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AN ANALYSIS OF SOLAR DOMESTIC HOT WATER SYSTEMS FROM A SYSTEM PERSPECTIVE*

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ABSTRACT

Six solar domestic hot water systems tested at the National Bureau of Standards have been analyzed. Results indicate that the thermosyphon system delivered the most solar energy to the load per dollar of initial investment (the air system delivered the least) and that direct systems performed better than indirect systems. Storage losses from the double tank systems were greater than expected, and this significantly reduced the relative performance of these systems. Further, the use of pumps, fans, controls, and solenoid valves in the pumped systems can reduce the net energy savings of the solar system by up to 30%.

Reliable freeze protection needs to be developed for direct systems, especially thermosyphon systems, to take advantage of direct heat transfer.

1. INTRODUCTION

The Solar Energy Research Institute (SERI) analyzed experimental data from six solar domestic hot water systems (SDHW) provided by the National Bureau of Standards (NBS).[1] The objectives of this study are to aid users and designers in understanding the relative benefits of existing systems[2,3,4,5] and to identify areas requiring further research. The systems tested in this study, selected as typical of those being installed at the time,** were exposed to the same climatic conditions and supported approximately the same thermal load. These systems, therefore, do not necessarily reflect the state of the art nor were they optimized to meet the thermal load. The six systems tested are shown in Fig. 1 and a description of each system is given in Table 1.

2. SYSTEM PERFORMANCE

This study included analysis of collector, piping, and storage tank losses as well as energy consumed by pumps, controls, and solenoid valves (parasitic energy consumption), and auxiliary heating necessary to meet the load. The thermal and system efficiencies were calculated. The solar fraction was calculated for each system as well as a net solar fraction. When an electric backup was used, the system efficiency and net solar fraction were also calculated considering the energy used at the fossil-fueled generating plant.*

The results from the thermal and system analyses are shown in Table 2.

The double tank systems had lower efficiencies than the single tank systems due to the larger tank heat transfer area. The two tank direct and indirect systems lost 32% and 25% of the energy input, respectively. The corresponding losses for the single tank systems were 18% and 11%. If the existing insulation (1.07 m^2 c/w) were increased, thus reducing losses, system performance could be significantly increased.

Indirect systems using an ethylene glycol mixture had lower efficiencies than the corresponding direct systems due to the presence of a heat exchanger and the use of an antifreeze with a heat capacitance 20% below that of water.

Parasitic energy consumption is a major factor in determining the system efficiency of a solar domestic hot water system. As seen in Table 2, the efficiencies of the single and double tank direct systems

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**Results discussed in this report are based on the performance evaluations of only those systems tested; therefore, the authors discourage generalizing these findings to apply them to systems with different thermal characteristics.

*For definitions of terms used, see nomenclature.

Table 1. SYSTEM DESCRIPTION

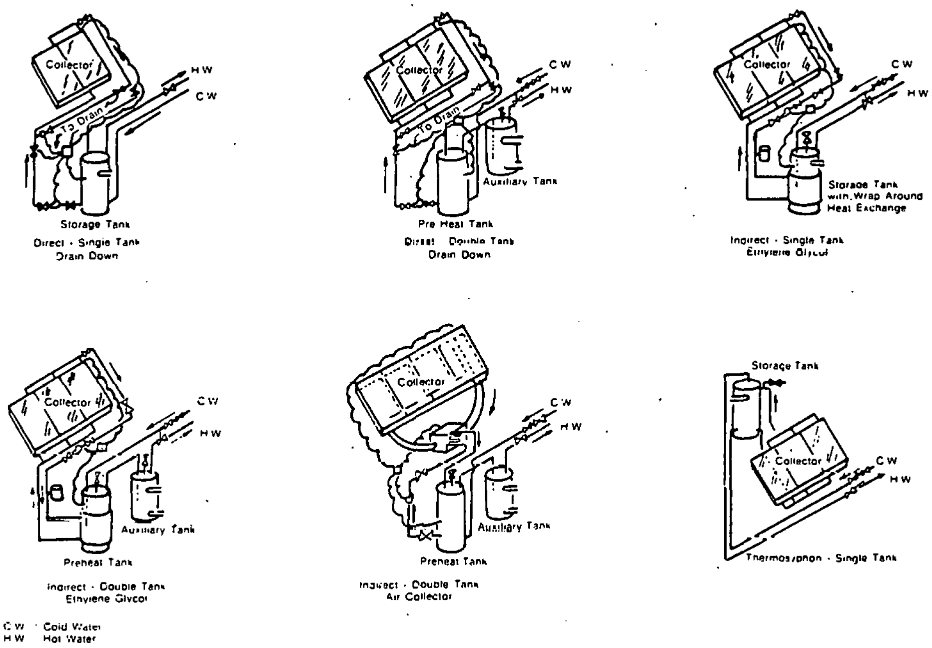
System	Collector Area m^2 (ft^2)	Solar Storage Tank ℓ (gal)	Auxiliary Tank ℓ (gal)	Days Tested	Hot Water Load (GJ)
Thermosyphon	5.0 (54)	250 (66)	- (--)	127	4.60
Single[a] Dir.[b]	3.3 (36)	310 (82)	- (--)	121	4.56
Single, Ind.	5.0 (54)	310 (82)	- (--)	127	4.53
Double, Dir.	5.0 (54)	310 (82)	159 (42)	127	4.44
Double, Ind.	5.0 (54)	310 (82)	159 (42)	127	4.50
Air System	7.3 (80)	310 (82)	159 (42)	127	4.47

[a] Single or double describes the type of system based on the number of tanks.
[b] Direct or indirect refers to the method of heat transfer.

