A Performance Prediction Methodology for Integral Collection-Storage Solar Domestic Hot Water Systems

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A performance prediction methodology is developed which is applicable to most commercially available integral collection-storage passive solar domestic hot water systems. A computer model of a general ICS component was created to be compatible with the transient simulation program TRNSYS [3], and was used to develop and verify the simpler monthly performance prediction method. The method uses the system parameters from available test methods, monthly average climatic data, and load size to predict long term performance of ICS systems.

I Introduction

Integral collection-storage (ICS) units are passive solar water preheaters which combine solar collection with thermal storage. They are usually roof or ground mounted in series with a conventional domestic water heater and supplied by mains water. An ICS unit is basically a black tank in an enclosure with an optical cover system. Today, many units are commercially available with variations on this design. Some units have several tanks plumbed in series within the box. Others have internal reflector systems, non-flat covers or finned tanks. Often these variations are combined and other design innovations are included. ICS solar domestic hot water (SDHW) systems usually cost less than active systems and are inherently simple to install and maintain. They often operate without heat exchangers, pumps or controllers.

A number of studies have proposed methods for predicting ICS monthly or annual performance. Huggins and Block [1] of Florida Solar Energy Center describe a methodology for using ASHRAE 95-1981 [2] test data to estimate the annual performance of ICS and other types of SDHW systems. Their procedure is to first determine the parameters of a TRNSYS [3] simulation model which results in good agreement between the simulation and experimental data for a one-day test period. These parameters are then used in the FCHART 4 program [4] to estimate monthly and annual performance. While this procedure does offer a previously unavailable method of estimating long-term average ICS performance, it requires the use of a detailed simulation program and it applies the f-Chart correlation to a purpose for which it was not developed.

The California Energy Commission [5] has adopted an interim annual performance prediction method for ICS and thermosyphon SDHW systems. Experimental data have not been compared to these annual predictions.

Robison [6] of the Oregon Department of Energy (ODOE) has presented a performance prediction method which uses ASHRAE 95-1981 test results and a computer model of a SDHW system by Reichmuth and Robison [7]. The program does not model the transient operation of ICS systems, but may accurately portray daily performance under the draw pattern modeled.

Cummings and Clark [8] have developed a detailed transient model (including a thorough treatment of sky radiation effects) of ICS units in which the surface of the absorber tank(s) completely fill a flat glazing area. This model has been used by Panico and Clark [9] to develop a correlation of monthly solar fraction with two dimensionless parameter groups, dependent on the ICS system design. Methods of determining these parameters from short-term tests are not described. A similar correlation method has been developed by Tully [10].

Lindsay and Thomas [11] have developed a detailed transient model of a system with an internal optical system. Simulations using the model were successful in predicting tank temperatures under no-draw conditions. Because of its complexity, the model is not easily adaptable to other internal geometries.

This paper suggests the use of existing test procedures to obtain performance parameters useful for predicting long term performance. A transient model of an ICS system is developed for use with TRNSYS [3] program. Simulations using this model are compared with experimental data for validation. An analytical procedure is then presented based on results obtained with the simulation model, which uses experimentally determined parameters to obtain an estimate of ICS system monthly performance.

II Test Methods

Currently ICS systems can be tested for overall performance by the ASHRAE 95-1981 test procedure. This is a

three to five day indoor test in which the system is operated under solar, and environmental conditions specified by an association such as the Solar Rating and Certification Corporation (SRCC) [12] until a steady state daily energy delivery is reached. While the output of competing ·systems for identical operating conditions may be compared using these test results, they do not provide estimates of long term performance, nor are system parameters directly revealed with which long term performance may be estimated. A second part of the current testing is specified by SRCC and consists of a energy loss test. The ICS unit(s) is filled with hot water and allowed to cool down over a 16 hour period under constant ambient conditions without solar irradiation. This test can be used to calculate an effective energy loss coefficient per unit aperture area, U_L, from equation (1)

$$U_L = \frac{M_f c_P}{A_c \Delta \tau} \ln \left[\frac{T_i - T_a}{T_f - T_a} \right] \tag{1}$$

where M_f is the mass of water in the tank, c_p is the specific heat of water, A_c is the aperture area, T_i and T_f are the initial and final average tank water temperatures, and T_a is the ambient temperature. The ambient temperature used here is the measured air temperature. However, a portion of the losses are radiation losses to a sky temperature. The sky temperature indoors where the test is performed is $3°C$ to $6°C$ above ambient [13] as opposed to $5°C$ to $15°C$ below ambient for typical outdoor conditions. The controlled indoor testing may yield a repeatable determination of U_L, but an adjustment of either U_L or the ambient temperature to which losses occur should be applied in order to use this value of the parameter to predict outdoor performance as discussed in Section VI.

Recently Reichmuth and Robison of the Oregon Department of Energy (ODOE) proposed an alternative test procedure [7] consisting of two basic parts: an outdoor collection test and an outdoor heat loss test. For the collection test, the ICS unit is filled with water at some initial temperature T_i, and then subjected to solar radiation for five hours without water draw. The integrated solar radiation upon the plane of the collector during the five hour period and the average ambient temperature, $\bar{T}_a$, are measured. At the end of the five hour period the average water temperature is measured again. An environmental parameter suggested by Robison and Reichmuth [14] is

$$P_E = \frac{T_i - T_a}{\frac{1}{\Delta \tau} \int_{\Delta \tau} G_T d\tau} = \frac{\bar{T}_i - \bar{T}_a}{\bar{I}_T} \tag{2}$$

where G_T is the instantaneous solar radiation per unit area on a tilted surface, $\Delta \tau$ is the period of test, in this case five hours, and $\bar{I}_T$ is the average hourly irradiation for the test period.[1] The collection test is performed for a number of values of this parameter. It is suggested that a test be run in the morning and afternoon of at least 2 (better 3 or 4) days. Starting the test at different initial temperatures is one way to cover a range of values of P_E if the solar radiation remains nearly constant for each day of the test.

