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

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PROJECT STATUS REPORT FOR THE MONTHS OF
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Submitted by

Solar Energy Applications Laboratory
Colorado State University

January 24, 1992

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January 24, 1992

Report No: SF-16306-32

Report Period: 1 November 1991 to 31 December 1991

PROJECT TITLE:

Developing, Testing, Evaluating and Optimizing Solar Heating and Cooling Systems

GRANT NUMBER: DE-FG03-86-SF16306

GRANTEE NAME: Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado 80523

GRANT PERIOD: 1 June 1986 to 29 February 1992

GENERAL STATUS:

1. Project Objective:

The objective is to develop and test various integrated solar heating, cooling and domestic hot water systems, and to evaluate their performance.

2. Technical Approach:

Systems composed of new, as well as previously tested, components are carefully integrated so that effects of new components on system performance can be clearly delineated. The SEAL-DOE program includes six tasks which have received funding for the 1991-92 fifteen-month period. These include: (1) a project employing isothermal operation of air and liquid solar space heating systems, (2) a project to build and test several generic solar water heaters, (3) a project that will evaluate advanced solar domestic hot water components and concepts and integrate them into solar domestic hot water systems, (4) a liquid desiccant cooling system development project, (5) a project that will perform system modeling and analysis work on solid desiccant cooling systems research, and (6) a management task. The objectives and progress in each task are described in this report.

3. Project Tasks:

SOLAR HEATING WITH ISOTHERMAL COLLECTOR OPERATION AND ADVANCED CONTROL STRATEGY

Status: Activity during November and December was devoted to finalizing the simulation (TRNSYS) parameter studies on constant temperature and constant flow solar heating. Eighteen seasonal TRNSYS runs have been performed which consist of constant flow/variable temperature and constant temperature/variable flow solar system operation for three locations: Denver, Madison, and Washington, DC. Under each of these six cases there is a comparison of three solar system sizes normalized to collector area. The solar system sizes correspond to that yielding a

fifty percent seasonal solar fraction, a size corresponding to one half that of fifty percent solar fraction, and the third being a size one and one half times the fifty percent solar fraction size.

GENERIC SOLAR DOMESTIC WATER HEATING SYSTEMS

Status: Design of the solar simulator for normal incidence testing is nearly complete. The goal is to irradiate a collector 2.44 m x 1.22 m with an average irradiance of 1000 W/m² with a uniformity of ± 10 percent of the average. A lamp-to-collector spacing of 2.95 m was selected for preliminary assessment of the 28-lamp array. In this configuration, uniformity of irradiance over the 2.97 m² collector is ± 20 percent of the average irradiance of 1010 W/m². The next step is to refine placement and power levels of each lamp to determine the final configuration. This task will be completed in the next week.

Construction of the solar simulator is underway at the Engineering Research Center. A new transformer and electrical connections have been installed and cabinets containing the ballasts and variacs for the lamps are complete.

Analyses of the experimental data from 12 generic anti-freeze DHW system trials is focused on the effects of flow rate and heat exchanger effectiveness. All necessary specifications are included for either FSEC or UW to carry out the equivalent TRNSYS ratings.

ADVANCED DOMESTIC HOT WATER (DHW) SYSTEMS

Status: During this period, the Advanced DHW Working Group meeting for the January 27 -February 1 Task XIV Meeting was organized and the conventional (and low) flow collector simulation model was refined.

LIQUID DESICCANT COOLING SYSTEM DEVELOPMENT

Status: Condensation rate studies are being continued for the structured packing (Munters CELDEK) installed in the dehumidifier. The slope of the graph of condensation rate versus the solution flow rate is found to be 0.84 and the value of the intercept obtained from the Wilson's plot is 0.009. The values of the slope and the intercept obtained from the evaporation rate studies carried out for the random packing in the regenerator are 0.82 and 0.009, respectively. The values of slopes obtained for both towers suggest that the towers are operated under well-mixed, nearly turbulent conditions for liquid flow. The values of the intercepts suggest that gas phase mass transfer resistance is negligible and the Lewis number is greater than 1, unlike that for the air/water operations.

A twin bulb apparatus is being considered for measuring the diffusivity of water in LiBr solution, using tritiated water

(TOH). However, the preliminary estimate of time (based on the diffusivity of water in LiCl solution) required to obtain a single measurement, is found to be very large (nearly 4 days). Therefore, alternative methods for measuring diffusivity are also being explored to reduce the duration and increase the accuracy.

