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A Rating Procedure for Solar Domestic Water Heating Systems

A rating procedure for solar domestic hot water systems is described which combines the advantages of short-term system tests and correlations of long-term thermal performance. The testing procedure consists of two indoor tests which are in accordance with ASHRAE Standard 95-1981, except for one additional measurement needed only for systems employing a heat exchanger between the collector fluid and the potable water. The test results are plotted in a manner in which they can be used to estimate the long-term performance of the solar water heating system for any location where site-specific, monthly-average meterological data are available. The annual solar function obtained in this manner provides the recommended rating indicator. The validity of this rating procedure is first demonstrated by simulations. Further support is provided by experiments conducted at the National Bureau of Standards.

1 Introduction

A variety of solar domestic hot water (SDHW) systems are commercially available. Because of the prevalent sale and use of packaged SDHW systems, the Steering Committee of the American National Standards Institute (ANSI) on Solar Energy Standards Development designated the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) to develop a test method for SDHW systems. The resulting test method, ASHRAE Standard 95-1981 [1], "Methods of Testing to Determine the Thermal Performance of Solar Domestic Hot Water Systems," was adopted by ANSI in 1981. The standard requires that the complete SDHW system be tested indoors using either a solar or thermal simulator. The test procedure is to measure the daily performance under prescribed meteorological and load conditions until the steady periodic one-day performance is achieved. The ASHRAE Standard specifies the method of testing but does not specify the test conditions to be used for obtaining a standard rating. Specification of rating conditions is left to rating associations.

The Solar Rating and Certification Corporation (SRCC) has defined a standard rating day to be used in conjunction with the ASHRAE Standard 95-1981 test method [2]. The Air-Conditioning and Refrigeration Institute (ARI) has selected two standard rating days [3] to be used in conjunction with ASHRAE Standard 95-1981. The difficulty with using these selected rating conditions is that they will not necessarily provide an accurate indication of the relative merit of SDHW systems for any weather conditions other than those specifically represented by the rating conditions.

Computer simulations such as the TRNSYS [4] program and correlations such as the f-Chart method [5] utilize site-specific weather data and thus may be used to predict system performance for any climatic region. Comparisons with measured performance have shown that these methods can provide reliable estimates of long term performance for SDHW systems [6, 7]. Each of these methods, however, has several disadvantages. Accurate measurements of component thermal performance specifications are required as input by both simulations and correlations in order to obtain useful results. Additionallly, f-Chart does not predict parasitic energy consumption and TRNSYS requires extensive computer facilities and hour-by-hour meteorological data. Finally, use of these component-based methods would result in predicting the performance of a hypothetical system, rather than the actual system.

A technique proposed by the Florida Solar Energy Center [8] uses a combination of experimental results and analytical modeling. This concept is based on side-by-side, single-day outdoor tests of the system and a "baseline" SDHW system. The ratio of the performance of the test system to the baseline system is called the daily relative solar rating. Long-term performance for the test SDHW system would be determined from the daily relative solar rating, a correlation based on computer simulations, and long-term measured performance results for the baseline system. Preliminary results indicate that this method is nearly independent of test day conditions in sunny climatic regions. The results for a cold climate were not encouraging, according to the authors.

Balon and Wood [9] have proposed a rating procedure which is similar, in several respects to the procedure described in this paper. They propose to rate SDHW systems in terms of their estimated annual performance. Annual performance estimates are obtained by interpolating between ASHRAE 95-1981 test points using correlations from the f-Chart, 4 design program [10]. A major assumption in their method is that the ASHRAE 95-1981 steady periodic one-day tests "can stand in accurately for data from long-term (monthly) outdoor testing."

A rating procedure is proposed in this paper which combines the advantages of ASHRAE Standard 95-1981 tests and correlation methods. The testing procedure consist of two indoor tests in accordance with ASHRAE Standard 95-1981

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except for one additional measurement needed only if a heat exchanger between the collector fluid and the potable water is used. The test results are plotted in a manner in which they can be used to estimate the long-term performance of the SDHW system for any location where site-specific meterological data are available. The annual solar fraction obtained in this manner provides the recommended rating indicator. The validity of this rating procedure is first demonstrated by simulations using TRNSYS. Further support is provided by experiments conducted at the National Bureau of Standards.

2 Theoretical Development

The basic problem faced in developing the rating procedure proposed in this paper was to devise a technique in which the ASHRAE Standard 95-1981 steady periodic one-day test results could be used to estimate the long-term performance of a SDHW system. A solution to this problem was found by using the concept of solar radiation utilizability. The utilizability concept allows SDHW performance to be presented in a manner independent of meteorological conditions.

Utilizability, ϕ, is defined as the fraction of the solar radiation incident on a surface which is above a specified level referred to as the critical level, I_c. Utilizability is a solar radiation statistic, analogous to degree-days, an ambient temperature statistic. When hourly (or shorter time period) radiation data are available for the period of interest, utilizability can be calculated directly from

$$\phi = \frac{\sum^{n} (I_T - I_c)^+}{\sum^{n} I_T} \qquad (1)$$

In equation (1), I_T is the average solar radiation per unit area incident on the surface of interest for a given time period, and n is the number of meaurements of I_T used in the summation. The superscript "+" sign is used to indicate that only positive values of $(I_T - I_c)$ are considered; negative values are set to zero.

Table 1

Base Case System

Collector Area: 4.19 m^2
Orientation: tilt = latitude, facing due south

$\frac{A_a}{A_g} F_R(\tau\alpha)_n$: 0.805

$\frac{A_a}{A_g} F_R U_L$: 4.73 W/m^2-°C

Collector Pump Control: 10°C upper dead band
1.7°C lower dead band
Collector Capacitance Rate: 268 kJ/hr-m^2-°C
Heat Exchanger Penalty Factor (F_R'/F_R): 0.833
Storage Capacity: 300 liters
Storage Tank Loss Coefficient: 1.14 W/m^2-°C
Daily Water Use: 263 liters
Tank Environment Temperature: 20°C
Main Supply Water Temperature: 10°C
Hot Water Delivery Temperature: 60°C

System A: Same as base case except

$\frac{A_a}{A_g} F_R U_L$: 6.71 W/m^2-°C

System B: Same as base case except

Collector Area: 8.0 m^2

System C: Same as base case except

Storage Tank Loss Coefficient: 0 W/m^2°C

System D: Same as base case except

Double-tank system with 150 liter auxiliary tank
Auxiliary Tank Loss Coefficient: 1.14 W/m^2-°C
Heat Exchanger Penalty Factor (F_R'/F_R): 1.0

Using the ASHRAE Standard 95-1981 test method, the solar radiation at short intervals is known and the utilizability for any critical level can be calculated directly from equation (1) for the test day. Long-term average values of utilizability (referred to as $\bar{\phi}$) depend on the distribution of solar radiation (i.e., the relative numbers of poor, average, and excellent days of sunshine which together compose the long-term average). Methods of estimating the long-term average value of utilizability without using actual hourly data have been devloped on both monthly-average [11, 12, 13] and annual [14] bases.

