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

**PROJECT STATUS REPORT FOR THE MONTHS OF
APRIL AND MAY 1995**

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Submitted by

**SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY**

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MASTER

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PART I (DOE, DOE Contractors, Grantees, and Awardees complete)

A. Product/Report Data

1. (Award) Contract No. DE-FG36-86SF16306

2. Title Developing, Testing, Evaluating and
Optimizing Solar Heating Systems

3. Product/Report Description

☒ a. Report (Complete all that apply)

(1) ☐ Print ☐ Nonprint (specify) _____

(2) ☐ Quarterly ☐ Semiannual ☐ Annual ☐ Final

☐ Topical ☐ Phase I ☐ Phase II

☒ Other (specify) Bimonthly Progress Report

Dates covered _____ thru _____

☐ b. Conference/Meeting/Presentation (Complete all that apply)

(1) ☐ Print ☐ Nonprint (specify) _____

☐ Published proceedings

☐ Other (specify) _____

(2) Conference Title (no abbreviations) _____

Location (city/state/country) _____

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☐ c. Software—Additional forms are required. Follow instructions on the back of this form.

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B. Patent Information

Yes No

☐ ☐ Is any new equipment, process, or material disclosed?

If yes, identify page numbers _____

☐ ☐ Has an invention disclosure been submitted?

If yes, identify the disclosure number and to whom it was submitted. Disclosure number _____

Submitted to _____

☐ ☐ Are there patent-related objections to the release of this STI product? If so, state the objections. _____

C. Contact (Person knowledgeable of content)

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Position Director

Organization Solar Energy Applications Lab
Colorado State University

PART II (DOE/DOE Contractors complete/or as instructed by DOE contracting officer)

A. DOE Identifiers

1. Product/Report Nos. SF-16306-47

2. Funding Office(s) (NOTE: Essential data) Golden Field Ofc.

B. Copies for Transmittal to AD-21 (OSTI)

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☐ 1. One for classified processing

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A. Patent Clearance ("X" one)

☐ Has been submitted for DOE patent clearance

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UNIQUE SOLAR SYSTEM COMPONENTS

INTEGRATED TANK/HEAT EXCHANGER MODELING/EXPERIMENTS

A potential problem has been identified (while solving a homework problem for Dr. Pat Burns) with the second order incidence angle modifiers (IAM's) published (SRCC, 1994) for the Thermodynamics collectors. The IAM curves for these collectors have a inflection point near $\theta = 60^\circ$. The IAM quickly becomes larger than one for $\theta > 60^\circ$. As a result, TRNSYS over estimates of the total useful energy collected during a typical clear summer day by more than 10%. Detail plots outline the problem and the propagation of the resulting errors into the TRNSYS simulations. The published IAM curves for these collectors should be examined and corrected.

A set of data manipulation utility programs has been written using the PERL programming language. The PERL language is a powerful combination of programming and scripting language that has proven very useful in automating the process of reducing experimental data, updating the corresponding TRNSYS simulation decks and normalizing the simulation results to the experimental data. These programs have been useful on several of the tasks under this grant.

INCIDENCE ANGLE MODIFIERS FOR THE THERMODYNAMICS COLLECTORS

Collector Performance and General Treatment of Incidence Angle Modifiers (IAMs)

The TRNSYS Type 1 Solar Collector model calculates the thermal performance of a flat plate solar collector modeled using a quadratic efficiency equation (TRNSYS, 1990 and 1994),

$$Q_u = A_c(F_R(\tau\alpha)K_{\tau\alpha}I_T - F_RU_L(T_i - T_a) - F_RU_{L2}(T_i - T_a)^2) \quad (1)$$

where the collector efficiency parameters $F_R(\tau\alpha)$, F_RU_L and F_RU_{L2} ($= 0$ for linear efficiency) are typically determined from an outdoor test of the collector at near normal incidence angles under clear sky conditions (ASHRAE, 1986). The factor $K_{\tau\alpha}$, the incidence angle modifier (IAM), corrects for incident solar radiation at off normal angles. In general, the effective IAM is estimated from a weighted average of the beam, sky diffuse and ground reflected components of the incident radiation.

$$K_{\tau\alpha} = \frac{I_{bT}K_{\tau\alpha,beam} + I_dF_{sky}K_{\tau\alpha,sky} + \rho_{gnd}I_dF_{gnd}K_{\tau\alpha,gnd}}{I_T} \quad (2)$$