ANALYSIS OF ADVANCED SOLID DESICCANT SOLAR COOLING SYSTEMS

Status: Activities during November and December were devoted to the selection of conditions, parameters, and components for the desiccant cooling cycle models. The simulation efforts will begin with the Pennington (ventilation) cycle and proceed to advanced cycles. Current recommendations for the advanced cycles are the SENC, SEAL, and DINC cycles. The models will be developed using silica gel as the desiccant.

MANAGEMENT AND COORDINATION OF COLORADO STATE/DOE PROGRAM

Status: Coordination of research activities continued on the five research tasks under the DOE grant, and accounts were maintained and updated. Bimonthly financial and technical reports as required.

SOLAR HEATING WITH ISOTHERMAL COLLECTOR OPERATION AND ADVANCED CONTROL STRATEGY

Research Team:

Charles C. Smith, Task Leader
George O.G. Löf, Senior Advisor
Douglas C. Hittle, Advisor
Ihsan A. Abbud, Graduate Research Assistant

Objectives:

As principally a systems performance laboratory, an objective in recent years at the Colorado State University Solar House I has been to increase overall system performance at negligible added cost. This effort has proven most successful in the areas of improved control strategy and temperature stratification in the water storage tank. Seasonal system efficiency, the ratio of useful energy to space heating divided by solar energy on the collector surface, increased from 36 to 50 percent. Or, in economic terms, the value added to the system is 39 percent without appreciable cost increase.

While increased system efficiencies continues to be an important objective of this task, it is recognized that other factors are critical to owner acceptance of solar heating. Comfort, convenience, and physical compactness of systems are equally important and shall be addressed in the project.

A companion objective is the improvement of indoor air quality by use of increased ventilation levels to the space while it is heated. Awareness of radon, formaldehyde, and other pollutants within tightly constructed buildings has brought this matter to a new importance.

The principal objectives of the 1991 solar heating project are to develop control options and to model the use of flat plate collectors and dual temperature zone, single tank storage for isothermal operation.

Work Plan:

1. Model the effects of employing commercial type flat plate collectors in isothermal operation under different load patterns and solar availability.

It is proposed to model the performance of flat plate collectors under isothermal operation. The flat plate collector will respond somewhat differently to isothermal control due to greater environmental sensitivity of flat plates compared with the presently employed evacuated tube type. We expect that isothermal control will benefit flat plate systems even more than evacuated tube systems.

2. Model the effects of a single storage volume capable of maintaining two temperature zones of 25 C (or greater) difference.

The use of a single, but highly stratified, storage unit will be modelled. This will be performed in order to specify the best

design, geometry, or configuration such as multiple smaller tanks in series.

3. Simulate and assess the use of solar (radiation) sensor controlled collector pump as a means of approximate isothermal collector operation without temperature feedback control.

Perfecting this control strategy could simplify the hardware and/or permit the use of a PV-powered pump.

4. Identify motor/pump units which will provide variable volume flow efficiently and economically.

Under this effort, we will collaborate with motor and pump manufacturers to select or develop an appropriate variable speed pumping system for typical solar heating systems.

5. Introduce advanced control strategies to control collector loop flow.

The present system will be operated with a newly installed PC computer data acquisition/control system. This system will be used to test the best strategies for pump control for isothermal operation. Problems associated with pump start-up for the drainback system need to be resolved and tuning criteria need to be developed.

Progress:

Activity during November and December was devoted to finalizing the simulation (TRNSYS) parameter studies on constant temperature and constant flow solar heating. Eighteen seasonal TRNSYS runs have been performed which consist of constant flow/variable temperature and constant temperature/variable flow solar system operation for three locations: Denver, Madison, and Washington, DC. Under each of these six cases there is a comparison of three solar system sizes normalized to collector area. The solar system sizes correspond to that yielding a fifty percent seasonal solar fraction, a size corresponding to one half that of fifty percent solar fraction, and the third being a size one and one half times the fifty percent solar fraction size.

Some preliminary results of the simulation study are presented in the figures. Figures 1, 2, and 3 show solar fraction of the heating loads provided under constant flow and constant temperature solar operation for the three locations mentioned. Figure 4 is a summary of electrical energy requirements showing the portions of energy used by the collector pump and the heating load loop pumps separately.

This information is currently being analyzed for final presentation in a more concise graphical form. The results indicate that seasonal solar fractions are slightly lower for constant temperature operation than for constant flow. This difference may be attributed to lower average temperature operation in constant flow. Under constant temperature operation, the collector outlet temperature is held at 60°C. This contrasts with constant flow operation in which collector outlet temperature varies from 42 to 60°C.

