DE/SF-16306-44
RECEIVED

DEC 27 1994

OSTI

**COLORADO STATE UNIVERSITY PROGRAM FOR
DEVELOPING, TESTING, EVALUATING
AND OPTIMIZING
SOLAR HEATING AND COOLING SYSTEMS**

**PROJECT STATUS REPORT FOR THE MONTHS OF
OCTOBER AND NOVEMBER, 1994**

Prepared for the

**U.S. Department of Energy
Conservation and Renewable Energy
Under Grant DE-FG36-86SF16306**

Submitted by

**SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY**

December 1994

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

for

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

RATING AND CERTIFICATION OF DOMESTIC WATER HEATING SYSTEMS

October/November 1994

Current work on this project has been to validate the Florida Solar Energy Center's (FSEC) models of the Solahart 302K and 302K-AS systems to prepare a rating for the Sacramento Municipal Utility District's rebate program for solar domestic hot water heaters. A preliminary rating has been issued by FSEC and updated ratings will be released as necessary. Two of the problems that were mentioned in the August/September report are addressed and a tank heat loss test is discussed. Work continues on improving and validating the models.

Energy Discrepancies

Discrepancies were found when running the same TRNSYS code on two machines. This was noticed when energy values from FSEC (running on a PC) and energy values from CSU (running on a unix system) did not agree. This problem arose from an undiscovered discrepancy between the two versions of the fortran code for the Type 45 Thermosyphon. One command in FSEC's version of the code was in the wrong column, but neither compiler caught the error. Energy comparisons using the same decks are now much better as the table below shows using an OG300 rating deck for the single tank system (302K). Comparisons are between FSEC and CSU using a PC (values agree exactly) and CSU using a unix compiler.

	Auxiliary Energy Required (kJ)	Energy Saved (kJ)
UNIX - CSU	19395	30036
PC - FSEC/CSU	19378	30053
Percent Difference (%)	0.09	0.06

The remaining discrepancies are very small, but still puzzling. The discrepancies could possibly be resolved by forcing all numbers to double precision when compiling the code. This would require some code modification, but will be looked into if the discrepancies become relevant.

Model Instability

A model instability was observed when adjusting the model to match a physical data set. The models are adjusted by multiplying a collector parameter ($F_R U_L$) by a constant so that the physical result can be matched by the TRNSYS result. As this 'knob' is adjusted,

energy values become unstable and energy imbalances calculated in the TRNSYS decks increase.

The most recent decks do not exhibit this instability in the ranges that they have been tested. However, an instability may still exist and is a potential problem.

Storage Tank Overall Heat Transfer Coefficient Test

A test was run using TRNSYS to see if the physical UA test for the Solahart storage tank described in previous work [Bickford, 1994] could be duplicated. If parameters that are identical to the actual test are input into TRNSYS, TRNSYS should duplicate the actual average tank temperature profile, and thus the UA value of the tank. This is a simple check to see that TRNSYS is doing what is expected and to see if the input decks use parameters correctly.

First, two corrections were made to the calculated experimental UA value. The previous value [Bickford, 1994] was calculated based upon the ambient temperature as a function of time and on water properties (density and specific heat) at the average tank water temperature over the entire test. There are two problems associated with this method. The first is that, in using the fitted slope of a $\ln(\Delta T/\Delta T_o)$ versus time plot to calculate the UA value, an assumption is made that the ambient temperature is constant [Solar Energy Applications Laboratory, 1994], thus the average ambient temperature over the entire test should be used. As the standard deviation of the ambient temperature over the 23 hour test was only 0.3 °C, the correction made here was small. However, had the ambient temperature fluctuated more, the error could have been more significant.

The second correction that was made arises due to the fact that TRNSYS uses only constant fluid property values (except in a limited number of calculations where property fluctuations drive the flow). As a result of this, property values must be selected and used universally in the calculation of numbers that are passed to TRNSYS as system parameters (such as UA_{tank}). The values used in the previous Solahart decks are different from those that were used in calculating the UA value [Bickford, 1994]. The property values for water selected to be used in the corrected UA calculation are those typically used in TRNSYS models:

Density:	$\rho = 1000$	kg/m ³
Specific Heat:	$C_p = 4.1867$	kJ/kg-K

With these corrections applied, the experimental UA value becomes 3.04 W/°C, which is different from the original calculation of 2.90 W/°C by about five percent.

The results above, along with the average ambient temperature, are then entered into a TRNSYS deck to simulate the experimental heat loss test. A plot of $\ln(\Delta T/\Delta T_o)$ versus time is made and the corresponding UA value of the tank is calculated from the slope of a line fitted to this data. Figure 1 shows both the experimental and TRNSYS data.

The TRNSYS result for UA_{tank} is 2.99 W/°C which is less than two percent different from the corrected experimental value of 3.04 W/°C. The final average tank temperature predicted by the TRNSYS model is 51.2 °C which is very close to the actual average temperature of 51.1 °C. Use of the previous UA_{tank} value of 2.90 W/°C results in a final average tank temperature prediction of 51.6 °C. Although the error associated with the recalculated UA value is relatively small in this case, it illustrates that fluid properties and system parameters that are passed to TRNSYS must be used carefully.

References:

Bickford, C., "Short Term Performance Comparison Between A Solar Thermosyphon Water Heater and Two Numerical Simulations," M. S. Thesis, Colorado State University, Fort Collins, CO, 1994.

Solar Energy Applications Laboratory, "Unique Solar System Components - Determination of the Tank Heat Loss Coefficient, U_{solar} ," *Colorado State University Program for Developing, Testing, Evaluating, and Optimizing Solar Heating and Cooling Systems - Project Status Report for the Months of June and July, 1994*, U.S. DOE grant DE-FG36-86SF16306 report, 1994.

Figure 1

UNIQUE SOLAR SYSTEM COMPONENTS

INTEGRATED TANK/HEAT EXCHANGER MODELING/EXPERIMENTS

The results of seven heat loss tests are summarized and recommendations are made for change the heat loss parameters used to model this tank for the SRCC ratings program. Preliminary results of additional constant temperature heat input tests are also reported.

Results of Additional Heat Loss Tests

Seven 24 hour heat loss tests have been performed on our 80 gallon Rheem wrap-around heat exchanger tank. Table 1 summarizes the results of these tests. The procedure for reducing the experimental data is described in detail in the June/July 1994 Progress Report. The results are presented in both SI units and I-P units for convenience.

Test 1 (0419_0) is the original heat loss test reported in the June/July 1994 progress report.

