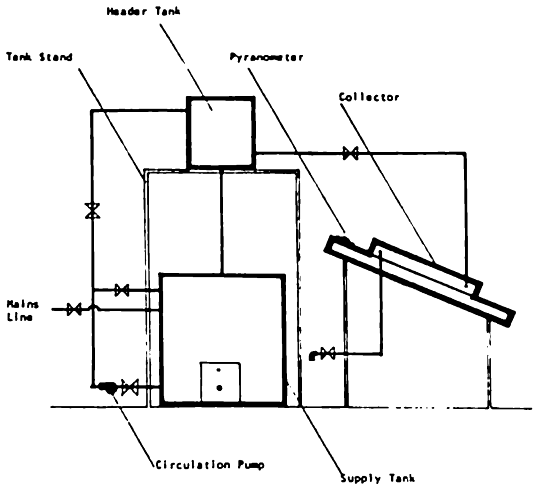


Figure 3. Schematic diagram of NCRD test facility.

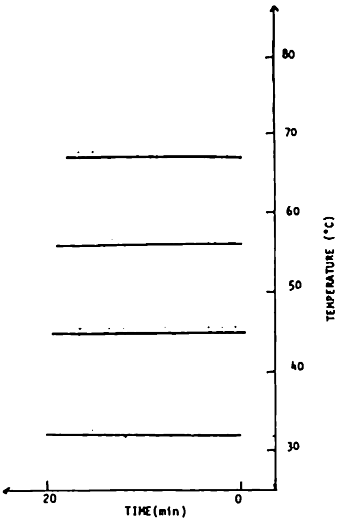
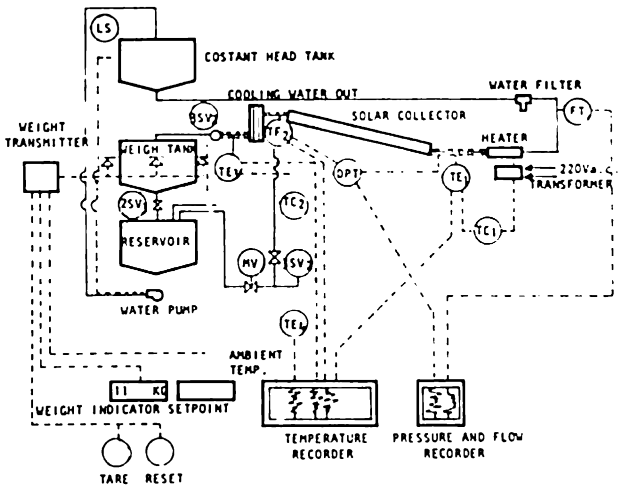


Figure 4. Constant inlet water temperatures.



LEGEND

LS	Level Switch
FT	Flow Transmitter
TC1	Temp. Controller # 1
TE1	Thermocouple Element # 1
DPT	Different Pressure Transmitter
TE2	Thermocouple Element # 2
2SV1	Two-way solenoid Valve # 1
TE3	Thermocouple Element # 3
TC2	Temp. Controller # 2
3SV2	Three-way solenoid valve # 2
2SV3	Two-way solenoid valve # 3
TE4	Thermocouple Element # 4
MV	Manual Valve
IP	Integrating Pyranometer
WS	Wind Sensor

Figure 5. Schematic diagram of ERDC test facility.