Figure 1
DENVER SOLAR FRACTION

Figure 2
MADISON SOLAR FRACTION

Figure 3
WASH DC SOLAR FRACTION

Figure 4
ELECTRIC ENERGY REQ'D
Const Flow vs. Const Temp

A very significant finding from the simulation data is a reduction in pump operation and in pumping energy use under constant temperature operation, both in the collector loop and the load loop. Overall pumping energy is typically one-fourth of the energy required in constant flow operation.

GENERIC SOLAR DOMESTIC WATER HEATING SYSTEMS

Research Team:

Jane H. Davidson, Task Leader
William S. Duff, Co-Task Leader
Mark Thornbloom, Graduate Research Assistant
Steve Kenny, Graduate Research Assistant

Objectives:

Certification of any solar domestic hot water (DHW) system by the Solar Rating and Certification Corporation (SRCC) currently requires an extensive laboratory system test in addition to the collector test. This procedure places a significant economic burden on a low sales volume industry and reduces the overall cost competitiveness of solar DHW versus gas and electric systems.

A research program supported by the Department of Energy to investigate the feasibility of a more cost effective rating method for solar DHW systems is now in progress at the Solar Energy Applications Laboratory (SEAL) at Colorado State University in conjunction with the University of Wisconsin, Solar Energy Research Institute (SERI) and SRCC. The main thrust of the research is to determine if ratings of solar DHW systems can be accurately based on computer simulations. The immediate goal is to determine if the simulation program, TRNSYS, can accurately predict the performance of drain-back, recirculation, anti-freeze, thermosiphon and internal collector storage solar DHW systems.

Work Plan:

1. Experimental study of the anti-freeze system is currently underway and results will be presented in July at a group meeting to be held in Washington, D.C. Study will focus on heat exchanger design and operation and system flow rates.
2. The single test of the recirculation system will be completed later in the summer. This delay is due to an agreement by project participants that additional study of flow rates in the anti-freeze system are needed.
3. A generic systems program for thermosiphon and internal collector storage (ICS) SDHW systems will be initiated. Colorado State, in cooperation with SRCC, representatives from the U.S. solar industry, SERI, and University of Wisconsin, will develop and carry out an experimental study of these systems. A solar simulator will be added to current outdoor testing facilities at SEAL to accomplish this phase of the project.
4. Thermosiphon system performance will be investigated for a system using a wrap-around heat exchanger. Stratification in horizontal tanks will also be explored. It is expected that the thermosiphon work will be completed during this project period.
5. Study of the ICS system will focus on determining if an analytical ray trace can be used to accurately predict incidence angle modifiers

for three complex geometries (tube storage tank in a "bread box", tube storage tank with parabolic shaped collector, and tube storage tank in a tubular collector). The ICS experimental results will be completed in the 1992 budget period.

6. Additional efforts in the 1992 budget period include validation of an analytical approach for predicting performance of non-generic DHW systems such as the Copper Cricket.

Progress:

Solar Simulator

To determine the optimal placement and power level of the twenty-eight 1000 W Thorn Compact Source Iodine (CSI) lamps in the final solar simulator design, radiation flux measurements from a single lamp are numerically combined. Irradiance measurements at normal incidence have been completed with and without the box collimator. Comparison of the irradiance contour plots of Figures 5 and 6, with and without the collimator respectively, shows that at a lamp-to-collector spacing of 2.95 m the box collimator focuses light over nearly a 13 percent smaller area with a corresponding increase in average irradiance. All data are obtained with lamp power levels set at 1000 W. Considering a 0.64 m^2 area, the average power level at the collector plane is 288 W without the collimator and 324 W with the collimator.

The effect of lamp-to-plane spacing on the spread and intensity of radiation levels at the collector plane are evident in a comparison of the data in Figures 7 and 8, obtained at spacings of 2.84 m and 3.05 m, respectively. As the lamp is pulled back from the collector plane, the highest irradiance is decreased from 957 W/m^2 to 830 W/m^2 . Total irradiated area increases 6.5 percent based on a reduction in average power from 197 W to 185 W over a collector plane area of 1.2 m^2 .

