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

PROJECT STATUS REPORT FOR THE MONTHS OF
JANUARY THROUGH AUGUST 1991

Prepared for the

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Conservation and Solar Applications
Under Grant DE-FG03-86-SF16306

Submitted by

Solar Energy Applications Laboratory
Colorado State University

October, 1991

MASTER

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October 28, 1991

Report No: SF-16306-30

Report Period: 1 January 1991 to 31 August 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 January, February and March was devoted to hardware and software development for control of collector flow by a solar radiation sensor. The hardware components for radiation sensor control are the same as those for temperature controlled flow rate with two exceptions: the temperature sensor was replaced by a pyranometer, and the pump motor controller was changed from a full range, variable power unit to one with nine steps of power variation.

Activities during April through August turned from system operation and monitoring to development and the running of TRNSYS computer simulations. The objective of computer simulation is to optimize the design parameters for isothermal operation, and to compare the estimated thermal performance of isothermal with constant flow collector operation in three strategic US locations. Preliminary results have been obtained for the case of flat plate collectors providing approximately fifty percent solar fraction of the space heating load in a residential style building in Denver.

GENERIC SOLAR DOMESTIC WATER HEATING SYSTEMS

Status: Experimental analyses of 9 rating trials of the generic anti-freeze system are completed. Analyses of the thermosiphon and ICS systems await the completion of the solar simulator facility. Kirk Collier indicates that the 28 collimator units will be delivered by November 1, 1991. Power for the facility is now being installed at the Engineering Research Center and our target date for installation of the facility is January 1, 1992.

ADVANCED DOMESTIC HOT WATER (DHW) SYSTEMS

Status: Primary short-term project emphasis is being placed on matched flow DHW systems and longer-term emphasis on integral collector storage systems. A matched flow system is defined as a SDHW system where collector flow allows the storage to be stratified optimally in regard to the load and storage volume. Other SDHW systems that are being examined are the passively vented American Solar Network system and the Copper Cricket.

Modeling is currently being carried out on one- and two-tank versions of five SDHW systems: (1) A baseline "most representative" United States system; (2) A variable flow control strategy system; (3) A low flow system with stratification manifold; (4) A low flow system with a stratification enhancing internal heat exchanger; and (5) The passively vented collector American Solar Network system.

Optimized designs of these systems will be experimentally evaluated in the next contract period beginning March 1992.

LIQUID DESICCANT COOLING SYSTEM DEVELOPMENT

Status: During this period, the main focus of research was the process of mass transfer in the dehumidifier and the associated parameters.

The plot of solution flow rate versus the condensation rate was found to be a straight line with slope of 0.8, which suggested that the dehumidifier was operated under well-mixed, near-turbulent conditions for liquid flow.

The plot of $(1/\text{condensation rate})$ versus $(1/\text{solution flow rate})^{0.8}$ was also found to be a straight line with intercept 0.02. The small value of the intercept indicated that the gas phase mass transfer resistance was negligible. Therefore, the Lewis number for these contact operations should be greater than one, unlike that for air/water operations.

The equivalent diameter of a piece of packing material was determined by measuring its terminal velocity. The average terminal velocity for the packing was found to be 0.078 m/s and its equivalent diameter was found to be 2.84 cm.

The vibrating U-tube of the digital density meter was found broken during this period. It was repaired, recalibrated and installed again.

ANALYSIS OF ADVANCED SOLID DESICCANT SOLAR COOLING SYSTEMS

Status: Since the grant renewal was not received during this period and there was no pre-existing account solely for solid desiccant work, activities were limited to planning discussions.

MANAGEMENT AND COORDINATION OF COLORADO STATE/DOE PROGRAM

Status: During this report period, SEAL operated with no grant renewal contract. From December 1, 1990 through August 31, 1991, Colorado State University carried all expenses of the SEAL-DOE research project. Coordination of research activities continued on the five research tasks under the DOE grant, and accounts were maintained and updated.