I_{bT} is the beam radiation incident on the collector surface, I_d is the horizontal diffuse radiation, and I is the total horizontal radiation. F_{sky} and F_{gnd} are the view factors from the collector surface to the sky and ground respectively. ρ_{gnd} is the diffuse reflectance of the ground (typically 0.2). The variation of the IAM for beam radiation, $K_{\tau\alpha,beam}$ with incidence angle is calculated from an empirical correlation determined from the ASHRAE/SRCC (1986, 1981) clear sky collector test data.

$$K_{\tau\alpha, \text{beam}} = 1 - b_0 \left(\frac{1}{\cos \theta} - 1 \right) - b_1 \left(\frac{1}{\cos \theta} - 1 \right)^2 \quad (3)$$

The IAMs for the diffuse sky radiation, $K_{\alpha\tau, \text{sky}}$, and ground reflected radiation, $K_{\alpha\tau, \text{gnd}}$ are estimated using this same correlation for the beam IAM (Eq. 3) with equivalent incidence angles defined for both the sky and ground reflected diffuse radiation (Brandemuthehl, 1980).

$$\theta_{\text{sky}} = 59.68^\circ - 0.1388 \cdot \beta + 0.001497 \cdot \beta^2 \quad (4)$$

$$\theta_{\text{gnd}} = 90^\circ - 0.05788 \cdot \beta + 0.002693 \cdot \beta^2 \quad (5)$$

β is the tilt angle of the collector. For a collector tilt angle of 45° , $F_{\text{sky}} = F_{\text{gnd}} = 0.5$, $\theta_{\text{sky}} = 56.5^\circ$ and $\theta_{\text{gnd}} = 69.4^\circ$. Note, even when the beam radiation is at near normal incidence, the incidence angles for the diffuse components are large.

IAM's for the Thermodynamics S32 Collectors

The Directory of SRCC Certified Solar Collector and Water Heating System Ratings Catalog lists the following IAM correlation's for the Thermodynamics S32-AC and S32-P collectors respectively.

$$K_{\tau\alpha} = 1.0 - 0.488 \cdot S + 0.234 \cdot S^2 \quad (6)$$

$$K_{\tau\alpha} = 1.0 - 0.366 \cdot S + 0.128 \cdot S^2 \quad (7)$$

where $S = (1 / \cos \theta - 1)$. The variation of $K_{\alpha\tau}$ with incident angle θ for the S32-AC collector (Eq. 4) is plotted in Figure 1. The behavior of this curve for incidence angles greater than 60° is not characteristic of a typical flat plate collector. The IAM should decrease continuously to zero at (or before) $\theta = 90^\circ$. Instead, the IAM begins increasing dramatically for $\theta > 60^\circ$ becoming greater than 1 for $\theta > 75^\circ$ ($K_{\tau\alpha} = 21.6$ for $\theta = 85^\circ$).

$$K_{\tau\alpha} = 1.0 - 0.359 \cdot S \quad (8)$$

Figure 2 is a plot of the IAM for this collector verses $S = (1 / \cos \theta - 1)$. The original test data was most likely obtained for a limited number of incidence angles between 0° and 60° (typically 0° , 30° , 45° , and 60° , ASHRAE, 1986 and SRCC, 1981). The atypical behavior of these IAM curves may result when the quadratic curve fit is applied outside of the range of the original test data. Figure 2 also shows a linear fit to IAM "data" generated from the SRCC second order equation for $0^\circ < \theta < 45^\circ$ (dashed lines).

The resulting variation of IAM with θ is plotted against the original curve in Figure 1. This curve behaves as expected. Note, this curve was generated as an example only and should not be

used to characterize these collectors. The originally IAM data should be employed to generate any changes to the IAM curve.

Notes on the Calculation of the Effective IAM in TRNSYS

Additional assumptions are written into the TRNSYS Type 1 IAM calculations (both in the version of 13.1 in use by the SRCC and in version 14.101). In TRNSYS 13.1 (1990), optical mode 7, a quadratic IAM curve is specified by the user. The IAM is calculated as in Eq. 3 except that the code limits the maximum value of $\theta_{\max} = 85^\circ$ (though not in Eqs. 4 and 5). The IAM becomes constant for $\theta > 85$.

