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ABSTRACT

The Solar Energy Research Institute (SERI) has modeled seven of the Department of Energy (DOE) sponsored solar Industrial Process Heat (IPH), field test experiments and generated performance predictions for each project. Additionally, these performance predictions have been compared with actual performance measurements taken at the projects. Performance prediction were generated using SOLIPH, an hour-by-hour computer code with the capability for modeling many types of solar IPH components and system configurations. Comparisons of reported and predicted performance resulted in good agreement and a high level of confidence in the ability to accurately estimate potential solar IPH system energy deliveries.

1. INTRODUCTION

Since 1977, DOE has funded a series of field tests of solar energy systems in industry. Several IPH applications have been utilized for these field tests, including hot water, hot air, low temperature (100-175°C) steam, and intermediate temperature (175-290°C) steam. Both small-scale and large-scale (up to 4680 m^2) systems have been built and monitored. In general, the earlier systems did not exhibit high levels of performance and reliability. The latest systems have faired better, but still have not met expectations. This is especially true in the area of energy delivery. In all cases, original performance predictions have been consistently over estimated due to a combination of inadequate weather data, optimistic component performance models and low system reliability. SERI was funded to utilize its SOLIPH capability to provide more realistic predictions of performance for several of these field tests.

SERI's prime objective was to provide performance predictions for seven of these DOE projects. These predictions were to include annual, monthly, and daily performance estimates using actual weather data for inputs if possible. Then these estimates were to be compared with actual measured performance. The purpose of the comparison was to identify those areas of field operation which were deficient and recommend repairs or changes to correct the problems.

2. METHODOLOGY

An hour-by-hour simulation of these projects was chosen in order to adequately model the overall system and retain the ability to quantify component level performance. A code developed at SERI, SOLIPH, had been used previously in preparing a design handbook for solar IPH systems (1). SOLIPH is versatile, allowing several types of configurations to be modeled using all components typically found in a solar IPH system. The details of the SOLIPH code and component analysis have been reported elsewhere (2). Additional descriptions of the current version of SOLIPH are reported in a detailed report of the present work (3). Once the configuration of each system was established, the input data which determine component performance was generated from several sources. Initial data was obtained from site contractor design and construction reports, specifications and drawings. Confirmation and clarification of the documented information was made during a visit to the site. Additional information, including operational characteristics, automatic control set points, plant process schedule, installation details and undocumented changes was also obtained while at the site.

After a complete set of input data describing the system was formulated, SOLIPH was then coded with the appropriate component subroutines to provide the complete system configuration. In order to drive SOLIPH, solar radiation and ambient weather conditions that exist at each site were required. The preferable source of this data would be that recorded by the site data acquisition system. Unfortunately, none of the seven sites had consistent or continuous records of data collection for long enough periods. The result was that actual site data could not be used for annual simulation runs. Fortunately, hourly weather and solar radiation is available for many sites throughout the country. This data represents calculated expectations of a typical year at each of over 200 sites. This typical meteorological year (TMY) information was utilized for these simulation runs as a result of its widespread acceptance and availability.

3. SYSTEM DESCRIPTIONS

The seven systems modeled represent a wide range of IPH applications with widely separated geographic locations and climatic conditions. Four of the seven systems produced saturated steam from unfired boilers for the industrial plant over a range of temperatures from 151°C to 191°C. One produced saturated steam at 174°C from a flash boiler. Another provided hot water preheat at 113°C to the parts washing facility of its industrial plant. The last was dually configured for both saturated steam at 160°C and hot water heating through a heat exchanger at 60°C. Table 1 lists the seven systems and provides a brief description of some of the system parameters. All of the systems use parabolic trough collector fields.

Caterpillar Tractor is one of two large-scale, cost-shared solar systems. It interfaces directly with the plant's process water system. Chemically-treated water at a temperature of 90°C enters the collector's field and is heated to a maximum outlet temperature of 113°C. The heated water then flows through a conventional water heater to preheat hot wash water for cleaning mechanical parts. The collector system (Solar Kinetics T-700A) is roof mounted and consists of two distinct collector fields, one of 22 rows and the other of eight rows. The circulating pumps and all the manifold piping is housed in the building under the collector field. Roof penetrations are made for the collector risers and downcomers for each collector row. Thus only the collectors, flex hoses and a minimal amount of piping and fittings are exposed to the outside environment. The plant has been running at such a low production level that the solar system output can exceed the total energy requirement for hot water. The load is matched by shutting down collector rows.