Table 1. Results of heat loss tests on the CSU 80 gallon Rheem wrap-around heat exchanger tank

		$-\left(\frac{UA}{MC_p}\right) = \text{slope} \left(\ln \left(\frac{\Delta T}{\Delta T_0} \right) \text{ vs. } t \right)$				$UA = -\frac{MC_p}{\Delta t} \cdot \ln \left(\frac{\Delta T_{\text{final}}}{\Delta T_{\text{initial}}} \right)$		
Test		Slope	UA	U	R=2/U	UA	U	R=2/U
		$\frac{1}{\text{sec}}$	$\frac{W}{K}$	$\frac{W}{m^2 \cdot K}$	$\frac{m^2 \cdot K}{W}$	$\frac{W}{K}$	$\frac{W}{m^2 \cdot K}$	$\frac{m^2 \cdot K}{W}$
1	0419_0	-3.22E-06	3.747	1.444	1.385	3.688	1.422	1.407
2	1118_0	-3.15E-06	3.67	1.415	1.414	3.635	1.401	1.427
3	1020_0	-2.97E-06	3.454	1.331	1.502	3.4	1.31	1.526
4	1120_0	-3.05E-06	3.548	1.368	1.462	3.558	1.371	1.458
5	1204_0	-3.04E-06	3.539	1.364	1.466	3.514	1.354	1.477
6	1207_0	-3.21E-06	3.73	1.438	1.391	3.822	1.473	1.358
7	1212_0	-2.65E-06	3.090	1.191	1.679	3.056	1.178	1.698

Test		Slope	UA	U	R=2/U	UA	U	R=2/U
		$\frac{1}{\text{sec}}$	$\frac{\text{Btu}}{\text{hr} \cdot \text{F}}$	$\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}$	$\frac{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}{\text{Btu}}$	$\frac{\text{Btu}}{\text{hr} \cdot \text{F}}$	$\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}$	$\frac{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}{\text{Btu}}$
1	0419_0	-3.22E-06	7.103	0.254	7.863	6.991	0.25	7.988
2	1118_0	-3.15E-06	6.957	0.249	8.028	6.891	0.247	8.105
3	1020_0	-2.97E-06	6.548	0.234	8.53	6.445	0.231	8.665
4	1120_0	-3.05E-06	6.726	0.241	8.304	6.745	0.242	8.28
5	1204_0	-3.04E-06	6.709	0.24	8.325	6.662	0.239	8.384
6	1207_0	-3.21E-06	7.072	0.253	7.898	7.245	0.259	7.709
7	1212_0	-2.65E-06	5.858	0.210	9.534	5.794	0.207	9.640

The values in Table 1 have been updated to reflect changes made to the parameter inputs to the model (reference the Aug/Sep Progress Report). Test 2 (1118_0) is a repeat the original heat loss test to confirm the original results. Tests 3 and 4 (1020_0 and 1120_0) were run with the tank as isolated as possible from the system piping in order to determine the influence of the system piping on the measured loss characteristics of the tank. In test 5 (1204_0), the insulation on the system piping was inspected and beefed up in several locations to reduce the chances on an unaccounted for thermal short. In Test 6, the cold side supply piping was flushed with mains temperature water at the beginning of the test to investigate the influence of the initial temperature of the water remaining in the system piping on the measured loss coefficient of the tank. Finally, in Test 7, all of the system piping was disconnected (except for the tank relief valve) and the ports were capped and insulated. This test is a reproduction of the results of two tank loss tests reported by Steven Long of FSEC.

Figures 1 through 7 are plots of the experimental results showing a summary of the variation of the tank and environment temperatures and a linear fit to the data.

The calculated results in Table 1 depend on the values of four parameters, the density and specific heat of water, and the volume and height of the storage tank. As discussed in the June/July progress report, the parameter values that will be specified to the TRNSYS model must be used to reduce the experimental results to insure that TRNSYS will reproduce the experimental results. The following values are being used in the CSU TRNSYS simulations. NOTE: THE RESULTS OF TABLE 1 MUST BE MODIFIED TO REFLECT ANY CHANGES MADE TO THESE FOUR TRNSYS PARAMETERS.

$$\begin{aligned}\rho &= 1000 \text{ kg/m}^3 = 62.428 \text{ lbm/ft}^3 \\ C_p &= 4.1867 \text{ kJ/kg-K} = 1.0 \text{ Btu/lbm-F} \\ V &= 0.278 \text{ m}^3 = 278 \text{ l} = 73.44 \text{ gal} \\ h &= 1.3716 \text{ m} = 54 \text{ in}\end{aligned}$$

The values for the density and specific heat of water are standard for the SRCC/SMUD TRNSYS decks. The height and diameter of the inside of our 80 gallon Rheem tank were measured to be 54 inches (1.3716m) and 20 inches (0.508m) respectively, see Figure 8. These measurements should be accurate to within 1/4 inch. The volume was calculated from these values assuming a cylindrical tank. TRNSYS calculates the surface area of the tank as,

$$A = \sqrt{\frac{4\pi V}{\pi h}} \cdot h + 2 \frac{V}{h} = 2.5943 \text{ m}^2 = 27.9253 \text{ ft}^2.$$

TRNSYS calculates the capacitance of the tank as,

$$MC_p = \rho VC_p = 1.1639 \times 10^6 \text{ J / K} = 612.903 \text{ Btu / F}.$$

Figure 9 shows a schematic of the 80 gallon Rheem tank installed on our test stand. The values are numbered to make the procedure used for these tests clearer. At the start of the each test, values V1, V4, V6, V8, and V12 are open. All other valves are closed (V15, the three-way is in the bypass position). The cold water circulation pump and the resistance heaters in both cold water tanks and the Rheem tank are enabled and water is circulated until the water in the

Rheem tank reaches a uniform temperature of approximately 60°C (50°C for Test 1). The heaters and pump are disabled, the data acquisition system is enabled, and the tank is allowed to cool for 24 hours. For Test 1 and 2, the position of the valves were not changed at the beginning of the run. For Tests 3-5, valves V8 and V12 were closed (V9, V10, and V11 were already closed) at the start of the run. The water in the inlet and outlet plumbing starts at the same temperature as the tank for test 1-5. In Test 6, at the before the beginning of the test, valve V8 was closed and valves V9, V10, V12, and V5 were opened to flush the supply piping with mains temperature water. All of the system piping on both the collector and cold water sides of the tank was remove at the beginning of Test 7. The fittings were capped an insulated.

On the inlet side of the tank, starting at the tank, the piping has a 4 inch rise, an elbow, a 8 inch horizontal section, an elbow, and then an 18 inch rise. Valve V3 and the check valve stop any natural convection circulation beyond this point. With valve V8 closed, the piping open to the tank is limited to the 4 inch vertical section and the 8 inch horizontal section. On the outlet side, the plumbing is identical with the addition of a 48 inch horizontal section (to valves V10, V11, and V12) at the top of the 18 inch vertical section. The expansion tank shown in Figure 9 is located below this horizontal section.

All of the pipe is 3/4 inch cooper with 3/4 inch wall polyethylene therma-cel insulation. The insulation is installed with mitered corners to insure uniform coverage. Larger diameter insulation is used where necessary to cover valves and other fittings. The valve stems and handles do extend through the insulation.

On the collector side of the tank, the three way valve, V15, is close coupled to the heat exchanger inlet, and in the bypass position does not allow any natural convection circulation. At the outlet of the heat exchanger, a check valve prevents natural convection circulation. All of the collector side plumbing is well insulated. The heat exchanger remained full of water for all of these tests.

The tank is sitting directly on the floor in the basement of Solar House II. The floor is tile on concrete coupled to the ground.

The results of Test 2 confirms the results of Test 1. We feel confident that they represent the loss characteristics of the CSU tank as installed. The tank losses are reduced only slightly in Tests 3, 4, and 5 with values V8 and V12 are closed. Test 5 did not identify any large holes in the piping insulation. Test 6 results are consistent with the results of Tests 1 and 2. This result should be expected for our tank. The mass of water remaining in the system piping coupled to the tank is small and will be quickly heated to the temperature of the tank (due to natural convection mixing resulting from the unstable temperature stratification).

The results of Test 7 show the only significant departure from the UA values first reported. The total UA calculated from Test 7 is 5.86 compared to 7.10 in Test 1. Clearly, buoyancy driven circulation of tank water into the system piping does increase the tank losses. This loss is, however characteristic of all installed storage tanks.