Nomenclature

A_a = collector aperture, area, m^2

$\frac{A_a}{A_g} F_R U_L$ = magnitude of the slope of the collector efficiency curve determined in accordance with ASHRAE Standard 93-77, W/m^2 – °C

$\frac{A_a}{A_g} F_R (\tau\alpha)_{e,n}$ = intercept of the collector efficiency curve determined in accordance with ASHRAE Standard 93-77, dimensionless

A_g = gross collector area, m^2

C_p = specific heat, kJ/kg – °C

f = solar fraction (excluding parasitic energy use) obtained during the short-term tests, dimensionless

f' = adjusted solar fraction defined by equation (11), dimensionless

$\bar{f}$ = monthly-average solar fraction, dimensionless. (Subscripts 10 and 20 indicate results calculated using short-term tests at 10 and 20°C, respectively, for the water main temperature.)

$\bar{f}_{NL}$ = monthly-average solar fraction which would be obtained if there were no tank energy losses, dimensionless

f_o = intercept value of f at $\phi Y = 0$ from the short-term test results, dimensionless

f_o' = adjusted intercept value defined by equation (10), dimensionless

F = annular solar fraction, dimensionless

F_R'/F_R = collector-heat exchanger penalty factor, dimensionless

$\bar{H}$ = monthly-average daily radiation on a horizontal plane, J/m^2-day

$\bar{H}_T$ = monthly-average daily radiation on the collector plane, J/m^2-day

I_c = critical radiation level defined by equation (5), W/m^2

I_T = average rate of solar radiation incident on the collector plane for a given hour (or shorter) time period, W/m^2

$K_{\tau\alpha}$ = incidence angle modifier, dimensionless

$\bar{K}_{\tau\alpha}$ = monthly-average incidence angle modifier, dimensionless

m = mass of hot water draw, kg

n = number of measurements of I_T used in the summation to calculate ϕ in equation (1), dimensionless

Table 2 Meteorologial data used in one-day tests

TIME	DAY 1		DAY 2		DAY 3		DAY 4		DAY 5		DAY 6		DAY 7	
	I_T W/m^2	t_a °C	I_T W/m^2	t_a °C	I_T W/m^2	t_a °C	I_T W/m^2	t_a °C	I_T W/m^2	t_a °C	I_T W/m^2	t_a °C	I_T W/m^2	t_a °C
													0	0
6:15- 6:45			38	0.0	122	16.1					141	20.6	0	0
6:45- 7:15			92	0.3	186	16.4					242	21.0	0	0
7:15- 7:45	44	-3.6	152	0.9	253	17.0	189	25.0	189	-3.6	348	22.0	0	0
7:45- 8:15	94	-2.7	217	1.8	322	17.8	293	25.0	293	-2.7	455	23.1	0	0
8:15- 8:45	150	-2.0	283	2.4	390	18.8	403	25.0	403	-2.0	562	24.5	0	0
8:45- 9:15	208	-1.2	349	3.9	456	20.1	514	25.0	514	-1.2	664	25.6	0	0
9:15- 9:45	265	-1.0	411	4.8	516	21.2	619	25.0	619	0.1	758	27.4	0	0
9:45-10:15	316	0.1	467	6.1	569	22.4	714	25.0	714	1.0	840	28.8	0	0
10:15-10:45	360	1.0	513	7.0	613	23.3	793	25.0	793	1.0	907	30.8	0	0
10:45-11:15	393	1.0	548	8.2	646	24.3	854	25.0	854	2.8	958	31.2	0	0
11:15-11:45	413	2.8	569	8.8	666	25.3	891	25.0	891	3.3	989	32.5	0	0
11:45-12:15	420	3.3	577	9.1	672	25.9	904	25.0	904	3.8	999	33.4	0	0
12:15-12:45	413	3.8	569	10.3	666	26.6	891	25.0	891	4.3	989	34.2	0	0
12:45-13:15	393	4.3	548	10.6	646	27.2	854	25.0	854	4.8	958	35.0	0	0
13:15-13:45	360	4.8	513	11.2	613	27.9	793	25.0	793	5.1	907	35 7	0	0
13:45-14:15	316	5.1	467	11.5	569	28.2	714	25.0	714	5.2	840	36.0	0	0
14:15-14:45	265	5.2	411	11.8	516	28.5	619	25.0	619	5.3	758	36.4	0	0
14:45-15:15	208	5.3	349	11.8	456	28.5	514	25.0	514	5.3	664	36.6	0	0
15:15-15:45	150	5.3	283	11.8	390	28.5	403	25.0	403	5.3	562	36.6	0	0
15:45-16:15	94	5.1	217	11.5	322	28.3	293	25.0	293	5.1	455	36.4	0	0
16:15-16:45	44	4.8	152	11.2	253	27.9	189	25.0	189	4.8	348	35.8	0	0
16:45-17:15			92	10.9	186	27.4					242	35.0	0	0
17:15-17:45			38	10.3	122	26.9					141	34.2	0	0
												33.0	0	0

2.1 Description of the Simulation Model and Meteorological Conditions. The TRNSYS program was used to simulate both the steady periodic one-day performance (representative of the ASHRAE Standard 95-1981 tests) and the annual performance of a variety of SDHW systems. The base case is a single-tank indirect system with single-glazed selective surface collectors. The base case was chosen to repesent closely the experimental system which is described in section 3. A number of variations from the base case were investigated including changes in the collector area, the collector parameters, and the tank heat loss coefficient. In addition, a double-tank direct system having the same collectors as the base case system was investigated. A summary of the parameters of the base case and other systems investigated is provided in Table 1.

The simulation model was constructed using standard component models available in the TRNSYS library. Constant values of $F_R(\tau\alpha)_{en}$ and $F_R U_L$ were used to represent the collector performance. A four-node stratified storage tank with the heating element in the top segment was used to represent the tank in the single-tank system. The internal heat exchanger was simulated in a indirect manner by use of the heat exchanger penalty factor [15]. The double-tank system used a two-node preheat tank and a fully-mixed auxiliary tank. The Rand Corporation load profile [16] was assumed in all of the simulations. The effect of load profile has been shown by simulations [17] and experiments [18] to have a small effect on overall SDHW system performance.

To establish a correlation of steady periodic one-day test results, the performance of each system in Table 1 was simulated for seven sets of test conditions. A daily hot water load of 263 L per day heated from 10°C to 60°C was assumed. The meteorological data used in these simulations are listed in Table 2. The first three test days were chosen to represent the average meteorological conditions in the Washington, D.C. area during January, March, and June, respectively. The solar radiation data for test days 4 and 5 were chosen to agree with the ARI recommended winter day

Nomenclature (cont.)

N = number of days for which experimental data were available each month

Q_{AUX} = auxiliary energy required by the SDHW system during the testing period not including parasitic energy use, J/day

$\bar{Q}_{AUX}$ = monthly-average daily auxiliary energy use excluding parasitic energy, J/day

Q_L = energy required to heat water during the test period, not including parasitic energy use, J/day

$\bar{Q}_L$ = monthly-average daily energy required to heat water, not including parasitic energy use, J/day

$\bar{Q}_{LOSS}$ = monthly-average daily storage tank energy loss, J/day

$\bar{R}$ = ratio of monthly-average solar radiation on the collector plane to that on a horizontal surface, dimensionless

t_a = ambient temperature, °C

$\bar{t}_a$ = daytime-average ambient temperature during the test period, °C

$\bar{\bar{t}}_a$ = monthly-average ambient temperature, °C

t_d = hot water delivery temperature, °C

t_{in} = collector fluid inlet temperature, °C

t_m = mains supply water temperature, °C

$\bar{t}_s$ = average water temperature in the solar-heated portion of the storage tank during the period in which the collector pump is operated in the test period, °C