The energy loss test proposed by ODOE is similar to the SRCC energy loss test, except that it is performed outdoors at night. The average ambient temperature during the test period is used to compute U_L in equation (1). The outdoor test inherently includes the long wave radiation losses to the sky temperature. However, the value of U_L quoted from the test would be dependent on the extent of the sky temperature depression below ambient and the wind speed on the night of the energy loss test.

The ODOE test procedure may be thought of as an extension of the ASHRAE 93-77 [15] test of flat plate collectors. The major difference is that the test results are integrated over a five hour period. The high thermal capacity of ICS systems requires a longer test than the instantaneous efficiency measurements used in flat-plate collector testing.

During the ODOE collection test there is no water draw and an instantaneous energy balance may be written about the tank where the net collected energy increases the internal energy of the water in the tank:

$$M_f c_p \frac{dT_t}{d\tau} = A_c [G_T(\tau \alpha) - U_L(T_t - T_a)] \tag{3}$$

Here, M_f is the total mass of the fluid in the tank, $(\tau \alpha)$ is the effective transmittance-absorptance product, and T_t is the spatial average tank temperature.[2] The use of T_t, the spatial average tank water temperature, rather than an average absorber temperature in the loss term of equation (3), assumes that the absorber fin efficiency factor and absorber-water conductance are high. Alternatively, $(\tau \alpha)$ and U_L in equation (3) may be considered to incorporate F', the collector efficiency factor [16] which accounts for these factors.

Integrating equation (3) over a finite test period, $\Delta \tau$, (five hours in the case of the ODOE collection tests) results in

$$\Delta E = A_c [\bar{I}_T(\tilde{\tau \alpha}) - U_L(\bar{T}_t - \bar{T}_a)] \tag{4}$$

where the tildes over $(\tau \alpha)$, I_T, T_t, and T_a refer to the integrated average values over the test period. E is the change in internal energy over the test period and may be calculated from the measured initial and final average tank water temperatures and the thermal mass of the system:

$$\Delta E = M_f c_p (T_f - T_i) \tag{5}$$

A modified collector heat removal factor, F_R^*, may be defined as the ratio of the actual useful energy gain during a test period to the energy gain if the stored water were to remain at T_i, the temperature at the start of the collection test. That is,

$$F_R^* = \frac{M_f c_p (T_f - T_i)}{A_c [\bar{I}_T \Delta \tau (\tau \alpha) - U_L \Delta \tau (T_i - \bar{T}_a)]} \tag{6}$$

Equation (4) can then be expressed in a form analogous to the classical Hottel–Whillier equation [16].

$$\Delta E = F_R^* A_c [\bar{I}_T(\tau \alpha) - U_L(T_i - \bar{T}_a)] \tag{7}$$

The collection efficiency over the test period is then

$$\eta_{\text{coll}} = \frac{\Delta E}{A_c \bar{I}_T \Delta \tau} = F_R^*(\tilde{\tau \alpha}) - F_R^* U_L \left[\frac{T_i - \bar{T}_a}{\bar{I}_T} \right] \tag{8}$$

and

$$\eta_{\text{coll}} = \frac{M_f c_p (T_f - T_i)}{A_c \bar{I}_T \Delta \tau} \tag{9}$$

Equation (8) is analogous to the equation used in the ASHRAE 93-77 test of flat plate collectors and forms the basis of the ODOE collection test outlined in this section.

Experimental data from the ODOE collection tests may be used in a manner similar to the way ASHRAE 93-77 data are used. The energy gain during a test period divided by the integrated solar radiation incident on the collector area gives the collection efficiency. Robison and Reichmuth [14] find that an experimentally obtained line is nearly linear. If this is the case, the line will have a slope and intercept which yield values for $-F_R^* U_L$ and $F_R^*(\tilde{\tau \alpha})$ respectively, in accordance with equation (8).

III Model Description

A transient computer model of an ICS component was

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[1] Actually, Robison and Reichmuth suggested $P_E / \Delta \tau$ as the parameter.

[2] The net instantaneous collected energy in equation (3) may be negative, unlike a conventional flat-plate collector with a controller.
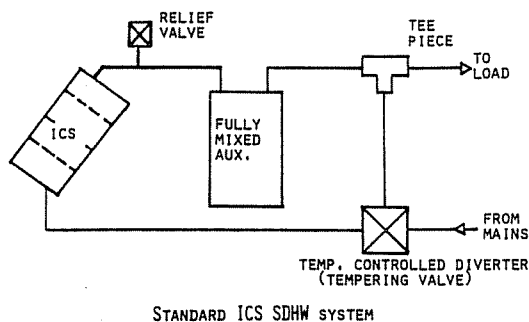
Fig. 1 Standard ICS SDHW system schematic

Fig. 2 14 day simulated and experimental tank and delivery temperatures

developed for use with the TRNSYS [3] simulation program. The system simulated represents the standard ICS SDHW system configuration as shown in Fig. 1. The ICS unit is installed in series with the conventional water heater as a preheater. A relief valve between the ICS unit and the auxiliary tank relieves steam from the system should it overheat. The auxiliary water heater is modeled as a fully mixed tank with a loss coefficient of zero. A tee-piece and a temperature controlled diverter form a tempering valve which operates whenever the water temperature from the auxiliary tank exceeds the set temperature.