The solar system at Dow Chemical consists of 15 rows of SUNTEC SH1655 parabolic trough collectors. The collector field is oriented N-S with a tilt of 10° to the south. The heat transfer fluid is Dowtherm LF which is used to provide energy to an unfired boiler producing steam at 187°C and 1034 kPa pressure. The entire solar system including the unfired boiler, expansion tank, and circulating pump is located outdoors. The unfired boiler is situated directly adjacent to the chemical plant boiler room and thus boiler feedwater and the steam delivery lines are very short. However, it is over 60 m from the unfired boiler to the nearest point in the collector field. The field piping is supported approximately every 3 m by fixtures that provide direct metal contact of the pipe to the environment. Similarly, the in-line circulating pump is rigidly anchored to a metal base plate, and the pump is not insulated. An expansion tank is sized to hold the total field inventory of organic working fluid. Valves and fittings throughout the system are generally only partially insulated or not insulated at all. At the end of each collector row there is a 0.5 m downcomer that is only half-insulated. This downcomer is rigidly attached to the collector support pylon. The entire assembly acts as a large heat fin and is a considerable source of heat leakage. In general, the Dow system has very high heat loss characteristics which are augmented by the outdoor location of the steam delivery equipment.

The Home Laundry solar thermal system consists of 406 DEL linear parabolic trough collectors in 58 rows. The collectors are mounted above the roof of the laundry in a N-S orientation on a specially built support structure. The collected energy is supplied to an unfired boiler to produce 740 kPa saturated steam. Production of domestic hot water at 66°C is an optional operation mode. Water is circulated at a constant flow rate between the collector array and either the 1) steam generator, 2) domestic hot water tank or, 3) high temperature storage tank. The storage tank is used as a buffer tank for either closed-loop over-temperature protection, collector preheating during start-up, or production of domestic hot water during periods of low irradiance. The solar process equipment is located in the same room with the plant steam boiler. Collector supply and return lines run up through the roof to the solar field. The existing domestic hot water tank was retrofitted with a multiple-pass, tube type heat exchanger to provide the additional system capability noted previously. The system is generally well insulated with a minimum of exposed pipe and fittings. Piping is arranged to minimize thermosyphoning between hot process lines, the storage tank, and the expansion tank. While the indoor piping has fairly low heat loss characteristics, the outside piping, namely collector field supply and return lines, has fairly large heat losses. This is primarily due to the long lengths and large number of pipe supports that exist. Since the DEL collector modules are quite small in aperture, there are correspondingly a higher

TABLE 1. SYSTEM DESCRIPTION

	Caterpillar Tractor	Dow Chemical	Home Laundry	Lone Star Brewery	Ore-Ida Foods	Southern Union	USS Chemicals
Location	San Leandro, CA	Dalton, GA	Pasadena, CA	San Antonio, TX	Ontario, OR	Lovington, NM	Haverhill, OH
Latitude	37.7	34.8	34.2	29.5	43.6	32.8	30.6
TMY Site	Oakland, CA	Chattanooga, TN	Los Angeles, CA	San Antonio, TX	Boise, ID	Roswell, NM	Cincinnati, OH
Coll. Area (m^2)	4684	923	604	878	927	937	4680
Orientation	NS	NS	NS	NS	11° W of N	EW	25° E of N
Tilt	0	10° to S	0	0	0	0	0
No. Rows	30	15	58	15	14	6	60
Row Length (m)	73.1	24.4	18.3	27.4	24.4	73.1	110
Row Spacing (m)	4.1	5.5	1.37	4.1	4.6	4.9	6.1
Grd. Cover Ratio	0.525	0.44	0.405	0.525	0.60	0.434	0.35
Process Type	HWPH	SB	SB/HWHX	SB	SF	SB	SB
Plant Schedule	24 hr/day, 6 day/wk	24 hr/day, 365 day/yr	7:00-3:30, 5 day/wk	24 hr/day, 365 day/yr	24 hr/day, 365 day/yr	24 hr/day, 365 day/yr	24 hr/day, 365 day/yr
Del. Temp. (°C)	113	187	166/66	177	174	191	151
FW Temp. (°C)	91	96	82/9.4	88	149	82	135
Collector Fluid	Water	Dowtherm LF	Water	Therminol 55	Water	Texatherm	T-60
Spec. Heat (kJ/kg°C)	4.20	2.22	4.21	2.37	4.60	2.54	2.08
Flow Rate (kg/hr)	98,320	11,271	15,840	13,200	10,500	17,900	72,450
Par. Energy (kJ/hr)	$6.4\ 10^4$	$7.0\ 10^3$	$2.6\ 10^4$	$5.3\ 10^3$	$2.5\ 10^4$	$5.7\ 10^4$	$7.3\ 10^4$