Using multiple lights, our goal is to irradiate a collector $2.44 \text{ m} \times 1.22 \text{ m}$ with an average irradiance of 1000 W/m^2 with a uniformity of ± 10 percent of the average. ASHRAE standard 93-1986 requires a minimum average irradiance of 790 W/m^2 . Based on these requirements, a lamp-to-collector plane distance of 2.95 m was selected for preliminary assessment of the 28-lamp array. Contour maps of the multiple bulb array are determined by overlaying the data to simulate a full-scale system. Figure 9 shows a simulated irradiance contour plot of 28 Thorn CSI lamps over an area of approximately $2.5 \text{ m} \times 3.8 \text{ m}$. The lamps are evenly spaced at 44.5-cm intervals in an array of 4 bulbs by seven bulbs. A first attempt at uniformity was made by increasing power 5 percent (to 1050 W) at the corners and decreasing power at the center of the array by as much as 20 percent as shown in Figure 10. Uniformity of irradiance over the 2.97 m^2 collector is ± 20 percent of the average irradiance of 1010 W/m^2 . The next step is to refine placement and power levels of each lamp to determine the final configuration. This task will be completed in the next week.

Construction of the solar simulator is underway at the Engineering Research Center. A new transformer and electrical connections have been installed and cabinets containing the ballasts and variacs for the lamps

Figure 5 - Irradiance contour plot of a single CSI lamp with a collimator. Distance from bulb-to-test plane is 2.95 m. The average irradiance is 324 W and the power level setting is 1000 W.

Figure 6- Irradiance contour plot of a single CSI lamp without a collimator. Distance from bulb-to-test plane is 2.95m and measurement grid spacing is 5.56cm. The power level setting is 1000 W and the average irradiance is 288 W.

Figure 7- Irradiance contour plot of a single CSI lamp with collimator at a power of 1KW. Distance from bulb-to-test plane is 2.85 m and measurement grid spacing is 5.56 cm. The maximum irradiance of this test is 957 W/m².

Figure 8- Irradiance contour plot of a single CSI lamp with collimator at a power of 1kW. Distance from bulb-to-test plane is 3.05 m and measurement grid spacing is 5.56 cm. The maximum irradiance of this test is 830 W/m².

Figure 9- The contour plot is a simulation of twenty-eight Thorn CSI lamps irradiating an area of approximately 2.5m x 3.8m at a distance of 2.95m from the bulb. The measurements are in W/m². The uniformity of irradiance over the area of a 1.25m x 2.5m solar collector is $\pm 20\%$ of the average irradiance. The average irradiance of that area is 1010 W/m². The ASHRAE standard calls for a uniformity of $\pm 10\%$ of the average.

1050	1000	1000	1050
1000	850	850	1000	
950	800	800	950	
950	800	800	950	
950	800	800	950	
1000	850	850	1000	
1050	1000	1000	1050	

Figure 10- Lamp power meter settings, in Watts, used to simulate the complete 28 bulb array. The power is increased at the corners and decreased in the center to uniformly irradiate the collector surface. The bulbs are evenly spaced at 44.5 cm and the power setting varies from 1050 W to 850 W.

are complete. Final wiring of the lamp controls should be complete next week. We have not received the final collimator and fan assemblies from Kirk Collier, but these should be here in time to install the lamps in February. Off-normal irradiation measurements have been initiated.

Generic Anti-Freeze

A summary of the 12 experimental ratings of the generic anti-freeze system were presented in the last bi-monthly report and are shown here in Table 1 for clarification of the analyses of error and heat exchanger effectiveness. The data are illustrated in Figures 11 and 12 along with error bars. The useful energy shown in Figure 11(a) for trial 11 is surprisingly high. A comparison of the measured value of Q_u along to the theoretical reference value in Figure 13 indicates that control of the boiler in this particular trial was inadequate. Normally, the boiler is controlled by increasing or decreasing electrical input by 10 percent until the measured daily energy input is within 30 kJ (about 0.1 % of a typical daily value of Q_u) of the reference value. With the low flow rates of trial 11, this adjustment was inadequate. We are now repeating this trial.

Figure 14 shows 15 minute values of heat exchanger effectiveness over the last day of each experimental trial. Values range from approximately 0.16 to 0.35. Statistical analyses are underway to determine the significance of a change in heat exchanger effectiveness within this range to a change in daily solar output.

Table 2 includes specifications needed for TRNSYS simulation of the SRCC ratings. In is our understanding that either FSEC or University of Wisconsin will carry out the simulations in a blind test.