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 January, February and March was devoted to hardware and software development for control of collector flow by a solar radiation sensor. The hardware components for radiation sensor control are the same as those for temperature controlled flow rate with two exceptions: the temperature sensor was replaced by a pyranometer, and the pump motor controller was changed from a full range, variable power unit to one with nine steps of power variation.

The pyranometer provides the control signal. The pyranometer method of control does not employ feedback to adjust the pump speed. Instead, a set of discreet flow rate values are assigned to specific ranges of solar radiation. There are ten such settings (nine adjustable and one a direct electrical power connection to the motor) between a minimum of 300 watts per square meter of solar input and a maximum of 1200 watts per square meter.

Figure 1 illustrates how the collector outlet temperature responds to the solar radiation control arrangement. Initially, as the radiation level increases at the beginning of each day, the temperature response is erratic for up to a half hour. This instability is inherent to the physical design of this system rather than due to a control characteristic. An empty collector (drain back) and large collector loop volume result in five to ten minutes of pump on time before fluid exits the collectors. This effect can be moderated by setting a low limit for turn-on of the pump and/or a time delay for the turn-off.

Activities during April through August turned from system operation and monitoring to development and the running of TRNSYS computer simulations.

SOLAR RADIATION, TEMPERATURES
AND COLLECTOR EFFICIENCY
SOLAR HOUSE I - 19 MAR 1991
COMBINED ARRAY

Figure 1

The objective of computer simulation is to optimize the design parameters for isothermal operation, and to compare the estimated thermal performance of isothermal with constant flow collector operation in three strategic US locations. Preliminary results have been obtained for the case of flat plate collectors providing approximately fifty percent solar fraction of the space heating load in a residential style building in Denver.

The effect of the lower temperature limit on the use of solar energy (the storage temperature) was explored for the constant flow case, allowing the application of solar to heating down to 30, 40 or 50 degrees C. In comparing control strategies, 30 degrees was used for the constant flow cases and five degrees below the collection temperature was used for isothermal cases.

The graph of Figure 2 illustrates the effects of the lower temperature limits on the annual solar fraction in the Denver case. The flow rate for a constant flow system corresponds to the manufacturer's recommended rate through a 30-square-meter collector of 2000 liters per hour.

The variable considered in the isothermal operation was the temperature level at which the isothermal condition is set. The results are shown in Figure 2. The temperature scale in Figure 2 refers to the isothermal setting in the isothermal cases and to the lower limit of energy usage in the constant flow cases.

The figure shows that operating temperature (or the lower temperature limit) appears to have greater influence upon seasonal performance than does the choice between isothermal and constant flow operation.

Figure 3 shows that the total volume of fluid passing through the collectors in isothermal operation is only about one-third of that required in constant flow operation. This difference has a substantial impact on electrical power requirements. As a result of this observation, attention has been turned toward obtaining accurate pumping power relationships and including them in the models. Seasonal electric energy requirements of the two types of operation will then be compared.

PRELIMINARY TRNSYS RESULTS

Isothermal & Constant Flow Operation

Figure 2

PRELIMINARY TRNSYS RESULTS

Isothermal & Constant Flow Operation

Figure 3

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:

Experimental analyses of 9 rating trials of the generic anti-freeze system are completed. Effects of changes in heat exchanger effectiveness, collector loop flow rate, and recirculation flow rates on SRCC energy values are shown in Table 1. At the request of Dr. Byard Wood of SRCC, additional trials with lower flow rates are completed. The decision to carry out the two additional tests was based on our discussion at the Denver ISES meeting. The purpose of these tests is to help establish performance over a broader range of operating conditions. The 3 remaining higher flowrate trials required new pumps and are in progress.

Analyses of the thermosiphon and ICS systems await the completion of the solar simulator facility. The Thorne CSI lamps and voltage regulators have been received. Flux maps of a single lamp with collimator are underway. Shown in Figure 4 is the radiation flux distribution 10 feet from a single lamp operating at 1 kW. Flux maps at varying distances from the lamp to the collector plane will be used to establish the final 28-lamp configuration. Kirk Collier indicates that the 28 collimator units will be delivered by November 1, 1991. Power for the facility is now being installed at the Engineering Research Center and our target date for installation of the facility is January 1, 1992.

