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SF-16306-41

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

**PROJECT STATUS REPORT FOR THE MONTHS OF
FEBRUARY THROUGH MAY, 1994**

Prepared for the

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Submitted by

**SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY**

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RATING AND CERTIFICATION OF DOMESTIC WATER HEATING SYSTEMS

Thermosyphon System:

The experimental setup for the Solahart 180 JK system was completed and tested for functionality at the end of February. The first preliminary irradiated test under the solar simulator occurred in early March and energy balances were performed to assess the physical reliability of the setup and data acquisition system. No problems were detected.

The flat plate collector performance was determined by plotting six performance points on a graph of efficiency vs. $\Delta T/G$. In order to obtain significantly different operating points (a difficult task with the single flux level solar simulator) a set of screens was developed and placed in the simulator's shadow board to provide a lower irradiance level. This, combined with varying collector inlet temperatures, provided an acceptable map of collector performance. While the efficiency intercept was similar to the quoted value from Solahart, the measured efficiency dropped off significantly faster than predicted. At the most common operating point ($G \approx 1000 \text{ W/m}^2$, Flow $\approx 42 \text{ kg/h}$) the observed efficiency was approximately eight percentage points lower than predicted by Solahart. Energy balances within the system proved that the collector could not possibly be operating at the predicted level. As a result, the measured performance was used in all TRNSYS modeling runs.

The irradiated testing plan included three 3 hour irradiated runs with an ASHRAE standard draw (0.2 l/s for 420 s) at $t = 2$ hours. Each of these was run with the storage tank temperature probe in a different axial location. Three 4 hour irradiated warm-up tests were run, each with a different initial storage tank temperature. A single 8 hour warm-up was also run to assess long term flow stability. The above test plan was completed in early May. A final irradiated test with the auxiliary heater in place is planned for the end of May. The auxiliary heater necessarily displaces the storage tank temperature stratification probe. Many system tests without a tank probe have already been performed by other researchers and, as a result, only a single run will occur at the solar simulator.

TRNSYS Modeling:

Modified versions of the TRNSYS models for the thermosyphon system and storage tank were obtained from Graham Morrison (University of New South Wales, Australia) and used to model all system runs completed under the simulator. These updated models allow incorporation of a tank-in-tank heat exchanger in the thermosyphon system. Several experiments were also modeled with TRNSYS 13.1 for comparison. Several disparities between experimental performance and the TRNSYS models were noted. A preliminary report of these results was sent to Graham Morrison for review and a copy is included here. Present effort concentrates on studying the Morrison mathematical models and updating those models to run with the new generation TRNSYS 14.1.

Solahart Indoor Testing Summary

The system being tested is a Solahart 180 JK thermosyphon unit with a closed loop circuit containing a 25% solution of propylene glycol and water. The Colorado State University solar simulator is used as the energy input source to the system. Instrumentation is shown in Figures 1 & 2. The storage tank temperature probe locates four equally spaced thermocouples vertically (aligned with gravity). All the data presented here was taken with the tank probe midway between the tank ends. Also located on the tank are twelve thermocouples which monitor HX outer jacket temperature. The results of these probes are not presented here. All TRNAUS extension results are based on the code as received by the CSU Solar Lab - no property changes for propylene glycol were incorporated.

Two types of tests are represented in the attached figures. The first incorporates three hours of irradiation and an ASHRAE standard draw at the two hour mark:

Collector Intercept = 0.846
Collector Slope = -6.5 W/m²-C
Time (Total) = 3 h
Time (Irradiation) = 3 h
Time (Draw): 420 s @ 2 h
Irradiation = 1039 W/m²
Tank Initial T = 24.8 C
Ambient T = 26.8 C
Mains T = 18.8 C
Draw Flow = 756 kg/h

The second test type was a four hour warm-up from three different initial tank temperatures:

Collector Intercept = 0.846
Collector Slope = -6.5 W/m²-C
Time (Total) = 4 h
Time (Irradiation) = 4 h
Time (Draw): N/A
Irradiation = 1049; 1048; 1025 W/m²
Tank Initial T = 24.3; 39.5; 14.3 C
Ambient T = 25.2; 25.2; 24.8 C
Mains T = N/A
Draw Flow = N/A

The three (3) hour test is summarized in Figure 3 and modeled (using the TRNAUS extensions) in Figure 4. The most glaring inconsistency is the disparity between the collector temperatures (in/out). During the experiment, the collector inlet temperature closely followed the average tank temperature (obtained by averaging the four probe readings). This trend occurred in every test to date. However, the collector temperature rise (Figure 5) is modeled quite well, and leads to fairly accurate predictions of storage energy collection. Figure 6 indicates that the TRNAUS flow models the test data reasonably well over this short time period (more about flow modeling later). Since the collector temperature rise and the flow compare favorably, the collector useful energy (Figure 7) matches well. Figure 8 shows storage tank stratification during the test - keep in mind that each thermocouple does not represent an equal volume of water. It is interesting to note that significant stratification can be maintained during and after the draw. Other tests were performed to determine if variation in the amount of stratification occurred when the probe was moved axially between the tank center and the load in/out connections. The results indicate a negligible change.