Summary of Experimental Results

Trial	Heat Exchanger Type	Collector Flow Rate [l/s]	Recirculation Flow Rate [l/s]	SF [%]	Q _{del} [kJ]	Q _s [kJ]	Q _{net} [kJ]	Q _{res} [kJ]	Q _{aux} [kJ]	Q _{par} [kJ]	Q _u [kJ]
1	1	0.114	0.170	41.24	49810	24829	20540	17978	29941	4289	31068
2	1	0.114	0.085	39.58	49810	23950	19714	17285	30560	4236	30042
3	1	0.228	0.170	44.27	49812	26466	22052	19600	28729	4415	31199
4	1	0.228	0.085	41.69	49815	25165	20769	18222	29715	4396	29710
5	2	0.114	0.170	36.16	49811	24329	18013	18549	31813	6316	29326
6	2	0.114	0.085	42.03	49814	25235	20937	17989	29842	4298	30642
7	2	0.228	0.170	37.82	49819	25489	18843	19101	30141	6646	29967
8	2	0.228	0.085	34.64	49812	23582	17257	18080	31835	6325	29863
9	1*	0.114	0.176	33.24	49812	20869	16558	16145	34275	4312	28086
10	1*	0.114	0.095	33.76	49811	21105	16817	15779	33777	4288	27842
11	1	0.057	0.043	35.52	49812	22116	17693	15214	32650	4423	31780
12	2	0.057	0.043	36.05	49810	22379	17964	15079	32621	4416	28509

* Inverted Heat Exchanger: Inlets are at the bottom

Table 1.

Useful Energy Collected, Q_u

Error Bands are Experimental Error

Figure 11a.

Auxiliary Energy, Q_{aux}

Error Bands are Experimental Error

Figure 11b.

Experimental Measurement of (a) Daily Useful Collected Energy Q_u and (b) auxiliary energy Q_{aux} for the Generic Anti-Freeze DHW System

Solar Energy Delivered, Q_s

Error Bands are Experimental Error

Figure 12a.

Net Solar Energy Delivered, Q_{net}

Error Bands are Experimental Error

Figure 12b.

Experimental measurement of (a) solar energy delivered Q_s and (b) net solar energy delivered Q_{net} for the Generic Anti-Freeze DHW system

Qu: Reference vs. Measured Trial 11

Summation of Qu Trial 11

Figure 13. Comparison of reference and measured values of daily useful collected energy Q_u over the last solar collection day of Trial 11.

Figure 14. Heat Exchanger Effectiveness of Trials 1-12
Generic Anti-Freeze DHW System

TABLE 2.

Anti-Freeze System Component Specifications

Component	Specification	Value	Notes
Collector loop fluid	50/50 ethylene glycol	Property values from ASHRAE Fundamentals	
Collector	Total Area	5.56 m ²	
	F _r α	0.602	
	F _r U _i	5.55 W/m ² /K	
	K _r α @ Beta = 0	1.00	
	15	0.97	
	30	0.90	
	45	0.75	
	60	0.58	
	mC _p /Area (test)	74.0 W/m ² /K	1
Solar Storage Tank	Volume	246 liter	2
	R-Value	2.10 C m ² /W	
Auxiliary DHW	Volume	159 liter	2
	R-Value	2.10 C m ² /W	2
	Set Point	55 C	
Heat Exchanger	1	Counter flow, copper, double wall, micro-finned	
		Heat exchange area	0.214 m ² 2
	2	Counter flow, 8-pass, copper, double wall, no fins	
		Heat exchange area	0.279 m ² 2
Pumps:			
Collector	Type	Grunfus Type UP 15-42-F	2,4
		Power (nominal) 85 W	
Recirculation	Type	Grunfus Type UP 26-96F	5,6
		Power (nominal) 205 W	
		Grunfus Type UP 15-18SU	2,4
		Power (nominal) 85 W	
		Grunfus Type UP 15-42-F	5
		Power (nominal) 85 W	
Piping	Size and Type	Grunfus Type UP 26-96F	6
		Power (nominal) 205 W	
	Insulation Type	Closed Cell Foam, 1.9 cm	
	Insulation R-Value	0.82 C m ² /W	
	<u>Lengths:</u>		
	Heat Exchanger to Collector	10.82 m	3
	Collector to Loop Heater	1.39 m	3
	Loop Heater to Heat Exchanger	11.71 m	3
	Heat Exchanger to Solar Storage Tank	2.90 m	3
	Solar Storage Tank to Heat Exchanger	3.15 m	3
Valves	Type	Gate	
	Size	19 mm	

- Notes
1. Value pertains to time of collector rating test.
 2. Manufacturer's rating.
 3. Value is based on measurements made in laboratory.
 4. Used in all Trials with HX 1, ie. Trial 1-4, and 9-11; and Trials 6 and 12 with HX 2.
 5. Used in Trial 8
 6. Used in Trials 5 and 7

ADVANCED SOLAR DOMESTIC HOT WATER (DHW) SYSTEMS

Research Team: William S. Duff, Task Leader
Jane H. Davidson, Co-Task Director
Ron Hill, Graduate Research Assistant

Objectives:

In the next few years, a renewed United States mass market for residential solar DHW systems is expected to develop as heightened environmental concerns spawn legislation and other incentives for alternative energies and energy conservation. This market will be accessible to products from other countries that are currently being developed with substantial research and development support from their governments. For United States manufactured solar DHW systems to remain competitive, cost effective solar DHW systems employing advanced materials, components, and concepts must be developed.