Table 2. SYSTEM TEST PERFORMANCE[a]

System	Incident Solar Energy (GJ)	Thermal Efficiency (%)	System Efficiency (%)	Solar Fraction[b]	Net Solar Fraction
Thermosyphon	9.946	26.4	25.7 (24.3)	0.57	0.56 (0.52)
Single, Dir.	6.631	35.3	28.5 (14.9)	0.51	0.42 (0.22)
Single, Ind.	9.946	24.7	22.3 (17.5)	0.54	0.49 (0.38)
Double, Dir.	9.946	23.3	18.1 (7.7)	0.52	0.41 (0.17)
Double, Ind.	9.946	22.5	20.0 (15.4)	0.50	0.44 (0.33)
Air System	14.740	11.5	8.1 (1.30)	0.38	0.26 (0.03)

[a] Figures in parentheses represent values if parasitic energy consumption were considered as energy required at a fossil-fueled electric generating plant (33% electric plant efficiency assumed).
[b] Collector areas must be considered when comparing solar fractions.



Direct · Single Tank Drain Down

Direct · Double Tank Drain Down

Indirect · Single Tank Ethylene Glycol

Indirect · Double Tank Ethylene Glycol

Indirect · Double Tank Air Collector

Thermosyphon · Single Tank

Fig. 1. Six Common SDHW Systems Currently in Use

Table 3. PARASITIC ENERGY CONSUMPTION

System	Hours of Operation (6 mo. total)	Estimated Energy Consumed by Pumps (kWh)	Estimated Energy Consumed by Solenoid Valves (kWh)	Measure Parasitic Energy-Total (kWh)
Thermosyphon	-	NA	32.4	19.4
Single, Dir.	681.66	68.2	91.4	125.3
Single, Ind.	690.24	69.0	NA	68.5
Double, Dir.	882.87	88.3	91.4	145.3
Double, Ind.	870.49	87.1	NA	71.0
Air System	644.94	64.5(+48 Fan)	NA	145.0

Table 4. TOTAL INSTALLED SYSTEM COSTS AND ENERGY DELIVERED

System	Total System Cost (Collectors at \$81/m^2)	Total System Cost (Collectors at \$162/m^2)	Solar Energy Delivered to Load over Test Period (GJ)
Thermosyphon	1267	1875	2.621
Single, Dir.	1718	2123	2.342
Single, Ind.	2397	3005	2.459
Double, Dir.	2325	2933	2.320
Double, Ind.	2802	3410	2.240
Air System	3329	4229	1.697

decreased 19% and 22%, respectively, due to the parasitic energy consumption. The efficiencies of the single and double tank indirect systems decreased 10% and 11%, respectively, due to the parasitic energy consumption. The direct systems used more parasitic energy than the indirect systems since two 15-W solenoid valves were employed for drain-down freeze protection. Similarly, the double tank systems used more parasitic energy than single tank systems due to the longer pump running times that were caused in turn by the larger temperature difference across the collectors of the double tank systems. (See Table 3).

The air system, the only double-glazed system tested, did not perform well as a stand alone* solar domestic hot water system. This was due to the poor heat transfer across the air-to-water heat exchanger, resulting in high collector inlet air temperatures and large collector losses. Only 22% of the incident energy on the collectors was absorbed by the air. The efficiency of the air system decreased by 30% due to parasitic energy consumption.

Of the systems tested, the thermosyphon systems had the best overall system performance due to low parasitic energy consumption and good thermal efficiency.**

3. SYSTEM ECONOMICS

The economics of solar domestic hot water systems depends on system cost and performance. The initial system cost was broken down into five areas: collector costs; storage costs; pumps, controls, and solenoid valves; miscellaneous component costs (relief valves, gate valves, expansion tanks, thermometers, air vents, heat exchangers, piping, and various fittings); and installation costs. Collector costs were assumed to vary from \$81/m^2 (\$7.50/ft^2) to \$162/m^2 (\$15/ft^2). Collector costs tended to be the largest and the most variable of these and most influenced the total system cost. The other four areas of the cost breakdown were essentially fixed costs. The total installed cost for a system varied substantially depending on the collector cost used, as seen in Table 4.

A rigorous life cycle economic analysis was not performed for these systems due to the many large and inherent uncertainties, including those associated with escallation and discount rates, insurance, maintenance, salvage value, and component replacement. However, for relative system comparisons, a helpful cost per performance index can be determined by using the initial system cost

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*As opposed to a combined water and space heating system.

