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A RATING PROCEDURE FOR SOLAR DOMESTIC HOT WATER SYSTEMS BASED ON ASHRAE-95 TEST RESULTS

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Abstract—A rating method for solar domestic hot water (SDHW) systems is presented that provides site-specific annual performance estimates based on ASHRAE-95 test results. An overall loss and overall gain coefficient are estimated by lumping the entire thermal behavior of the actual system exhibited during the ASHRAE-95 test into the collector parameters of a simplified system model. The performance of the simplified model can then be predicted using either the F-chart or TRNSYS and presented as an estimate of the annual performance of the actual system. Experimental performance measurements taken from relevant literature as well as extensive simulations, indicate that this method is capable of predicting the annual performance of a wide range of SDHW system types to within 5%, independent of location.

1. INTRODUCTION

There are two approaches to rating solar domestic hot water (SDHW) system performance, each of which has a number of limitations. The first approach is to subject the system to some form of short-term test, similar to those presently conducted on conventional hot water systems. Many tests of this type have been proposed[1], and one in particular, the ASHRAE-95 test[2], has become an accepted standard in the United States. The performance measured by the ASHRAE-95 test, however, is only indicative of a system's performance under a specific set of test conditions. The performance realized under actual outdoor conditions may be quite different due to the variability of local climate.

A second approach is to estimate the system's performance with either a detailed computer simulation package such as TRNSYS[3] or a performance correlation such as F-chart[4]. Although TRNSYS simulations can provide accurate estimates of actual installed system performance in any location for which hourly weather data is available[6,7,11], the parameters necessary as inputs to these simulations are often unknown unless many additional tests are performed on individual components. The F-chart method can also provide accurate performance estimates[7,8,10] using monthly average weather data, but it too requires a number of unknown inputs and applies only to certain system types.

The SDHW rating method described in the article links these two approaches thereby overcoming the limitations of either approach individually. The results of a short-term test (the ASHRAE-95) are used to estimate system parameters that can be used as input to either F-chart or a simplified TRNSYS model. In this manner, site-specific annual performance predictions can be provided without extensive testing of individual components.

2. THE ASHRAE-95/SRCC SHORT-TERM TEST

The ASHRAE-95 is an indoor, repeatable system test that attempts to recreate the climatic conditions and use patterns of a "typical" water heating day. The test methodology is fixed, but the test conditions must be specified by a rating agency, the most prevalent of which is the Solar Rating and Certification Committee (SRCC)[5]. Incident solar radiation is simulated through one of two methods. If the collector gain and loss coefficients have been previously determined experimentally, energy absorbed by the collector at a given level of irradiation can be estimated as described by Fanney and Thomas[13]. An in-line heater can then be used to simulate a radiation profile by providing an equal amount of absorbed energy. If the collector parameters are unknown, a solar simulator consisting of movable high intensity lamps is employed.

The ASHRAE-95/SRCC test is conducted by installing the SDHW system of interest under the test apparatus, following manufacturer's instructions regarding set points, physical configuration, and any other system settings that effect its operation. The system is then subjected to the load and radiation profiles specified by the SRCC, and the solar energy delivered during the test day is measured by one of two methods. If the system has an auxiliary heater, the electrical energy supplied to that heater is subtracted from the load to determine the delivered solar energy. If the system has no auxiliary heater, the energy content of the delivered hot water is integrated over the test day by monitoring the temperature and flow rate of the delivered hot water at 10 minute intervals. The daily test procedure is repeated until the delivered solar energy changes from the value of the previous day by less than 3%. The solar fraction of the final test day, defined as the ratio of the delivered solar energy to the load, is presented as the system's ASHRAE-95 test performance.

Although this test result can be viewed as a partial indicator of system performance, it by no means represents the installed performance a consumer can expect in a given location, since that performance is a function of local weather conditions. It is furthermore inadvisable to compare SDHW systems on the basis of ASHRAE-95 test performance alone, because the relative merit of one system over another may also depend on local climate.

3. PERFORMANCE PREDICTION WITH TRNSYS

TRNSYS is capable of linking existing models of various components, such as collectors, storage tanks, pumps, and controllers, to simulate the behavior of almost all SDHW system types, including thermosyphon, forced circulation, and integral collector storage (ICS) systems. Several studies[6,7,9,11] have found that TRNSYS is capable of predicting the performance of each of these system types typically to within 5%. A large number of system parameters (on the order of 30–50), however, are required as inputs to these models. These include physical parameters, such as collector area, tank volume, and flow rates, as well as thermal parameters such as heat exchanger efficiencies and heat loss coefficients.