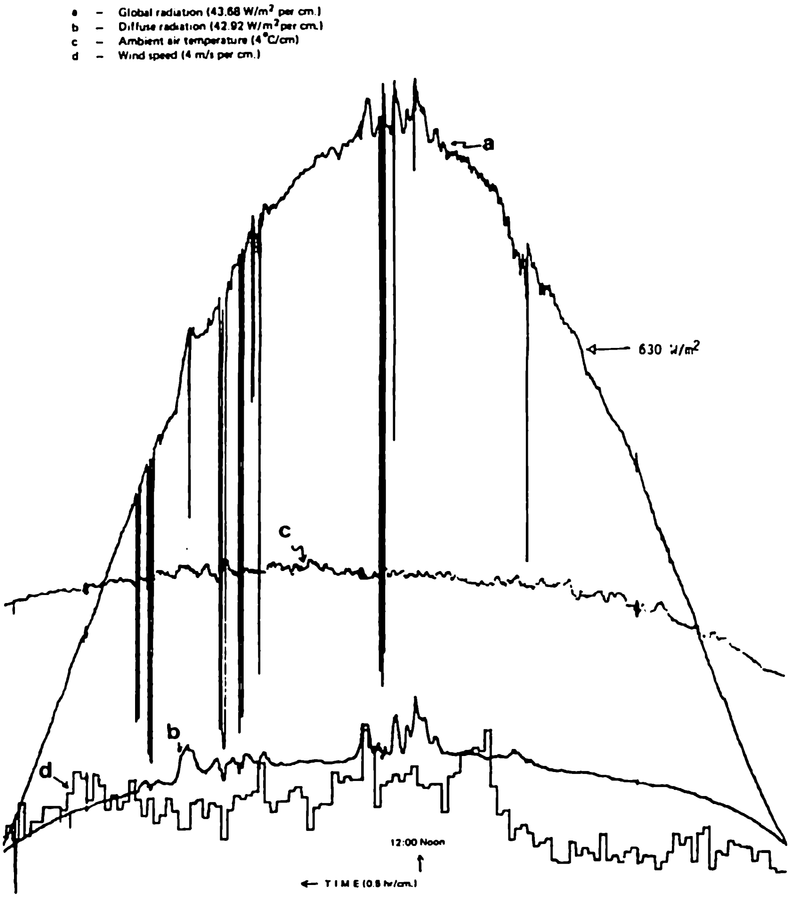


Figure 6. Climatic conditions during a bright sunny day.

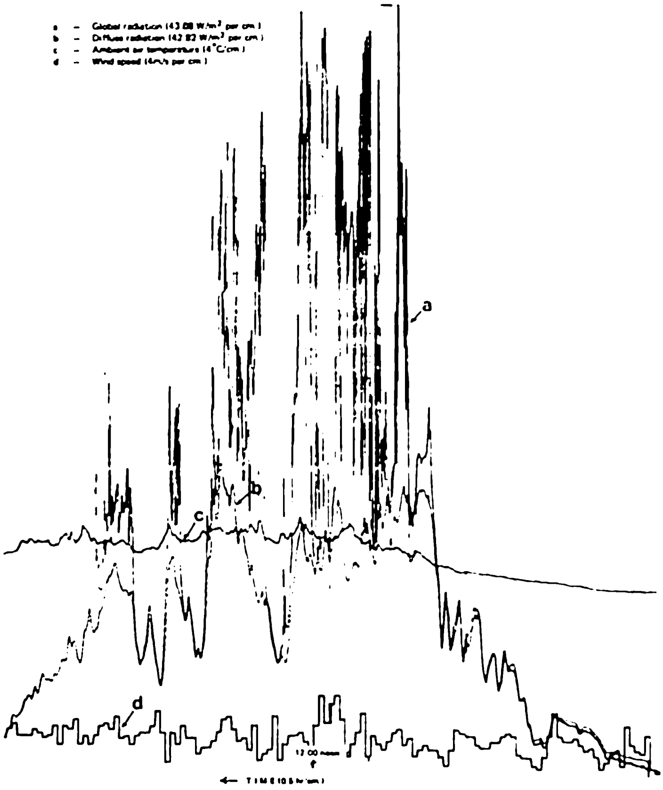


Figure 7. Climatic conditions during a cloudy day.