HWPH: Hot Water Preheat
SB: Steam-Unfired Boiler
HWHX: Hot Water-Heat Exchanger
SF: Steam-Flash Tank

number of header connections, more expansion loops, and more opportunities for energy to be lost.

At Lone Star the system uses SKI T-700 collectors which are roof-mounted and oriented N-S in 15 rows. The system is designed to produce 860 kPa saturated steam. Therminol 55 is circulated through the collector field producing steam in an unfired boiler. The solar system is located on the roof of a warehouse building housing the heat transfer equipment. The roof is penetrated by the main collector inlet and outlet headers in a direct-return configuration. The boiler makeup water is piped from a distant central plant treatment facility, but steam feeds directly into an adjacent plant header. The steam generator is maintained at a minimum pressure of 100 kPa from the plant steam line to prevent any possible leakage of collector heat transfer fluid into the steam system. By using small diameter piping and stepping down the pipe sizes along the collector header, the thermal capacity of the piping system was kept low. Insulating this piping system with a reasonable amount of insulation results in a low system heat loss. The expansion tank is thermally isolated from the piping system by the use of a long, small diameter connecting line. Valves and fittings are fully insulated leaving only handles exposed.

The system at Ore-Ida was designed to supply saturated steam at either 2.1 MPa or 9.9 MPa to heat cooking oil for potatoe frying. The solar system consists of 14 rows of SUNTEC SH1655 parabolic trough collectors oriented nearly N-S. This system uses water as the collector working fluid. Boiling in the collector field is suppressed by a back pressure valve located at the inlet of a steam-separator or flash tank. As pressure falls across the back-pressure valve, some of the water flashed to steam, is separated from the water flow, and delivered to the plant system. Liquid water is recirculated through the collector field together with makeup feedwater supplied at the pump suction to maintain the system inventory. At the upper steam delivery pressure the pressure drop across the flash valve is as high as 2 MPa. Consequently, electric power consumption is high and the circulating pump has a 40 hp rating. The collectors of the Ore-Ida solar system, in the original design, were located on the roof of the main production building allowing an efficient interface with the plant steam system. However, when structural considerations precluded a roof-mounted array, a new location at ground level was selected. Unfortunately, this location is over 200 m remote from the flash tank and circulating pump, located inside, close to the plant steam and water lines. The collector ground cover ratio, 0.60, dictated by the original roof-mounted design, is high for a site at this north latitude. Considerable row-to-row shading results, particularly in the winter months.

The Southern Union solar thermal system is designed to generate dry saturated steam to supplement the refinery's steam production. The solar system's 72 parabolic trough collectors (SKI T-700) are ground-mounted in six parallel rows, oriented E-W. A high temperature oil (Texatherm) is circulated through the receiver tubes then fed to an unfired steam generator where refinery feedwater is converted to steam at 190°C and a pressure of 1.28 MPa. The heat transfer equipment including the unfired steam generator, the expansion tank, the circulating pump, and much of the instrumentation, is located in a small building adjacent to the collector field. However, feedwater and product steam must be transported to and from refinery headers that are located over 400 m from the solar system. To inhibit scaling in the steam generator, water was originally blown down at a rate 10% of the steam flow whenever the steam flow exceeds 227 kg/hr. Present procedures call for manual boiler blow down during cloudy days. All piping is thoroughly insulated with fiberglass covered with a waterproof aluminum jacket. However, pipe supports are directly connected to the pipe. Fittings, such as valves, strainers, checks are partially insulated. The pump itself is not insulated so as to allow easy access. There is some thermosyphoning between transport piping and the uninsulated expansion tank.