Another physical disparity is indicated by Figures 9 & 10. The TRNAUS storage temperature rises more quickly than the test data during warm-up, and drops below test data during the draw (Figure 9). Figure 10 indicates a much higher modeled load temperature than was actually found, and the temperature drop during the draw was also larger than observed. All these trends suggest the model predicts excessive tank stratification. The degree of tank stratification in the model is determined by the size (volume) of the conduction element (V_{max}). The suggested value was 0.1 (one-tenth of the total tank volume) and this value was used to produce Figures 1-10, 15, & 16. Varying V_{max} does not affect the average tank temperature during warm-up, but does change the tank temperature upon draw completion (Figures 11 & 12). A larger value of V_{max} results in less stratification and more closely models test data. A larger value of V_{max} also brings the load temperature closer to observed levels (Figures 13 & 14). However, with the improved prediction of load temperature comes a dramatic decrease in temperature drop during the draw (Figure 13). In order to match the load temperature ($V_{max} = 0.4$), the temperature drop during the draw becomes unreasonably small; predicting load temperatures after draw that are much too high. Similarly, matching the draw temperature drop ($V_{max} = 0.2$) necessitates overestimating the load temperature by, at least, five degrees.

Collector flow prediction suffers in two areas, indicated by Figures 15 & 16. The TRNSYS model is much more sensitive to initial tank temperature (which directly affects collector inlet temperature) than the actual system. While higher initial tank temperatures do result in higher thermosyphon flow rates, the increase is much less noticeable in the experiments. The second disturbing flow trend is the steady increase in predicted flow over time (Figure 16). A small degree of increase is expected from the test results, but the model goes far beyond that. If the warm-up time is extended (to eight hours) the TRNSYS model predicts flows that approach approximately 59 kg/h while an eight hour experimental run peaks at around 44 kg/h. This degree of difference can produce significant changes in overall storage energy increase, and is

the reason the model predicts higher average storage temperatures - even over the short term testing performed.

In conclusion, there are three significant physical differences between the Solahart experiments and the TRNAUS model predictions. The collector inlet temperatures do not compare well; the model indicates a fairly constant value while the test results show direct correlation with average tank temperature. The stratification is exaggerated by the model and this results in high load temperatures and larger than expected temperature drops during timed draws. Finally, the collector thermosyphon flow prediction is too sensitive to initial tank temperature; and predicted increase in flow over time is too large. I do not dispute the assertion that the TRNAUS extensions are capable of estimating the overall performance of solar thermosyphon water heaters (with heat exchangers) to within +/- 5%. However, I find that the physical disparities indicated during short term testing warrant investigation.

Plumbing Schematic

Note: Load In/Out Connected to Water Conditioning System

FIGURE 1

Storage Tank / HX Instrumentation

FIGURE 2

3 Hr Test w/ Draw @ 2 Hr

4/24/94: T Probe at Tank Center

FIGURE 3

3 Hr Test w/ Draw at 2 Hr

TRNSYS (G. Morrison): 4/24/94

FIGURE 4

Collector Temp Rise

3 Hr: 4/24/94

FIGURE 5

Collector Flow Comparison

3 Hr: 4/24/94

FIGURE 6

Collector Energy

3 Hr: 4/24/94

FIGURE 7

Tank Stratification

Draw Test: 4/24/94

FIGURE 8

Storage Temperature

3 Hr: 4/24/94

FIGURE 9

Load Temp Comparison

3 Hr Test w/ Draw: 4/24/94

FIGURE 10.

Storage Temperature

$V_{max} = 0.4$

FIGURE 11

Storage Temperature

$V_{max} = 0.2$

FIGURE 12

Load Temp Comparison

$V_{max} = 0.4$

FIGURE 13

Load Temp Comparison

$V_{max} = 0.2$

FIGURE 14

Test Collector Flows

Variations in Tank Initial Temp

FIGURE 15

Specific Flow: Flow [kg/h] Divided by Test Irradiation [W/m²]

TRNSYS Collector Flow

Variation in Tank Initial Temp

FIGURE 16

UNIQUE SOLAR SYSTEM COMPONENTS

Integrated Tank/Heat Exchanger Modeling/ Experiments

The 80 gallon Rheem wrap-around heat exchanger tank has been installed in generic systems test stand in Solar House II. Extensive modifications to the control, instrumentation, and fluid supply systems are complete. Temperature and flow instrumentation are labeled.