$\bar{\bar{t}}_s$ = monthly-average temperature of the water in the solar-heated portion of the storage tank estimated from equation (12), °C

Y = ratio of absorbed solar radiation to the load during the test period, defined by equation (4), dimensionless

$\bar{Y}$ = monthly-average ratio of absorbed solar radiation to the load, defined by equation (6), dimensionless

$\Delta\tau$ = time period over which I_T is measured

η = collector efficiency, dimensionless

θ = solar radiation incidence angle, deg

ϕ = solar radiation utilizability defined in equation (1), dimensionless

$\bar{\phi}$ = monthly-average solar radiation utilizability, dimensionless

[3]. Two amibient temperature profiles were considered. Test day 4 assumes a constant 25°C ambient temperature in accordance with [3] whereas test day 5 assumes a typical ambient temperature profile for January in the Washington, D.C. area. Test day 4 is unrealistic in that the solar radiation is representative of a clear January day in Washington, D.C. but the ambient temperature is inapproptiate for a winter day. This test case demonstrates that the tests conducted in accordance with ASHRAE Standard 95-1981 need not use representative (or realistic) meteorological data to provide information useful for long-term performance estimates. Test day 6 is similar to the ARI recommended summer day; it is a very clear summer day at 40°N latitude. Test day 7 is a day with zero solar energy. With zero solar input, the collectors are inoperative and the water heating load (plus storage tank energy losses) must be entirely supplied by auxiliary energy.

Monthly and annual results were obtained by simulating system performance with TRNSYS for one-year periods. Typical meteorological year (TMY) meteorological data [19] for Madison, Wisconsin; Albuquerque, New Mexico; and Seattle, Washington were used in these simulations. The effects of collector size, collector thermal parameters, hot water usage, and mains water temperature were investigated in the annual simulations.

2.2 Correlations of Steady Periodic One-Day Thermal Performance. Solar fraction is used as the index of system thermal performance. The solar fraction, f, is defined here as

$$f = 1 - \frac{Q_{\mathrm{AUX}}}{Q_L} \tag{2}$$

where Q_{AUX} is the auxiliary energy required including that needed to supply tank energy losses, but excluding the energy to operate pumps, blowers and controls. Q_L is the energy required to heat the required amount of water from the mains supply temperature, t_m, to the delivery temperature, t_d. Q_L is measured by summing the products of the mass of water drawn, m, the specific heat, C_p, and the difference between the delivery and mains supply temperatures over the test day as indicated in equation (3). Tank energy losses and parasitic energy consumption are not included in Q_L.

$$Q_L = \Sigma\, mC_p (t_d - t_m) \tag{3}$$

Both an energy balance and previous investigations [20, 21] suggest that the solar fraction can be correlated to the product of ϕ and a dimensionless parameter, Y. Y is defined

$$Y = \frac{A_g \dfrac{A_a}{A_g} F_R (\tau\alpha)_{e,n}\, \Sigma\, (I_T K_{\tau\alpha}) \Delta\tau}{Q_L} \tag{4}$$

where

A_g is the gross collector area

$\dfrac{A_a}{A_g} F_R (\tau\alpha)_{e,n}$ is the intercept of the collector efficiency curve determined in accordance with ASHRAE Standard 93-77 [22]

$\Delta\tau$ is the time period over which I_T is measured

$K_{\tau\alpha}$ is the incidence angle modifier averaged over the hourly period

The product of I_T and $K_{\tau\alpha}$ is summed over the test day. Physically, Y is related to the ratio of the total energy absorbed on the collector surface to the total load during the test period.

The utilizability, ϕ, for the test day can be calculated from equation (1) once the critical level, I_c, is specified. Collector theory [23] indicates that the critical level should be defined as follows:

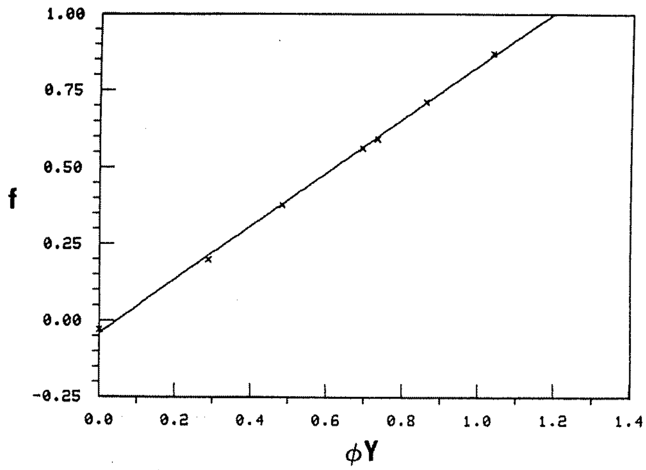

Fig. 1 Steady periodic one-day test results for the base-case system

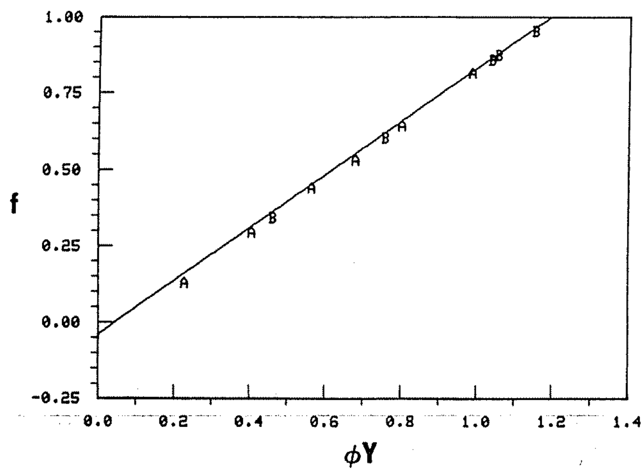

Fig. 2 Steady periodic one-day test results for systems A and B

$$I_c = \frac{\dfrac{A_a}{A_g} F_R U_L}{\dfrac{A_a}{A_g} F_R (\tau\alpha)_{e,n}} (\bar{t}_s - \bar{t}_a) \tag{5}$$

where

$\dfrac{A_a}{A_g} F_R U_L$ is the magnitude of the slope of the collector efficiency curve determined in accordance with ASHRAE 93-77 (22)

$\bar{t}_s$ is a daily average system operating.temperature

$\bar{t}_a$ is the daytime-average ambient temperature

The average system operating temperature, $\bar{t}_s$, could be defined in a number of ways. The choice for $\bar{t}_s$ should minimize the amount of test data required. When $\bar{t}_s$ is defined as t_m, t_d, or $(t_m + t_d)/2$, a nonlinear relationship of f to ϕY is observed; three (or more) test points would be needed to establish this relationship. A linear relationship of f to ϕY is obtained when $\bar{t}_s$ is defined either as the average collector inlet temperature or the average temperature in the solar-heated portion of the storage tank. Unless the heat exchanger penalty factor [15], F_R'/F_R, is known, however, the monthly performance of systems having an (internal or external) heat exchanger cannot be found from short-term tests when $\bar{t}_s$ is defined as the average collector inlet temperature.

