Renewable Energy Review Journal: Vol. 9, No. 2, December 1987

Solar Collector Testing

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ABSTRACT

This paper presents a brief description of the different methods of testing flat-plate solar collectors to evaluate their thermal performance. For the testing of collectors under steady state conditions, an outline of the NBS, ASHRAE and CEC methods of testing collectors is also included. A transient method of testing collectors to evaluate thermal performance, which is under development in the Department of Mechanical Engineering, is described. This method employs the single-blow technique which is commonly used for testing heat transfer surfaces. The steady state parameters of the collectors are extracted from the transient test.

INTRODUCTION

The testing of flat-plate solar collectors is necessary to determine reliable quantified information on their performance. This allows the evaluation of the relative performance of collectors marketed by different manufacturers and is likely to prevent some manufacturers claiming unrealistic performance values for their collectors for sales promotion purposes. Moreover, designers require the collector performance values for the design of complete solar thermal systems.

It is difficult to check and compare the performance of collectors unless they are tested by a standard method enabling the results to be compared easily. A large number of parameters, such as solar radiation, wind speed, humidity, sky conditions etc. are involved in the test procedure, and make it difficult to maintain steady state conditions. It is necessary to set some limitations to enable the results of the test to be comparable and reproducible.

The potential users of solar energy have devoted considerable research effort to develop a test procedure to evaluate the thermal performance of flat-plate collectors. In 1959, Robinson and Stotter[1] proposed a standard test procedure for the determination of efficiency of flat-plate solar collectors. Doron[2] described a method used in the National Physical Laboratory for testing solar collectors. Hill and Streed[3] proposed a test procedure, developed at the National Bureau of Standards, for rating solar collectors based on thermal performance which subsequently became the widely used NBS[4] standard. ASHRAE[5] developed a test procedure which enables the determination of collector time constant and incidence angle modifier, in addition to collector efficiency. Several other methods, such as, BSE[6], AFNOR[7] and CEC[8] have also been developed by different countries and are similar to the ASHRAE method.

This paper presents a brief description of the standards which are widely used for testing solar collectors and the conditions under which the tests are carried out. A transient test procedure under development at the Department of Mechanical and Production Engineering, National University of Singapore is also discussed.

TESTING METHODOLOGY

Solar collectors were tested to determine (a) the efficiency of the collector, (b) the heat loss coefficient, and (c) the pressure drop. Items (a) and (b) provide an indication of the useful energy which may be collected and item (c) is a measure of the pumping power required.

The solar collector testing methods can be broadly classified into two types:

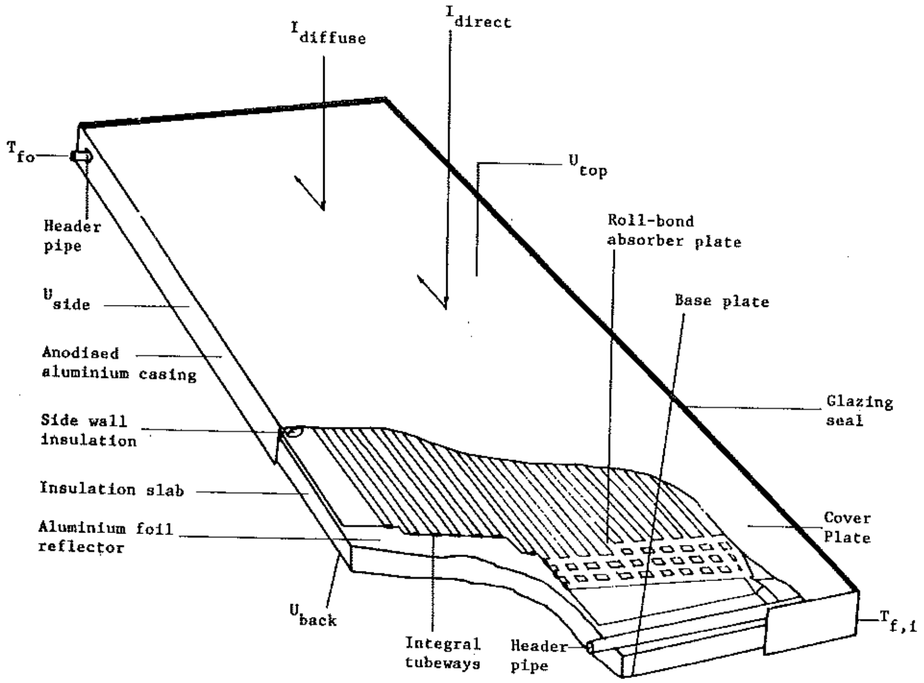
(1) steady state tests, and

(2) transient tests.

