THE DESIGN, CONSTRUCTION, AND EVALUATION
OF A THERMOSIPHON SOLAR WATER HEATER

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TITLE The Design, Construction, and Evaluation of a Thermosiphon Solar Water Heater

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. List of Tables</td>
<td>iv</td>
</tr>
<tr>
<td>II. List of Figures</td>
<td>v</td>
</tr>
<tr>
<td>III. Object</td>
<td>1</td>
</tr>
<tr>
<td>IV. Theory</td>
<td>2</td>
</tr>
<tr>
<td>V. Design-Build</td>
<td>4</td>
</tr>
<tr>
<td>VI. Materials and Equipment</td>
<td>8</td>
</tr>
<tr>
<td>VII. Analysis and Calculations</td>
<td>10</td>
</tr>
<tr>
<td>VIII. Results</td>
<td>12</td>
</tr>
<tr>
<td>IX. Discussions and Conclusions</td>
<td>17</td>
</tr>
<tr>
<td>X. Appendix</td>
<td>19</td>
</tr>
<tr>
<td>XI. References</td>
<td>23</td>
</tr>
</tbody>
</table>
# I. LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Experimental Data</td>
</tr>
<tr>
<td>II.</td>
<td>Equipment List</td>
</tr>
</tbody>
</table>
## II. LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Left Side View of System</td>
<td>5</td>
</tr>
<tr>
<td>2.</td>
<td>Top View of System</td>
<td>6</td>
</tr>
<tr>
<td>3.</td>
<td>System Temperature Vs. Time</td>
<td>13</td>
</tr>
<tr>
<td>4.</td>
<td>Incident Insolation Vs. Time</td>
<td>14</td>
</tr>
</tbody>
</table>
III. OBJECT

The purpose of this senior project was to design, construct and evaluate a thermosiphon solar water heater. The project was to be used as a department demonstration of a passive solar water heating system. Overall, maximum dimensions of the system needed to be maintained to insure the system's transportability through doors and corridors.
IV. THEORY

The main force which creates the flow of fluid in a thermosiphon system is the difference in densities of the low temperature fluid in the tank and the high temperature fluid in the collector. This buoyancy pressure can be calculated by multiplying the density difference of the two points by the buoyancy difference. This will be the pressure difference. This pressure difference is what drives flow through the system.

The flow rate of the fluid is determined by the pressure drop in the system due to friction and fitting losses. When the flow rate produces a pressure drop equal to the buoyancy pressure rise, the system will maintain a constant flow.

The flow rate of the system is very sensitive to pressure drop because the buoyancy pressure rise is so small. A major contributor to frictional pressure drop is the system piping. This is closely related to pipe size as shown in a study done by Lawrence Berkeley Laboratory (LBL). At solar noon, peak solar input, the study shows maximum flow was obtained. Flow through a 1" tube was three times that of a ½" tube. Also contributing to the frictional pressure drop are fittings and flow control devices.

The system efficiency is also affected by flow rate. A low flow rate through the collector produces a larger
temperature rise in the collector which raises plate and pipe temperatures, thus increasing losses. A high flow rate therefore can remove and store more energy than a slow rate of flow.
V. DESIGN-BUILD

The system was designed and built as a demonstration of passive solar water heating. The system consists of a 14.3 square foot collector, a nominal 30-gallon storage tank, support frame and connecting piping.

The maximum allowable height for the system was six feet, nine inches. This insured clearance of the system through most institutional doors. A three feet, six inches width clearance was also maintained. This maximum height forced the bottom of the tank to be below the top of the collector. As stated in the LBL study, this had the effect of reducing flow rate during operating hours and causing reverse thermosiphoning in non-sunlit hours. Reverse siphoning can be prevented by the use of a check valve. Since this system was only designed to be a demonstration project, the check valve was not installed. Scaled schematics showing the height and width of the system are shown in Figures 1 and 2.

The frame for the tank and collector is constructed of one and one-half inch schedule 40 black steel and one inch steel angle with welded connections. The frame needed considerable structural integrity to support and transport the water-filled system. Complete construction details can be obtained from Figures 1 and 2.

The system was piped with three-quarter inch copper water
FIGURE 1: LEFT SIDE VIEW OF SYSTEM
Scale: $\frac{3}{4}'' = 1'0''$
FIGURE 2: TOP VIEW OF SYSTEM
Scale: 3/4" = 1'0"
pipe, type L, with soldered fittings. Two valves were placed in the piping system, one at the low point for filling and draining and one at the high point for air venting.

To minimize construction costs, the system was designed as an open system. During operation, the system was always at atmospheric pressure. Since the system was a thermosiphoning system, there could not be any breaks in the fluid circuit; that is, the system must always be full, and there can be no air gaps in the system. A one foot high by four inch diameter standpipe was used to keep the system full and allow for fluid expansion.

Measurement of flow by conventional means (i.e., orifice or velocity flowmeter) required a mechanical connection to the fluid. This would produce a pressure drop which would reduce considerably, or more likely prevent, flow in the system. Therefore, no flowmeter was used. A hope for the future is to obtain a flowmeter which uses a temperature difference over a known length of pipe to calculate the flow. This flowmeter would be completely external.