In optical mode 1, a linear IAM ($b_1 = 0$) curve is specified and the IAM curve is calculated using the FORTRAN function definition,

$$\text{TAUALF(THETA)} = 1 - B_0 * (1 / \text{AMAX1}(0.5, \cos(\text{THETA} * \text{RDCONV})) - 1) - (1 - B_0) * (\text{AMAX1}(60., \text{THETA}) - 60.) / 30. \quad (9a)$$

which translates to,

$$K_{\tau\alpha}(\theta) = \begin{cases} 1 - b_0 \left(\frac{1}{\cos \theta} - 1 \right) & 0 \leq \theta \leq 60^\circ \\ K_{\tau\alpha}(60^\circ) \left(1 - \frac{(\theta - 60^\circ)}{30^\circ} \right) & 60^\circ < \theta \leq 90^\circ \end{cases} \quad (9b)$$

That is, the first order curve is used for $0^\circ \leq \theta \leq 60^\circ$, then, the IAM decreases linearly to zero at $\theta = 90^\circ$. The effect of this modification on the "generated" first order IAM curve (for $\theta < 60^\circ$) is shown in Figure 1.

Note that when a first order IAM is specified (b_1 is set to zero in Eq. 3) using the TRNSYS 13.1 optical mode 7, the IAM calculated at incidence angles greater than 60° is not the same as will be calculated if optical mode 1 were used (Eq. 8).

The TRNSYS 14.101 (1994) code combines the TRNSYS 13.1 optical modes 1 and 7 into a single mode 1. If $b_1 = 0$, a Eq. 9 is used to calculate the IAM. If $b_1 \neq 0$, Eq. 3 is used with $\theta_{\max} = 85^\circ$.

Example from a CSU data set

Figure 3 shows the measured variation total solar radiation incident on the collector surface, I_T , the total horizontal radiation, I , the horizontal diffuse radiation, I_d , and the angle of incidence, θ during an outdoor test of the a Thermodynamics S32-AC collector on July 27, 1994. As the data shows, the sky was generally clear on this day and majority of the solar radiation incident on the collector was beam. Figure 4 shows the relative magnitude of the beam, diffuse sky, and ground reflected components of I_T .

Figure 5 shows the overall IAM (Eq. 2) calculated using the TRNSYS 13.1 Type 1 model with the SRCC quadratic curve (Eq. 6) using optical mode 7 and using the "generated" linear curve fit (Eq. 8) with both optical modes 7 ($b_1 = 0$) and optical mode 1. The collector was mounted at a 45° slope and the ground reflectance was assumed to be 0.2. The variation of the incidence angle through the day is overlaid on the plot. The SRCC quadratic curve results in an overall IAM larger than one (as large as 7.5) early and late in the day when the beam radiation is incident at large angles. In addition, the IAM at solar noon ($\theta = 23.8^\circ$) is approximately 3% higher than is calculated with the linear fit even though the values of $K_{\tau\alpha}$ calculated using Eqs. 6 (quadratic) and 8 (linear) are nearly identical for $\theta = 23.8^\circ$. This occurs because the IAM's for the diffuse components, $K_{\alpha\tau,sky}$, and $K_{\alpha\tau,gnd}$, are overestimated for $\theta_{sky} = 56.5^\circ$ and $\theta_{sky} = 69.4^\circ$ when the quadratic curves used (reference Figure 1).

Figure 6 shows the collector outlet temperature calculated by TRNSYS plotted against the experimental value. The experimental variations in collector inlet temperature and flow rate were specified in the simulation. The quadratic IAM curve clearly over estimates the outlet temperatures early and late in the day. The collector outlet temperature predicted using the "generated" linear fit follows the experimental curve much more closely. At solar noon, the quadratic curve predicts an outlet temperature approximately 2°C higher than the first order curves. The measured total useful energy collected during the day was 48.1 kJ. The calculated values were 53.3 kJ (11% high) using the quadratic IAM curve, 44.9 kJ (6 % low) using the linear curve with optical mode 7 and 46.0 kJ (4 % low) using the linear curve with optical mode 1.

Recommendations

The published IAM curves for the Thermodynamics S32-AC and S32-P collectors should be examined. The undesirable behavior of the SRCC IAM correlations at large incidence angles is quite likely a result of applying the quadratic fit outside of the data range. Perhaps a linear correlation of the original data would provide a better estimate of the variation of the IAM with incidence angle.

The assumptions about the variations of the IAM at high incidence angles (Eq. 9) built into the TRNSYS 13.1 and 14.101 Type 1 collector models should be better documented in the users manual. Perhaps the assumption in Eq. 9 should be used with a quadratic IAM curve also.

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Figure 1. Plot of IAM Correlations for the Thermodynamics S32-AC Collector

Figure 2. Generation of 1st Order IAM Correlations from SRCC 2nd Order Correlation for the Thermodynamics S32-AC Collector

Figure 3. Irradance data for July 27, 1994.

Figure 4. Normalized irradiances for July 27, 1994.