The results of Test 7 are much closer to the values of 5.03 and 5.27 reported by FSEC for similar tests. Note, the FSEC results were calculated with a slightly smaller tank volume of 72

gallons (approximately). When adjusted to a volume of 73.44 gal. the FSEC numbers become 5.14 and 5.38 respectively. Once again, the UA values used must be consistent with the four TRNSYS parameters, density, specific heat, volume of the tank, and height of the tank.

All of the measured UA values reported by CSU and by FSEC are larger than the nominal value currently in use in the SRCC ratings programs. This result is not surprising. Rheem's nominal value of R-16.7 corresponds to a uniform 2 inch thickness of R-Foam (polyurethane foam) insulation. On this tank, however, the insulation on the lower half of the tank is displaced by the heat exchanger coils. The insulation on this half is only 1.375 inches thick which corresponds to an R-value of 11.5 ($16.7 \times 1.375 / 2.0$). This may explain the larger than normal difference between the nominal value of UA that calculated from Rheem's specifications and the values measured at CSU and at FSEC.

Potential Errors in the Nominal Test Loss Coefficient in use for the SRCC Ratings Program

The nominal UA from Rheem's specification of R-16.7 insulation and advertised dimensions of the outside surface of the tank, $h = 85.625$ in and $d = 24.4375$ in. is

$$UA_{\text{nomial}} = \frac{A}{R} = \frac{\pi dh + 2 \frac{\pi d^2}{4}}{R} = \frac{37.77 \text{ft}^2}{16.7 \frac{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}{\text{Btu}}} = 2.26 \frac{\text{Btu}}{\text{hr} \cdot \text{F}}$$

In order for TRNSYS to calculate an identical UA with the tank volume specified as 80 gallons (0.3028m^3) and the tank height as 85.625 in (1.489m), you would have to specify a U-value of

$$U_{\text{tnsys}} = \frac{UA_{\text{nomial}}}{A_{\text{tnsys}}} = \frac{UA_{\text{nomial}}}{\sqrt{\frac{4\pi V}{h}}h + 2 \frac{V}{h}} = \frac{2.26 \frac{\text{Btu}}{\text{hr} \cdot \text{F}}}{30.0 \text{ft}^2} = 7.53 \times 10^{-2} \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}$$

which corresponds to an R-value of $13.27 \text{ hr} \cdot \text{ft}^2 \cdot \text{F} / \text{Btu}$. TRNSYS would then calculate a total UA of $2.26 \text{ Btu/hr} \cdot \text{F}$.

The value currently in use for the SRCC ratings program is calculated by halving Rheem's nominal R-value. For the same tank parameters (volume of 80 gallons and tank height of 85.625 in), TRNSYS calculates a UA of

$$UA_{\text{nomial}} = \frac{\sqrt{\frac{4\pi V}{h}}h + 2 \frac{V}{h}}{\frac{R_{\text{nomial}}}{2}} = \frac{30.0 \text{ft}^2}{16.7 \frac{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}{\text{Btu}} \cdot \frac{1}{2}} = 3.59 \frac{\text{Btu}}{\text{hr} \cdot \text{F}}$$

If the intent is to double the Rheem nominal UA to 4.52 Btu/hr-F for the SRCC ratings program, then an R-value of 6.637 hr-ft²-F/Btu should be to TRNSYS (R-value = 13.27 hr-ft²-F/Btu divided by 2 in the deck). If the TRNSYS tank geometric parameters are changed to V=73.44 gallons and h=54 inches, TRNSYS calculates an area of 27.9253 ft² and the required R-value becomes 6.17 hr-ft²-F/Btu (12.35/2).

The UA results in Table 1 are appropriate for use with the V=73.44 gallons and h=54 inches dimensions. If other dimensions are used, they should be corrected also.

Additional Constant Temperature Tests

Table 2 compares the average log-mean temperature difference, ΔT_{lm} , and effective overall heat exchanger conductance, UA_{hx} , determined from experiment to those predicted by TRNSYS simulation for the seven combinations of Q_{input} and $\dot{V}_{coll}$.. This table has been updated (from the last progress report) to reflect changes in reduction of the data and the updated model parameters outlined in the Aug/Sep 1994 Progress Report. The results are presented in no particular order

A potential instrumentation error has been identified. The instrument zero (at no flow) of the collector turbine flow meter has been drifting with changes in the room temperature from day to day. A preliminary look at the error caused by this zero drift suggests that the error is small in most cases. The error is correctable from the recorded data and a complete correction of the data set is in progress. Model normalization to the full data set will not be reported until the experimental results have been corrected.

Table 2. Comparison of measured and predicted values of log-mean temperature difference and effective heat exchanger conductance.

Test	Q_{input} W	Flow Rate lpm	Flow Rate gpm	Experiment		TRNSYS	
				ΔT_{lm} K	UA_{hx} kW/K	ΔT_{lm} K	UA_{hx} kW/K
0511_1	922	3.98	1.1	5.551	166	1.97	464
0607_0	1873	3.78	1.0	10.341	181	3.529	532
0517_0	2475	3.73	1.0	15.67	158	4.462	557
0521_0	3476	3.7	1.0	21.725	160	5.692	613
0811_0	1800	7.61	2.0	10.479	172	2.831	631
0812_0	1729	11.78	3.1	10.481	165	2.483	685
0813_0	1207	1.06	0.3	7.213	169	4.038	299
0929_0	1723	1.91	0.5	8.717	199	4.178	413
1001_0	1586	3.76	1.0	8.995	177	3.113	510
1003_0	1530	3.66	1.0	8.804	174	3.054	501
1004_0	1529	5.7	1.5	8.785	174	2.672	573
1005_0	1557	8.17	2.2	8.881	175	2.492	619
1007_0	1615	3.71	1.0	10.194	159	3.168	510
1010_0	787	1.88	0.5	4.438	179	2.193	360
1012_0	792	3.77	1.0	4.698	169	1.771	444
1017_0	719	5.77	1.5	4.637	155	1.449	495
1024_0	749	7.93	2.1	4.878	154	1.397	530
1025_0	2370	1.83	0.5	15.916	149	5.552	427
1026_0	2445	3.64	1.0	17.607	139	4.47	549
1027_0	2442	5.77	1.5	16.175	151	3.861	634
1028_0	2475	8.03	2.1	16.128	153	3.581	689
1030_0	3015	1.82	0.5	20.905	144	6.675	452
1031_0	3126	3.58	0.9	23.228	135	5.397	580
1101_0	3164	5.78	1.5	21.648	146	4.629	685
1102_0	2789	7.8	2.1	18.229	153	3.906	715

Figure 1. Results of heat loss test 0419_0 performed on April 19, 1994.

Figure 2. Results of heat loss test 1118_0 performed on November 18, 1994.

Figure 3. Results of heat loss test 1020_0 performed on October 20, 1994.

Figure 4. Results of heat loss test 1120_0 performed on November 20, 1994.

Figure 5. Results of heat loss test 1204_0 performed on December 4, 1994.

Figure 6. Results of heat loss test 1207_0 performed on December 7, 1994.

Figure 7. Results of heat loss test 1212_0 performed on December 12, 1994.

Figure 8. Schematic of the wrap-around heat exchanger tank. Locations of thermocouple tree sensors are shown. All measurements are from the top of the outer shell of the tank. Internal geometry and dimensions are inferred from external measurements. All dimensions to 1/4".

Figure 9. Schematic of the Colorado State Universities solar storage tank test stand with the wrap-around heat exchanger installed. Piping symbols follow ASHRAE standards.