Before describing the steady state and transient tests procedures, it is desirable to know the factors which are likely to affect the collector performance.

A typical single glaze flat-plate solar collector is shown in Fig. 1. An energy balance at the glass cover gives:

I	$=$	$I\rho$	$+$	$I\alpha_c$	$+$	$I\tau$
Total radiation incident on cover		Reflected radiation		Radiation absorbed in cover		Radiation transmitted through cover



A large fraction of the energy transmitted through the glass is absorbed by the collector. The amount absorbed is given by $I(\tau\alpha_r)_e$ where α_r will depend on the type of collector and τ depends on the nature of the glazing. The effective transmittance-absorptance product, $(\tau\alpha)_e$, takes into account the dependence of τ and α on the angle of incidence of the incoming radiation. Some of this absorbed energy, $I(\tau\alpha_r)_e$, will be lost due to the temperature difference between collector and environment.

$$\text{Available energy} = I(\tau\alpha_r)_e - U_L(\overline{T}_p - T_a)$$

In the steady state, this must be equal to the heat carried away by the working fluid passing through the collector, i.e.

$$\frac{Q_u}{A} = I(\tau\alpha_r)_e - U_L\,(\overline{T}_p - T_a) \tag{1}$$

This expression is known as the Hottel-Whillier equation. Equation (1) can be rewritten in terms of the efficiency of the collector

$$\eta = \frac{Q_u/A}{I} = (\tau\alpha_r)_e - \frac{U_L\,\Delta T}{I} \tag{2}$$

where $\Delta T = \overline{T}_p - T_a$.

Equation (2) shows that a decreasing amount of useful energy will be removed from the collector when the plate temperature, $\overline{T}_p$, increases. Figs. 2 and 3 show the efficiency of the collector as a function of plate temperature under the conditions stated therein. The graphs show that the efficiency of the collector also depends on the level of insolation and the wind speed, in addition to the receiver temperature. At the same collector temperature, the single glaze collector gives different efficiency values when subjected to different wind speeds (Figs. 2 and 3).

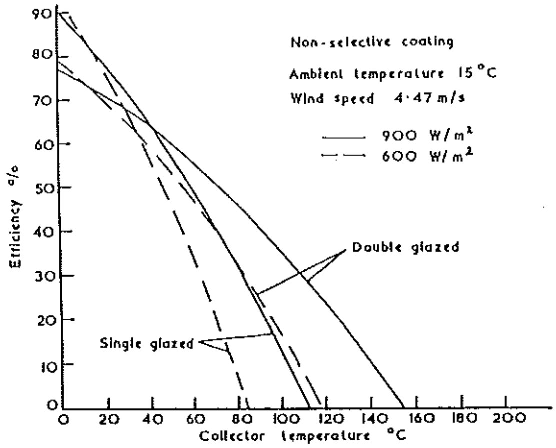


Fig. 2 Collector efficiency as a function of average collector temperature for different levels of insolation[18].

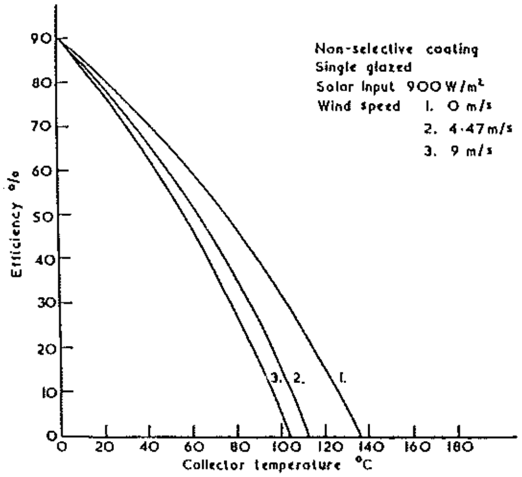


Fig. 3 Variation of collector efficiency with temperature for different wind speeds[18].

In this section, three factors, which strongly affect the efficiency of the collector, have been identified. The influence of these parameters should be taken into account while evaluating the thermal performance of flat-plate solar collector.

STEADY STATE TEST

For the successful completion of these tests it is necessary that the collector attains equilibrium with the environment during the period of the test. As mentioned previously, there are several standards for testing collectors under this condition. The thermal performance standards most widely used, at present, throughout the world are given below:

(i) NBS Standard[4], developed by the US National Bureau of Standards;

(ii) ASHRAE Standard[5], developed by the American Society for Heating, Refrigeration and Air-Conditioning Engineers; and

(iii) European Solar Collector Test Methods[8], developed by the Commission of European Communities.