Rather than attempt to compute the optical and thermal parameters via detailed analysis, the approach taken in the development of the model was to have the component described by (geometric) sizing parameters, an optical efficiency, $(\tau\alpha)$, and an energy loss coefficinet, U_L, assumed to be constant. Stratification is modelled by dividing the storage tank into a number of isothermal nodes. During each simulation timestep, an energy balance is solved at every node. As expressed in equation (10), the rate of change in internal energy of each node is equated to the solar gain, $\dot{S}$, less the rate of energy withdrawn and heat loss from the node:

$$\frac{M_f c_p}{N} \frac{dT_n}{d\tau} = \frac{\dot{S}}{N} + \dot{m}_D c_p (T_{n-1} - T_n) - \frac{A_c U_L}{N} (T_n - T_a) \quad (10)$$

The subscript n refers to the particular node in question, N refers to the total number of nodes and $\dot{m}_D$ is the draw flow rate through the ICS unit. The first node always receives water at mains temperature and the final node always represents the delivered water temperature (from the ICS unit to an auxiliary water heater). This model assumes the aperture area and the solar gain are equally divided among the nodes and also the effective loss coefficient per unit area, U_L, is the same for each node. The quantity $M_f c_p/N$ represents the thermal mass of the water in the node; the heat capacity of the ICS unit itself is neglected. The model neglects heat transfer between nodes when there is no load flow. $\dot{S}$, the instantaneous solar gain per unit area, is computed as

$$\dot{S} = A_c (\tau\alpha)_n K_{\tau\alpha} G_T \quad (11)$$

where $(\tau\alpha)_n$ is the transmittance-absorptance product at normal incidence (constant for a given system) and $K_{\tau\alpha}$ is an incidence angle modifier which can be computed from Fresnel's equations [16] or held constant.

TRNSYS simulations were compared with experimental data of ICS SDHW operation to verify that the simulation accurately represents the dynamic performance of an ICS system. Data on an experimental ICS SDHW system in Bozeman, Mont. [17] were obtained. Hourly solar radiation on a tilted surface, ambient temperature, ICS tank temperatures, inlet temperatures and delivery temperatures were recorded for the experimental system operated under a RAND [18] draw profile. Both U_L and $K_{\tau\alpha}$ were set to constant values in the simulation. Neither ASHRAE 95 nor ODOE test data were available for the particular ICS unit that was used in the experiment. The values of U_L and $(\widetilde{\tau\alpha})$ were obtained from an ASHRAE 95 test on a similar unit. A value of $(\widetilde{\tau\alpha})$ was also
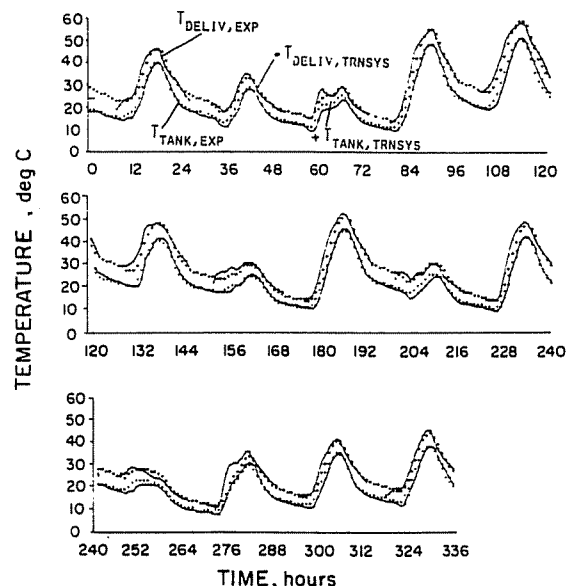
determined by trial and error which caused the delivered energy for a three day simulation to match the experimental delivered energy for the same three day period. The value of $(\widetilde{\tau\alpha})$ was 10 percent higher than that obtained from the ASHRAE 95 test. The parameters determined from the three-day simulation were then input to the model along with hourly climatic data for a two week period of a different month. A plot of simulated vs. experimental tank temperature and delivered water temperature is shown in Fig. 2. Table 1 shows the TRNSYS versus experimental delivered energy and average tank temperature for each day of the simulated period. The difference in delivered energy for the two week period is 2.6 percent. This comparison indicates that the simulation will accurately represent the performance of an ICS unit provided that correct values of U_L and $(\tau\alpha)_n K_{\tau\alpha}$ are input to the simulation.