ADVANCED RESIDENTIAL SOLAR DOMESTIC HOT WATER (SDHW) SYSTEMS

Experimental tests are being conducted on three side by side systems: ASN, NEG and Thermodynamics.

Experimentally, several concerns were addressed:

- 1) A severe water hammer was corrected.
- 2) A 1 GPM pump was installed in place of the 0.5 GPM pump in the ASN system. Testing has not yet been accomplished due to problems mentioned later.
- 3) A lower pressure drop Micro Motion flow meter was installed in the natural convection loop of the Thermo Dynamics system. This new flow meter has a flow passage of 1/2" and only one U-tube. The old flow meter used two U-tubes and had a flow passage of 1/4". The new flow meter was instrumented to determine the flow direction as well as the flow rate. The software "Lab Tech Notebook" was changed to include a reading for the flow direction.
- 4) Flow meters were repaired and recalibrated.

Other news:

- 1) The reviews from the Maui Conference paper were received and the paper was corrected accordingly. A copy of the revised paper is included.
- 2) An abstract was prepared for the ASES Minneapolis 1995 conference (copy included). This includes the results from an initial analysis of the ASN load side heat exchanger.
- 3) Many runs of the TRNSYS program were accomplished to try and isolate why there are differences between the TRNSYS program output and experimental data for the NEG system. Much progress was made. It has been determined that the TRNSYS program does not handle roof reflectance properly and that the collector spacing between modules is important.
- 4) The data reduction program has been refined for more accurate analysis of the experimental data.

ANALYSIS OF A LOAD-SIDE HEAT EXCHANGER FOR A SOLAR DOMESTIC HOT WATER HEATING SYSTEM

ABSTRACT

One of the solar domestic hot water heating systems currently installed in the Colorado State University's test stand is an unpressurized drainback system with a load-side heat exchanger. This drainback system has been fully instrumented to yield all data appropriate for an in-depth analysis of its performance. The goal of this paper is to present the results of the analysis of the load-side heat exchanger. An analytical calculation of the heat exchanger performance will be compared to the experimental data. The results will also be compared to TRNSYS simulations.

A comprehensive instrumentation plan has been designed to effect system measurements of temperatures, electrical power input, flow rate, and differential pressure across the pumps. In addition, an outdoor ambient weather station has been designed and installed specifically for these tests. Measurements from the ambient weather station constitute inputs while system measurements constitute system states and outputs.

Outdoor and system measurements are made as indicated in Figures 1 (a) and (b). Measurements are taken every 8 seconds and averaged to yield 5-minute data. For analysis specific to draw data (e.g. energy drawn from the tank) the non-averaged 8-second data are used. The test data was acquired for the time period of July 24 - 29, 1994.

All temperature measurements are made with high-grade type T (Copper/Constantin) thermocouples. It is essential that extremely accurate temperature measurements be made, as the temperature differences are directly proportional to the energy balances on components. All thermocouples are shielded using electrical conduit, and electrically isolated from the shields to prevent ground loops.

Thermocouple arrays have been designed to measure tank temperatures at eight heights, where the spacing between thermocouples in the tank is uniform at one-eighth of the height of the tank.

The drainback system uses an EPDM collector, which is a pliable plastic claimed to be not subject to damage by freezing. The collector consists of about 292.6 m (960 ft) of black EPDM tubing, 0.0089 m (0.35 in) outside diameter and 0.0057 m (0.225 in) inside diameter, with a Lexan cover. The collector area is 6 m² (65 ft²). The cover bows due to thermal expansion (similar to a bimetallic strip) creating a vent to ambient, thereby protecting against high stagnation temperatures.

The collectors are mounted on the collector test bed about 6.1 m (20 ft) south of the basement of Solar House 1, where the storage tanks are located. The plumbing between the basement and the test bed is located outside, except for 2.4 m (8 ft).

The return flow from the drainback collector enters a custom 0.35 m³ (91 gal) unpressurized solar storage tank. The pump circulates the solar storage tank water to the collectors and back to the solar storage tank with a flow rate of 3.9E-05 m³/s (0.6 gpm). The pump motor size is 29.8 W (1/25 hp). Heat is removed from the solar storage tank using a load-side heat exchanger. The heat exchanger is 36.58 m (120 ft) of 0.0191 m (3/4 in) copper tubing that is coiled through the

entire height of the solar storage tank. The coil is situated near the outer edge of the inside of the tank.

Three hot water draws are accomplished each day at 8 a.m., noon, and 4 p.m., as per ASHRAE standard 95-85. The draw flow rate is $1.96\text{E-}04 \text{ m}^3/\text{s}$ (3.1 gpm). During a draw potable water from main supply flows to the bottom of the solar storage tank through a dep-tube, then spirals through the heat exchanger coil; moving in an upward direction through the solar storage tank. The water then flows into the bottom of a standard 0.14 m^3 (36 gal) auxiliary storage tank. Energy is transferred between the tanks only when there is a hot water draw.

Fluid pumping of the system is accomplished using a bang-bang controller, with operation controlled by the temperature difference between the collector outlet and a point on the wall of the solar storage tank. Except for the 0.0127 m (1/2 in) sweated copper piping near the pumps, all piping is 0.0191 m (3/4 in) sweated copper. All lines are well insulated. To minimize pressure drop, all valves are 0.0191 m (3/4 in) or 0.0127 m (1/2 in) through-flow ball valves.

As an indirect example of the heat exchanger performance, the solar storage tank temperatures versus time for July 27, 1994 are shown in Figure 2. An average stratification of 10°C is achieved in the lower half of the tank. This stratification is more pronounced during a draw; the temperature in the bottom of the tank is seen to decrease by as much as 15°C . The top node of the tank may actually increase in temperature by one to two degrees. This suggests that the mains supply water gains most of its energy in the bottom of the tank, and may actually lose heat at the top. It is observed that the top node in the tank remains cooler than almost every other node in the tank. This can be attributed to the fact that the tank top node is probably an air measurement since there is a minimum 0.051 m (2 in) air gap at the top of the tank. The air gap width is variable depending on whether the pump is on or off. The heat loss out the top of the tank is also significant.

For the analytical heat exchanger effectiveness calculation, $C_{\min}$ was calculated as C_{draw} . This is justifiable since the capacitance of the solar storage tank is enormous. The natural convection flow around the heat exchanger is determined to be laminar using correlations for an isothermal vertical heated cylinder. The forced flow through the heat exchanger is turbulent. The calculated UA is $1452 \text{ Btu/hr}^\circ\text{F}$. The effectiveness is determined to be 0.65. The calculated average effectiveness, using experimental data, is 0.78. The experimental effectiveness may be calculated using a variety of tank temperatures; for this calculation the hottest nodal temperature is used. A comparison with different temperatures will be given later. An analysis using a log mean temperature difference still remains.

It is also important to assess the performance of the solar system vis a vis the SRCC efforts, which seek to rate system performance using TRNSYS [Klein et al., 1994] simulations [Burch et al., 1993]. One of the overall goals is to match the model to experimental data by adjusting the model parameters to represent more accurately the physical properties of the system. One of the parameters to adjust is the heat exchanger effectiveness. The simulations will be performed with the average heat exchanger effectiveness, a variable effectiveness (correlation), and a calculation using the log mean temperature difference method. It will be interesting to determine whether collector pump operation has any influence on the effectiveness of the heat exchanger. Also, the effect that changing the collector circulation pump size, from a 0.6 gpm to a 1 gpm, has on the heat exchanger performance will be examined. To assess this, a higher flow rate pump will be installed and data attained.