The NBS Method

Equation (2), which is reproduced below, forms the basis of these tests.

$$\eta = \frac{Q_u/A}{I} = (\tau\alpha_r)_e - U_L\,(\frac{\bar{T}_p - T_a}{I})$$

So far, the average collector temperature, $\bar{T}_p$, has been used to identify the collector operating temperature. Normally, it is convenient to use the temperature of the working fluid passing through the collector and this can be done by introducing a correction factor, F', into equation

(2), the factor being defined as follows:

$$F' = \frac{\text{actual useful energy collected}}{\text{useful energy collected if the entire collector surface were at the average fluid temperature}}$$

This factor, F', is also known as the collector efficiency factor. Introducing this correction factor into equation (2), the following equation is obtained:

$$\eta = \frac{Q_u/A}{I} = F'[(\tau\alpha_r)_e - U_L \frac{(T_m - T_a)}{I}] \qquad (3)$$

where $T_m = T_{fi} + (T_{fo} - T_{fi})/2.$

The quantities $(Q_u/A)/I$ and $(T_m - T_a)/I$ are obtained by experimental method. When a plot of η vs $(T_m - T_a)/I$ is produced using equation (3), the slope of the line will be some function of U_L and the intercept at $(T_m - T_a)/I = 0$ will be some function of $(\tau\alpha_r)_e$, as shown in Fig. 4.

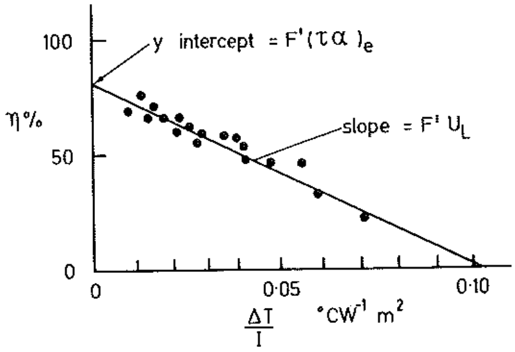


Fig. 4 Variation of collector efficiency with ΔT/I[18].

The ASHRAE Method

It has been shown earlier that the performance of a flat-plate solar collector operating under steady state condition can be described by equation (2). In order to assist in obtaining detailed information about the performance of flat-plate solar collectors and to avoid the necessity for determining the mean temperature of the collector plate, it has been found convenient to introduce a parameter, F_R, such that

$$F_R = \frac{\text{actual useful energy collected}}{\text{useful energy collected if the entire receiver surface were at the inlet fluid temperature}}$$

The factor, F_R, is known as the heat removal factor and when this factor is introduced into equation (2), it gives

$$\eta = \frac{Q_u/A}{I} = F_R\ [(\tau\alpha_r)_e - \frac{U_L}{I}\ (T_{fi} - T_a)] \tag{4}$$

In equation (4), $Q_u = mC_p\ (T_{fo} - T_{fi}), A, I$ and $(T_{fi} - T_a)$ are determined from experiments. Hence, equation (4) indicates that when efficiency is plotted against $(T_{fi} - T_a)/I$ a straight line will result where the slope of the line is equal to $F_R U_L$ and the intercept on the y-axis is equal to $F_R(\tau\alpha)_e$. In fact, U_L is not a constant but a function of collector temperature and ambient weather conditions. A straight line fit may be sufficient for some flat-plate collectors but some collectors may require polynomial fit due to variation of U_L with plate temperature, as shown in Fig. 5. The collectors of Figs. 4 and 5 are different from each other and also different from those in Figs. 2 and 3.

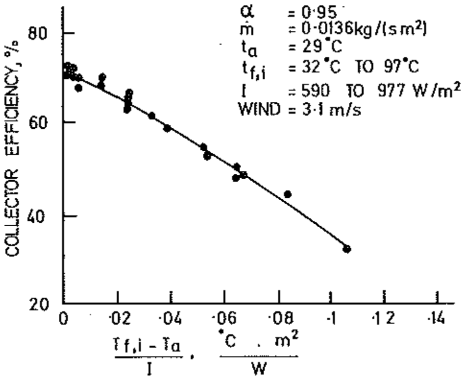


Fig. 5 Collector efficiency curve for a double glazed collector with selective coating[5].

CEC Method of Testing

This method is similar to the NBS and ASHRAE test procedures but it includes some additional recommendations to make collector testing a reasonable proposition for European weather conditions.

In the CEC method of testing, the plate temperature, $\overline{T}_p$, is replaced by T_m where

$$T_m = T_{fi} + \frac{\Delta T}{2} \quad \text{and} \quad \Delta T = (T_{fo} - T_{fi}) \tag{5}$$

The efficiency curve for the steady state condition can thus be derived from the following equation.

$$\eta = \eta_o - U_m\ (\frac{T_m - T_a}{I}) \tag{6}$$

where $\eta_o = F'(\tau\alpha)_e$ and $U_m = F'U_L$.