Many of these parameters are not determinable from the physical configuration of the system. The collector loss and gain coefficients, for example, must be determined experimentally. The loss coefficients of the tank and connecting pipes are also typically unknown and additional tests must be performed to determine their values. The experimental derivation of all these system parameters can become prohibitively expensive and time consuming.

4. DERIVING LUMPED SYSTEM PARAMETERS

Clearly, it is impossible to derive the values of up to 50 separate system parameters from a single test result. It is found, however, that the impact many of these parameters have on annual performance can be adequately described by a lumped overall gain and overall loss coefficient. In this manner, the number of variable parameters required to describe even a complex SDHW system can be reduced to a total of four: collector area, storage tank volume, and the overall gain and loss coefficients.

4.1 *The simplified system*

Using idealized assumptions, a simplified system model is defined as a means of lumping the many thermal parameters of an actual SDHW system into an overall loss and overall gain coefficient. The characteristic components and behavior of this simplified model are described below.

Stratification. The simplified system is defined as having one, well-mixed tank at uniform temperature at any instant in time. The system's thermal behavior can therefore be fully modelled by a single instantaneous energy balance.

Pipe losses. Pipe losses are considered negligible. Thus both the collector inlet temperature, T_i, and the draw temperature, T_d, are equal to the isothermal tank temperature, T_t, at any instant in time.

Incidence angle modification. The collector efficiency is assumed to be independent of the angle of incident radiation. The transmittance-absorptance product, $(\tau\alpha)$, is therefore constant, and equal to the transmittance absorptance at normal incidence, $(\tau\alpha)_n$.

Tank losses. The tank loss coefficient, U_t, of the simplified system is assumed to be equal to 1.51 W/m^2 °C.

Controller operation. The controller is assumed to be perfect, meaning the pump is activated whenever the collector outlet temperature is infinitesimally higher than the inlet temperature. When modelling this controller in TRNSYS, a one degree dead band is employed to prevent numerical instability.

Collector configuration. The collector is defined as consisting of a single panel, regardless of the total area. Modification of the collector parameters to account for the effect of parallel or series-mounted panels is therefore unnecessary.

Collector loop. The working fluid in the collector loop of the simplified system is water. No heat exchanger is used. No modification of collector parameters is necessary to account for heat exchanger efficiency.

Given these simplifications, only four variable parameters affect the performance of the simplified system: collector area, A_c (m^2), tank volume, V_t (m^3); collector gain coefficient, $F_r(\tau\alpha)_n$; and collector loss coefficient, F_rU_l (W/m^2 °C).

The thermal behavior described by the numerous parameters of an actual system can be lumped into the collector parameters of the simplified model in the following manner. The actual system is subjected to the ASHRAE-95 test, resulting in a measured value of daily performance. There must exist a simplified system having the same collector area and tank volume as the actual system, for which some combination of collector gain and loss coefficients would theoretically result in the same test performance as the actual system. A simplified system having these characteristics will be referred to as an equivalent simplified system.

The only unknown parameters of this equivalent simplified system are the collector loss and gain coefficients. Thus, the equivalent simplified system, by definition, accounts for the entire thermal behavior of the actual system through its collector performance. If, for example, an actual system exhibits a high degree of stratification, the equivalent simplified system would require either a higher collector gain coefficient or a lower collector loss coefficient to account for the increase in performance that accompanies stratification. Estimating the overall loss and gain coefficients of the actual system is thus achieved by solving for the collector parameters of the equivalent simplified system. The annual performance of the equivalent simplified system can then be simulated using TRNSYS or F-chart to provide an estimate of the annual performance of the actual system.