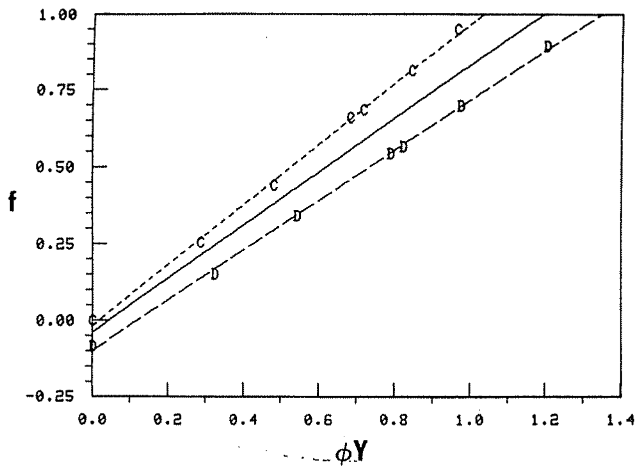

Fig. 3 Steady periodic one-day test results for systems C and D

The final choice for $\bar{t}_s$ is the daily average temperature of the water in the solar-heated portion of the storage tank during the period in which the collector pump is operated. The solar-heated portion of the storage tank is defined as that portion of the tank which can be heated by solar energy, but is not heated by an auxiliary energy supply. In a double-tank system, the solar-heated portion consititutes the entire preheat tank, but excludes the auxiliary tank. In a single-tank system having an electric heating element in the upper section, the solar-heated portion of the tank consists of that portion of the tank located below the electric heating element. $\bar{t}_s$ can be measured in either of two ways. For system configurations in which water is pumped from the tank to either a collector array or a heat exchanger, $\bar{t}_s$ is the average temperature of the water exiting the tank during the period in which the collector pump is operated. For indirect heat exchanger systems, $\bar{t}_s$ must be determined by measuring the temperatures at several representative positions within the solar-heated portion of the tank and averaging these over the period in which the collector pump is operated. Thus, for all systems employing heat exchange between the collector fluid and the potable water, a measurement of the average temperature in the solar-heated portion of the storage tank is required in addition to those measurements specified in the ASHRAE Standard 95-1981 test method.

Shown in Fig. 1 is a plot of f versus ϕY obtained by simulating the steady periodic one-day performance of the base case system for each of the test days conditions listed in Table 2. The average tank temperature, $\bar{t}_s$, was calculated by the simulation program and used in the evaluation of the simulation utilizability. An important feature of this plot is that f is very nearly a linear function of ϕY. A linear least squares fit to these seven points is shown by the solid line. A negative solar fraction occurs at $\phi Y = 0$. When solar fraction is defined as indicated in equation (2), it should be negative at $Y = 0$ (i.e., zero collector area) since tank energy losses cause Q_{AUX} to be greater than Q_L.

Figure 2 is a plot of f versus ϕY for systems A and B. The straight line is the linear least squares fit to the base case results from Fig. 1. The points for systems A and B lie very close to the line obtained for the base case system. Changes in the collector area and/or the collector parameters affect the value of ϕY, but not the relationship between f and ϕY, since the collector parameters and area are already considered in determining ϕY.

Figure 3 is a plot of f versus ϕY for systems C and D. The solid straight line is again the linear least-squares fit to the base case system results. The short and long dashed lines represent linear least-squares fits to the results for system C and D, respectively. System C differs from the base case only in the respect that the storage loss coefficient is 0; i.e., there are no tank energy losses. System D is a double-tank system. This system has more tank surface area, and correspondingly larger tank energy losses, than the base case system. Clearly, a different relationship between f and ϕY is needed for each of these systems. Changes in the system configuration, storage tank design, heat exchanger performance, pump controller operation, piping losses, and hot water delivery temperature affect f but are not accounted for in ϕY. Changes in these design variables will thus affect the relationship between f and ϕY.

2.3 Correlation of Long-Term Thermal Performance. The steady periodic one-day system performance results were presented in the manner described in section 2.2 with the presumption that they would then be useful for estimating monthly and annual system performance. In this section, the validity of this presumption is investigated. The monthly and annual performance calculated using the steady periodic one-day results is compared with the performance predicted by TRNSYS simulations for a yearly period.

The monthly solar fraction, f, is defined as in equation (2), except that in this case Q_{AUX} and Q_L represent the monthly auxiliary energy use and water heating load. A monthly value of the dimensionless factor Y is defined analogously to equation (4) as follows:

$$\bar{Y} = \frac{A_g \dfrac{A_a}{A_g} F_R (\tau\alpha)_{e,n} \bar{H} \bar{R} \bar{K}_{\tau\alpha}}{\bar{Q}_L} \tag{6}$$

where

- $\bar{H}$ is the monthly-average daily radiation per unit area on a horizontal surface
- $\bar{R}$ is the ratio of the monthly radiation on the collector plane to that on a horizontal surface
- $\bar{K}_{\tau\alpha}$ is the monthly average incidence angle modifier
- $\bar{Q}_L$ is the monthly-average daily hot water load

Monthly-average daily horizontal radiation data are available for more than 200 locations in North America [24]. $\bar{R}$ can be estimated (when tilt radiation data are not available) as described in [25]. A method of calculating $\bar{K}_{\tau\alpha}$ can be found in [26].

Methods in estimating $\bar{\phi}$, the monthly-average solar radiation utilizability, are available [11, 12, 13]; in the results which follow, the algorithm of [12] is applied. In order to estimate $\bar{\phi}$, a monthly-average critical level, $\bar{I}_c$, must be specified. $\bar{I}_c$ is defined in analogy with I_c in equation (5).

$$\bar{I}_c = \frac{\dfrac{A_a}{A_g} F_R U_L}{\dfrac{A_a}{A_g} F_R (\tau\alpha)_{e,n}} (\bar{t}_s - \bar{t}_a) \tag{7}$$

where

- $\bar{t}_s$ is a monthly-average system operating temperature
- $\bar{t}_a$ is the monthly-average ambient temperature. (As indicated by Evans et al. [13], using the daytime-average in place of the 24-hour monthly-average ambient temperature has little effect on the calculated value of $\bar{\phi}$.)

The system operating temperature for the short-term tests is measured during the test procedure as described in section 2.2. On a monthly-average basis, however, measurements are not available. A monthly-average system operating temperatures, $\bar{t}_s$, is needed in order to evaluate the utilizability

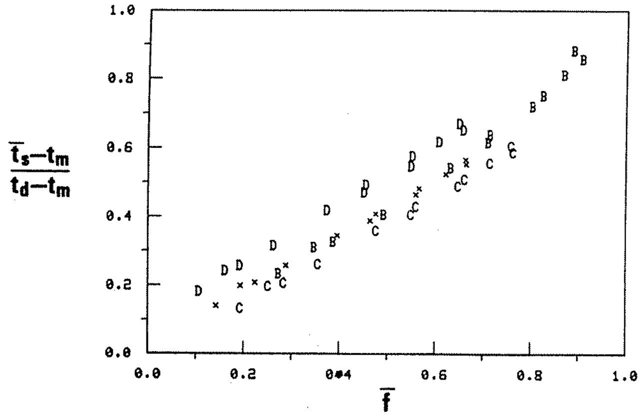

Fig. 4 $(\bar{t}_s - t_m)/(t_d - t_m)$ versus f for the base case and systems B, C, and D in Madison, Wisconsin