A research project funded by the Department of Energy to identify, analyze, design, build, and experimentally evaluate such solar DHW systems is currently underway at the Colorado State University Solar Energy Applications Laboratory. The objective of this project is to substantially lower costs and improve performance of commercial solar DHW systems in the United States. Several United States manufactured solar DHW systems with desirable features will be chosen as starting points for the design improvement process. As a means of identifying many promising materials, components, and concepts, this project is participating as the United States solar DHW installation in the International Energy Agency Task on Advanced Solar Energy Systems. Results from this project, as well as results from the International Energy Agency activities, will be disseminated to the United States solar energy industry.

Work Plan:

- 1) Represent the United States DOE as the United States Advanced DHW project leader in IEA Task XIV. This activity includes preparing reports on the United States single-pass and internal collector storage DHW systems work and discussing this and other United States solar DHW work at the meetings.
- 2) Represent the United States DOE as the leader of the IEA Task XIV working group. This activity includes preparing for and leading the working group meetings, summarizing the results, preparing the working group work plans, reminding participating countries of their deadlines, and working with the Task XIV Operating Agent to insure that working group goals are met. (In a later contract period this activity will include writing a Task XIV Advanced DHW Systems report.)
- 3) Report other information to working group participants as may be necessary.
- 4) Simulate the behavior of single-pass solar DHW system variable flow and radiation switch controllers. Study the effects of stratification and stratification enhancing devices. Develop a systems simulation for the single-pass DHW and baseline systems that incorporates component models developed by us, SERI, and other participating IEA countries. Develop an optimum design for the single-pass system based

on cost, performance and reliability. Prepare a plan for building and testing this system.

- 5) Assemble and integrate the Colorado State University Generic Systems incident angle modifier studies and other work for the Internal Collector Storage systems into IEA Task XIV activities.
- 6) Communicate the results and planned activities of the Colorado State University Advanced DHW task to the United States solar industry.

Progress:

The primary activities for November and December were:

- 1) Organizing the Advanced DHW Working Group meeting for the January 27 - February 1 Task XIV Meeting.
- 2) Refining the conventional (and low) flow collector simulation model by verifying constituent areas, flow rates, operating ranges, flow passage diameters, fin areas and thicknesses, absorptances, transmittances, insulation thicknesses, and so forth, and by comparing resultant performance models to SRCC rating results.

LIQUID DESICCANT COOLING SYSTEM DEVELOPMENT

Research Team: Terry G. Lenz, Task Leader
Shailesh Potnis, Graduate Research Assistant

Objectives:

Primary objectives of this project include the development, testing, and performance evaluation for a liquid desiccant cooling system on Solar House II at Colorado State. Our existing experimental cooling system comprises solar collectors, two simple packed-bed contactors (a dehumidifier and a regenerator), heat exchangers, blowers, pumps, air pre-conditioning equipment, and data-acquisition hardware, as shown on the accompanying schematic diagram.

Work Plan:

1. Determine the characteristic mass transfer dimension for our Tripak random packing.
2. Obtain water diffusivity data for concentrated liquid desiccant solutions.
3. Carry out further mass transfer studies on the dehumidifier to complete the reciprocal coefficient analysis for random Tripak packing and structured Munters packing.
4. Conduct detailed mass transfer studies on the regenerator, analogous to those carried out on the dehumidifier, to assess the relative resistance to mass transfer for the gas and liquid films.
5. Provide bi-monthly progress reports and a final technical report covering our liquid desiccant system work.

Progress:

Condensation rate studies are being continued for the structured packing (Munters CELDEK) installed in the dehumidifier using various flow rates to get a wider range and to check the repeatability of the results obtained earlier. The slope of the graph of condensation rate versus the solution flow rate is found to be 0.84 (Figure 15), which is very close to the value obtained for the random packing (0.8). This value of the slope also suggests that the dehumidifier is operated under well-mixed, nearly turbulent conditions for liquid flow, as was the case for random packing.