The efficiency can be evaluated as a function of $(T_m - T_a)/I$ by measuring the flow rate through the collector, the temperature difference between collector inlet and outlet, the incident solar radiation, and ambient air temperature.

Therefore

$$\eta = \frac{\dot{m}Cp\,\Delta T}{AI} \tag{7}$$

where

$$T_m = T_a,\ \eta_o = \frac{\dot{m}Cp\,\Delta T}{AI}. \tag{8}$$

It should be remembered that this equation does not take into account the effect of the thermal capacity, MC_p, which may have a significant influence over the integrated performance of the flat-plate solar collector.

The assumptions that η_o and U_m are constant requires careful consideration, as pointed out by Aranovitch[9]. The absorption coefficient depends on the incidence angle and wavelength of radiation. The heat transfer coefficient is affected by the ambient temperature and wind speed. The natural convection in the closed space between the absorber and cover will be affected by the collector inclination.

Of the three standard methods described here, CEC and NBS provide a technique of measuring the efficiency of the flat-plate collector. The thermal capacity of the collector is assumed to have a negligible effect on the performance. On the other hand, the ASHRAE method provides a procedure for measuring collector time constant and incidence angle modifier, in addition to the measurements of efficiency. The CEC test method also provides a test procedure to evaluate the global collector loss coefficient and pressure drop across the collector.

Collectors are tested using a standard test procedure under controlled conditions, each procedure having a set of conditions to be fulfilled during the test, as shown in Table 1.

Table 1
Conditions under which solar collectors are tested

Parameters	Standards		
	NBS	ASHRAE	CEC
Ambient temp., T_a °C	< 30	< 30	as read
Insolation, I W/m^2	>630	>315	>600
Flow rate, m' kg/s.m^2	0.02	0.02	0.02
Range of fluid inlet temperature, T_{fi} °C	$= T_a + 10, 30, 50, 70$	= 10, 30, 50, 70% of stagnation temperature	$= T_a$ or less to stagnation temperature
Incident angle of beam radiation, degrees	< 45	< 45	< 45
Pre-conditioning period	A 30 min. pre-conditioning period to allow equilibrium to be attained	30 min.	30 min.

CONVERSION OF TEST RESULTS

Collector performance test results are presented by manufacturers in different forms. Usually, these take either the NBS (also CEC) form, which uses the mean fluid temperature, or the ASHRAE form, which uses the inlet fluid temperature. However, design procedures for system sizing may use either of these collector representations. It is, therefore, useful to have a convenient method of converting performance characteristics from one form to the other. A simple graphical technique for this purpose is outlined below.

The performance equations given by the test methods can be written as

$$\eta = F'[(\tau\alpha_r)_e - U_L \frac{(T_m - T_a)}{I}] \tag{9}$$

for the NBS (CEC) method, and

$$\eta = F_R\ [(\tau\alpha_r)_e - U_L \frac{(T_{fi} - T_a)}{I}] \tag{10}$$

for the ASHRAE method. Also,

$$T_m = \frac{T_{fi} + T_{fo}}{2} = T_{fi} + \frac{\Delta T}{2}$$

The efficiency can also be expressed as

$$\eta = \frac{Q_u}{IA} = \frac{m'C_p\Delta T}{I} \tag{11}$$

m' being the fluid mass flow rate per unit collector area.

Considering the NBS test characteristic shown in Fig. 6(a), for the zero efficiency point P, $T_{fo} = T_{fi} = T_m$, ideally. Therefore, the corresponding ASHRAE characteristic must also pass through the point P. Now when $(T_m - T_a)/I = O$, at point O for the NBS-line, the corresponding ordinate for the ASHRAE-line is obtained by observing that

$$\frac{T_{fi} - T_a}{I} = \frac{(T_m - T_a)}{I} - \frac{\Delta T}{2I} \tag{12}$$

where $\frac{\Delta T}{2I} = (\frac{\eta}{2m'C_p})$ from equation (11).

The following graphical construction satisfies these conditions. A horizontal line is drawn through A, in Fig. 6(a), to intersect the vertical line drawn through the point Q, $[-((\tau\alpha)_e F')/2m'C_p]$, at B. The line BP intersects the η-axis at C. It is seen that CP gives the ASHRAE-characteristics for the collector. Also, OC = $F_R(\tau\alpha)_e$ and the slope of the line PC is equal to $(F_R U_L)$.