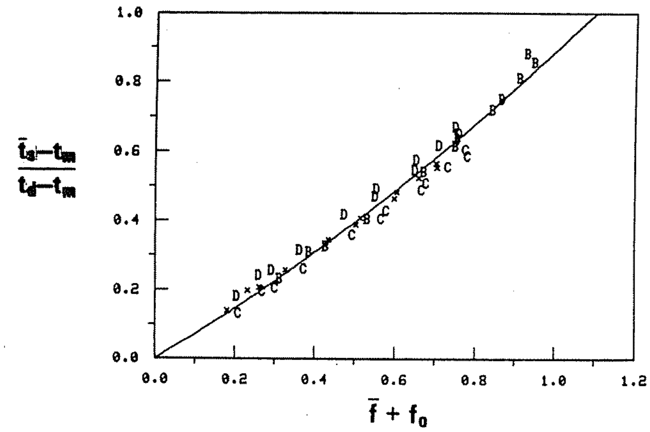

Fig. 5 $(\bar{t}_s - t_m)/(t_d - t_m)$ versus $(f + f_o)$ for the base case and systems B, C, and D in Madison, Wisconsin

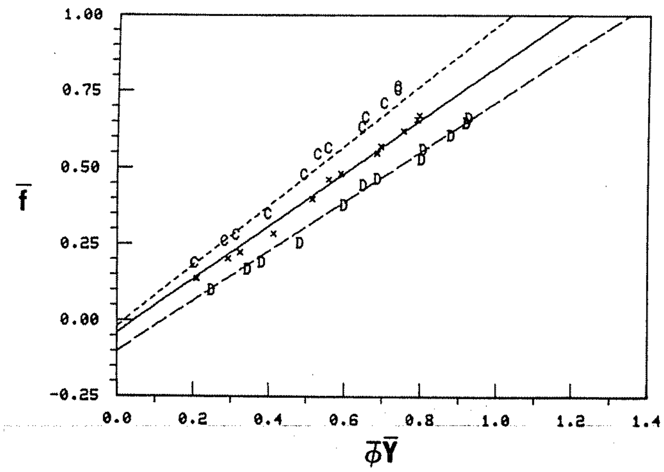

Fig. 6 f versus $\overline{\phi Y}$ for the base case and system C and system D in Madison, Wisconsin

and thereby use the steady periodic one-day test results to estimate monthly performance. An appropriate definition of $\bar{t}_s$ for this purpose is the monthly-average temperature of stored water heated by solar energy. $\bar{t}_s$ was calculated in the TRNSYS simulations. For single-tank systems, $\bar{t}_s$ was taken to be the monthly-average value of the average temperature in the lower 3 sections of the storage tank. (The top section is maintained at the delivery temperature by the heating element). For double-tank systems, $\bar{t}_s$ was simply the monthly-average temperature in the preheat tank.

Intuitively, one would expect $\bar{t}_s$ to increase as $\bar{f}$, the monthly solar fraction, increases. $\bar{t}_s$ should also be affected by the mains supply and delivery temperatures. Shown in Fig. 4 is a plot of $(\bar{t}_s - t_m)/(t_d - t_m)$ versus $\bar{f}$ obtained from annual TRNSYS simulations of the base case system (x) and systems B, C, and D for the Madison Wisconsin TMY meteorological data. A relationship between $(\bar{t}_s - t_m)/(t_d - t_m)$ and $\bar{f}$ is evident, although a different correlation is needed for each of the systems shown.

A single correlation does not describe the results in Fig. 4 because storage energy losses are not accounted for. The storage energy loss characteristics of these systems are quite different. System C has no tank energy losses. The base case and system B are both single-tank systems with a well-insulated tank. System D has greater energy losses than the base case system, because it is a double-tank system with a larger total tank surface area.

The monthly solar fraction for systems having storage losses can be written

$$\bar{f} = \bar{f}_{NL} - \frac{\bar{Q}_{\rm LOSS}}{\bar{Q}_L} \qquad (8)$$

where

$\bar{f}_{NL}$ is the solar fraction which would be obtained if there were no tank energy losses

$\bar{Q}_{\rm LOSS}$ is the monthly-average daily energy loss from the storage tank(s)

$\bar{Q}_{\rm LOSS}$ cannot be directly calculated unless an estimate of the energy loss coefficient of the storage tank(s) is available. However, an estimate of $\bar{Q}_{\rm LOSS}/\bar{Q}_L$ is provided by the negative of the intercept value of f at $\phi Y = 0$ from the steady periodic one-day test results. This intercept is defined to be f_o.

$$f_o = -f \text{ at } \phi Y = 0 \quad f_o \approx \frac{\bar{Q}_{\rm LOSS}}{Q_L} \qquad (9)$$

The values of f_o (from Fig. 3) are 0.017, 0.037, and 0.098 for system C, the base case, and system D, respectively.

Equation (9) assumes that the average daily load used in the monthly performance calculations, $\bar{Q}_L$, is the same as the load used in the steady periodic one-day test, Q_L. If this is not the case, f_o no longer provides an estimate of $\bar{Q}_{\rm LOSS}/\bar{Q}_L$. A modified value, f_o', adjusted (approximately) for different loads resulting from changes in the daily water usage or the mains water temperature can be obtained by multiplying the intercept from the test data by the ratio of Q_L to $\bar{Q}_L$.

$$f_o' = f_o \, Q_L / \bar{Q}_L \qquad (10)$$

The values of f read from the f versus ϕY plot of steady periodic one-day test data should then be adjusted as follows.

$$f' = f + f_o - f_o' \qquad (11)$$

When the average daily load for the month differs from that used in the steady periodic one-day test, the modified values of solar fraction, f' and f_o', should be used in all of the following calculations in place of f and f_o.

Simulation results indicate that $\bar{f}_{NL}$, the monthly solar fraction which would be obtained if there were no storage energy losses, is well-correlated to the dimensionless temperature $(\bar{t}_s - t_m)/(t_d - t_m)$. Equations (8) and (9) indicate that an estimate of $\bar{f}_{NL}$ for any system is provided by the quantity $(\bar{f} + f_o)$. Shown in Fig. 5 is a plot of $(\bar{t}_s - t_m)/(t_d - t_m)$ versus $(\bar{f} + f_o)$ for the same four systems considered in Fig. 4. Plotted in this manner, the data for these systems are more closely represented by a single correlation, although differences are still distinguishable. The solid line in Fig. 5 is a least-squares curve fit to the data for the four systems, which results in

$$\left(\frac{\bar{t}_s - t_m}{t_d - t_m}\right) = 0.688\,(\bar{f} + f_o) + 0.201\,(\bar{f} + f_o)^2 \qquad (12)$$

Table 3 Comparison of simulated and calculated annual solar fractions

SYSTEM DESCRIPTION	MADISON, WI		ALBUQUERQUE, NM		SEATTLE, WA	
	F_{TRNSYS}	F_{CALC}	F_{TRNSYS}	F_{CALC}	F_{TRNSYS}	F_{CALC}
Base Case	0.441	0.443	0.729	0.722	0.350	0.367
System A	0.372	0.372	0.640	0.616	0.295	0.312
System B	0.670	0.691	---	---	0.551	0.578
System C	0.521	0.508	0.819	0.808	0.421	0.425
System D	0.420	0.424	0.733	0.723	0.322	0.341
Base Case, Daily draw = 210 liters	0.502	0.514	0.813	0.832	0.398	0.426
System C, t_m = 20°C	0.566	0.552	0.881	0.886	0.450	0.454
System D, t_m = 20°C	0.412	0.448	0.780	0.807	0.294	0.350
System D, Daily draw = 210 liters	0.460	0.484	0.801	0.821	0.350	0.388
Base Case, Collector Area = 2.5 m^2	---	---	0.477	0.483	---	---
System A, Collector Area = 2.5 m^2	---	---	0.433	0.434	---	---