Figure 5. Overall incidence angle modifier calculated by TRNSYS for the July 27, 1994 test.

Figure 6. Effect of IAM on calculated collector outlet temperature for the July 27, 1994 test.

RATING AND CERTIFICATION OF DOMESTIC WATER HEATING SYSTEMS

April/May 1995

Current work on this project has been in two areas. The first is continued work on the Solahart thermosyphon solar domestic hot water system. The second area involves a new apparatus being constructed at the Solar Energy Applications Laboratory to enable heat exchanger, tank, and system testing.

Thermosyphon SDHW System

An abstract of the work reported in the last monthly report [February/March 1995] was submitted and accepted for the 1996 ASME International Solar Energy Conference in San Antonio, Texas. The submitted abstract appears below.

A SYSTEMATIC APPROACH TO IMPROVING THERMOSYPHON SDHW MODEL PERFORMANCE

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The rating of solar domestic hot water heating systems is important to enable energy saving predictions in different environments. Computer simulation models based upon limited data are used for these predictions. As a result, it is important that the models be tested for accuracy and that adjustments be made if necessary. Complex, highly coupled systems, such as passive thermosyphon systems, have a large number of parameters that affect system performance. Often, only one parameter, such as the collector's $F_R U_L$ value, is adjusted in the model to match one experimental energy draw value. This method of adjusting the model is questionable due to the fact that the resulting model frequently does not acceptably match experimental temperature profiles or other energy values in the system. This could lead to erroneous energy predictions when the model is used for annual simulations.

A systematic procedure is used here to adjust three parameters in a TRNSYS deck of a thermosyphoning, horizontal tank solar domestic hot water heating system to better match experimental performance. The system is mounted at the Colorado State University Solar Simulator facility where a four hour solar-only constant irradiation test with a load draw at two hours is conducted. A TRNSYS model of the same experiment is first modified so that collector flow (normally a thermosyphon) and collector inlet temperature can be forced to their experimental values throughout the four hour simulation. This effectively disables the thermosyphon calculation and allows testing of the collector equations in the model. After confirming that the collector outlet temperature profile is accurate, an

adjustment is made to the heat exchanger's UA value to match the experimental temperature profile coming out of the heat exchanger and returning to the collector. The effective conductivity term between water layers in the tank is then adjusted to match the experimental water draw temperature. These modifications applied to the unforced model result in very accurate useful collector and draw energy predictions, but under predicted collector flow rate and over predicted collector temperature rise (which compensate to achieve the accurate energy prediction). Finally, the friction factor in the collector loop is adjusted to match the experimental collector flow rate and thus temperature rise.

Good agreement with the experiment is achieved with the collector useful energy gain and the energy delivered during the draw by ensuring that the model gives an accurate prediction of the temporal history of both the system flow rates and temperatures. As a result, confidence in an annual performance prediction is increased.

An attempt is being made to obtain more data on the system to enable testing of the adjusted parameter model. The system may be moved to the outdoor test facility at CSU to collect additional data if a suitable data set cannot be obtained elsewhere.

Portable Testing Apparatus

A semi-portable apparatus is being assembled that will facilitate performance measurements of hot water tanks, heat exchangers, and similar equipment. The apparatus will include a circulator pump, a direct-reading in-line flow meter, a low pressure drop Coriolis mass flow meter, a hydronic heating system consisting of two 2600 Watt heating elements, and appropriate thermocouples and plumbing.

Control of the system will be performed either manually or by computer. Computer control will allow automatic, timed switching of the pump and heating elements and control of the water temperature set point via an electronic controller. Flow rate and temperature data will be acquired by the computer.

The entire system, including electronics, will be assembled on a uni-strut frame that will be semi-portable in that it can be moved provided that an ample electric circuit is installed in each location. The completed size will be approximately four feet by four feet square and two feet deep.

Immediate use of the apparatus will include testing of a solar domestic hot water system with a thermosyphon potable water tank loop and an heat exchanger designed for solar domestic hot water system use.

ADVANCED RESIDENTIAL SOLAR DOMESTIC HOT WATER (SDHW) SYSTEMS

This report is for April and May 1995. Experimental tests are being conducted on three side by side systems: ASN, NEG and Thermodynamics.

Experimental Work

Our system tests are conducted with the solar collectors outdoors, so that we capture the effects of the natural variation of the weather. Each test requires five days of average or above average sunshine. Due to unseasonably poor weather in April and May 1995 (this is a year of El Nino), there were no periods of weather suitable for conducting tests. The data sets we did collect are for very cloudy, stormy days, and lack sufficient signal (solar gain) to be useful. Therefore, our efforts were devoted to a variety of other tasks.