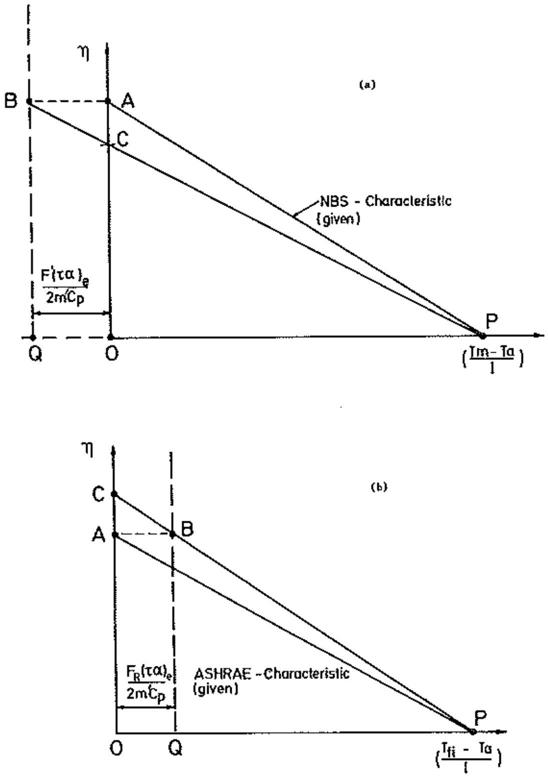


Fig. 6 Conversion of results from NBS to ASHRAE.

The reverse procedure of converting a given ASHRAE-characteristic to the corresponding NBS-characteristics is illustrated in Fig. 6(b). In this case, the vertical line BQ is drawn through the point, $[+ (F_R\ (\tau\alpha_r)_e)/2m'C_p]$, to intersect the horizontal line through the point A. The line PB, when extended, intersects the η-axis at point C. The NBC test characteristic is given by CP, where OC = $F'\ (\tau\alpha_r)_e$ and the slope of the line PC is $F'U_L$.

INDOOR/OUTDOOR TESTS

Using any of the standard procedures described earlier, solar collectors can be tested under indoor or outdoor conditions. Fig. 7 shows the diagram of a typical test rig used for testing a solar collector.

For testing collectors under indoor conditions, a solar simulator is required. It is not difficult to find lamps whose radiation spectrum is similar to the sun but such simulators are quite expensive. Fig. 8 shows such a simulator where Compact Source Iodide (CSI) lamps are used to simulate the sun. The spectrum of radiation emitted by the lamp and that of the sun are shown in Fig. 9. The spectral distributions of a few more lamps are also included for comparison. It is seen that the CSI lamp gives a better approximation of the solar spectrum. Nowadays, this lamp is widely used for solar simulators. In spite of its high costs, testing solar collectors under indoor

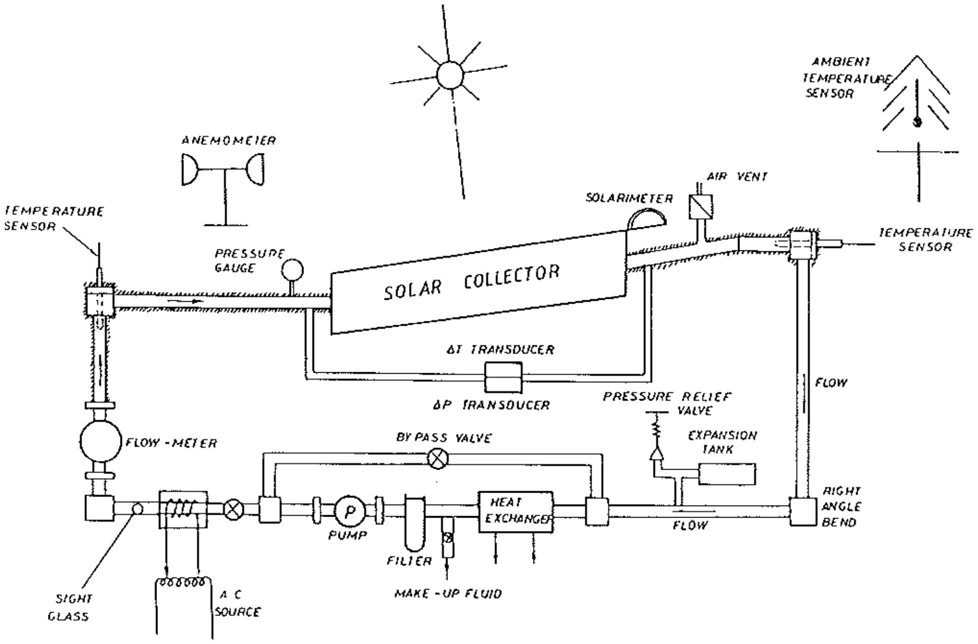


Fig. 7 Schematic diagram of a closed loop test installation for thermal performance test.