**Solenoid valves were added to this system midway through the testing. The degradation of the system efficiency due to the parasitic energy consumption, therefore, should not be compared directly to the other systems.

and the total expected lifetime delivered energy. The results of applying this approximation to the test data are shown in Table 5. These results assume a 20-yr lifetime and a test period corresponding to one-third of the annual energy delivered by the system. Also, the effect of including or not including parasitic energy for two collector costs are shown with results expressed in $/GJ delivered.

To facilitate comparison of those systems, the relative ranking was normalized with the best system equal to one unit of cost per GJ delivered to the thermal load.

With further research and development, parasitic energy consumption can be reduced. Therefore, the cost per GJ neglecting parasitic energy consumption calculated for each system can serve as an incentive to reduce parasitic energy consumption.

The relative rankings of the various systems are shown in Table 6. Notice the same order results regardless of whether parasitic energy consumption or collector cost is considered. However, considerable differences do exist among the relative rankings depending on the collector cost and the inclusion or exclusion of parasitic energy consumption. Note that comparisons should be made only within a given column in Table 6 because of the normalization.

4. CONCLUSIONS AND RECOMMENDATIONS

There are a number of significant insights that can be gained from the experiment and analyses. However, it should be mentioned that an almost limitless number of possible system configurations make generalization of these tests to all systems at different locations very difficult.

The thermosyphon system was clearly the most cost effective system tested because of its low cost, good thermal efficiency, and low parasitic energy consumption. However, to take advantage of the apparent benefits of thermosyphon systems in large regions of this country, efficient and reliable freeze protection systems must be developed. This last point also holds for the direct pumped systems that have inherently higher effective heat transfer relative to indirect pumped systems. Further, other system effects, such as corrosion on both direct and indirect systems, must be determined and factored into the reliability and maintenance evaluations.

The tests and analysis show a relatively strong preference for single tank systems; however, it should be noted that these systems were not optimized and significant changes in optical collector area and/or tank insolation may reverse these trends. Further, other considerations, such as

Table 5. ENERGY COST BASED ON 20 YEARS OF OPERATION, $/GJ

	Collectors at $81/m^2		Collectors at $162/m^2	
System	Without Parasitics	With Parasitics	Without Parasitics	With Parasitics
Thermosyphon	8.06	8.28	11.93	12.25
Single Dir.	12.23	15.13	15.11	18.70
Single Ind.	16.24	18.05	20.37	22.63
Double Dir.	16.71	21.55	21.07	27.18
Double Ind.	20.85	23.52	25.37	28.62
Air System	32.72	47.19	41.56	59.95

Table 6. RELATIVE SYSTEM RANKINGS

	Collectors at $81/m^2		Collectors at $162/m^2	
System	Without Parasitics	With Parasitics	Without Parasitics	With Parasitics
Thermosyphon	1.00	1.00	1.00	1.00
Single, Dir.	1.52	1.83	1.27	1.53
Single, Ind.	2.02	2.18	1.71	1.85
Double, Dir.	2.07	2.60	1.77	2.22
Double, Ind.	2.59	2.84	2.13	2.34
Air System	4.06	5.70	3.48	4.88

greater capacity, increased system reliability due to decreased thermal shock, and use of existing equipment in retrofit situations, may favor two tank systems. These issues should be investigated.

The air system that was tested performed considerably below all the other systems. Since the relative performance was so low, this system is not preferable to hydronic systems; however, an air SDHW may be desirable if it is coupled with an air space heating system. Care must be taken to minimize the parasitic energy consumption.

The effects of variations on load use profile were not addressed in these experiments; however, calculations for an indirect two tank system, presented in Reference 5, indicate that only a moderate change in total annual delivered energy (less than 10%) resulted when a drastic shift in load use profile was used. Moderate shifts in load profiles had minimal effect. It is expected that this will probably hold true for all system types, but further investigation may be warranted.

Considering the components tested, the most needed component development and improvement appears to be in the area of reliable and efficient pumps and freeze protection systems.* Since parasitic power consumption degraded system performance from 10% to more than 30%, a significant contribution can be made. Reliability of these components, as well as other components, represents a major uncertainty in determining the cost performance of these and similar systems.

To define the optimal system configurations for a given location, reliability data and analyses on state-of-the-art components must be developed. Further proven analytical models for thermosyphon and other systems, such as the "bread box" or integral type[5] system, must be available to the optimization process.

5. NOMENCLATURE

Net solar fraction: Solar energy used at the thermal load minus the parasitic energy consumption divided by the thermal load.

Parasitic energy consumption: Energy consumed by pumps, fans, controls, and solenoid valves in a solar energy system.

Solar fraction: Percentage of the thermal load met by solar energy.

System efficiency: Solar energy delivered to the thermal load minus the parasitic energy consumption divided by the solar energy incident on the collector surface.

Thermal efficiency: Percentage of the incident radiation used at the thermal load.

Thermal load: Thermal energy required to meet the hot water load, excluding storage tank losses.

Thermosyphon system: System that depends on density gradients for fluid circulation instead of mechanical pumps.

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*It should be noted that pumps and solenoid valves that are more efficient than the ones used in this experiment are now available.

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