IV   Analysis

The TRNSYS ICS model was first to investigate the linearity between the environmental parameter P_E, and the daytime collection efficiency that is necessary to obtain meaningful results from ODOE test procedure. Morning and
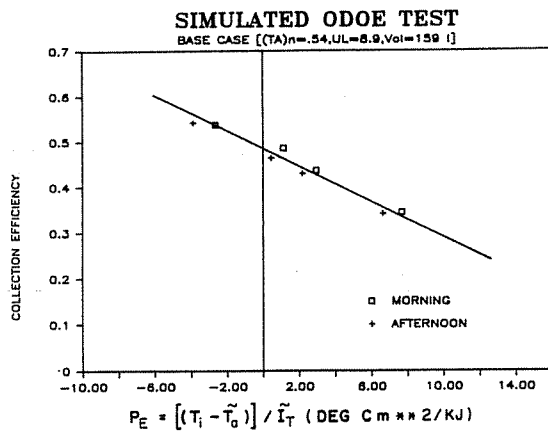
Table 1   Daily results of a 14 day simulation
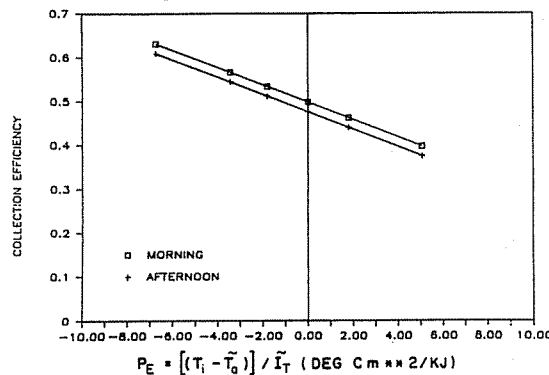
DAY	TIME	ENERGY DELIVERED (kJ)		AVERAGE TANK TEMP. (°C)	
		EXP	TRNSYS	EXP	TRNSYS
1	24	33,720	34,030	23.14	24.12
2	48	24,230	24,360	18.03	19.24
3	72	21,119	21,440	15.41	16.86
4	96	38,885	37,910	25.01	25.99
5	120	46,690	44,920	31.55	31.79
6	144	40,160	38,000	28.78	28.61
7	168	25,420	23,930	19.97	19.98
8	192	36,510	34,680	24.60	24.78
9	216	24,540	24,800	19.76	20.93
10	240	32,870	31,760	22.80	23.52
11	264	22,320	22,830	18.34	19.65
12	288	23,440	21,430	16.93	17.02
13	312	27,830	27,240	20.08	21.10
14	336	31,740	30,920	22.62	23.46
SUM	336	429,500	418,300	21.93	22.65

Fig. 3 Simulated ODOE test

$$P_E = [(T_i - \tilde{T}_a)] / \tilde{I}_T \text{ (DEG C m **2/KJ)}$$

MORNING
AFTERNOON

Fig. 4 Simulated ODOE test for symmetrical days

$$P_E = [(T_i - \tilde{T}_a)] / \tilde{I}_T \text{ (DEG C m **2/KJ)}$$

MORNING
AFTERNOON

Fig. 5 Difference between morning and afternoon tests

MORNING TEST   AFTERNOON TEST

G_T, $\dot{S}$, $\dot{Q}_{net}$, $\dot{Q}_{LOSS}$

kJ/hr

AM   PM

Fig. 6 Simulated ODOE tests varying tank capacity

$$P_E = [(T_i - \tilde{T}_a)] / \tilde{I}_T \text{ (DEG C m **2/KJ)}$$

$F_R^* = 1.$

Mf= 159 Kg (REF)
Mf=7900 Kg (RUN 5)
Mf= 32 Kg (RUN 6)
Mf= 790 Kg (RUN 7)
Mf=7900 Kg, K =1.0 const. (RUN 8)

afternoon five-hour tests from four different days of the typical meteorological year (TMY) [19] in Madison, Wis., were simulated, and the results plotted in Fig. 3. The results demonstrate the nearly linear relation suggested Robison and Reichmuth. After simulating the tests for the base case system, the transmittance-absorptance product at normal incidence, $(\tau\alpha)_n$, and the effective loss coefficient U_L were varied. Again, a linear relationship of efficiency to P_E was observed. As expected, the intercept increases with increasing $(\tau\alpha)_n$ and the magnitude of the slope increases with increasing U_L.

An obvious characteristic of the data shown in Fig. 3 is the separation of the morning and afternoon points which is due to an inherent characteristic of the test method. Figure 4 shows the results of simulated tests using days that were perfectly symmetrical with respect to irradiation, incidence angle, and temperature. These results show the afternoon tests always have a lower efficiency. Figure 5 helps to explain this effect. The absorbed energy at any instant is shown by the middle curve. The area under this curve represents the total absorbed solar energy without losses and is the same for both mornings and afternoons. The lowest curves in Fig. 5 show the losses during the morning and afternoon. The net collected energy is shown as the crosshatched area of the absorbed energy minus the losses. This area is greater for the morning than for the afternoon for the symmetrical day, and usually greater for typical days as well. It is therefore emphasized that the test be performed in both the morning hours and afternoon hours of each day it is tested to arrive at results that are applicable to diurnal operation.

Additional simulations of ODOE tests were run in which only the tank capacity was varied from system to system. The results of these tests are shown in Fig. 6. The separation between morning and afternoon results is directly affected by capacity changes. Systems with large thermal capacities per unit of collector area heat up less so losses become less significant (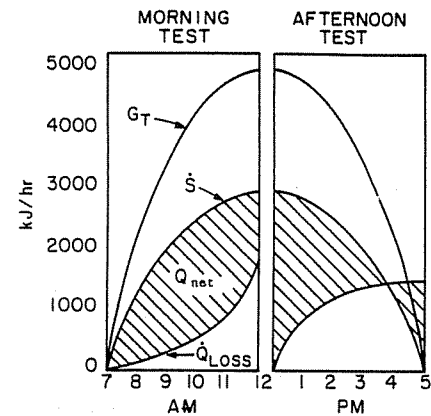assuming the ICS effective heat loss coefficient is independent of its capacity). Although the water temperature may not be raised significantly, the larger capacities result in a higher collection efficiency and a decrease in the morning and afternoon deviation of efficiency from the best fit line.