The Wilson's plot obtained from this graph is again found to be a straight line with intercept 0.009 (Figure 16). This small value of the intercept suggests that the gas phase mass transfer resistance is negligible, as it was for the random packing, and the Lewis number is greater than 1, unlike that for the air/water operations.

Experiments are also being continued for carrying out evaporation rate studies for random packing in the regenerator. The slope of the graph of evaporation rate versus solution flow rate is found to be 0.82 (Figure 17) with R^2 of 0.93. This value of the slope suggests that the regenerator is being operated under well-mixed, nearly turbulent conditions for liquid flow.

Fig.15 Variation of condensation rate
with solution flow rate.

Fig.16 Wilson's plot for the structured packings in the dehumidifier.

Fig.17 Variation of evaporation rate
with solution flow rate.

A straight line is obtained for the Wilson's plot constructed using this graph (Figure 18) and the intercept is found to be 0.009. The value of the intercept suggests that the gas phase mass transfer resistance is negligible and the Lewis number is greater than 1, unlike that for air/water operations.

Efforts are in progress to set up an apparatus for measuring the diffusivity of water in LiBr solution using tritiated water (TOH). Figure 19 shows the conceptual apparatus. LiBr solution of known concentration will be filled in both the flasks and in the tube connecting the two flasks. The valve in the connecting tube will then be closed and a small amount of TOH will be injected into flask 1. The valve in the connecting tube will be opened after the concentration of TOH in flask 1 is uniform. The increase in the radioactivity in flask 2 will then be measured using a Liquid Scintillation Counter (LSC). From this data, the diffusivity can be found using the following equation,

$$\frac{\Delta C}{\Delta t} = D \frac{\Delta' C}{\Delta X} \times \frac{a}{V} \quad (1)$$

where,

- ΔC = concentration difference for flask 2
- Δt = time interval between two measurements
- ΔX = distance between two flasks
- D = diffusivity
- a = cross-sectional area of the connecting tube
- $\Delta' C$ = concentration difference between two flasks
- V = volume of the liquid in flask 2

The preliminary estimate of the time (Δt) required for sufficient activity increase in flask 2 is obtained using the diffusivity of water in LiCl solution. Even though the experimental procedure appears to be simple, this time duration is very large (nearly 4 days). Therefore, alternative methods for measuring the diffusivity are being explored to reduce the duration and increase the accuracy.

Fig.18 Wilson's plot for the random packings in the regenerator.

Fig.19 Apparatus for measuring diffusion of water in LiBr solution

ANALYSIS OF ADVANCED SOLID DESICCANT SOLAR COOLING SYSTEMS

Research Team:

Charles C. Smith, Task Leader
George O.G. Löf, Senior Advisor
Douglas C. Hittle, Advisor
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Objectives:

Research on solar cooling with solid desiccant systems began with the ASK Energymaster unit in the summer of 1987. The first system employed a process known as the Pennington cycle. All of the conditioned air for cooling was supplied from the outside. It was dehumidified, and cooled by heat exchanger, then by evaporative cooling. This cycle exhibited the expected cooling capacity for the unit (3 tons), and a COP of 1.0. The following year an advanced cycle (SENC) was introduced which provides sensible cooling in the recirculated house air duct and yields a higher COP. The COP increased to approximately 1.5; however the capacity dropped substantially to the range of 1.0 to 1.5 tons.

The 1988 experiments were aimed primarily at increasing the capacity of the SENC cycle. The best available commercial cooling tower was not suited for this application. It provided too little residence time for the cooling water and wasted much of the dehumidifying effect provided by the ASK. The cooling tower was rebuilt with new packing, improved water distribution, and provisions for greater air and water flow adjustments. The duct cooling coil was also increased in size by fifty percent to better match the increased cooling tower capacity. Although these changes resulted in some improvement in the cooling capacity, the desired 3-ton target was not reached.

During 1989, important information was generated from an analysis based upon the tests of previous years. The analysis employed a TRNSYS computer model with values of specific engineering parameters based on the actual equipment used in the experiments. This work revealed that some earlier modeling used unrealistic performance values for components and thus explained partially the shortfall in experimental performance. Most important, the analysis revealed some improvement recommendations which involve adjustments in air flow, cooling water flow, and desiccant wheel speed. It was also shown that the cooling capacity could be significantly increased with modest increases in regeneration temperature. A major item identified in this study was a shortfall in the experimental cooling tower capacity.