A student has now begun work on developing an analytical ray trace for an evacuated tube ICS system.

Table 1

Summary of Experimental Results

Trial	Heat Exchanger Type	Collector Flow Rate [l/s]	Recirculation Flow [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	41.2	49810	24829	20540	17978	29941	4289	31068
2	1	0.114	0.085	39.6	49810	23950	19714	17285	30560	4236	30042
3	1	0.228	0.170	44.3	49812	26466	22052	19600	28729	4415	31199
4	1	0.228	0.085	41.7	49815	25165	20769	18222	29715	4396	29710
5	2	0.114	0.170								
6	2	0.114	0.085	42.0	49814	25235	20937	17989	29842	4298	30642
7	2	0.228	0.170								
8	2	0.228	0.085								
9	1*	0.114	0.176	33.2	49812	20869	16558	16145	34275	4312	28086
10	1*	0.114	0.095	33.8	49811	21105	16817	15779	33777	4288	27842
11	1	0.057	0.043	35.5	49812	22116	17693	15214	32650	4423	31780
12	2	0.057	0.043	36.1	49810	22379	17964	15079	32621	4416	28509

*Inverted Heat Exchanger: Inlets are at the bottom

CSI Lamp Flux Map (W/m2)

Power 1KW Distance 10 ft Grid Spacing 2.2 inches Test 1

Figure 4

ADVANCED SOLAR DOMESTIC HOT WATER (DHW) SYSTEMS

Research Team: William S. Duff, Task Leader
Jane H. Davidson, Co-Task Leader
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:

This project is being conducted in conjunction with the International Energy Agency Solar Heating and Cooling Program's Task XIV on Advanced Active Solar Energy Systems. Modeling, design, experimentation, and analyses conducted by this project provides the United States SDHW contribution to Task XIV. Additionally, Professor Duff is the leader of the advanced SDHW systems activities of Task XIV.

Primary short-term project emphasis is being placed on matched flow DHW systems and longer-term emphasis on integral collector storage systems. A matched flow system is defined as a SDHW system where collector flow allows the storage to be stratified optimally in regard to the load and storage volume. Other SDHW systems that are being examined are the passively vented American Solar Network system and the Copper Cricket.

Modeling is currently being carried out on one- and two-tank versions of five SDHW systems:

- 1) A baseline "most representative" United States system
- 2) A variable flow control strategy system
- 3) A low flow system with stratification manifold
- 4) A low flow system with a stratification enhancing internal heat exchanger
- 5) The passively vented collector American Solar Network system

Optimized designs of these systems will be experimentally evaluated in the next contract period beginning March 1992.

Daily load variations in matched flow systems have been investigated through consultation with the recognized leaders in the field (especially Terry Hollands and Cris Van Koppen), examination of the literature, and simulation. Other participating countries have performed simulation and experimental evaluations. Daily load variations have minimal effect as long as proper stratification enhancement is achieved (via low or variable flow or stratification manifolds).

Day-to-day load variations have been investigated through examination of the literature. Other participating countries have performed simulations and have some relevant experimental results. The analysis is as yet inconclusive (for most participants) and is continuing.

Six basic stratified storage designs, with variations within several designs, have been identified. Each of these designs and variations is being evaluated by simulation and experimentation by one or more participating countries.

The Integral Collector Storage activity has been initiated among the United States and two other Task XIV countries, the Netherlands and Germany. Interest in a cooperative activity between the United States and the Netherlands based on the United States Copper Cricket SDHW system has been expressed. This activity will be formalized before the next Task XIV meeting in January.

There was agreement among the participating countries that the state-of-the-art in modeling low flow systems was inadequate. A number of advancements in low flow system modeling have been accomplished by several participating countries and some of these models have been validated against experiment. Several issues remain, but these will be resolved at the January 1992 Task XIV meeting, either by modeling advancements or by acceptance of and accommodation to the limitations. Modeling advancements are being shared by the participants.