TRNSYS simulations were run to judge the sensitivity of monthly performance to a number of operating conditions. The effect of draw profile, thermal stratification, number of daily tank turnovers, transmittance-absorptance product, and loss coefficient were investigated. Seventy-two monthly solar fractions were obtained from yearly simulations in Madison, Wis., Seattle, Wash., and Albuquerque, N. Mex., using TMY hourly data, at a ratio of load flow to ICS tank capacity of 0.75 and 1.89. These base case simulations were run for a fully mixed (i.e., one node) ICS unit with a continuous draw load profile. The solar fraction from this fully mixed, continuous draw case is denoted $f_{m,c}$.

Six different daily draw profiles were examined for the fully mixed system. Each draw profile was simulated for the 72 months. The load profiles simulated include RAND, SRCC-200-82 (morning, noon and evening draws), afternoon weighted, evening, and dawn draw patterns. The last two patterns correspond to the best case and worst case, respectively. Except for the limiting cases, the monthly solar fraction of the different profiles matched the continuous draw quite well; this was especially true for the RAND profile. The upper and lower bounds of the draw profile effect on the fully mixed ICS are shown in Fig. 7. It appears that the performance of ICS systems is insensitive to load profile as found for active SDHW systems by Buckles and Klein [20] and Fisher and Fanny [21].

Various degrees of stratification were investigated. Maximum stratification was found to be adequately represented by 10 nodes. The effect on monthly solar fraction of this maximum stratification with the continuous draw profile (denoted $f_{s,c}$) is shown in Fig. 8. The other draw profiles respond in the same manner as the continuous draw
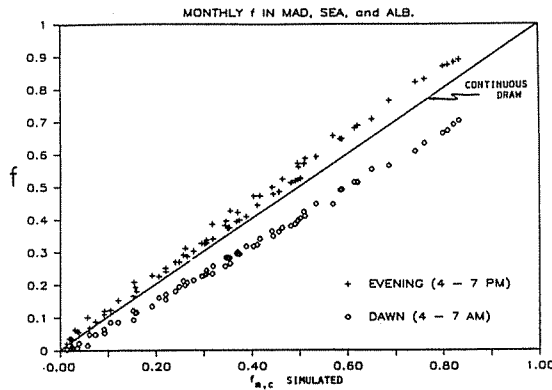
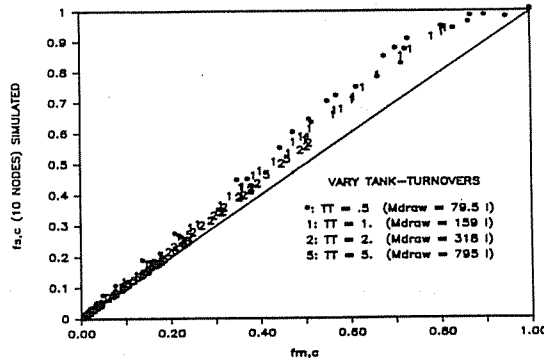**Fig. 7 Maximum effect of draw profile on $f_{m,c}$**

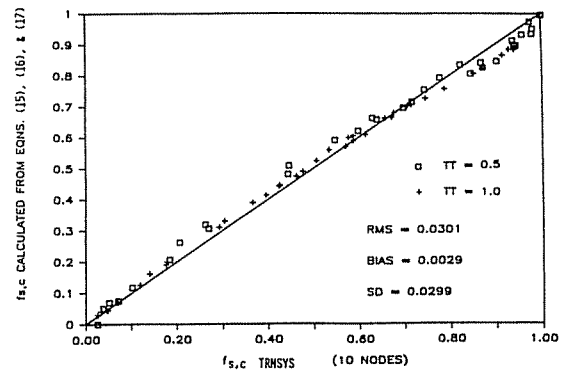**Fig. 8 Effect of stratification and load size on solar fraction**

Fig. 9 Calculated and simulated performance for stratified, continuous draw case

Here $\Delta\tau$ is the number of seconds or hours in the month and N is the number of days in the month, M_D is the mass of water withdrawn over the month, $\bar{H}_T$ is the monthly average daily solar radiation on a tilted surface, and the bars over other quantities indicate monthly average values.

For the fully mixed tank, if the condition of a continuous draw load profile is imposed, then the average draw temperature is equal to the average tank temperature i.e.,

$$\bar{T}_D = \bar{T}_t \qquad (14)$$

With this substitution, the monthly average draw temperature is

$$\bar{T}_D = \frac{\bar{H}_T N A_c\,(\overline{\tau\alpha}) + M_D c_p \bar{T}_m + U_L A_c \Delta\tau \bar{T}_a}{M_D c_p + U_L A_c \Delta\tau} \qquad (15)$$

A monthly solar fraction defined as the fraction of the load met by solar neglecting auxiliary jacket losses, is expressed as

$$f_{m,c} = \frac{(\bar{T}_D - \bar{T}_m)}{(T_s - \bar{T}_m)} \qquad (16)$$

The subscripts m and c represent a fully mixed system with continuous draw and T_s is the hot water set temperature.