4.2 *The integrated energy balance*

A function relating the collector gain and loss parameters of a simplified system can be developed from an instantaneous energy balance, integrated over the last day of the ASHRAE-95 test. For any given instant in time, an instantaneous energy balance on the tank of the simplified system can be expressed as:

$$M_f C_p \frac{dT_t}{dt} = A_c[F_r(\tau\alpha)_n G_t - F_r U_l(T_i - T_a)]^+ - U_t A_t(T_t - T_{env}) - \dot{m}_d C_p(T_d - T_m). \quad (1)$$

The superscripted addition sign shown in eqn (1) signifies that the net collector gain is constrained to positive values by the operation of the pump controller. Equation (1) can be integrated over the last 24-hour period of the ASHRAE-95 test, to produce the daily energy balance shown below:

$$\Delta E = A_c[F_r(\tau\alpha)_n H_{t,on} - F_r U_l(\bar{T}_i - T_a)\Delta t_{on}] - U_t A_t(\bar{T}_t - T_{env})\Delta t_{tot} - M_d C_p(\bar{T}_d - T_m). \quad (2)$$

Several of the variables and parameters shown in eqn. (2) can be eliminated. On the last day of the ASHRAE-95 test, the system has reached a periodic steady state, and the total change in internal energy over this period is therefore negligible (i.e., $\Delta E \approx 0$). In addition, the tank environment temperature, T_{env}, is equal to the ambient temperature, T_a, as the collector and tank are both exposed to the same environment during the ASHRAE-95 test. Some parameters, which describe the operating conditions during the ASHRAE-95, such as set temperature, mains temperature, and total draw mass, are known constants. Others are known physical parameters of the system, such as collector area and tank volume. There remain, however, seven unknowns in eqn (2). They are: the time of pump operation; the incident radiation during that time; the average draw, tank and collector inlet temperatures, and the collector gain and loss coefficients.

If the first five of these unknowns can be determined, eqn (2) effectively becomes a functional relationship between the two collector parameters of the simplified system.

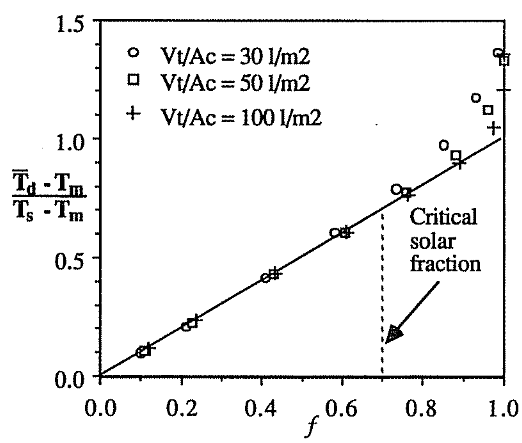

Fig. 1. Right-hand side of eqn (6) vs. solar fraction, obtained from TRNSYS simulations of simplified systems.

4.3 *Average simplified system temperatures*

The average draw temperature of the simplified system can be approximately related to f, the fraction of the load met by solar energy, through the following expression:

$$f = \frac{Q_{solar}}{Q_{load}} \quad (3)$$

where

$$Q_{solar} = \int \dot{m} C_p(T_d - T_m)dt = M_d C_p(\bar{T}_d - T_m) \quad (4)$$

$$Q_{load} = M_d C_p(T_s - T_m) \quad (5)$$

and T_s is the hot water set temperature. Combining eqns (3) to (5) and solving,

$$f = \frac{\bar{T}_d - T_m}{T_s - T_m}. \quad (6)$$

The approximation arises from eqn (4), which implicitly assumes that the draw temperature never exceeds the set temperature during the draw period. To investigate the potential error this assumption may introduce to eqn (6), TRNSYS simulations of the ASHRAE-95 test were performed for simplified systems having three different values of storage volume per unit collector area, V_t/A_c. The collector area of these systems is varied (keeping V_t/A_c constant) to produce a range of average draw temperatures. The solar fraction on the final day of these simulations is compared to the right-hand side of eqn (6) in Fig. 1.

Figure 1 indicates that the solar fraction of an actual system, as measured during the ASHRAE-95 test, can be used in eqn (6) to estimate the average draw temperature of its equivalent simplified system if $V_t/A_c \geq 30\ L/m^2$ and $f \leq 0.7$. (It is possible to ensure that the solar fraction measured during the ASHRAE-95 test remains below 0.7 by adjusting the SRCC radiation profile such that the daily total incident radiation on the collector surface, $H_t A_c$, is less than or equal to the total daily load, $M_d C_p(T_s - T_m)$. Numerous simulations have shown that such adjustments have no significant effect on the accuracy of the rating method[15].