A uniform Task XIV reporting format, instrumentation requirements and reporting guidelines have been developed for the Task. The reporting guidelines were developed by the United States with assistance from the Netherlands. One convention that was specified was the use of arithmetic or integrated mean collector fluid temperature for graphics and reporting, rather than inlet temperature, so that results from different investigations can be directly compared.

The participating countries in IEA SHAC Program Task XIV are evaluating SDHW system and component designs including internal heat exchangers, mantle heat exchangers, side arm heat exchangers, thermosiphon heat exchangers, low flow collectors, piping, controls, low flow pumps, photovoltaic powered pumps, drainback, antifreeze, and several stratification manifolds. A low flow, low cost, low power, high head pump is being developed by one of the countries. As a culmination of the matched flow effort, starting early in 1992 a concept Task XIV optimized matched flow SDHW system will be developed. This system will have several variations to accommodate particular needs of various countries.

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:

During this period, the main focus of research was the process of mass transfer in the dehumidifier and the associated parameters.

The rate of moisture condensation in the dehumidifier depends on various parameters such as air flow rate, solution concentration, height of the packed bed, air and solution inlet temperatures, and the solution flow rate. All these variables except the solution flow rate were maintained at a constant level (with solution concentration 51 percent by weight) in a decoupled mode to study the dependency of condensation rate on solution flow rate. The enthalpy change in solution due to latent heat of condensation was obtained from the enthalpy changes in the cooling water and air, and the pump power.

$$\Delta H_{La} = \Delta h_w + \Delta h_a - W_p \quad (1)$$

where,

ΔH_{La} = latent heat of vaporization per unit time

Δh_w = sensible heat change in water per unit time

Δh_a = sensible heat change in air per unit time

W_p = pump power

The mass of moisture condensed per unit time was obtained from

$$M_L = \Delta H_{La} / H_v \quad (2)$$

where,

H_v = latent heat of vaporization per unit mass

A plot of the Sherwood number (Sh) versus the Reynold's number (Re) is usually used to correlate various flow parameters. However, since all other parameters except the flow rate were kept constant, a plot of condensation rate versus solution flow rate was constructed to represent the conventional plot. Figure 5 shows this plot is a straight line with a slope of 0.8. This value of the slope suggests that the dehumidifier is operating under well-mixed, near-turbulent conditions for liquid flow.

The overall mass transfer coefficient and the individual phase mass transfer coefficients can be related by the equation,

$$\frac{1}{K_O} = \frac{1}{k_L} + \frac{1}{k_G} \quad (3)$$

For a small change of concentration and temperature over the dehumidifier,

$K_O \propto \text{Sh}$ and $\text{Sh} \propto \text{condensation rate}$

$k_L \propto \text{Re}^{0.8}$ and $\text{Re} \propto \text{solution flow rate}$

Fig.5 Variation of Condensation
with the Solution Flow Rate.

Thus a plot of (1/condensation rate) versus (1/solution flow rate)^{0.8} should be a straight line for a constant air flow rate. Figure 6 shows this graph with an intercept 0.02. The small value of the intercept indicates that the gas phase mass transfer resistance is negligible. Therefore, the Lewis number for these contact operations will be greater than one, unlike that for air/water operations.

To calculate the Sherwood number and the Reynold's number, it is essential to obtain equivalent diameter of the packing material and the diffusivity of water in a LiBr solution. Experiments to obtain the diffusivity will be conducted in the future.