MEASURED AND SIMULATED PERFORMANCES OF TWO SOLAR DOMESTIC HOT WATER HEATING SYSTEMS

Toni R. Smith, Arun B. Menon, Patrick J. Burns and Douglas C. Hittle
Solar Energy Applications Laboratory
Colorado State University
Fort Collins, CO

ABSTRACT

In this paper, a detailed experimental system used for evaluating the overall performance of solar systems and their individual components is described. Two solar systems are evaluated and tested side by side as they respond to the actual ambient conditions from July 24-29, 1994. The systems consist of a low-cost drainback system and an integral collector-storage (ICS) system. The measured performances of the two systems are compared with each other and against the results of TRNSYS simulations. This paper concludes with recommendations for improvements to the systems.

INTRODUCTION

In today's solar market, emphasis is placed on the design of solar systems which exhibit to the consumer a higher ratio of performance to price. The current solar domestic hot water systems project at Colorado State University is underway to assist in this endeavor.

Two solar domestic hot water heating systems that are presently on the market have been installed and instrumented in detail at Colorado State University. The two systems are distinct from each other in at least one respect and are being tested simultaneously to assess differences in performance. The two systems are: (1) a relatively low-cost unpressurized drainback system with a load-side heat exchanger, and (2) an integral collector storage (ICS) system which uses a pump to circulate water between the solar storage (collectors) and the auxiliary storage tank.

It is also important to assess the performance of solar systems vis a vis the SRCC efforts, which seek to rate system performance using TRNSYS [Klein et al., 1994] simulations [Burch et al., 1993]. Many parameters are used in a TRNSYS simulation to define a system; therefore, many degrees of freedom exist when attempting to match simulated overall

TABLE 1: SYSTEM DETAILS

System Characteristic	Drainback	ICS
Collector Area, m ² (ft ²)	6.0 (65)	2.6 (28)
Solar Tank Volume, m ³ (gal)	0.35 (91.4)	0.15 (40)
Aux. Tank Volume, m ³ (gal)	0.14 (36)	0.14 (36)
Collector Flow Rate, m ³ /s (ft ³ /s)	3.9 x 10 ⁻⁵ (1.4 x 10 ⁻³)	5.9 x 10 ⁻⁵ (2.1 x 10 ⁻³)
Pump Motor Size, W (hp)	29.8 (1/25)	7.46 (1/100)

system performance to that measured experimentally. For this reason, the systems have been instrumented in great detail to enable selected individual components to be "isolated" experimentally [Burch and Christensen, 1993]. One of the goals of this paper is to match the models to experimental data by adjusting the model parameters to represent more accurately the physical properties of the system.

DETAILED DESCRIPTION OF SYSTEMS

A schematic of the collector plumbing and instrumentation for the systems is given in Figure 1(a), and Table 1 provides the system characteristics.

The drainback system uses an EPDM collector, which is a pliable plastic claimed to be not subject to damage by freezing. The collector consists of about 292.6 m (960 ft) of black EPDM tubing, 0.0089 m (0.35 in) outside diameter and 0.0057 m (0.225 in) inside diameter, with a Lexan cover. The cover bows due to thermal expansion (similar to a bimetallic strip) creating a vent to ambient, thereby protecting against high stagnation temperatures.

The ICS system consists of two collector modules, each with four evacuated tubes. Each evacuated tube contains 0.019 m³ (5 gal) of integral storage. The heat loss coefficient of these collectors is sufficiently low such that they are able to maintain temperatures above freezing and no additional freeze

FIGURE 1(a). COLLECTORS AND WEATHER STATION

protection is required. However, the pipes to and from the collector are subject to freezing, and consequently, rupture. This is prevented by draining down the pipes at night, during freezing weather. A pump circulates the water between the collector storage and auxiliary tank. The pump also prevents overheating of the collectors.

The collectors are mounted on the collector test bed about 6.1 m (20 ft) south of the basement of Solar House 1, where all storage tanks, except the ICS collector, are located. The plumbing between the basement and the test bed is located outside, except for 2.4 m (8 ft).

The return flow from the drainback collector enters a custom 0.35 m³ (91 gal) unpressurized solar storage tank (Figure 1(b)). The pump circulates the solar storage tank water to the collectors and back to the tank. Heat is removed from the solar storage tank using a load-side heat exchanger. During a draw potable water from main supply flows through the heat exchanger coil located in the solar storage tank and then into the bottom of a standard 0.14 m³ (36 gal) auxiliary storage tank. Energy is transferred between the tanks only when there is a hot water draw. The ICS system is a hybrid system since it uses a pump to circulate the collector storage water to the bottom of the auxiliary tank. The pump was initially installed to prevent overheating of the water in the collectors. During a draw, the pump is inactivated due to the mains supply pressure, and mains supply flows out to the collectors. Since a draw is about 0.079 m³ (21 gal), essentially the water from one collector module is displaced with mains supply water. The displaced collector water flows into the bottom of a standard auxiliary tank. During a draw, energy is removed from the top of the auxiliary tank.

Fluid pumping of the systems is accomplished using bang-bang controllers, with operation controlled by the temperature difference between the collector outlet and a point on the wall of the solar storage tank for the drainback system, and between a point on the outlet manifold and a point on the wall of the

FIGURE 1(b). SYSTEM COMPONENTS AND TANKS

auxiliary tank for the ICS system.

Finally, all systems are connected in parallel to both the water main supply line and the hot water draw line. Except for the 0.0127 m (1/2 in) sweated copper piping near the pumps, all piping is 0.0187 m (3/4 in) sweated copper. All lines are well insulated. To minimize pressure drop, all valves are 0.0187 m (3/4 in) or 0.0127 m (1/2 in) through-flow ball valves.

INSTRUMENTATION

A comprehensive instrumentation plan has been designed to effect system measurements of temperatures, electrical power input, flow rate, and differential pressure across the pumps. In addition, an outdoor ambient weather station has been designed and installed specifically for these tests. Measurements from the ambient weather station constitute inputs while system measurements constitute system states

TABLE 2: INSTRUMENTATION

Instrument	Characteristic		Error
Thermocouple	Type T	High Grade	$\pm 0.1^\circ\text{C}$
Flowmeter	Turbine, Vol.	Drainback, Supply ICS, Draw	$\pm 0.4\%$ $\pm 0.5\%$
Pressure Xducer	Differential	Across the Pumps	$\pm 1\%$ full scale
Pyranometers		Horizontal, Tilt	$\pm 0.75\%$
Watt Xducers	Hall Effect	On Pumps, Controllers	$\pm 0.5\%$

and outputs. Such measurement detail meets the dual objectives of analysis: (1) correlation of inputs with outputs, and (2) detailed system and component analyses. Table 2 presents the types of instrumentation used and their associated errors.

Except for the differential pressure sensors, which are new and calibrated by the manufacturer, all instruments (to ensure greater accuracy) were calibrated through the Data Acquisition System (DAS) used to measure and store all of the experimental data. The pyranometers were calibrated versus a known pyranometer at the Colorado State University Atmospheric Sciences Laboratory in the summer of 1993. The type T thermocouples were calibrated versus a precision mercury thermometer, readable to 0.05°C . Six thermocouples were calibrated - four from one roll of wire, and two from a second roll of wire. All of the turbine flow meters were calibrated using a manometer and an ASME calibrated venturi - such devices directly yield the volume flow rate. An equation of state is required to determine the mass flow rate. One of the Hall effect transducers was sent back to the factory in the summer of 1993 for factory calibration, and the remainder of the Hall effect transducers were calibrated against this device.