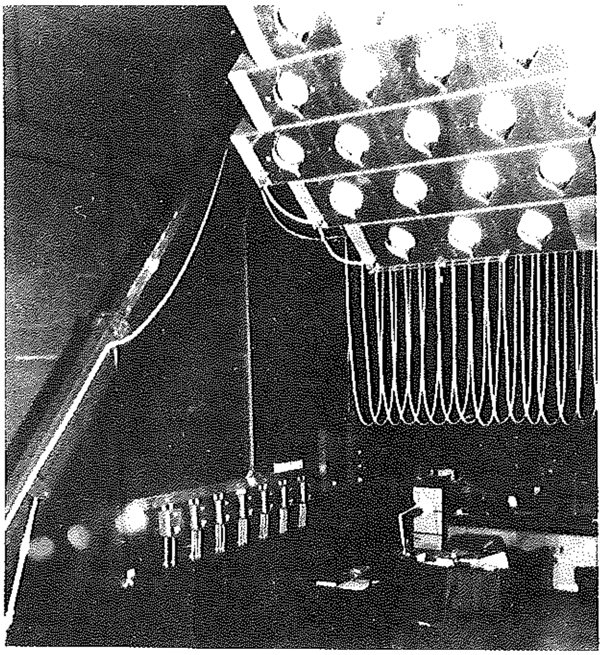


Fig. 8 Solar simulator at Solar Energy Unit, University College, Cardiff, UK.

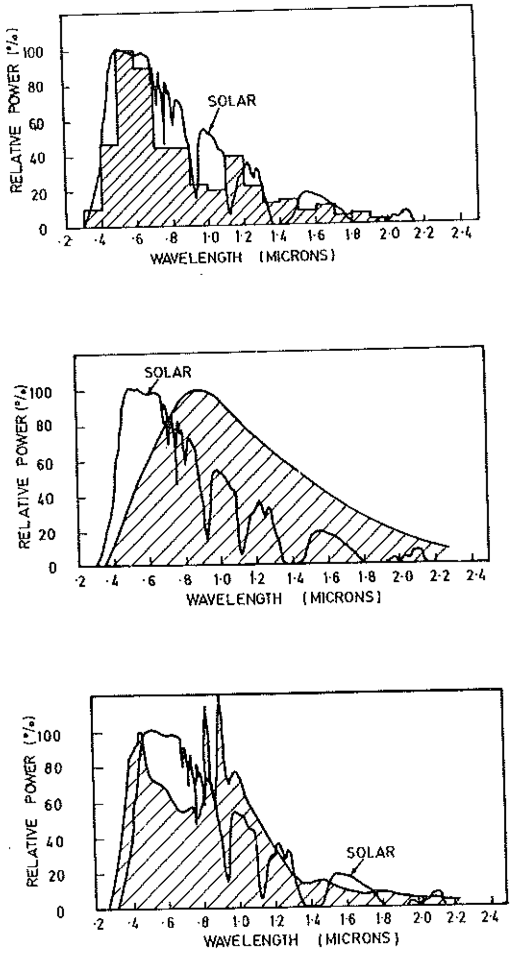


Fig. 9 Radiation spectrum of different lamps[19].

conditions allows a greater degree of freedom to control the conditions set out in the test procedures.

When testing a solar collector under outdoor conditions, it is difficult to maintain the specified stable conditions over a long period of time. This is more so in locations where there are frequent changes in the solar radiation level.

During testing of a solar collector, considerable scatter in collector efficiency values has been found. This is evident from the results of the round robin collector tests by the Commission of the European Communities (CEC) which have been reported by Moon and Gillett[10]. The scatter may be attributed to the environmental conditions and the degree of accuracy of measurements.

It has been found that a small drift in inlet temperature may cause large variations in efficiency. The accuracy of temperature measurement should be around ±0.1°C. Similarly, the fluctuation in flow rate can also cause variations in efficiency. It is suggested that the flow measurement should be accurate within ±1%. Another possible source of error is the calibration of pyranometers. According to Moon and Gillett[10], the scatter in results of round robin tests is most likely due to the calibration of the pyranometers. Wernick and Tully[11] have shown that the scatter can be eliminated by introducing an efficiency correction function.