For temperature measurement, five type "T" (copper-constantan) thermocouples were placed in the system, as shown in Figure 1. Three thermocouples were placed inside the tank to check stratification and obtain an average tank temperature.
VI. MATERIALS AND EQUIPMENT

A list of the equipment used to collect data for the analysis of the system is shown in Table II.

The Honeywell Strip chart recorder was used to transduce and record the data from the six type "T" thermocouples placed on the system. The Micromax strip chart recorder was used for recording the voltage output of the Eppley Pyranometer in units of gram-cal/min cm$^2$. The equipment recorded the data precisely, but their accuracy was not checked. The value of the data collected was close to anticipated values.

The system equipment, the tank and panel, were not ideal for application in a solar thermosiphon water heater, but they seemed to perform reasonably well. The tank was a standard 30-gallon nominal electric water heater converted for use as a solar storage tank. The tank did not have the proper connections to be used as a solar storage tank. Since the system was to be run under no load, no water had to be drawn off or added to the tank, so the available fittings were sufficient for use. The tank was also poorly insulated. There was no insulation on the top and bottom of the tank, and the side had only one inch of fiberglass.

The solar panel was manufactured by Sun Works and had 14.3 square feet of single sheet, etched glazing. The panel itself was back painted copper tubing with copper plate and
backside insulation. Dimensional data is shown in Table II.

The materials used in the construction were selected for their availability in the department. Fortunately what was available was sufficient for the structural frame. One inch angle iron was used for the collector frame and the tank platform frame.

All connections were arc-welded. The welding of the frame took much longer than anticipated due to the difficulty of welding pipe.

Nominal three-quarter inch copper water pipe was used for all the plumbing, as opposed to five-eighths inch pipe which was also available, because the larger diameter would produce a smaller pressure drop. All connections were soldered. The piping was insulated with one-half inch of polyurethane with glued connections.
VII. ANALYSIS AND CALCULATIONS

The solar energy incident upon a south-facing surface tilted at 45 degrees was calculated from the solar data in Table I. This data had already been converted from the pyranometer output of gram-cals/min cm\(^2\) to BTU/hr ft\(^2\) by the following conversion:

\[
(x) \left( \frac{\text{gram-cals}}{\text{min cm}^2} \right) \left( \frac{221.2 \text{ BTU/hr ft}^2}{\text{gram-cals/ min cm}^2} \right) = (x) \left( \frac{\text{BTU}}{\text{hr ft}^2} \right)
\]

Since instantaneous values for incident solar energy were recorded every 15 minutes, for seven hours, each value was multiplied by 15 minutes and the total incident was:

\[ S = 24,114 \text{ BTU} \]

The heat into the tank was calculated by multiplying the total fluid mass in the system by the temperature rise over the test period as shown below

\[ Q = (M)(C_P)(\Delta T) \]

\[ M = (27.5 \text{ gal}) \left( \frac{8.34 \text{ lb}}{\text{gallon}} \right) = 230 \text{ lb.} \]

\[ \Delta T = 58^\circ F \]

\[ Q = (230 \text{ lb})(1 \text{ BTU/lb}^\circ F)(58^\circ F) = 13,340 \text{ BTU} \]

Efficiency was 55 percent using this equation:

\[ \text{Efficiency} = \frac{Q}{S} \left( \frac{\text{output}}{\text{input}} \right) \]

A computer simulation of the system was also used. The measured values of solar input and ambient temperature were used in the program. Besides environmental data, the input
to the program was as follows:

\[
\begin{align*}
AC &= 14.3, \text{ ft}^2 \\
UL &= 5.0, \text{ BTU/hr ft}^2 \text{°F} \\
FPRIME &= 0.85 \\
TAUALF &= 0.85 \\
ST01 &= 27.5, \text{ gallons} \\
UASI &= 5.0, \\
BTU/hr \text{°F} \quad TCW &= 68°F \\
ALAT &= 35° \\
TILT &= 45° \\
NHRF &= 1 \\
NHRL &= 8 \\
HR &= 5, \text{ ft} \\
DR &= 0.25 \text{ in} \\
XNR &= 6 \\
DP &= 0.75 \text{ in} \\
FP &= 17 \text{ ft} \\
HP &= 2 \text{ ft}
\end{align*}
\]

The program utilization and variables are explained and defined in Appendix I, page 20 and 21.
VIII. RESULTS

The results of the system test are shown in Figures 3 and 4. The temperature profiles shown in Figure 3 represent the time variations of the temperature of the points as indicated below:

- T1 - Tank inlet
- T2 - Top third of tank
- T3 - Middle third of tank
- T4 - Bottom third of tank
- T5 - Tank outlet
- T6 - Ambient temperature

The locations of thermocouples 1-5 are shown in Figure 1. The graph shows the effects of stratification. T3 lags behind T2 by about an hour and T4 lags behind T3 also by an hour. At 9:00, when the test was started, the average tank temperature was about 68°F and at 41:00, at the end of the test, the tank average was 126°F. As the tank heated up, the temperature rise across the collector was reduced. The higher temperature of the water flowing through the panel caused more losses and decreased heat transfer because the temperature difference between plate and fluid was reduced.