Outdoor and system measurements are made as indicated in Figures 1 (a) and (b). Measurements are taken every 8 seconds and averaged to yield 5-minute data. For analysis specific to draw data (e.g. energy drawn from the tank) the non-averaged 8-second data are used.

All temperature measurements are made with high-grade type T (Copper/Constantin) thermocouples. It is essential that extremely accurate temperature measurements be made, as the temperature differences are directly proportional to the energy balances on components. All thermocouples are shielded using electrical conduit, and electrically isolated from the shields to prevent ground loops.

Thermocouple arrays have been designed to measure tank temperatures at eight heights, where the spacing between thermocouples in the tank is uniform at one-eighth of the height of the tank.

EXPERIMENTAL RESULTS

Data were collected for five days, beginning July 24, 1994 at 8:00 A.M., and ending July 29, 1994 at 8:00 A.M. The outdoor and indoor temperatures and pyranometer measurements are shown in Figure 2. The average prevailing conditions, as well as the average indoor temperature measurements (supply, drain, and ambient) are given in Table 3. Days 1, 2 and 5 were days of moderate solar radiation; day 3 was a day of poor solar

FIGURE 2
WEATHER CONDITIONS vs.
TIME

5 a.m. July 27 to 5 a.m. July 28, 1994

radiation; and day 4 was a day of strong solar radiation.

As can be seen from Table 3, the drainback system average mains supply temperature is on average 1.4°C higher than the ICS system. This is because the supply line is heated by axial conduction up the copper piping from the solar storage tank. Once a draw is begun, this measured supply temperature drops rapidly to the "true" mains temperature. The energy contained in this heated supply water is about 1% of the total draw energy. These particular tests were run without the operation of the auxiliary heaters in the auxiliary storage tanks. Draws according to the ASHRAE standard (0.07 m^3 (20 gal) per draw at 8 A.M., noon and 4 P.M.) [ASHRAE 95-1985] were accomplished manually by dumping the draw water into a large plastic tank with graduated markings. To augment this method, volume flow rate and temperature measurements are collected by the instrumentation.

Both systems were run using the controllers provided from the manufacturer. The average forced flow rates for each system are $4.0\text{E-}5$ and $5.5\text{E-}5\text{ m}^3/\text{s}$ for the drainback and ICS systems, respectively. The systems were being operated on "auto" for several days before the tests began, so the initial states are a result of actual weather conditions and normal operation. Operating the systems in this manner, instead of starting the systems at the same initial state, allows the systems to start and end at their "natural" operating points. This will help shorten the running time required such that the internal energy of each system over the period of the test is negligible.

Space limitations mandate that only a small portion of the data collected be shown. As most illustrative of overall system performance, a plot of the solar storage tank temperatures vs. time for July 27, for the drainback system is provided. However, since the solar storage tank for the ICS system is integral with the collector the auxiliary tank temperatures vs. time are shown.

The solar storage tank temperatures shown in Figure 3 for the drainback system illustrate a stratification of about 10°C in the lower half of the tank. The temperatures in the bottom half of the tank are observed to decrease by as much as 15°C

TABLE 3: SYSTEM AVERAGES

Meas.(all °C, except ITilt=MJ)		July 24		July 25		July 26		July 27		July 28	
		Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
ITilt		398	0	353	0	394	0	522	0	365	0
Out Amb		26.1	17.3	24.5	16.4	20.5	16.2	25.0	17.2	24.3	18.2
Ind Amb		24.8	24.0	24.3	23.6	23.7	23.3	24.4	24.0	24.3	23.5
Main Tank	Drain	17.4	26.1	17.4	25.4	17.1	26.0	17.5	26.0	17.4	24.8
	ICS	16.0	26.1	15.9	25.4	15.8	26.0	16.1	26.0	16.2	24.8
Draw Tank	Drain	39.9	26.5	38.5	26.2	37.3	26.4	40.9	28.9	45.3	27.9
	ICS	42.1	26.5	41.7	26.2	39.9	26.4	45.6	28.9	47.3	27.9

a. The values given during the day are the averages over only time of a draw.

when a draw is being done; this is especially pronounced at the bottom node of the tank. The top node of the tank may actually increase in temperature by one to two degrees, suggesting that the mains supply water in the heat exchanger actually gains most of its energy in the lower half of the tank, and may actually lose heat at the top. An interesting observation is that most of the time the temperature at the top of the tank is significantly lower than that of all but the bottom node. The top node of the solar storage tank may actually be measuring an air temperature since there is a 0.051 m (2 in) air gap at the top. Also, the size of the air gap is variable, depending on whether or not the pump is on. There may also be significant heat loss out the top of the solar storage tank. Finally, note the warming experienced at night by the bottom node of the tank, while the other nodes become cooler - this is due to conductive heat transfer from the hotter nodes in the tank.

The ICS auxiliary tank temperatures (Figure 4) indicate that very little stratification (less than 0.5 °C) exists in the tank; this is due to the mixing caused by the injection of the hot water return from the collectors into the bottom of the auxiliary tank. The periods during which draws were done are observable each day as three small upward "blips," most notable in the bottom node of the tank. This is because the supply water goes out to the collectors, causing the hot water from the solar storage to enter the bottom of the auxiliary tank.

In Table 4, daily and total energy summaries are provided for both of the systems. The "Quantity" items in column 1 are defined as follows:

$$\dot{Q}_{Draw} = \int (\dot{m}C_p)_{Draw} (T_{Draw} - T_{Supply}) dt \quad (1)$$

$$\dot{Q}_{Aux} = \int \{ (\dot{m}C_p)_{Draw} (T_{Set} - T_{Draw}) + UA(T_{Set} - T_{Amb}) - UA(T_{Aux} - T_{Amb}) \} dt \quad (2)$$

$$SSF = \frac{\dot{Q}_{Draw}}{\dot{Q}_{Draw} + \dot{Q}_{Aux}} \quad (3)$$

FIGURE 3
SOLAR STOR. Tank TEMPS vs.
TIME-DRAINBACK SYSTEM

5 a.m. July 27 to 5 a.m. July 28, 1994

FIGURE 4
AUXILIARY TANK TEMPS vs.
TIME-ICS SYSTEM

5 a.m. July 27 to 5 a.m. July 28, 1994

where:

C_p = specific heat at constant pressure (J/kg-°C)

$\dot{m}$ = flow rate (kg/s)

Q = heat transfer (J)

SSF = solar savings fraction ()

T = temperature (°C), $T_{Set} = 55$ °C

t = time (s)

The subscripts: (1) supply, (2) draw and (3) aux, respectively, refer to: (1) the supply line (water mains), (2) the fluid drawn from the system (i.e. going to the load) and (3) the auxiliary tank. Since the auxiliary heaters for the systems were not operated during the test, it was necessary to compute the energy required to heat the systems to T_{Set} . For this purpose, an energy balance encompassing the entire solar system is applied. Equation (2) is used to compute the amount of auxiliary energy required if the system were to supply hot water at T_{Set} . Since the measured draw temperature is used in equation (2), the auxiliary energy is the amount required to heat all the load hot water to T_{Set} from T_{Draw} plus that needed