The solar system at the USS Chemicals plant supplies saturated steam at 151°C for continuous production of industrial chemicals. The system consists of 60 rows of SKI T-700A trough collectors oriented 25° west of south. Honeywell suntrackers and controllers are used. Therminol 60 is circulated through the collectors and then fed to an unfired boiler where the steam is produced. The 60 rows of collectors are each 110 meters long and consist of three drive strings. Both the supply and return headers are stepped down in size along their lengths. All valves and pipes are extremely well insulated. No bare, uninsulated metal surfaces exist at all within the collector field. Even the valve hand wheels have removable insulated coverings. Pipe anchors are insulated to ground level. Pipe supports are constructed to completely eliminate metal-to-metal contact and thereby minimize thermal loss. The unfired steam generator and expansion tank are contained within a mechanical room adjacent to the collector field. The circulation pumps are located outdoors immediately next to the mechanical room. The pumps are well insulated.

4. COMPARISON OF SOLIPH WITH REPORTED DATA

The results of the SOLIPH predictions on an annual basis is summarized in Table 2. Not surprisingly, the two hot water preheat systems, Caterpillar and Home Laundry, perform better than the steam systems. This is due to the lower operating temperature. There is a large variation in the steam system performance due to the relative levels of thermal losses and thermal capacitances. Generally, however, a steam system can perform with efficiencies in the 30-35% range and preheat systems can expect performance in the 40-50% range. Performance on an annual basis was not compared since no system had reported sufficient data to make such a comparison. However, the monthly summary data reported by the site contractors was compared with SOLIPH predictions on a system efficiency basis. System efficiency was utilized to normalize the site data, which is based on actual solar irradiance, with the TMY solar irradiance data used by the SOLIPH code. In many cases, there were large differences between actual and TMY data, partly due to data acquisition or system downtime and natural yearly variations from the "typical" year modeled. Additionally, few of the systems were able to maintain consistent data collection over long periods, making comparisons difficult. Table 3 lists the monthly comparisons for those months where data was available from the contractor reports. Gaps in the listing indicates either solar system or data acquisition downtime, system shutdown for maintenance or repair operations, system construction or in one case, system decommissioning. A brief discussion of each system performance comparison follows.

At Caterpillar Tractor, where the reduced plant load can be exceeded by the solar system output, comparisons are nearly meaningless. To match the load sections of the field are not utilized and thus there is little plant incentive to clean the collectors. System performance is far from optimal under those conditions as evidenced by low reported performance compared to SOLIPH predictions. Since this system is by far the simplest, when and if production levels at the plant increase, comparison with predictions should be straightforward and hopefully provide a validation point for the SOLIPH code.

Performance at Dow Chemical is quite low due to the high heat losses experienced by the system. Apparently, system losses in the field are much higher than the SOLIPH model anticipated. Since the SOLIPH code estimates degradation in collector optical performance based on several fairly crude factors, there could be considerable difference between the estimated value and the actual degradation at the site. Some spot reflectivity checks were made at the site, however, glazing transmittance was not measured. The Dow system has recently completed a system upgrade which was designed primarily to reduce heat losses. This upgrade should improve the performance of the system considerably.

The dual operating modes at the Home Laundry and the continual shifting of modes to meet the changing process requirements result in a difficult modeling effort. No attempt to model the shifting modes was attempted. Separate runs for the steam and hot water modes were prepared. The comparisons in Table 3 represent a mixture of the modes in the reported data and an average of the two in the tabulated SOLIPH predictions. Except for the more recent months the predictions are reasonably close to the reported data. It appears that the actual performance has deteriorated over time for this system.

Maintenance problems at Lone Star, specifically flex hose failures, have resulted in poor system performance. The data in Table 3 indicates some months with very good agreement, when the system was operating nominally. Significant differences during other months are the results of operational difficulties. Lone Star is currently being modified from a steam system to feedwater preheat. This change should improve the performance due to a lower operating temperature and increase reliability due to a simplified system configuration.

Ore-Ida has had a very poor operational record, with significant periods of downtime, primarily due to pump failures. The plant managers no longer provide maintenance of the system due to the poor reliability and low energy delivery. The system has, unfortunately, ceased operation and only a single month's data has been acquired.