In August of 1990 a meeting of Colorado State, ASK, and Texas A&M experts was held to review the status of the solid desiccant cooling project and offer recommendations for its future course. The findings of the Colorado State analysis were confirmed by this group. Evaluation of the results showed, moreover, that the desiccant wheel had not been dehumidifying up to specifications, and that there had been physical loss of the desiccant material itself. The desiccant wheel was resupplied with the proper quantity of lithium chloride.

Wheel speed and air flow adjustments were also performed. These improvements were tested for short periods and only with respect to ASK unit

performance (not the overall system performance), due to limited time and funding. These tests indicated that significant improvement in overall cycle performance is possible, both for the Pennington and SENC processes.

Work Plan:

The primary objective of the solid desiccant cooling project is to analyze and model the advanced, high efficiency cooling cycle based upon recent and increased knowledge of potential improvements. Specific tasks to be accomplished in this grant period include:

1. Summarize existing simulation and experimental results in a form and format to assist DOE program managers in the continued refinement of the solar desiccant cooling program.
2. Use TRNSYS to simulate the SENC solar cooling cycles using improved desiccant and heat wheel models (with the TRNSYS 13.1 and later versions).
3. Simulate and analyze the SENC cycle with separation of the process and building air streams through the cooling coil.

This modification has been reported as the CHILLC cycle, but with no performance information. By separating the process and building air streams at the cooling coil, two advantages are realized. A second law performance penalty is avoided by preventing the mixing of two streams of air at different psychometric conditions. Secondly, the process air flow rate can be optimized independently of the building air flow rate.

4. Simulate and analyze the SENC cycle with building return air used as supply air to the dehumidifier.

Another variation to the present SENC cycle which needs to be analyzed is one in which the building return air is used as supply air to the dehumidifier. One advantage of using the building return air is to again increase the air flow rate through the desiccant and heat exchanger elements of the system. A second advantage is that this air usually has lower humidity. Lower humidity conditions would not prevail at all times, and thus modeling of the overall performance is needed.

Progress:

Activities during November and December were devoted to the selection of conditions, parameters, and components for the desiccant cooling cycle models. The simulation efforts will begin with the Pennington (ventilation) cycle and proceed to advanced cycles. Current recommendations for the advanced cycles are the SENC, SEAL, and DINC cycles. The models will be developed using silica gel as the desiccant.

As an intermediate determination of parameters and performance the models will be run at steady-state ARI conditions. Comparison with the results of other investigators will be made. These cycles can be simulated

with different regeneration (solar input) temperatures at ARI conditions for initial evaluation.

For seasonal evaluation, a cooling unit of three tons capacity will be matched with buildings at three geographic locations as the design cooling load. Los Angeles, Chicago, and Washington D.C. have been selected. A solar system which provides approximately fifty percent of the cooling load will be employed.

Depending upon results at ARI conditions, seasonal simulations at three sites with constant flow/variable temperature solar and with constant temperature (isothermal) solar at selected settings (i.e., 60, 70, and 80°C) will be run. Seasonal cooling output, solar fraction, thermal COP, and thermal plus electrical COP will be determined.

Supporting activities include:

- Determine practical effectiveness values for use in the models. Discuss pros and cons of equipment selections. Establish RELATIVE costs of the desiccant systems.
- Determine the electrical power associated with the equipment selected and the flow rates used.
- Select and justify the control strategies.
- Obtain monthly cooling load and ambient temperature/humidity data for the candidate sites from TMY weather tapes and the BLAST building load model library.

MANAGEMENT AND COORDINATION OF COLORADO STATE/DOE PROGRAM

Research Team: Douglas C. Hittle, Director
George O.G. Löf, Senior Advisor
Janice M. Stapleman, Administrative Assistant

Objectives:

Coordinate SEAL-DOE task efforts, provide assistance to DOE, and attend programmatic meetings as requested by DOE.

Work Plan:

1. Collaborate with leaders of the five technical tasks in coordination of SEAL program.
2. Organize team and sub-team planning sessions necessary for the conduct of the tasks.
3. Provide and manage necessary facilities and services to leaders and personnel involved in each task.
4. Provide timely bimonthly reports on all tasks as required by contract.
5. Maintain fiscal control of program.
6. Attend meetings and technical reporting sessions as requested by DOE.
7. Assist DOE in developing multi-year program plans.
8. Respond to DOE requests for information on solar equipment and its operation, for review of reports, and for panel and committee participation.
9. Provide technical consultation from director and senior advisor to task leaders and research personnel.

Progress:

Coordination of research activities continued on the five research tasks under the DOE grant, and accounts were maintained and updated. Bimonthly financial and technical reports as required.

END

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