TABLE 4: SYSTEM PERFORMANCE -
EXPERIMENTAL MEASUREMENTS

Quantity	System	Day					Total	Error %
		1	2	3	4	5 ^a		
Incident Solar Flux (MJ)	Drainback	107	111	118	139	146	643	1.2
	ICS	46.5	48.2	51.3	69.1	63.6	279	
Q_{Useful} (MJ)	Drainback	31.6	29.6	38.4	52.3	34.0	186	0.54
	ICS	29.8	31.3	30.3	41.8	37.1	170	0.69
Q_{Draw} (MJ)	Drainback	22.2	20.8	20.8	22.6	27.5	114	0.75
	ICS	26.1	26.5	23.6	28.8	30.8	136	
$SSF_{THERMAL}$	Drainback	57%	52%	49%	58%	70%	57%	2
	ICS	63%	60%	55%	70%	74%	64%	
E_{MOTOR} (MJ)	Drainback	1.33	1.30	1.60	1.99	1.39	7.60	0.5
	ICS	0.27	0.34	0.41	0.54	0.44	2.00	

a. Includes from midnight to 8 AM on day 6.

to make up for the additional tank losses were the auxiliary tank to be held at T_{set} . Note that the tank losses due to the measured tank temperatures (T_{Amb}) will not be part of the Q_{Aux} because they have already been accounted for. At no time, for either of the systems, was the draw water temperature equal to or greater than T_{set} . The UA values used in equation (2) were determined from a heat loss test. The tanks were filled with water at a constant temperature and then allowed to sit over night. The natural log of the temperature differences between the tank and ambient were plotted versus time; the slope of that plot yields UA/MC_p . The errors associated with this measurement/calculation are at worst 2%. Finally, the incident solar flux is that measured with the tilt pyranometer, and the useful energy is the measured energy gain of the collector.

Some observations are pertinent to summarize here. Note that the energy incident upon the ICS system is less than 1/2, by comparison to the drainback system. However, the energy collected by the ICS system is about 85% of that collected by the other system. This is evidence of the high performance of the ICS collectors. Also, because of the pump operation, the hot collector fluid (useful energy) is entered directly into the auxiliary tank. Given these two factors, the ICS system exhibits the higher energy in the draws and the higher solar savings fraction. Finally, note that the energies consumed by the pump motors are 6.7% and 1.5% of that in the draws, respectively for the drainback and ICS systems. These values are not very significant in terms of the energy balances on the systems. However, given that the cost of electrical energy is typically about four times that of thermal energy (at least for thermal energy produced directly from the combustion of fossil fuels), the poor motor performance (the combined pump-motor efficiency is less than 2% for both systems) significantly detracts from the systems economic performance.

Finally, to illustrate the quality of the instrumentation, Table 5 is provided, which gives the overall energy balances on the tanks for the entire test period. The energy balance on the drainback solar storage tank is quite good. However, the energy balances on the auxiliary tanks are not as good. Because less energy flows through these tanks, if the same absolute error is made, a larger relative error results. Albeit,

TABLE 5: ENERGY BALANCES ON TANKS -
EXPERIMENTAL MEASUREMENTS

System	Energy Balance (%)	
	Solar Tank	Auxiliary Tank
Drainback	1.9%	6.9%
ICS	a	4.6%

a. A detailed energy balance was not performed on the ICS solar tank due to its being integral with the collector.

we are quite pleased with the experimental system. The ability to assess the performance of individual components has allowed us to isolate the factors influencing overall performance to individual components (see the conclusions section for more detail).

OVERALL PERFORMANCE OF THE SYSTEMS - TRNSYS SIMULATIONS

In this section, TRNSYS simulations of the systems are summarized. In these simulations, measured draw profiles, measured weather data, and measured initial states were used, but parameters for the system components were derived from SRCC input decks [Long, 1994]. The measured lengths of piping, for the calculation of piping losses, and the measured heat loss coefficients from the tanks were also used. Finally, the ground reflectance value used in the TRNSYS simulations was determined as the value which yielded the best fit to the measured total radiation on the tilt to that computed using the TRNSYS Type 16 solar radiation processor [Erbs, 1980], which assumes the diffuse radiation is isotropic. The modelling of the diffuse radiation as isotropic is questionable, as significant variations in the split between direct normal and sky diffuse (and consequently ground reflected) radiation can occur when using different sky models. However, a plot of total radiation on the tilted surface using Erbs' model against the experimental measurements yielded excellent agreement at $\rho_g=0.5$. Agreement for nearly all of the several hundred points was within 0.5%. The maximum disparity was 26% at only three data points, which were peaks. This is fairly compelling evidence that the total radiation on the tilted surface is being modelled well, as the days simulated were subject to a wide variations in beam and diffuse radiation. Furthermore, $\rho_g=0.5$ is a reasonable value since the foreground is a light, dirt parking lot.

Table 6 provides overall energy quantities computed by TRNSYS corresponding to some of those quantities in Table 4. For the drainback system, the agreement of Q_{Useful} is excellent, which can be expected since the system is fairly simple. The agreement in Q_{Draw} for the drainback system is also quite good.

For the initial states in Table 6 for the ICS system, Q_{Useful} and Q_{Draw} are both significantly underpredicted by the TRNSYS simulation. The initial state uses the loss coefficient determined from an earlier work involving TRNSYS and experimental results from an identical ICS system [Mason, 1993]. Mason's [1993] work showed excellent agreement. However, the earlier work involved indoor testing in a solar

TABLE 6: 5 DAY SYSTEM PERFORMANCE
COMPARISON

Quantity	System	Total Energy (MJ)		Difference
		TRNSYS	Measured	
Q_{Useful} (MJ)	Drainback	197	186	-5.9%
	ICS: Initial	134	170	21%
	Final	170	170	0%
Q_{Draw} (MJ)	Drainback	116	114	-1.8%
	ICS: Initial	103	136	24%
	Final	124	136	9%

simulator, with only beam incident radiation and no back-plane reflection. By contrast, the results reported herein are based on real weather conditions; much of the incident radiation is diffuse, and the collectors are mounted on a test stand with a backplane reflector painted flat white (diffuse reflectance of between 0.7 and 0.85). To determine the source of the disagreement, a parametric analysis of the TRNSYS model was undertaken. Factors considered are discussed below.

Manifold Losses

The manufacturer of the ICS system has incorporated a new manifold with lower losses than the one tested. As the TRNSYS deck models the new manifold design, changing to a "lossier" collector would tend to increase the disparity in the results.

Controller Setpoint

The pump is operated by a traditional bang-bang controller. Experimental data indicated that ΔT_{off} was about 2.0 °C, but that ΔT_{on} varied substantially. Therefore, several TRNSYS runs were made, varying ΔT_{on} , but very little effect upon Q_{Useful} was observed. However, a strong dependence on ΔT_{on} was observed for the total mass flow through the collector in a day. Thus, ΔT_{on} was calibrated to be 4.5 °C. Varying ΔT_{on} from 0 °C to 15 °C changed Q_{Useful} by less than 3%.

IAM Calculations and Backplane Reflectance

Additional efforts to isolate the cause of the disparity were then focused upon the collector model, type 46 in TRNSYS. The original flat plate model for the type 46 model was developed at the University of Wisconsin [Zollner, 1984], and then enhanced to enable modelling of the collector as an assemblage of tubes by Barker at NREL [Burch, 1992]. Optical mode 4 (two-dimensional IAM's) and collector mode 2 (tubular collectors) were used in this simulation. The effects of the shortwave radiation model were first investigated by re-computing the Incidence Angle Modifiers (IAM's), using the IAM program developed at Colorado State University [Menon, 1994]. This is the same program used by Mason [1993] which yielded excellent agreement. This gave assurance that: (1) the IAM's and $(\tau\alpha)_n$ were based upon a consistent aperture area (gross collector area, including longitudinal extensions of 1/2 the tube to tube spacing on each side was used), and (2) ensuring that the reflectance of the

back plane is modelled correctly. It was found necessary to model a much larger area than the gross collector area to capture the full extent of end and edge reflections (the sky dome that eventually was used extended over an area more than five times greater than the gross collector area). The backplane reflectance was determined by incorporating the backplane reflector into the IAM computations so that end and edge effects, and specular reflection from the tubes was accounted for. During this exercise, the dimensions of the ICS system for input into the IAM calculation were carefully re-measured. Earlier IAM calculations had been modelling the collector as two separate units, each with a gross collector area extending 1/2 the tube to tube spacing. However, the actual experimental system consists of two four-tube modules separated by a distance of 34.9 cm (0.89 in) between the outer edges of the tube glazings. After including this in the IAM program, the absorbed energy was observed to increase by more than 12% - a very significant effect indicating that a wider spacing of the collector tubes would yield substantially increased collected energy.