Now consider the fully mixed restriction of equations (15) and (16). Figure 8 showed the increased performance due to stratification to be a function of solar fraction and the number of daily tank turnovers. Correlation of the increase in solar fraction due to stratification suggests a correction factor of the following form to account for stratification.

$$\frac{f_{s,c}}{f_{m,c}} = 1 + \frac{a}{TT}(1 - f_{m,c}) \qquad (17)$$

$f_{m,c}$ is computed via equations (15) and (16) and TT (tank turnovers) is the ratio of daily draw volume to ICS tank volume. The value of a in equation (17) depends on the number of nodes used in the model to simulate stratification. For a two-node model, a is 0.170. For ten-nodes (maximum stratification), a is 0.326. A comparison of $f_{s,c}$ predictions using equations (15), (16) and (17) to those obtained through computer simulation for 1.0 and 0.5 tank turnovers and 10 nodes is shown in Fig. 9.

The continuous draw profile restriction may be relaxed to include the RAND and SRCC profiles. As mentioned in the previous section, TRNSYS simulations showed a negligible difference in monthly solar fractions among these three profiles. However, if a draw profile is considerably weighted toward the evening or morning, then an increase or decrease in performance may be expected by as much as 15 percent, as shown in Fig. 7.

VI Obtaining Design Method Parameters From Test Data

The design method provides an estimate of the monthly

profile to maximum stratification, and again, the RAND profile points match those for the continuous draw exceptionally well. The extent to which stratification improves monthly performance increases with increasing solar fraction and as the ratio of daily tank turnovers decreases. Figure 8 shows the effect of stratification when compared to the fully mixed case for four different ratios of daily draw volume/ICS volume (tank turnovers denoted TT).

V Design Method for ICS Systems

The main objective of this study has been to produce a simple method for accurately predicting the long-term average performance of ICS systems. The following derivation is given to obtain a first approximation of the monthly solar fraction. The assumptions inherent in the derivation are pursued later in this section using the TRNSYS simulation results.

If a fully mixed ICS tank is considered, an instantaneous energy balance may be written about the tank which equates the change in tank internal energy with the absorbed solar radiation less losses to ambient and delivered warm water to the conventional water heater. The energy balance is expressed as

$$M_f c_p \frac{dT_t}{d\tau} = G_T A_c\,(\tau\alpha) - U_L A_c\,(T_t - T_a) - \dot{m}_D c_p\,(T_D - T_m) \qquad (12)$$

where $dT_t/d\tau$ is the instantaneous change in the tank average water temperature, T_D is the delivered water temperature from the ICS, T_m is mains water temperature and $\dot{m}_D$ is the instantaneous draw flow rate.

Integrating (12) over a month, the change in internal energy becomes small compared to the other terms. Thus,

$$0 \cong (\bar{H}_T N) A_c\,(\overline{\tau\alpha}) - U_L A_c \Delta\tau(\bar{T}_t - \bar{T}_a) - M_D c_P\,(\bar{T}_D - \bar{T}_m) \qquad (13)$$

fraction of the load met by the ICS system through equations (15), (16) and (17). To apply these equations, values of $(\overline{\tau\alpha})$, U_L, and n, the number of nodes needed to simulate stratification effects, must be supplied. In this section, it is shown that appropriate values of these parameters can be obtained from existing test methods.

Both the ASHRAE 95-1981 procedure (under SRCC test conditions) and ODOE test methods include an energy loss test. An estimate of U_L can be obtained from either of these tests using equation (1). If the energy loss test is done indoors, then the radiant sink temperature does not reflect sky temperature as would be the case in actual application. Cummings and Clark [22] report that omission of the sky temperature depression effects may lead to overestimations of about 15 percent in winter months in cold climates. In order to correct for a sky temperature below the ambient, an effective sink temperature, T_e, can replace $\bar{T}_a$ in equation (15) to account for both convective and radiative losses. The effective temperature depends primarily on the ambient and sky temperatures, but in general, it will also depend on the wind speed, ground temperature and collector tilt. Following Cooper [23], it is suggested that a value of 1/4 of the monthly average sky temperature depression be subtracted from the monthly average ambient temperature to obtain an appropriate T_e with which to replace $\bar{T}_a$ in equation (15). The manner in which $(\overline{\tau\alpha})$ is found differs for the two test methods.

A test result from the ASHRAE 95-1981 test is QNET, the daily energy delivered by the tested solar system once a steady state daily energy delivery has been reached. A daily solar fraction can be defined

$$f_{s,c} = \frac{QNET}{\text{daily load}} \tag{18}$$

where the daily load is the energy required each day during the test. (It is shown in Fig. 7 that the continuous draw profile adequately approximates the SRCC draw profile. This is implied by the subscripted c in equation (18)). Using this value of $f_{s,c}$ an estimate of $(\bar{\tau}\bar{\alpha})$ can be found by solving equations (15), (16) and (17) in reverse, which results in

$$f_{m,c} = \frac{(1+A) \pm \sqrt{(1+A)^2 - 4Af_{s,c}}}{2A} \tag{19}$$

$$\bar{T}_D = f_{m,c}(T_s - \bar{T}_m) + \bar{T}_m \tag{20}$$

$$(\widetilde{\tau\alpha}) = \frac{\bar{T}_D[M_D C_P + U_L A_C \Delta\tau] - M_D C_P \bar{T}_m - U_L A_C \bar{T}_a \Delta\tau}{H_T N A c} \tag{21}$$

where $A = a/TT$, $\Delta\tau = 24$ hours, $N = 1$ day, and H_T is the daily solar radiation during the test. The tildes (¯) indicate average values over the test period. The daily solar fraction from the ASHRAE test is obtained under steady-state conditions. The $\Delta E = 0$ approximately made in equation (13) is valid for the final test day of the ASHRAE test also because there is no change in internal energy over a day once the system performance has converged. The average value of the transmittance-absorptance product obtained for the test day, $(\bar{\tau}\bar{\alpha})$, incorporates an average incidence angle modifier representative of the test conditions. A method of estimating the monthly average incidence angle modifier, $(\overline{\tau\alpha})$, can then be obtained by the method given by Klein [24].