Figure 4 shows a profile of the incident solar energy as a function of solar time. Solar input peaked at 12:45, 272 BTU/hrft². The graph shows the effect of facing the collector south, rather than having it track the sun. If the collector
SYSTEM TEMPERATURE VS. TIME
Day of Test: 4-27-82

Drawn by J. Coughlin
Date: 5-8-82

FIGURE 3: SYSTEM TEMPERATURES VS. TIME
SOLAR INPUT VS. TIME
Day of Test: 4-27-82
Weather Conditions: Clear and Warm, Calm

Eppley Pyranometer
Drawn by J. Coughlin
Date: 5-8-82

FIGURE 4: INCIDENT INSOLATION VS. TIME
tracked the sun, the intensity profile would have been flatter. By 4:00 p.m., the sun was so far west it was no longer contributing any usable heat to the tank.

The solar and temperature data are shown in tabular form in Table I.

The same solar and ambient air temperature as measured were used as input for the computer simulation. The total amount of solar energy incident upon the collector and stored as measured and as simulated by the computer are as follows:

- Solar incident: \( S = 24,114 \) BTU
- Stored (measured): \( Q = 13,340 \) BTU
- Stored (computer): \( Q = 6,348 \) BTU

The measured tank temperature rise was 58°F while the computer simulation predicted only a 27.5°F rise. The efficiencies are as follows:

- Measured efficiency: 55%
- Computer efficiency: 26%
<table>
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<tr>
<th>TIME</th>
<th>T1*</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
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<td>164</td>
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</table>

*Temperature = °F
Solar Input = BTU/hrft²
IX. DISCUSSION AND CONCLUSIONS

Due to the fact that this project only involved the design, construction, and evaluation of one variation of a thermosiphon system, it is hard to make any conclusions about the best system configuration for maximum performance. Due to the need for this system to be transportable, it was not designed for best performance. This project does prove that a thermosiphon system will heat water with reasonable efficiency.

In a report on thermosiphon water heaters by LBL (ref. 2), some general conclusions are drawn:

Reverse flow can be prevented if the tank is completely above the top of the collector.

No significant performance advantage results from having the tank above the top of the collector other than preventing reverse flow.

System performance is essentially independent of flow resistance (pipe size) over a wide range of values.

Tank elevation, tube and pipe size do have a substantial effect upon flow rate, but the flow rate has little effect on performance.

There appears to be some problem in the simulation program (ref. 1) used to simulate the system performance. The measured efficiency of 55 percent does not compare closely with the computer generated efficiency of 26 percent. The measured solar data appears to be accurate when compared with tabulated
data from Duffie and Beckman (ref. 3).

The computer seems to predict excessive losses. The system input parameters were conservative estimates since actual values were not known. This seems to support the idea that the computer program used does not accurately predict a thermosiphon system.

If a flow meter could be obtained, a better comparison could be made to the computer simulation because an important portion of the program depends upon the computer predicting a flow rate. The program's prediction could be checked against the actual flow, thus giving one more checkpoint.

This system as designed and built would be too small for the average residential application. Using twenty gallons of hot water per person for a family of four, or 80 gallons, twice the storage and twice the panel area would be needed. Thermosiphon systems would seem to have a lot of potential for areas where no power is available, and there is periodic, rather than continuous, usage.
APPENDIX I: EXPLANATION OF SIMULATION PROGRAM

The computer program that was used was a simulation program that calculates the monthly performance of a thermosiphon system based upon a weather tape. This program was developed as a senior project by Tom Barrington (ref.1) and has been slightly modified since, by Mr. Niles of the Environmental Engineering Department.

The program as written had several operations which did not fit this system and test method. The program had to be modified to fit for use in this project. The first problem was that the system was a single tank with no load. This was a simple problem to solve by setting the demand, the backup set point, the mixing set point, and the backup tank heat loss coefficient to zero. The backup tank size could not be set to zero, because the computer would have to divide by zero, so the tank size can be set to any number other than zero.

The most difficult modification to the program was to use synthetic weather tape that was made from the test data of the experiment. Since the data collected was the total insolation on the collector, the part of the subroutine, Insol, that calculates the total insolation from the diffuse and horizontal insolation had to be deleted from the program. The line that reads the weather tape had to be modified to read only the hour, outdoor temperature and total insolation.
With these modifications to the program and the input data, the program could be run to fit our system and weather tape.
### APPENDIX II

#### TABLE II: EQUIPMENT LIST

1. **Honeywell strip chart recorder**  
   Type "T" thermocouples  
   Range: 0-150°F  
   Least Count: 1.0°F  
   CP #77271

2. **Micromax strip chart recorder**  
   Leeds and Northrup Co.  
   Philadelphia, PA  
   Range: 0-2 gram-cal/min cm²  
   Least count: 0.1 gram-cal/min cm²

3. **Eppley Pyranometer**  
   Model 10, No. 2312  
   Eppley Laboratories, Inc.  
   Newport, RI  
   Millivolts/gram-cal/min cm²
XI. REFERENCES