Discussion

After making all the corrections mentioned above, the TRNSYS model still underpredicted Q_{Useful} by 21%, and consequently Q_{Draw} by 24%. Due to the excellent agreement obtained by Mason [1993] between TRNSYS and experiment, we hypothesize that the remaining disagreement is due either: (1) to the way that the incident diffuse is handled in TRNSYS, (2) to the manner in which the backplane reflectance is handled, or (3) to collector losses which do not match those of the experimental system.

It is worthwhile to comment that the two-dimensional IAM's used in TRNSYS are integrated over the hemisphere to yield an IAM for incident diffuse radiation, assuming that the incident diffuse radiation is isotropic. It is noted that the IAM's for incident angles approaching the grazing angle can be quite large (e.g. for incident angles of 60°, the IAM is 1.17). Thus, if a solar radiation model incorporating a non-isotropic diffuse sky were used, a more sophisticated calculation of the IAM for the sky diffuse (involving a new integration for each hour) would need to be incorporated. Note that these comments also apply to the incident diffuse from ground reflected, for which the same isotropic, diffuse IAM is used. During the period of the test, the systems experienced diffuse radiation primarily from the sky, due to the small view of the ground. So, to test the effect of the directionality of the IAM for diffuse, the TRNSYS simulation was modified to take all of the incident diffuse radiation (sky plus ground), and treat it as beam radiation (i.e., as if it were all circumsolar). This changed Q_{Useful} by less than 3%, so this does not explain the disparity.

Next, the collector loss coefficient was investigated. The measured value of 7.51 W/°C [Mason, 1993] was decremented to the point where good agreement was obtained in Q_{Useful} . The value of the UA that yields the agreement to within 1% of Q_{Useful} is 2.55 W/°C, or 34% of the value measured by Mason [1993]. At this value of UA, Q_{Draw} is 124 MJ (low by

8.8%). These are the final values given in Table 6. To identify why this value of UA works will require additional investigation. Finally, it is noted that the disparity in results could be resolved by either decreasing UA, or by increasing the optical efficiency. Currently, there is little justification for choosing to modify UA, other than our faith in the IAM calculations.

CONCLUSIONS AND RECOMMENDATIONS

First, we are pleased with the exceptional performance of the experimental system, although some minor changes will be made for further testing. The level of detail of the instrumentation allows us to observe the performance of the total system and the performance of individual components. Excellent energy balances were obtained on the solar storage tanks, and adequate energy balances were obtained on the auxiliary tanks.

Another of our objectives was to compare with SRCC TRNSYS simulations. The TRNSYS simulation of the drainback system yielded extremely good agreement, but the ICS system will require more thoughtful and involved modeling to acquire agreement. Here, closer inspection of the performance of individual components will most certainly be beneficial - especially a measured UA value. Attention should also be focused on the modelling of the collector since there is such a large disparity in Q_{useful} .

Finally, the insight into system performance developed over the course of this work has led us to several recommendations to improve the performances of the systems:

The performance of the drainback system could benefit from a design change which permits continuous flow of energy between the solar storage and auxiliary tanks. As it is now, heat is transferred between these two tanks only when there is a draw. This would require a new solar storage tank design and changes in the plumbing.

The thermal performance of the ICS system is extremely good. The economic performance of the ICS system could be improved by reducing the collector area (the TRNSYS simulation illustrated that the second collector module contributed only about one-third of the useful energy). Perhaps they could be plumbed in parallel, instead of series as we have done. The ICS collectors are so good that overheating sometimes occurs when using a two-module, eight-tube system (this was observed on day 4 - the strong solar day). In situations of overheating, the controller runs the pump to keep the collector fluid from overheating. In the event of extreme overheating, the pressure relief valve on the collectors opens and releases steam. Also, the superlinear increase observed in $(\tau\alpha)_n$ when the spacing between the collector modules was included in the calculation of IAM's indicates that spacing the tubes *much* further apart than they are now would be of benefit.

Finally, we note that to date all of our efforts have addressed only thermal performance, while the ultimate goal should be improving the ratio of overall system performance to overall system cost (e.g. Life Cycle Cost).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Department of Energy, contract DE-FG02-86SF16306, under the technical direction of Mr. Jay Burch of NREL. We also thank Messrs. John Arent and Ihsan Abbud for performing the TRNSYS runs, and Mr. Steve Long of FSEC who provided the SRCC input decks.

REFERENCES

- ASHRAE, 1985, "Standard 95-85: Method of Testing to Determine the Thermal Performance of Solar Domestic Hot Water Systems," ASHRAE, Atlanta, GA.
- Burch, J. and Christensen C., 1993, "An Overview of Approaches to SHWS Field Monitoring," to be published, available from authors, NREL, 1617 Cole Blvd., Golden, CO.
- Burch, J., Huggins, J., Wood, B. and Thornton, J., 1993, "Simulation-Based Ratings for Solar Hot Water Heating Systems."
- Burch, J., 1994, personal communication, NREL, Golden, CO.
- Erbs, D. G., 1980, "Methods for Estimating the Diffuse Fraction of Hourly, Daily and Monthly Average Global Solar Radiation," MS Thesis, University of Wisconsin, Madison, WI.
- Klein et al., 1994, "TRNSYS - A Transient System Simulation Tool, Ver. 14.1," Solar Energy Laboratory, University of Wisconsin, Madison, WI.
- Long, S., 1994, SRCC TRNSYS input decks, personal communication, Florida Solar Energy Center, Cape Canaveral, FL.
- Mason, A. A., "Stratification and Performance Prediction in an Evacuated-Tube, Integral Storage Solar Collector," MS Thesis, Dept. of Mechanical Engineering, Colorado State University, Fort Collins, CO, 1993.
- Menon, A. B., 1994, "Optical Performance of Cylindrical Absorber Collectors with and without Reflectors," MS Thesis, Dept. of Mechanical Engineering, Colorado State University, Fort Collins, CO.
- SRCC, January, 1993, "Standard OG-300: Directory of Solar Water Heating Systems Meeting Minimum Operating and Performance Requirements," Publication of the Solar Rating and Certification Corporation, Washington, D.C.
- Zollner, A., 1984, "A Performance Prediction Methodology for Integral Collector Storage Solar Domestic Hot Water Systems," MS Thesis, Dept. of Mechanical Engineering, University of Wisconsin, Madison, WI.

MANAGEMENT AND COORDINATION OF COLORADO STATE/DOE PROGRAM

Director Doug Hittle participated in conference calls regarding various aspects of the SEAL/DOE research.

Coordination of research activities continued on the four technical research tasks under the DOE grant, and accounts were maintained and updated. Financial and technical reports were submitted as required.