An empirical correlation can be used to estimate the integrated-average collector inlet temperature. Although the simplified system is defined such that the instantaneous draw and collector inlet temperature are equal, their integrated-averaged values often are not, as seen in Fig. 2. The inequality arises from the fact that these two temperatures are averaged over different integration periods: the draw temperature over three separate hour-long draw periods; the collector inlet temperature over the period of pump operation. During the hour-long draw periods, the tank temperature may decrease markedly, due to the accompanying addition of make-up water at mains temperature. These

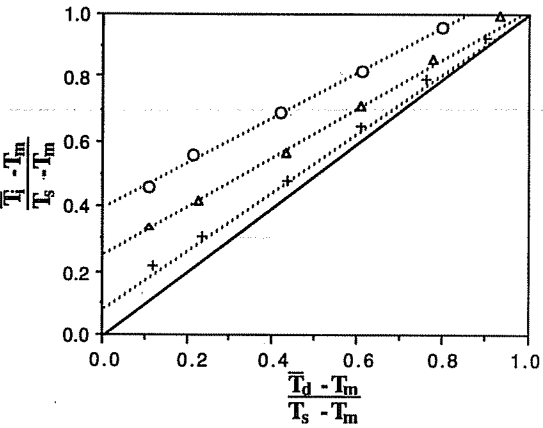

Fig. 2. Dimensionless collector inlet temperature vs. dimensionless draw temperature, from TRNSYS simulation of simplified systems.

decreases have the effect of reducing the average draw temperature below the average collector inlet temperature.

A linear regression of the form

$$\frac{\bar{T}_i - T_m}{T_s - T_m} = A\left[\frac{\bar{T}_d - T_m}{T_s - T_m}\right] + B \quad (7)$$

can be employed to accurately fit the data shown in Fig. 2, where the slope A, and the y-intercept, B, are both functions of the total incident radiation per unit volume, A_cH_t/V_t. A least squares analysis of the data yields:

$$A = 1.0 - 8.753 \times 10^{-4}\left(\frac{A_cH_t}{V_t}\right) + 5.28 \times 10^{-7}\left(\frac{A_cH_t}{V_t}\right)^2, \quad (8)$$

$$B = 6.72 \times 10^{-4}\left(\frac{A_cH_t}{V_t}\right) + 1.04 \times 10^{-7}\left(\frac{A_cH_t}{V_t}\right)^2 \quad (9)$$

with area in m^2, volume in liters and H_t in kJ.

For certain combinations of high solar fraction and high storage volume per unit area, eqn (7) predicts values of average collector inlet temperature that are lower than the average draw temperature. Such predictions are clearly erroneous. In systems with these combinations, the average collector inlet and draw temperatures are nearly identical. As a result, the value predicted by eqn (7) and the average draw temperature predicted by eqn (6) should be compared, and the greater of the two used as the collector inlet temperature. With this modification, the rms difference between average collector inlet temperatures calculated by TRNSYS and the values predicted by eqn (7) is 0.15°C.

The average tank temperature also has a period of integration different from that of the average draw temperature. The same set of simulations used to create Fig. 2, however, also established that average tank and draw temperatures are essentially equal. The rms difference between the two is 0.77°C. Tank losses from the simplified system during the ASHRAE-95 test are quite small; on the order of 2–5% of the delivered solar energy. Hence, an error of 0.77°C in the tank temperature will introduce negligible error to eqn (2).

4.4 *Applying the utilizable fraction*

The variables $H_{t,\text{on}}$ and Δt_{on} can be eliminated from eqn (2) by applying the concept of utilizability[12]. Utilizability is based on the definition of a critical level of incident radiation, G_{tc}, at which the rate of useful energy gain from the collector, q_u, is exactly zero. This critical radiation level can be determined by setting the Hottel–Whillier equation equal to zero.

$$q_u = 0 = A_c[F_r(\tau\alpha)_n G_{tc} - F_rU_l(T_i - T_a)]^+. \quad (10)$$

Thus,

$$G_{tc} = \frac{F_rU_l(T_i - T_a)}{F_r(\tau\alpha)_n}. \quad (11)$$

The daily utilizable fraction[16], ϕ, defined as the fraction of the total daily incident radiation, H_t, that is above the average critical radiation level, can therefore be expressed as:

$$\phi = \frac{\int (G_t - \bar{G}_{tc})^+ dt}{H_t} \quad (12)$$

where

$$\bar{G}_{tc} = \frac{F_rU_l(\bar{T}_i - T_a)}{F_r(\tau\alpha)_n}. \quad (13)$$

Combining eqns (12) and (2) yields:

$$\Delta E = 0 = A_cF_r(\tau\alpha)_n\phi H_t - U_tA_t(\bar{T}_t - T_{\text{env}})\Delta t_{\text{tot}} - M_dC_p(\bar{T}_d - T_m). \quad (14)$$

Applying the concept of utilizability has therefore eliminated the variables $H_{t,\text{on}}$ and Δt_{on}.