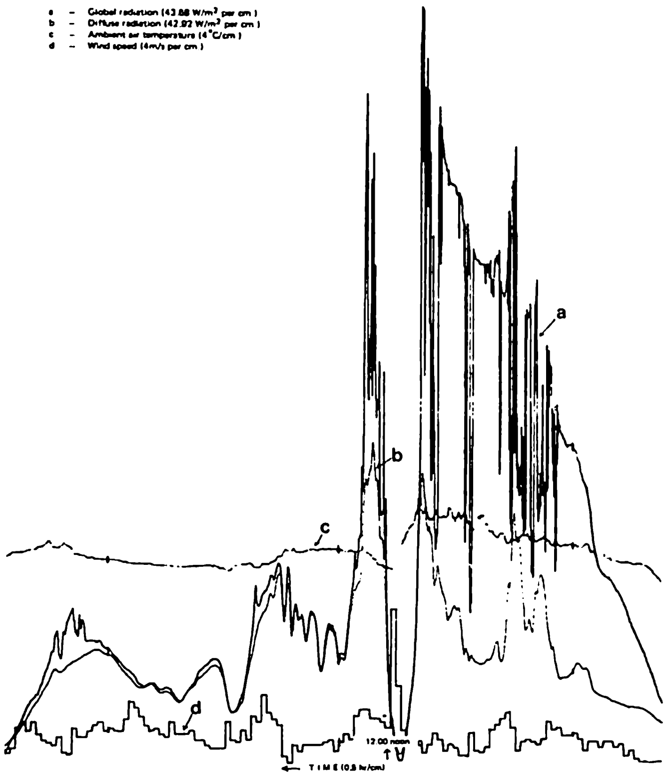


Figure 8. Climatic conditions during a cloudy day.

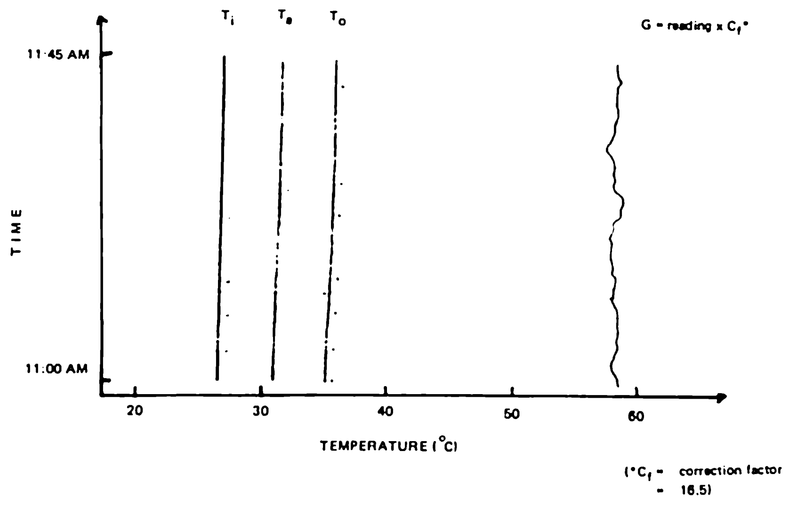


Figure 9. Curves showing the obtained parameters during a test run.

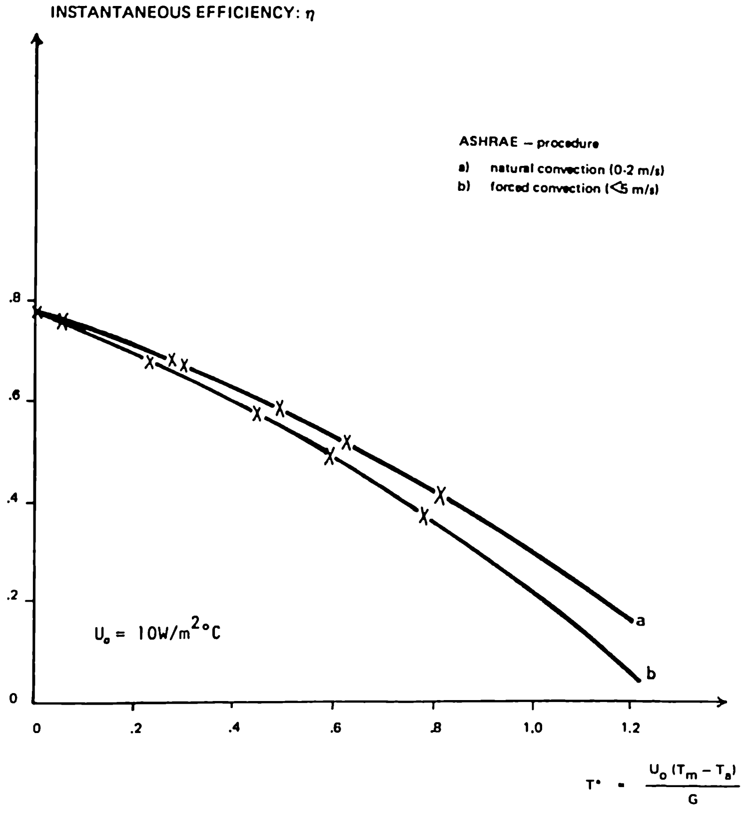


Figure 10. Efficiency curve of a collector tested with the ERDC test facility.