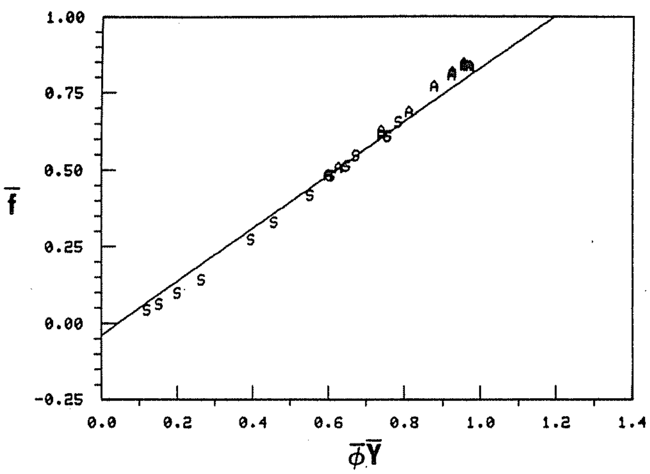

Fig. 7 $\bar{f}$ versus $\overline{\phi Y}$ for the base case in Albuquerque, New Mexico and Seattle, Washington

Deviations from this corrrelation occur because f_o is not necessarily a precise estimate of $\bar{Q}_{\rm LOSS}/\bar{Q}_L$, as evident by the nonzero value of f_o which results in Fig. 3 for system C, a system having no tank energy losses. The estimate of $\bar{t}_s$ provided by equation (12) is, however, adequate for the purpose at hand, as shown below.

Equation (12) provides a means of estimating $\bar{t}_s$, which is used in equation (7) to calculate $\bar{I}_c$, the critical level at which $\bar{\phi}$, the monthly-average utilizability is evaluated. Simulation results illustrate that the plot of $\bar{f}$ versus $\overline{\phi Y}$ which results in this manner for a particular system is closely represented by the $\bar{f}$ versus $\overline{\phi Y}$ plot of steady periodic one-day test results for that system. Shown in Fig. 6 is a plot of monthly values of $\bar{f}$ versus $\overline{\phi Y}$ for the base case (x) and systems C and D in Madison, Wisconsin. The lines in Fig. 6 are the steady periodic one-day test results from Fig. 3 for these three systems. Figure 7 shows the simulation results for the base case system in Albuquerque, New Mexico and Seattle, Washington. The solid line in Fig. 7 is again the test results for the base case system from Fig. 3. Albuquerque, Madison, and Seattle were chosen for this simulation study because they represent widely different climates. The results in Fig. 7 (along with the additional comparisons in Table 3) indicate that the steady periodic one-day results can be used to accurately predict the monthly-average system performance in these three very different climates.

This procedure for estimating the long-term average thermal performance from the steady periodic one-day test results is as follows.

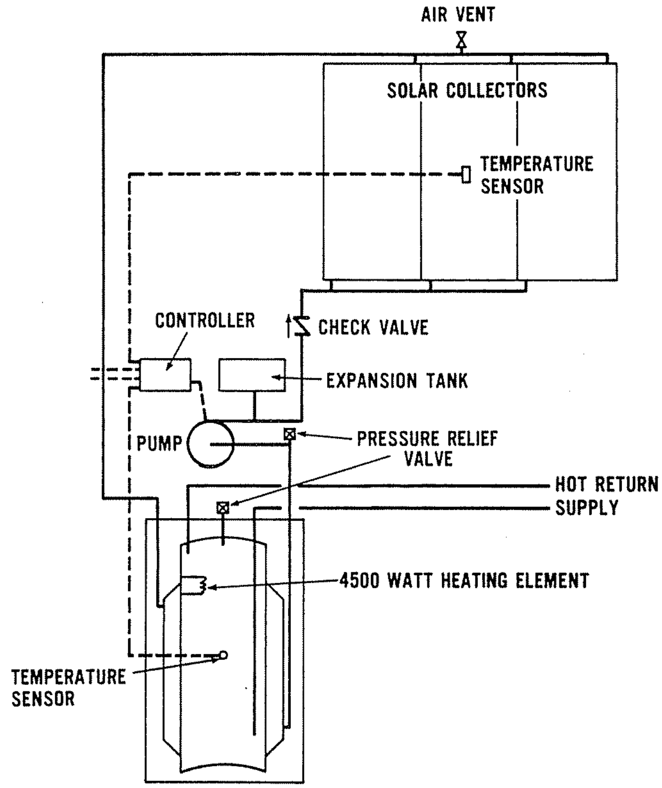

Fig. 8 Schematic of single-tank indirect system subjected to outdoor meterological conditions

Step 1: $\bar{Y}$ is evalauted using equation (6).
Step 2: A guess is made for $\bar{t}_s$.
Step 3: $\bar{I}_c$ is calculated using equation (7).
Step 4: $\bar{\phi}$ is evaluated at a critical level of $\bar{I}_c$ using the algorithm in either [12] or [13].
Step 5: The product of $\bar{\phi}$ and $\bar{Y}$ is calculated and used (in place of ϕY) to obtain a value of $\bar{f}$ from the correlation based on short-term ASHRAE Standard 95-1981 test results.
Step 6: $\bar{t}_s$ is calculated using equation (12). If this value of $\bar{t}_s$ differs significantly from that used to calculate $\bar{I}_c$ in step 3, steps 3–6 are repeated until convergence is obtained. Convergence can be achieved by successively substituting the newly calculated value of $\bar{t}_s$ back into step 3; however, at high solar fractions, the use of an iterative solution technique such as Newton's method greatly reduces the number of iterations required.
Step 7: The annual solar fraction, F, is calculated from

$$F = \frac{\sum_{i=1}^{12} \bar{f}\,\bar{Q}_L}{\sum_{i=1}^{12} \bar{Q}_L} \tag{13}$$

The annual solar fraction should be used (along with a consideration of parasitic energy consumption reported with the short-term test results) as the basis for rating SDHW systems. Table 3 compares the annual solar fractions estimated in this manner with TRNSYS simulation results. The data in this table demonstrate that short-term test results can be used to estimate the annual solar fraction. More importantly, these data indicate that the short-term test results can be applied even if the collector thermal parameters, the collector area, the daily water use, and the mains water temperature for the annual calculation are different than those used in the short-term tests. Experimental data supporting this rating procedure appear in the next section.

3 Experimental Investigation

An experimental investigation of the proposed rating procedure for SDHW systems was performed at the National Bureau of Standards (NBS). The investigation consisted of collecting monthly data for a single-tank indirect system subjected to normal outdoor meteorological conditions and subsequently testing the system using the ASHRAE Standard 95-1981 test method.

3.1 Experimental Apparatus and Instrumentation. A single-tank indirect SDHW system, Fig. 8, was used in this experimental investigation. The system consists of three solar collectors connected in parallel, a water storage tank with a wrap around heat exchanger, an on-off differential temperature controller, and a pump.