TRANSIENT TESTS FOR SOLAR COLLECTORS

The testing of a solar collector under steady state conditions using the methods described earlier requires the tests to be carried out under well defined conditions which are considered to be difficult and time consuming. It is difficult to achieve steady state conditions during outdoor tests since wind speed and solar radiation change with time. Moreover, in such experiments, the temperature change of fluid circulating through the collector often may be about 3 to 4°C and thus a high degree of accuracy in measurement is required in order to obtain reliable results. Tests may be carried out under indoor conditions using a solar simulator where the conditions of the test procedure can be met very closely, however the simulator is an expensive piece of equipment.

In order to overcome some of these problems associated with steady state tests, attempts have been made by several authors[12,13,14] to evaluate collector performance parameters such as efficiency and global heat loss coefficient from transient test results using an appropriate dynamic method of analysis.

A transient test method is described here which is similar to the single-blow technique[15-17] that has been successfully applied for testing heat transfer equipment such as heat exchangers.

Methodology

The diagram of the test rig is shown in Fig. 10, which is a general purpose experimental set-up for indoor testing of solar collectors. The hot water produced in a tank is circulated by a pump in a closed loop arrangement, where the flow rate is measured with a rotameter. In order to stabilize the fluid flow rate and inlet temperature before a transient test, a by-pass path is introduced into the circuit. An additional oil heater is used to provide a finer control of temperature at the inlet to the collector. Moreover, when the by-pass circuit is in operation, cold water can be circulated through the collector in order to ensure uniform temperature over the entire length of the receiver panel. Once the fluid flow rate and temperature are stabilized, the inlet and exit valves are opened and the hot water is allowed to flow through it. The temperatures of fluid at the inlet and the exit of the collector are measured with a thermocouple and recorded by an automatic data logger. A number of thermocouples were also located at various points on the absorber panel. The mid-point temperature of the absorber plate was also recorded. Fig. 11 shows the variation of fluid and plate temperatures at different locations when the fluid is passed through the collector. The record shows a period of time during which the temperature remains unchanged. This is the time required by the hot fluid front to reach the measurement point.

The data recorded from the transient test were analysed using a two-region mathematical model developed by Wijeysundera and Hawlader[14]. In the two region model the capacitance of the cover is lumped with the plate and the fluid is treated as a separate region. An energy balance for the fluid element gives[14]:

$$\frac{\partial}{\partial t}\left[A_f C_p \rho_f T_f\right] = -\dot{m}\, C_p \frac{\partial T_f}{\partial x} - h_i\, \pi D\, (T_f - T_w) \qquad (13)$$

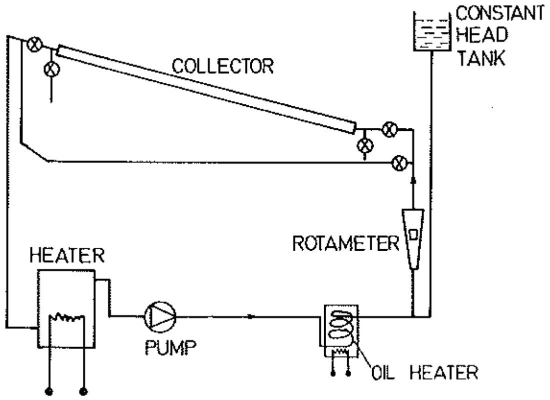


Fig. 10 Schematic diagram of the test rig for transient tests.

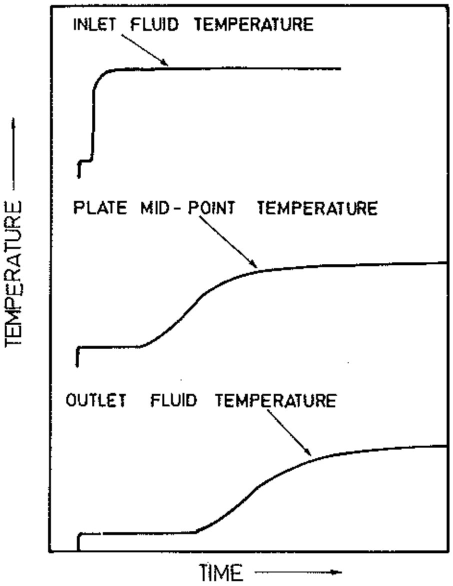


Fig. 11 Variation of temperature with time.