As it stands, eqns (12) to (14) constitute an implicit relationship between $F_r(\tau\alpha)_n$ and F_rU_l, since the three expressions can be solved iteratively through numerical integration of the SRCC radiation profile. A simplifying assumption, however, converts eqn (14) to an explicit relationship, without detracting from the accuracy of the expression. If the SRCC radiation profile is approximated by a triangular profile having the same total daily radiation, as shown in Fig. 3, the following relationship results between utilizable fraction and average critical radiation level:

$$\phi = 1 - 2\frac{\bar{G}_{tc}}{G_{\max}} + \left(\frac{\bar{G}_{tc}}{G_{\max}}\right)^2 \quad (15)$$

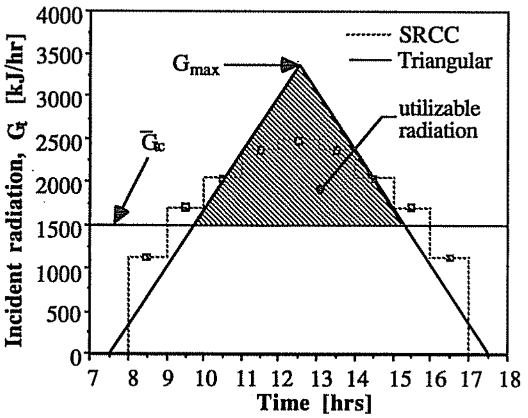

Fig. 3. Triangular approximation of SRCC radiation profile.

where G_{max} is the peak radiation of the triangular profile (3404 kJ/h). Substituting this expression into eqn 15, and solving for G_{tc} yields,

$$\bar{G}_{tc} = G_{max} K \quad (16)$$

where

$$K = \left(1 - \sqrt{\frac{U_t A_t(\bar{T}_t - T_{env})\Delta t_{tot} + \overline{M_d} C_p(\bar{T}_d - T_m)}{A_c F_r(\tau\alpha)_n H_t}}\right). \quad (17)$$

Thus,

$$F_r U_l = \left[\frac{F_r(\tau\alpha)_n G_{max}}{(\bar{T}_i - T_a)}\right] K. \quad (18)$$

Equation (18) is an explicit relationship between the collector gain and loss coefficients of the simplified system under ASHRAE-95 test conditions.

4.5 *Overall gain and loss coefficients*

The collector parameters of the equivalent simplified system describe, by definition, the entire thermal behavior of the corresponding actual system. Equation (18) is therefore also a functional relationship between the overall loss and gain coefficients of that actual system. These overall coefficients will be referred to as $F_r(\tau\alpha)'_n$ and $F_rU'_l$, where the prime denotes that these are not simply collector parameters.

It will be shown that TRNSYS simulations of equivalent simplified systems can be used to provide accurate yearly performance estimates for the corresponding actual systems. The overall gain and loss coefficient of this equivalent simplified system are the only unknown parameters required as inputs to such a simulation. Equation (18) explicitly relates these overall loss and gain coefficients based on the ASHRAE-95 solar fraction of the actual system; but a unique solution cannot be achieved using this equation alone. It is found, however, that if two constraints are imposed, any pair of collector gain and loss coefficients that satisfy eqn (18) produce nearly identical predicted performance when supplied as inputs to a TRNSYS or F-chart yearly simulation of that equivalent system. These two constraints are:

1. The load profile and set temperature used during the yearly simulations must be equal to those used during the ASHRAE-95 test (i.e., the SRCC values).
2. The average of the mains temperature profile assumed during the yearly simulation must be approximately equal (±3°C) to the yearly average ambient temperature of the location in question.

Both of these constraints are reasonable conditions to impose, for the following reasons. The primary motivation behind the development of this prediction method is the ability to rate SDHW systems, and any typical draw profile and set temperature are sufficient for this purpose. The SRCC values were developed as typical residential profiles and therefore fulfill this criterion.