- The cold water supply (supplies temperature conditioned water to the domestic water side of the hot water system for tank setup and make-up water during hot water draws) side of the fluid supply system is complete and has been pressure tested. Flow meters, thermocouples, and thermistors have been installed and calibrated. The circulation pump has been installed and tested.
- The hot water/collector loop is complete. A collector (part of the original generic systems test stand) has been removed from the hot water loop to simplify operation. Flow meters, thermocouples, and thermistors have been installed and calibrated. The circulation pump has been installed and tested.
- Control algorithms for the cold water supply system and the hot water (collector) loop have been developed and tested.
- Constant heat flux tests were carried out using the following protocol:
 1. Fill the Rheem tank with water at constant temperature.
 2. Turn on the upper (conventional) electric heater and wait for the upper portion of the tank to reach the set point temperature.
 3. Turn on the "solar" electric heater and circulate hot water through the wrap-around heat exchanger, observing and recording temperatures, flow, etc.
 4. Stop the test when the entire tank is above the set point temperature.

Tests were run for the following wrap-around flow rates and heat fluxes.

<u>Flow Rate</u>	<u>Heat Rate</u>
1 GPM	1,000 W 2,000 W 3,000 W 4,000 W
1/2 GPM	2,000 W
2 GPM	2,000 W

Data is currently being analyzed using Excel. This process will be expedited with the arrival of a newly acquired Power Mac.

Additional tests

- During the period when the new control algorithms were being developed and tested, a thermocouple tree was installed in the 42 gallon auxiliary storage tank and tank was connected to the cold water supply system. Data was collected as the tank was allowed to heat up overnight. Tank temperature profiles and auxiliary heater energy usage were recorded.
- The overall heat loss coefficient of the tank and the apparent volume heated by the upper and lower electric heating elements were measured. The tank was enabled and allowed to reach its set point. Half of the tank volume was drawn and the tank was allowed to recover, then a full tank volume was drawn. This test was repeated for draw flow rates of 3, 6, 9, and 12 liters per minute.
- The data acquired during these tests will be used to test the ability of the TRNSYS Type 4 storage tank model to accurately predict auxiliary tank performance.

A solid state relay and controller for the "solar" electric heater have been purchased. This new controller will replace the existing motor-driven Variac. The new controller was required in order to run constant inlet temperature and simulated solar day tests on the wrap-around heat exchanger.

ADVANCED RESIDENTIAL SOLAR DOMESTIC HOT WATER (SDHW) SYSTEMS

This report is for February through May, 1994. Experimental tests are being conducted on three side by side systems: ASN, NEG and Thermodynamics.

The data acquisition system was made operational through the donation to the project of a new DOS 80386 computer and monitor. These were installed during this period of time. LABTECH notebook, the data acquisition software, was configured for the present system, encompassing 63 temperature, 2 pyranometer, 6 fluid flow rate, 6 electrical power and 3 differential pressure measurements.

Additionally, a data reduction program was written in FORTRAN, to take as input the raw data, collected at 8 second intervals on 84 channels, and average it over time. Furthermore, the program partitioned the data as applicable to the three individual systems.

Two preliminary data sets were collected in system "shake-down" mode during the periods March 14-15, and March 21-25, 1994. This allowed us to identify several problems with the physical systems, and the data reduction procedure. The ultra-low flow Micromotion fluid flow rate sensor was found to have caused a vapor lock, preventing flow, and was moved to a low point in the system. The Watt transducer on the ASN system was rewired to the controller, to yield correct power readings.

The collector cover on the ASN system, which was fouled due to outgassing, was replaced on March 31.

An Ethernet card was installed in the 80386 data acquisition system, to permit the transfer of the large data files (60 MBytes for one week of data) to the central computer for processing. Powerstation FORTRAN was installed on the 80386, to allow the data reduction program to be run locally (the old FORTRAN would not allow enough files to be opened). An additional FORTRAN program was written to allow energy balance calculations to be done. This additional program uses output from the first program which performs averaging of the data over time. A Macintosh Centris 650 was installed to analyze the data. Procedures were implemented to plot and analyze the data in Microsoft Excel. A data reduction procedure was devised to perform parameter estimation using integrated energy balances.

The wind direction and speed sensors were installed and made operational. This required a digital frequency to voltage circuit to be built and debugged. Now, all sensors are fully operational.

Data sets were collected over the periods: April 12-19, and May 26-31, 1994. These were the first data sets where draws were done.

Several system improvements were made. A new ASN collector was installed, as the old one had experienced severe fouling due to outgassing, and the new design has improved venting. The end caps on all thermocouple probes were re-plumbed by soldering (previously, the end caps had been glued - now, we devised a way to inject thermocouple paste deep into the probes after soldering). The NEG pump and snap switch were replaced with a new pump and controller, including new thermistor sensors. A new thermistor was installed on the Thermodynamics collector, as the old one had failed. A new controller

was also installed on the Thermodynamics system on May 24, 1994; the old controller had also failed.

We met with NEG principals and explained our efforts to them.

MANAGEMENT AND COORDINATION OF COLORADO STATE/DOE PROGRAM

Director Douglas Hittle attended the SOLTECH conference in March. He participated in bi-weekly conference calls with other DOE grant participants to discuss directions and approaches of DOE work.

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.

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