$(\bar{\tau}\bar{\alpha})$ is obtained more simply from the ODOE test. A straight line through the test data yields $F_R^*(\bar{\tau}\bar{\alpha})$ and $-F_R^* U_L$ as the intercept and slope, respectively. U_L is found from the energy loss test, which allows F_R^* and thus $(\bar{\tau}\bar{\alpha})$ to be calculated.

The ICS simulation model was used to investigate the accuracy in which $(\overline{\tau\alpha})$ can be determined from test results. Simulations of the ASHRAE 95-1981 and ODOE tests were run for a number of ICS systems with constant values of U_L
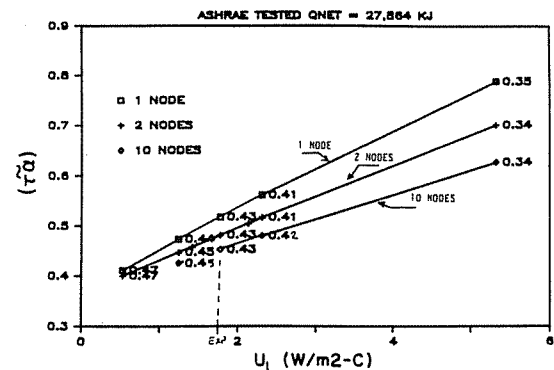

Fig. 10 Parameter sets which result in QNET = 27,860 kJ and corresponding annual solar fractions

and $K_{\tau\alpha}$. The simulated test results were used to determine $(\overline{\tau\alpha})$ in the manner just described. The value of $(\overline{\tau\alpha})$ obtained in this manner compared in all cases to the known value input to the simulation model within 1.5 percent [25]. In addition, it was found that number of nodes had no bearing on the use of the ODOE tests to determine $(\overline{\tau\alpha})$. There is no draw during an ODOE collection test and therefore no draw induced stratification. The results of the ODOE test of the system modeled with 10 nodes were the same as the system modeled with 1 node.

The remaining topics which need to be addressed are the sensitivity of annual performance estimates to uncertainty in the value of U_L and the degree of stratification. An ASHRAE 95-1981 test may be performed which gives the daily energy delivery QNET. If the degree of stratification is known, and U_L is determined from an energy loss test, then there is a unique value of $(\overline{\tau\alpha})$ which leads to this value of QNET. With a different value of U_L, another value of $(\overline{\tau\alpha})$ would lead to the same value of QNET. Because there is uncertainty in the experimentally determined value of U_L, it is of interest to determine whether different pairs of $(\overline{\tau\alpha})$ and U_L which lead to the same value of QNET, would lead to the same long term performance. To address this question, a system was selected which had the actual ASHRAE 95-1981 test and the SRCC energy loss test performed by DSET Laboratories with the results published by SRCC [26]. The tested system consisted of two ICS units with $A_c = 4.5\text{m}^2$, $M_f = 276$, $U_L = 1.77$ W/m²-C. From the test results, QNET = 27,864 kJ. The system was then modeled with 2 nodes, but the appropriate $(\tau\alpha)$ was unknown. The ASHRAE 95 test was simulated under the SRCC specified operating conditions with different values of $(\tau\alpha)$. A trial and error procedure was followed until the value of $(\tau\alpha)$ was chosen which gave the same value of QNET from the simulated test as from the actual test. Six other values of U_L were chosen that were related to the reference loss coefficient by factors, 0.3, 0.7, 0.8, 1.2, 1.3, 3.0. The same trial and error procedure was followed for each value of U_L to get corresponding values of $(\tau\alpha)$ which led to the simulated ASHRAE test to QNET = 27,864 kJ. This process was repeated for 10 nodes and for one node representing stratification. The pairs of $(\tau\alpha)$ and U_L which give the identical ASHRAE test result, QNET, are plotted in Fig. 10.

Next, annual simulations were run to determine if these pairs of parameters that gave the same ASHRAE test result would give the same yearly performance. The annual simulations used hourly TMY data for Madison, Wis., in 1/4 hour timesteps with a daily load of 300 l/day and a continuous draw load profile. The ICS component was modeled with 1, 2 and 10 nodes, as appropriate for the pairs of parameters from Fig. 10. The annual solar fractions from these simulations are shown in Fig. 10 next to the appropriate pairs of points. A major conclusion based on these results is estimated annual performance in insensitive to errors in U_L and $(\overline{\tau\alpha})$. If there is a 30 percent error in the experimental

determination of U_L, but $(\overline{\tau\alpha})$ is determined so as to achieve the experimental value of QNET in a simulated ASHRAE 95 test, then $(\overline{\tau\alpha})$ will have compensated for most of the error in U_L. The difference in annual performance with these parameter values was found to be less than 5 percent from what it would be with the correct parameters.