A similar equation is obtained for the wall element, as shown below:

$$\frac{\partial}{\partial t}\left[C_{ew}T_w\right] = \pi D h_i \left(T_f - T_w\right) - WF''U_L\left(T_w - T_a\right) \tag{14}$$

The boundary conditions for equations (13) and (14) are as follows:

$$T_w\ (x, 0) = T_a$$
$$T_f\ (x, 0) = T_a$$
and $$T_f\ (0, t) = T_o \qquad \text{for } t > 0.$$

Equations (13) and (14) have been solved by Laplace's transform method described by Arpaci[20] and the resulting equations in non-dimensional form are given

$$\theta_w = z\, e^{-y(1-z)} - z\, e^{-(y+\tau'/z)}\, g(z, \tau', y) \tag{15}$$

and

$$\theta_f = e^{-y(1-z)} - e^{-y(y+\tau'/z)} \left[g(z, \tau', y) - I_o\left(2\sqrt{y\tau'}\right)\right] \tag{16}$$

where

$$\theta_w = \frac{T_w - T_a}{T_{fi} - T_a} \quad \text{and} \quad \theta_f = \frac{T_f - T_a}{T_{fi} - T_a}$$

$$y = \left(\frac{AU_L}{\dot{m}C_p}\right)\left(\frac{1}{1/F' - 1/F''}\right)\left(\frac{x}{L}\right)$$

$$z = \frac{1}{1 + \dfrac{WF''U_L}{\pi D h_i}} = \frac{F'}{F''}$$

$$\tau' = \left(\frac{AU_L}{\dot{m}C_p}\right)\left(\frac{1}{1/F' - 1/F''}\right)\left(\frac{\dot{m}C_p}{C_{ew}L}\right)\left(t - \frac{x}{V}\right)$$

$$g(z, \tau', y) = \sum_{n=0}^{\infty} \frac{(yz)^n}{(n!)} \sum_{k=0}^{n} \frac{(\tau'/z)^k}{(k!)}$$

The details of the derivation and solution of equations (13) and (14) are given in references(14) and(20).

From equations (15) and (16), it is seen that the first term is a steady state solution and the second term represents the transient variation of temperature. A least square error minimization procedure is used to extract steady state collector parameters, U_L and F', from transient test results.

Figs. 12(a) and (b) show plots of the experimental and predicted results of plate mid-point temperature. Within the accuracy of measurements, the agreement is considered to be satisfactory.

Further studies at the Department of Mechanical and Production Engineering, National University of Singapore, are underway to extend the single-blow technique of testing a solar collector under outdoor conditions to obtain the performance parameters of the collector.

NOMENCLATURE

A	collector area
A_f	area of fluid duct
C_p	specific heat of fluid
C_{ew}	equivalent heat capacity of duct per unit length

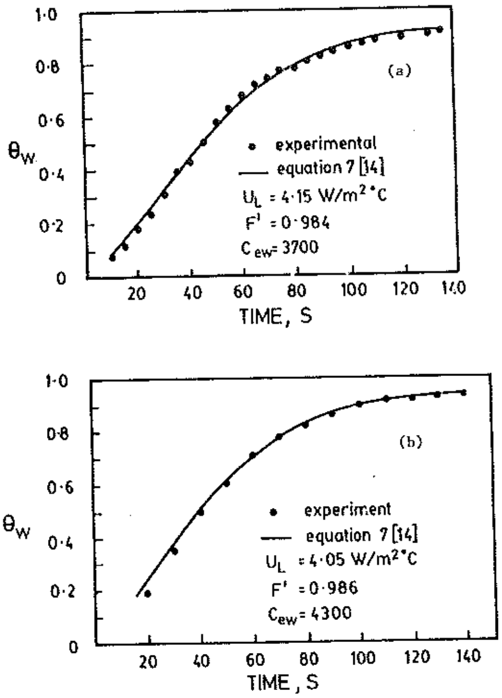


Fig. 12 Comparison of experimental and analytical temperatures for transient tests.

D	diameter of fluid duct
F''	equivalent fin factor
F'	collector efficiency factor
F_R	collector heat removal factor
h_i	heat transfer coefficient between fluid and duct wall
I	total irradiation
I_o	modified Bessel function
L	length of flow duct
$\dot{m}$	mass flow rate of fluid
M	mass of collector and its contents
Q_u	useful energy gain
t	time
$\bar{T}_p$	average plate temperature
T_a	ambient temperature
T_f	fluid temperature at x and t
T_{fi}	fluid temperature at collector inlet
T_{fo}	fluid temperature at collector exit

T_w	tube wall temperature at x and t
U_L	plate to ambient loss coefficient
V	mean fluid velocity in duct
W	distance between tubes
x	axial coordinate along the duct
y	nondimensional axial coordinate
z	collector parameter
α_c	absorptance of cover
α_r	absorptance of receiver plate
ρ	reflectance of cover
ρ_f	density of fluid
θ_w	nondimensional wall temperature
θ_f	nondimensional fluid temperature
τ	transmittance of cover
τ'	nondimensional time
$(\tau\alpha)_e$	effective transmittance absorptance product
η	efficiency of collector

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