The equivalent diameter of a piece of packing material was determined by measuring its terminal velocity. The experiments were conducted in a vertical, square (4 ft. x 4 ft.) glass tank, filled with water. The packing piece was dropped at the center of the tank to avoid wall effects. The terminal velocity was then used to obtain the equivalent diameter from the following equations:

$$C_D = 24 \times \frac{\mu}{D_e u_t \rho}$$

$$u_t = \sqrt{\frac{2g (\rho_p - \rho)m}{A_p \rho_p C_D \rho}}$$

where,

C_D = drag coefficient

μ = viscosity of water

D_e = equivalent diameter

u_t = terminal velocity

ρ = density of water

ρ_p = density of packing material

$A_p = \pi D_e^2$

The average terminal velocity for the packing was found to be 0.078 m/s and its equivalent diameter was found to be 2.84 cm.

To have a more direct measure of the condensation rate it is necessary to measure the concentration of LiBr solution more precisely. An attempt was made to set up a vapor pressure apparatus for the same purpose. Most of the equipment required was obtained from an earlier apparatus. To measure the concentration, it is

Fig.6 Wilson's Plot
 $1/K_o = 1/k_g + 1/k_l$

essential to calibrate this apparatus using variation of vapor pressure over the small range of concentration (1.54 to 1.65 specific gravity). However, the required data was not found in the literature or from the manufacturer and therefore, the efforts have been discontinued.

The vibrating U-tube of the digital density meter was found broken during this period. It was repaired, recalibrated and installed again. Other maintenance tests such as a pH test and a Chromate test were also carried out regularly.

Future Plans:

Structured packings (for example, Munters CELDEK) will be used in the dehumidifier for further condensation rate studies. The performance of the packings will be compared with that for the random Tripak studies with respect to the extent of mixing provided (which can be obtained from the slope of the Sherwood number versus the Reynold's number plot) and pressure drop.

Evaporation rate studies will be conducted for the regenerator in a manner similar to the condensation rate studies in the dehumidifier. These studies will be carried out using Tripak packings (used earlier) with the bed height of 28 cm. (which is the same as in the dehumidifier). These parameters are chosen to obtain a direct comparison of the dehumidifier and regenerator performance under similar conditions.

The diffusivity of water in LiBr solution will be measured using T_2O as a tracer. As these experiments will involve radioactivity, paperwork is required before we actually start the experiments. However, the level of radioactivity required in these experiments is low, and only a "short form" need be used for approval and formal training may not be required. The Radiology Department has a scintillation detector which can be used after gaining the required approval.

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
Ihsan A. Abbud, Graduate Research Assistants

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:

Since the grant renewal was not received during this period and there was no pre-existing account solely for solid desiccant work, activities were limited to planning discussions. Nearly all the staff efforts were placed on the heating program so that maximum attention to cooling could begin in September.

Preliminary plans for analysis of SENC and other high performance desiccant cooling cycles were considered. Previous experimental work and discussions with other specialists had indicated the need to explore the effects of regeneration temperature, cooling tower capacity, desiccant wheel

speed, and regeneration air flow ratio. Since relatively constant regeneration temperature had been found advantageous, and since isothermal system operation was being developed in the parallel heating task, that simulation study also contributed to the cooling task.

Activities starting in October include development of the TRNSYS component models for the Pennington (ventilation), SENC, and other cycles to compare with previous studies by Colorado State and others. Thereafter, parameters will be varied in the models to optimize the cycles. The optimal cycles will be simulated for different U.S. cities.

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:

Jane Davidson and Bill Duff attended a DOE Generic Systems and Cooling Program Review meeting in San Francisco March 23-25, 1991.

Doug Hittle and George Löf traveled to Washington, D.C. April 24-26, 1991, to meet with DOE officials and representatives of the Solar Energy Industries Association regarding SEAL research.

Doug Hittle, Bill Duff, and Jane Davidson attended a DOE Program Review and Planning Meeting in Boston July 30 through August 1, 1991.

On August 28, SEAL hosted Ted Kapus, John Ryan and Robert Hassett for a tour of the facilities and discussion of future activities.

During this report period, SEAL operated with no grant renewal contract. From December 1, 1990 through August 31, 1991, Colorado State University carried all expenses of the SEAL-DOE research project.

Coordination of research activities continued on the five research tasks under the DOE grant, and accounts were maintained and updated.

END

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12/13/91