As for the second constraint, mains temperature profiles can be largely divided into two categories, according to the source of mains water. If the principle source is a deep water well, the mains temperature will remain essentially constant, at 1–3°C above the yearly average ambient temperature. If the source is a river, lake, or reservoir, the mains temperature will roughly follow the ambient temperature sinusoid, but with a decreased amplitude and time lag dependent on the mass of the body of water. In either case, the second constraint is satisfied.

The following procedure was conducted to establish that any pair of collector parameters that satisfy eqn (18) will yield the same simulated performance. TRNSYS simulations of the ASHRAE-95 test were performed on four simplified systems, A through D, having the parameters shown in Table 1. The solar fractions provided by these simulations were used to estimate the average draw, tank, and collector inlet temperatures of each system, using eqns (6) and (7). These values of temperature were input to eqn (18) to determine the function relating the collector parameters of each system.

Each of these functions defines a family of collector parameter pairs, $(F_r(\tau\alpha)'_n, F_rU'_l)$, that satisfy the daily energy balance of that particular system. Table 2 shows four members from each of the parameter pair families corresponding to systems A through D, and the annual solar fraction produced by each of these parameter pairs when input to a TRNSYS simulation.

Table 1. Parameters of simplified systems A–D

System	A_c, m^2	V_t/A_c, L/m^2	F_rU_l, W/m^2 °C	$F_r(\tau\alpha)_n$
A	2	30	2.0	0.7
B	1	100	2.0	0.7
C	2	150	4.0	0.7
D	4	150	8.0	0.7

Table 2. Families of collector parameter pairs and resulting annual solar fractions for Madison, WI

	A		B		C		D	
F_rU_l'	$F_r(\tau\alpha)_n'$	f	$F_r(\tau\alpha)_n'$	f	$F_r(\tau\alpha)_n'$	f	$F_r(\tau\alpha)_n'$	f
2.0	0.694	0.132	0.698	0.250	0.655	0.354	0.503	0.365
4.0	0.773	0.136	0.736	0.254	0.707	0.369	0.571	0.373
6.0	0.849	0.139	0.772	0.257	0.759	0.366	0.636	0.381
8.0	0.922	0.142	0.808	0.261	0.808	0.371	0.698	0.390

The simulations were performed using typical mean year (TMY) weather data for five locations, Madison, Nashville, Albuquerque, New York, and Miami. Only the Madison results are included in Table 2, but the results achieved using data from the other locations were essentially identical. In each case, the mains temperature was set equal to the average yearly ambient temperature of that location. The daily draw profile and set temperature used during the simulations were the same as those specified by the SRCC for the ASHRAE-95 test.

Table 2 confirms that for a given simplified system, any pair of collector parameters that satisfied eqn (18) produces virtually identical simulated performance. The rms difference (for all systems and locations combined) between the yearly solar fraction produced by the parameter pairs corresponding to $F_rU_l' = 2.0$ W/m^2 and $F_rU_l' = 8.0$ W/m^2, is 1.6%.

5. RESULTS

The accuracy of the rating method was investigated by comparing the simulated annual performance of actual systems to the simulated performance of their equivalent simplified systems using TMY weather data from five locations. Three categories of actual system types were investigated: thermosyphon systems, highly stratified active systems, and well-mixed active systems having high incidence angle dependence and high tank losses. The procedure used to perform all comparisons was as follows. A simulated ASHRAE-95 test of the actual system is conducted using an appropriate detailed TRNSYS model. The resulting daily solar fraction is used to relate the collector coefficients of the equivalent simplified system, through eqn (18). As all the parameter pairs that satisfy this function yield essentially the same simulated annual performance, a moderate value of $F_rU_l' = 5.0$ W/m^2 is selected for all annual simulations of equivalent simplified systems. This value of F_rU_l', and the corresponding value of $F_r(\tau\alpha)_n'$ that satisfies eqn (18), are input to a year-long TRNSYS simulation of the equivalent simplified system using TMY weather data from the five locations previously mentioned. The yearly operation of the actual system is simulated for the same locations and the resulting values of performance are compared.

Figure 4 shows the results of these comparisons for four highly stratified active systems, A–D. The effect of stratification was modelled by dividing the tank into 10 thermal nodes and setting the collector flow rate to 25 L/h. The parameters used in modelling these stratified systems are summarized in Table 3. (See Minnerly[15] for a more detailed discussion of the various system parameters.) The ASHRAE-95 solar fractions are included to demonstrate the increase in performance that accompanies a high degree of stratification.