The software for the data acquisition system was upgraded. Several minor problems with the hardware were fixed. The past two months have been spent on additional analysis of the ASN load-side heat exchanger as well as defining a clearer dissertation project, including a thorough literature review supporting that project.

Optimization of Evacuated Tube Collectors

Work has begun on the optical analysis of the evacuated tube collectors. The following summarizes that work.

Evacuated tube collectors (ETC) have the benefit of absorbing the sun's radiation from both the top and back of the collector. An increase in the radiation entering from the back of the collector can be achieved by using a backplane reflector. Our past work has shown that end and edge effects are very important in determining the total solar absorption for ETC collectors. The goal of this work is to investigate performance enhancements from increased tube-to-tube spacing (pitch), and increased backplane size so that trade-offs between performance and other factors such as esthetics can be made.

The most effective design for the maximum absorbed radiation per unit area is one where the tubes are placed as close together as possible. In this situation, a backplane reflector is not beneficial. Increasing the pitch allows more radiation to pass between the tubes, which may then be reflected and partially absorbed from the back of the ETC. However, very large pitches present difficulties in assembly, transport, installation and are not esthetically appealing. Increases in performance by increasing the pitch need to be assessed versus these factors to yield an "optimal" design, with all factors considered.

Our approach to assessing the performance enhancements involves a two-step process: 1) for a given geometry and set of optical properties, the optical absorption is computed using a Monte Carlo program to generate a matrix of IAM's, and 2) these IAM's are used as input to an annual TRNSYS simulation (we use the SRCC input deck from FSEC). The geometry and optical properties are then varied parametrically, and additional runs are performed. The variations currently being considered include:

- tube pitch
- backplane-to-tube spacing
- backplane dimensions
- type of backplane (diffuse or specular).

Numerous methods can be used to evaluate the benefits of each variation, however computer simulation offers quick and consistent results. The Monte Carlo ray-tracing

program developed by Kevin Knappmiller is being used to calculate the biaxial incident angle modifiers (IAM's) of the various collector geometries. IAM's are calculated at 50 different incident angles over a quarter of a hemisphere (assumes biaxial symmetry). These IAM's are then post-processed and input into a TRNSYS deck to calculate the annual energy absorbed by the collector in a given location.

The tubes being used in the simulations are cylindrical tubes with the same dimensions and characteristics as the tubes manufactured by Nippon Electric Glass (Sun Family Collectors).

Since the program being used to calculate the IAM's is very computer intensive (up to 2 hours for a single angle), initial estimates of collector performance were performed using the tau alpha product at normal incidence $(\tau\alpha)_n$. This product is the fraction of radiation that passes through the aperture plane and is actually absorbed by the collector tubes. Increasing the tube pitch reduces $(\tau\alpha)_n$. However, multiplying this product by the aperture area gives an estimate of the amount of energy absorbed at normal incidence. This multiplied value increases with the pitch and asymptotes to some value.

IAM calculations have been completed for various tube pitches from 16 cm up to 96 cm. To date, the backplane has been 100% diffuse with the reflectance varying between 0.6 and 1.0. The backplane-to-tube spacing has been held constant at 17 cm and the size of the backplane has been varied between 100% and 900% of the aperture area (pitch*no. of tubes*tube length).

The type of backplane reflector is a critical component in estimating the collector's performance. When a photon strikes a diffuse surface, two different types of "diffuse" reflectance can be assumed:

As can be seen, the isotropic reflectance distributes outgoing (reflected) photons in a random direction, while the Lambertian reflectance concentrates the reflected photons about the surface normal. If isotropic reflectance is assumed, significantly more energy is absorbed by the tubes since a photon hitting far away from any tubes can still be reflected at a grazing angle and hit the collector. With Lambertian reflectance, spacing the tubes further apart does not significantly increase the amount of energy absorbed, since most of the photons will again miss the collector after being reflected. The attached graphs illustrate the difference at normal incidence from these two types of outgoing directional distributions.

Additional computer simulations will be performed for the variations previously mentioned. The use of a specular reflector will be evaluated and compared to that of a diffuse reflector. Experimental tests will be conducted in the near future to determine the validity of the computer-generated IAM's. Several different backplane materials will be used along with a pitch approximately twice that being used currently in production.

MANAGEMENT AND COORDINATION OF COLORADO STATE/DOE PROGRAM

Coordination of research activities continued on the three technical research tasks under the DOE grant, and accounts were maintained and updated. Financial and technical reports were submitted as required.