TABLE 2. SYSTEM PERFORMANCE PREDICTIONS

System	Incident Solar Energy		Energy Collected GJ	Collector Efficiency %	System Losses		Energy Delivered GJ	System Efficiency %
	Direct Normal GJ	Collector Plane GJ			Operating GJ	Non-Operating GJ		
Caterpillar Tractor	26450	22070	12420	56	510	480	11430	52
Dow Chemical	4060	3450	1540	45	510	230	790	23
Home Laundry								
Hot water	3090	2310	1220	53	130	95	980	42
Steam	3090	2310	1160	50	220	160	780	34
Lone Star Brewery	5140	4340	1810	42	250	190	1380	32
Ore-Ida Foods	6310	5100	2370	46	800	480	1130	22
Southern Union Refining	8440	6460	2800	43	430	320	2050	32
USS Chemicals	18200	13080	6260	48	510	990	4750	36

Collector and system efficiency based on incident energy in collector plane.

TABLE 3. COMPARISON OF REPORTED PERFORMANCE EFFICIENCIES WITH SOLIPH PREDICTED EFFICIENCIES (REPORTED/SOLIPH)

Month	Caterpillar Tractor	Dow Chemical	Home Laundry	Lone Star	Ore-Ida	Southern Union	USS Chemicals
June 1982	-	-	-	20/36	-	-	-
July	-	-	-	28/37	-	-	-
August	-	-	-	34/36	4/25	9/32	-
September	-	-	-	32/34	-	18/32	-
October	-	-	-	19/30	-	23/33	-
November	36/41	-	-	5/25	-	22/32	-
December	26/35	-	-	5/21	-	21/31	-
Jan. 1983	15/39	10/13	-	18/23	-	17/32	-
February	19/45	15/22	36/42	29/32	-	24/31	28/25
March	23/49	15/22	36/42	29/32	-	24/31	32/33
April	33/53	23/26	41/37	29/32	-	26/31	33/39
May	-	16/27	34/38	19/34	-	25/31	51/41
June	-	16/25	36/40	-	-	19/32	40/42
July	-	-/22	31/42	-	-	22/33	43/40
August	-	-/26	30/41	-	-	18/32	35/41
September	30/54	-/26	27/39	-	-	-	42/38
October	20/48	-/23	-	-	-	-	-

The operational record at Southern Union is longer than any other system modeled, however, within the reported data there are many small periods of operational difficulties. There have been several tracking and drive system problems which has reduced the performance of the system. During the best months SOLIPH still overpredicts the performance at this field experiment. Southern Union is also currently being upgraded to reduce the thermal losses and system capacitance and to improve reliability. Early results from the upgrade are encouraging.

Since its start-up the system at USS Chemicals has been by far the most reliable and consistent. The generally higher performance levels exhibited in the table show this clearly. On the average, SOLIPH predicts performance very well for this system. The variation in reported performance is due almost entirely to the cleaning schedule at the site. It is certainly not reasonable to say that SOLIPH is validated based on the data from USS Chemicals. It is a step closer to believing that SOLIPH can predict system performance when compared with a highly reliable, well instrumented system like that at USS Chemicals.

5. SUMMARY

The SOLIPH code has been shown capable of providing performance predictions for several solar IPH system configurations. When compared with the reported data from the field experiments, it appears that SOLIPH generally overpredicts system performance. However, the reliability and consistency of system operation in the field tends to cloud that conclusion. For the one system where high reliability and availability existed, SOLIPH predicted performance very well. It is possible that as system reliability improves with continued operation and experience that the SOLIPH code can provide reasonable estimates of system performance.

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7. REFERENCES

(1) Kutscher, C. F., et al., August 1982, Design Approaches for Solar Industrial Process Heat Systems, SERI/TR-253-1356, Solar Energy Research Institute, Golden, CO.

(2) Kutscher, C. F., "The Development of SOLIPH--A Detailed Computer Model of Solar Industrial Process Heat Systems," Solar Engineering - 1983 Proceedings of the ASME Solar Energy Division Fifth Annual Conference, Orlando, FL, April 18-21, 1983.

(3) Lewandowski, A. A., R. C. Gee, and E. K. May, January 1984, Industrial Process Heat Data Analysis and Evaluation: Final Report, SERI/TR-253-2161 (Draft), Solar Energy Research Institute, Golden, CO.