Lennox Model LSC18-1S solar collectors are used.[1] This is a single-glass-cover, flat-plate collector. A steel absorber plate is formed around copper flow tubes and then coated with black chrome. Each collector has an aperture area of 1.40 m^2. Instantaneous efficiency tests of the Lennox LSC18-1S were performed at NBS. A least-squares curve fit to the data, based on aperture area, resulted in a linear efficiency of

$$\eta = 0.805 - 4.73\,((t_{in} - t_a)/I_T) \tag{14}$$

The measured incident angle modifier is represented by

$$K_{\tau\alpha} = 1.0 - 0.10\,[\cos\theta)^{-1} - 1] \tag{15}$$

The Solarstream 310 L water storage tank has an integral 4500 W heating element located in the upper portion of the tank. Thus during periods of insufficient solar energy, the heating element set at 60°C satisfies the load requirements. The outside dimensions of this tank are 1.42 m in height by 0.71 m in diameter. A double-wall heat exchanger jacket surrounding the water tank allows the heat transfer fluid to heat the water within the tank. The heat transfer fluid composition is a mixture of ethylene glycol (40 percent by weight) and distilled water. The heat exchanger jacket has an area of 1.58 m^2 and is attached to the surface by mechanical bonding. Insulation surrounding the heat exchanger and tank consists of 76-mm-thick glass fiber. A 76-mm insulation slug also exists at the top and bottom of the tank.

A Honeywell differential temperature controller actuates the pump when a temperature difference of 10°C exists between the absorber plate and a tank surface temperature sensor. The tank sensor is located at a height of 0.74 m. The flow rate is 0.0833 l/s when the pump is actuated. Circulation ceases when the temperature difference becomes 1.7°C.

Upon completion of 12 months of outdoor testing, system modifications were made to accommodate testing using the ASHRAE Standard 95-1981 test method. The irradiated collector array was replaced with a nonirradiated collector array with a downstream electric heat source, Fig. 9. The electric heat source consists of three immersion heaters. Each immersion heater, having a maximum capacity of 1 kW, is encased within a 19.1-mm-dia copper tube. The three rod heaters and associated piping are located within an insulated vacuum jar. Power input to the electric heaters is controlled by a motor-driven autotransformer. The quantity of power delivered to the electric heat source is determined in accordance with [27]. A Hewlett-Packard 9825 computer controls the autotransfmormer such that the power input is within 3 W of the desired quantity. A storge tank bypass loop allows outdoor collector stagnation conditions to be duplicated indoors. When a 10°C temperature difference exists between the pipe leaving the heat source and the storage tank sensor, the controller positions two three-way zone valves such that the flow path is identical to that of the irradiated system. When the temperature difference becomes less than 1.7°C, the storage tank is bypassed. In this mode of operation, power supplied by the electric heat source is partially dissipated as heat from the nonirradiated array.

A normally closed solenoid valve, located at the hot water outlet of the storage tank, releases the hot water to a drain when actuated. An electric timer combined with a stepping relay selects an interval timer corresponding to the desired hourly draw. The automatic reset interval timers range from 1.5 to 10 min in duration. A constant flow control valve maintains the load flow rate at 3.79 L/min. The Rand load profile [16] was used in both the outdoor testing and indoor testing using the ASHRAE Standard 94-1981 test method.

The SDHW system is extensively instrumented. Located within each water storage tank are Type T copper-constantan thermocouples spaced 15.24-cm increments. Thermocouples also monitor the collector inlet and outlet temperature for each system. The inlet and exit potable water temperatures are measured with thermocouples, and a three-junction thermopile measures the temperature difference during hot water withdrawn.

Two W-hr meters are used to measure the auxiliary energy consumed by the electric heating element and the energy used by the pump and controller. The quantity of water supplied to the load is measured using two flow totalizers. A turbine flowmeter measures the flow rate of the fluid circulating through the collector array.

Meteorological information, recorded during the outdoor tests, includes horizontal surface radiation, tilted surface radiation, windspeed, wind direction, and ambient temperature. A watt transducer was utilized to measure the instantaneous power input to the electric heat source during indoor testing.

3.2 ASHRAE Standard 95-1981 Test Method Results. Nine separate tests were conducted using the test methods described in ASHRAE Standard 95-1981. Test numbers 1–7 correspond with the meteorological conditions listed in Table 2, test number 8 used the same meteorological conditions as test 7, but with 20°C mains supply water temperature, as indicated in Table 4. Test number 9 is a repeat of test number 3. An average of 279 L of water were withdrawn at 60°C each day. The temperature of the supply water was 10°C for four of the tests and 20°C for the remaining tests. Each test was conducted until the measured solar fraction was within 0.03 of that measured the previous day.

The thermocouples located within the storage tank provided the information necessary to calculate $\tilde{t}_s$. The average water temperature in the solar-heated portion of the tank was calculated at half-hour intervals using the

Table 4 Short-term experimental results using ASHRAE Standard 95-1981

Test Number	$\tilde{t}_a$	t_m(°C)	Q_L(kJ)	$\tilde{t}_s$(°C)	ϕ	Y	f
1	2.2	10.6	56,280	22.8	0.581	0.530	0.204
2	8.1	19.9	44,714	34.6	0.591	1.018	0.360
3	24.0	19.7	42,961	40.0	0.787	1.327	0.650
4	25.0	10.9	54,080	37.9	0.874	1.232	0.750
5	2.2	10.8	57,946	34.4	0.686	1.150	0.577
6	31.0	20.5	47,578	50.0	0.826	1.747	0.925
7	-	19.6	44,132	-	-	0	-0.077
8	-	~~20.0~~ 11.0	~~44,000~~ 54000	-	-	0	~~-0.024~~ 0.003
9	24.0	19.9	42,376	39.6	0.792	1.345	0.644

[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

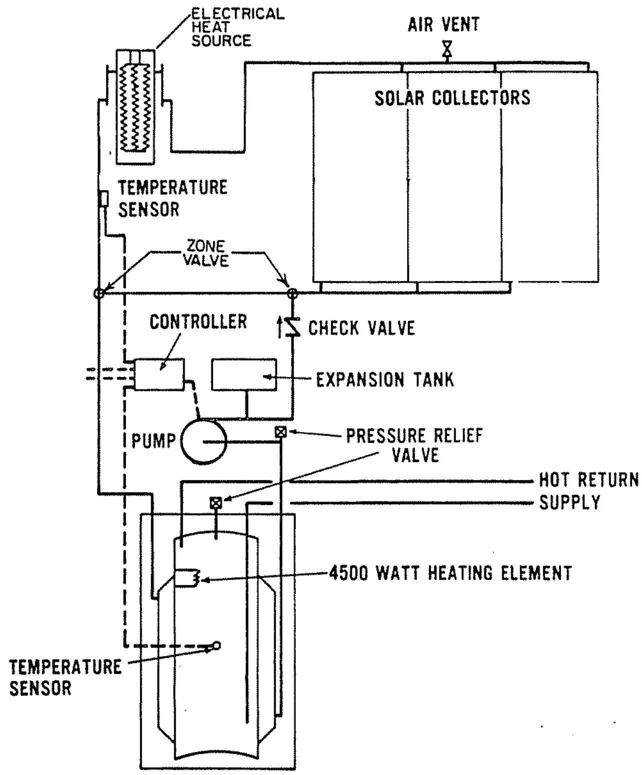

Fig. 9 Schematic of single-tank indirect system used in short-term tests

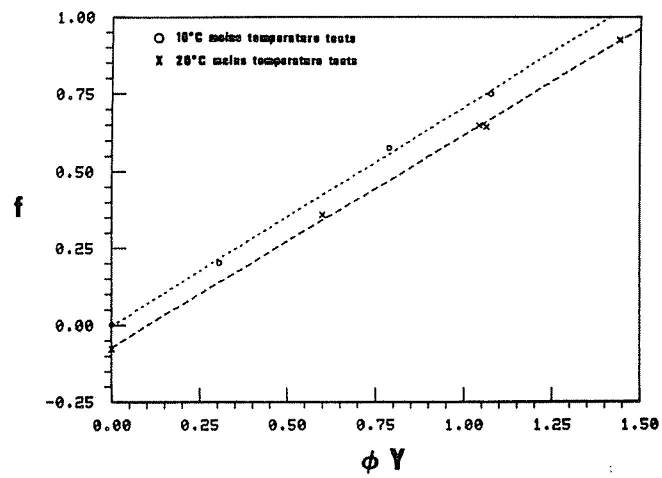

Fig. 10 Solar fraction versus ϕY for ASHRAE 95-1981 test results

thermocouples located below the heating element. These measured temperatures were then averaged over the period in which the collector pump was operated to obtain $\bar{t}_s$.