Performance is increased with greater stratification. For two systems with a given U_L, if the same performance is to be reached with a high and a low degree of stratification, the system with higher degree of stratification has a lower $(\overline{\tau\alpha})$. This is apparent in Fig. 10 by the locus of points for 10 nodes plotted below the locus for 2 nodes plotted below the locus for 1 node. For a given number of nodes, and a given QNET, Fig. 10 shows the curve of $(\overline{\tau\alpha})$ versus U_L is nearly linear. Other lines drawn for system modeled with a different number of nodes will have different slopes, but all these lines must converge at $U_L = 0$, where stratification adds no benefit. Most significant, however, is the insensitivity of annual performance estimates to the degree of stratification. For a given value of U_L, there is less than a 1 percent difference between the annual solar fraction obtained from the 2-node model with $(\overline{\tau\alpha})$ obtained for 2 nodes and the 10 node model with $(\overline{\tau\alpha})$ obtained for 10 nodes. In fact there is less than a 1 1/2 percent difference in solar fraction with any assumed degree of stratification. This observation can ease concern of what is an appropriate number of nodes to assume for a system. If the long term performance of a system is to be predicted, Fig. 10 implies that it would not matter how many nodes are assumed. It is only important that the same number of nodes be selected for obtaining $(\overline{\tau\alpha})$ from the ASHRAE 95 test as is selected when using equation (17) in the prediction method. If the same number of nodes is chosen for both calculations, Fig. 10 indicates performance predictions would agree regardless of this choice.

The ODOE test does not yield information on stratification. Consequently, in order to use the parameters estimated from this test to predict long-term performance, an assumption must be made concerning the number of nodes necessary to model the draw-induced stratification.

VII Conclusions

A simple method of estimating the monthly performance of integral collection-storage SDHW systems has been developed. The method used parameters that are obtained from either the ASHRAE 95-1981/SRCC 200-82 or the ODOE test methods. A sample calculation is given in the Appendix.

An evening or morning-weighted draw pattern can effect performance by up to 20 percent. However, performance is insensitive to draw patterns which are not heavily weighted toward morning or evening. The RAND and SRCC draw patterns show nearly identical annual performance.

Uncertainty exists in the test parameters, U_L and $(\overline{\tau\alpha})$, and also in the degree of stratification. The ODOE test does not reveal any information concerning draw-induced stratification, since no water is drawn during the test period. A two-node model of stratication is recommended in this case for the annual performance calculations. For the ASHRAE test, it is shown that the sensitivity of annual performance estimates to uncertainties in U_L and degree of stratification is small when $(\overline{\tau\alpha})$ is obtained from the test data using the same U_L and number of nodes as employed in the annual performance calculation.

The performance prediction methodology has been developed from computer simulations. Experimental measurements of the long-term performance of ICS systems along with corresponding climate data and test results are needed to fully validate this methodology.

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APPENDIX

Sample Calculation of Monthly Performance

Given:

$\bar{H}_T = 18.9 \, \text{MJ/m**2}$

$N = 30 \, \text{days}$

$A_c = 2.07$ m**2 (Cover area to which U_L is referenced)
$(\overline{\tau\alpha}) = 0.54$
$U_L A_c = 4.26$ W/C $= 15.33$ kJ/hrC
$M_f = 159$ l (Internal storage capacity)
$M_D = 300$ l/day $\times$ 30 days $= 9000$ kg
$c_p = 4.19$ kJ/kg°C
$\overline{T}_m = 10$°C $= 283$K
$T_s = 50$°C $= 323$K
$\overline{T}_a = 19$°C $= 292$K
$\overline{T}_{sky} = 7$°C $= 280$K
$\Delta\tau = 24$ hrs $\times$ 30 days $= 720$ hrs

Determine an effective sink temperature as

$$T_e = \overline{T}_a - 1/4(\overline{T}_a - \overline{T}_{sky})$$

$$= 19 - 1/4(19 - 7) = 16°C = 289K$$

The monthly average draw temperature is obtained from (15) using T_e:

$$\overline{T}_D = \frac{18.9E3(30)(0.54)(2.07) + (9000)(4.19)(283) + (15.33)(720)(289)}{(9000)(4.19) + (15.33)(720)}$$

$$= 297K = 24.4°C$$

The first approximation of monthly solar fraction is then obtained from equation (16):

$$f_{m,c} = \frac{(9000)(4.19)(24.4 - 10)}{(9000)(4.19)(50 - 10)} = 0.359$$

Determine the number of tank turnovers per day.

$$TT = 300 \,(1/day)/159(l) = 1.89 \text{ day}^{-1}$$

Now use equation (17) to correct for stratification.

$$f_{s,c} = 0.359\left[1 + \frac{0.326}{1.89}(1 - 0.359)\right] = 0.399$$

While this value of $f_{s,c}$ is useful for comparing design methods, or systems themselves, a useful way of defining solar fraction includes auxiliary tank jacket losses, i.e.

$$f = \frac{Q_{col}}{L + L_o}$$

where Q_{col} is the thermal energy provided by solar, L is the monthly load, and L_o is the monthly auxiliary jacket loss given by

$$L_o = (UA)_{aux}\Delta\tau(T_s - T_{env})$$

If $(UA)_{aux}$ is 4.0 W/C $= 14.4$ kJ/hr°C and the environmental temperature is $T_{env} = 20$°C, then

$L_o = 14.4 \,(720)(50 - 20) = 311E3$ kJ/month

$L = (9000)(4.19)(50 - 10) = 1.51E6$ kJ/month

and

$$f = \frac{Q_{col}}{L + L_o} = \frac{(f_{s,c} - L_o/L)L + L_o}{L + L_o}$$

$$= \frac{(0.399 - 311E3/1.51E6)1.51E6 + 311E3}{1.51E6 + 311E3} = 0.331$$