Figure 4 confirms that the annual performance of highly stratified systems can be closely approximated by the simulated annual performance of their equivalent simplified systems, independent of location. The root mean square (rms) difference between the simulated performance of the stratified and equivalent simplified systems is 2.2%.

The comparisons conducted for the other two categories of actual SDHW system types yielded similar results[15]. The rms difference in performance for the thermosyphon and incidence angle dependent systems was 1.7% and 1.4%, respectively.

Experimental measurements taken by Fanney and Klein[7,14] at the National Bureau of Standards (NBS) were also used to test the accuracy of the rating method. Fanney subjected a two tank active system with a wrap-around heat exchanger to the ASHRAE-95 test, as well as monitoring its annual outdoor performance. The results of the ASHRAE-95 test were used to estimate the collector coefficients of the equivalent simplified system, as previously described. The annual performance of the equivalent simplified system was simulated using F-chart, as only monthly average weather data were available. The simulated per-

Table 3. Parameters and ASHRAE-95 solar fractions

System	A_c, m^2	V_t/A_c, L/m^2	F_rU_l, W/m^2 °C	$f_{1\ \text{node}}$, well-mixed	$f_{10\ \text{nodes}}$, stratified
A	2	30	2.0	0.595	0.657
B	1	100	2.0	0.637	0.684
C	2	150	4.0	0.564	0.685
D	4	150	8.0	0.394	0.676

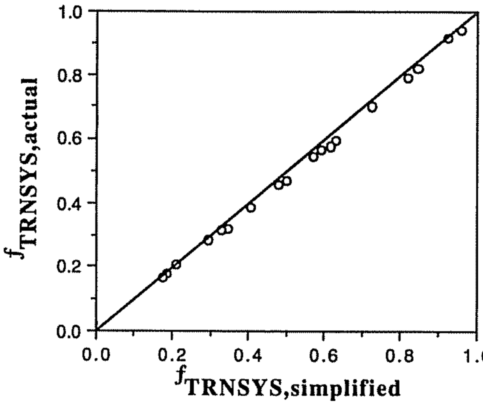

Fig. 4. Annual solar fractions of stratified systems A through D vs. annual solar fractions of their equivalent simplified systems; from TRNSYS simulations.

formance agreed with the measured annual performance of the actual system to within 1.0%[15].

6. CONCLUSIONS

The rating method presented in this article is capable of accurately estimating the annual performance of a wide range of SDHW system types, based solely on ASHRAE-95 test performance and known physical system parameters. ASHRAE-95 test results can therefore be converted into site-specific performance information applicable to rating methodologies analogous to those already in existence for conventional domestic hot water systems.

NOMENCLATURE

- A slope of linear correlation, eqn (8)
- A_c collector area, m^2
- A_t surface area of storage tank, m^2
- B y-intercept of linear correlation, eqn (9)
- C_p specific heat
- ΔE change in internal energy, kJ
- f solar fraction
- $F_r(\tau\alpha)_n$ collector gain coefficient
- $F_r(\tau\alpha)'_n$ overall gain coefficient
- F_rU_l collector loss coefficient W/m^2 °C
- $F_rU'_l$ overall loss coefficient, W/m^2 °C
- G_{max} peak radiation of triangular approximation, W/m^2
- G_t instantaneous radiation incident on collector surface, W/m^2
- G_{tc} instantaneous critical level of radiation on collector surface, W/m^2
- H_t total daily radiation on a tilted surface, kJ/m^2
- $H_{t,on}$ total incident radiation during pump operation, kJ/m^2
- $\dot{m}_d$ mass flow rate of hot water draw, kg/s
- M_d mass of total daily draw, kg
- Q_{load} total hot water load, kJ
- Q_{solar} total delivered solar energy, kJ
- T_a ambient temperature, °C
- T_d draw temperature, °C
- T_{env} temperature of tank environment, °C
- T_i collector inlet temperature, °C
- Δt_{on} total time of pump operation, sec
- T_s hot water set temperature, °C
- T_t tank temperature, °C
- Δt_{tot} length of test day, sec
- U_t tank loss coefficient, W/m^2 °C
- V_t tank volume, liters

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