Table 4 gives a summary of the steady periodic one-day test results using the ASHRAE Standard 95-1981 test method. The average daytime outdoor ambient temperature is given in column 2. Columns 3 and 4 list the mains water supply temperature, and the thermal load. Column 5 shows the measured $\bar{t}_s$ used in the calculation of the critical level. ϕ, shown in column 6, is computed for each test from equation (1). Column seven gives Y calculated in accordance with equation (4). The measured solar fraction appears in column 9. A comparison of the solar fraction for test numbers 3 and 9 shows repeatability within 0.01.

Figure 10 shows the resulting correlation of solar fraction to ϕY. The circles and crosses represent the results for the tests in which the mains supply water temperature was 10 and 20°C, respectively. The measured solar fractions are nearly linear with respect to ϕY as indicated by the least squares fits in Fig. 10. Because of the linearity, only two test points would have been required to establish each curve. Both curves are used to independently predict the monthly performance in the next section.

3.3 Experimental Results from Outdoor Testing. The single-tank indirect system was subjected to outdoor meteorological conditions from January through December, 1980. Table 5 gives a monthly performance summary. Due to operational problems with instrumentation, gaps exist in the experimental data. The number of days for which data were recorded, N, is given in the second column. Columns 3 and 4 list the average daily radiation on the collector array and the average average outdoor ambient temperature for each month. The water supply temperature is given in column 5. The average daily thermal load, column 6, and the average daily energy required for the electric heating element, column 7, are used to determine the monthly solar fraction given in column 8. The monthly solar fractions calculated using technique described in section 2 appear in columns 9 and 10. The solar fractions in column 8 were obtained using the upper curve in Fig. 10; column 9 was obtained using the lower curve. The greatest discrepancy between predicted and measured results occurs for the month of August. The small number of days for which data were recorded during August may be responsible for its difference. Over the twelve-month interval the predicted solar fraction using the upper curve in Fig. 10 (10°C inlet mains temperature) overpredicts the measured annual solar fraction by 4.4 percentage points. Using the lower curve (20°C inlet mains temperature) the predicted solar fraction is 2.8 percentage points less than measured. Estimates of the solar fractions for the mains water temperatures in column 5 were obtained by interpolating (or extrapolating) the 10 and 20°C values in columns 9 and 10. The resulting values appear in column 11. The annual solar fraction obtained in this way was 2.2 percentage points higher than the experimental value. In a rating application, a constant mains supply temperature, specified by the rating organization, is recommended for both the steady periodic one-day tests and the monthly predictions. The relative ranking obtained in this manner is not sensitive to the actual mains supply water temperature.

4 Discussion

If a rating procedure for SDHW system is to be useful, it must provide accurate estimates of the relative merits of competing sytems. It is insufficient to learn that system A will perform better than system B; it is necessary to know how much better system A will perform so that economic considerations can be applied. The annual solar fraction provides this information and it is thus a logical choice for a rating index.

The performance of a SDHW system depends on both its design and the climate in which it is located. The performance of a particular system is thus site-dependent and site-specific meteorological data are needed to estimate its performance. The major contribution of this proposed rating procedure is that it offers a means of using site-specific data along with the ASHRAE Standard 95-1981 test method. The ASHRAE Standard 95-1981 test results obtained for any given test conditions (such as those proposed by SRCC [2] and ARI [3]), no matter how realistic or representative, have no value other than for ranking the system performance for the particular meteorological conditions represented during the test.

The simulation and experimental results presented here indicate that the choice of meteorolgical conditions for the short-term tests is not critical. They need not be representative of a particular climate type; in fact, they need not even be

Table 5 Monthly experimental results from outdoor testing

Month	N	$\bar{H}_T$ (MJ/(m^2-day))	$\bar{t}_a$(°C)	t_m(°C)	$\bar{Q}_L$ (MJ/day)	$\bar{Q}_{AUX}$ (MJ/day)	$\bar{f}$	$\bar{f}_{10}$	$\bar{f}_{20}$	$\bar{f}_I$
January	27	8.19	0.0	8.2	52.3	42.0	0.197	0.243	0.193	0.252
February	23	14.75	0.0	9.6	45.8	26.3	0.426	0.468	0.406	0.470
March	27	13.57	6.1	10.4	51.9	32.4	0.376	0.418	0.361	0.416
April	18	19.09	12.4	12.5	52.1	20.8	0.601	0.598	0.535	0.582
May	24	16.78	19.3	17.7	46.5	19.3	0.584	0.600	0.522	0.540
June	22	18.00	20.1	19.1	44.0	16.0	0.636	0.669	0.582	0.590
July	19	18.41	25.0	19.5	43.1	14.6	0.661	0.728	0.638	0.642
August	16	16.18	24.0	24.9	34.6	15.8	0.545	0.732	0.611	0.552
September	23	18.34	21.2	26.1	37.1	13.0	0.649	0.762	0.644	0.572
October	22	14.91	11.1	20.8	45.6	26.2	0.426	0.495	0.411	0.404
November	30	11.75	6.0	13.1	52.6	33.2	0.369	0.363	0.303	0.344
December	25	9.76	0.3	10.4	50.8	37.4	0.264	0.290	0.235	0.288
Annual		-	-	-	-		0.449	0.493	0.421	0.471

realistic. At least two (and preferably more) steady periodic one-day tests are required to establish the relationship between solar fraction and ϕY. To minimize the effect of experimental errors, the testing conditions should be chosen such that low (<20 percent) and high (>60 percent) solar fractions are achieved. Conditions which cause the solar fraction to be nearly unity should be avoided. The zero solar input condition presents a logical choice for one of the tests for systems capable of meeting the entire load with auxiliary energy. This choice simplifies the testing procedure since, in this case, only one steady periodic one-day test with solar energy input is required. Details regarding the testing conditions will have to be specified by the appropriate rating agencies.

Parasitic energy (i.e., the electrical energy required to operate pumps, fans, and controls) has not been addressed. The parasitic energy use during the steady periodic one-day tests is measured in accordance with the ASHRAE Standard 95-1981 testing procedure. Methods of estimating the average monthly parasitic energy using the test day measurements were investigated, but a reliable method was not found. Parasitic energy use should be a secondary consideration in that is generally is a small fraction of the solar contribution. In any case, the parasitic energy use during the steady periodic one-day tests should be considered, along with the estimated annual solar function, in rating SDHW systems.

As presented here, the rating procedure is applicable only to active SDHW sytems. The applicability of this proposed rating procedure to thermosyphon and integral storage should be investigated.

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