

~~FINAL~~ REPORT

TO THE

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SIMULATION AND DESIGN OF SOLAR THERMAL PROCESSES

by the

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ABSTRACT

Methods of simulation and design of solar thermal processes have been developed and used in process system studies. During the period of this contract, new process component model formulations have been developed, including: transient LiBr-H₂O absorption cooler; CPC and other "advanced" collectors; and windows, storage wall and shading devices for passive solar heating. Systems studies have included: parallel and series solar/heat pump combinations; phase change storage in solar heating; absorption cooling with and without cooler transients. The general solar process simulation program, TRNSYS, has been further developed, documented, distributed and supported.

Design procedure studies have led to development of a method for calculating the $\bar{\phi}$, the average solar radiation availability, and the development of the $\bar{\phi}$, f-chart method for design of closed-loop solar heating systems which (a) can have load temperatures other than 20°C, and (b) have approximately constant COP of any energy converters between storage and load.

I. INTRODUCTION

This report covers the activities of the Solar Energy Laboratory-University of Wisconsin during the two year period, 1977-78. Prior to this contract, the research had been supported by the NSF/RANN and by the Energy and Research Development Administration. Thus this contract covered a two year span of an on-going research program.

This summary is a brief report on the two years of research. A more detailed report and an extensive set of attachments (publications from the Laboratory) were submitted to the Department of Energy on August 20, 1978).

II. THE RESEARCH PROGRAM

The general objective of this research has been to develop methods for simulating and designing solar energy thermal processes. The approach has been to develop a modular solar process simulation program, TRNSYS, with which the user can assemble systems and "operate" them in the climate of his choice (13). With TRNSYS and TRNSYS-related programs, we have also developed design methods for common types of solar heating systems and we have programmed these methods with life cycle economics in a program called FCHART (14). As per agreement with the Department of Energy, we have carefully documented these programs and made them widely available through sales from the University (at prices to cover the costs of their distribution). Both TRNSYS and FCHART are in widespread use in this country and abroad.

In addition to distributing programs and manuals, the work of the laboratory has been made widely available through the usual channels for scientific and engineering research, i.e., publications and presentations at meetings and workshops. These are indicated in section V.

A. Capability for Simulations

During the period of this research, the capabilities for simulations of systems has been tremendously increased, and the cost of doing simulations significantly decreased, through developments of the TRNSYS program. Some of the specific areas of expansion and improvements in TRNSYS have been in the following areas: heat pumps and heat pump systems; improved models of absorption air conditioners including transient operations (25); modeling of heat exchangers and heat/mass exchangers for desiccant cooling; models for phase change energy storage; new methods of calculating building loads (16); models of "advanced" collectors such as the compound parabolic concentrator; and models for passive components for solar heating (26).

Along with these developments of component models and associated TRNSYS subroutines we have exercised these models and in doing so studied particular kinds of solar thermal processes using these components. These systems studies include: comparative studies of parallel and series combinations of solar energy and heat pumps (4); phase change energy storage in solar heating (5,28); preliminary systems studies of desiccant cooling systems (1); and comparative studies of simulations with and without absorption cooler transients in air conditioning (25). These systems studies have been or will be reported in publications in the literature.

The component models are programmed in TRNSYS-compatible subroutines and ultimately become part of the TRNSYS program which becomes available to outside users. Thus this work becomes available not only through publications but also through widely distributed programs.

B. Design Procedures

The laboratory has developed the f-chart design procedure for standard configurations of air-based and liquid-based solar heating systems and domestic hot water systems. This method has been combined with detailed life cycle cost analysis, and based on this combination the program FCHART has been prepared. The f-chart design method and particularly the FCHART program are in wide use in the emerging solar heating industry.

Two further steps have evolved from the f-chart method. First, a new method (2) has been developed for estimating the monthly average solar radiation availability, $\bar{\phi}$; this method is easy to use and is easily programmed. Second, a new design procedure, the $\bar{\phi}$,f-chart procedure (10) has been developed which removes a basic limitation of the f-chart method in that it allows estimation of long term performance of systems which deliver energy at temperatures other than room temperatures. The $\bar{\phi}$,f-chart method will be applicable to a range of processes including industrial process heating and absorption air conditioning, as long as the systems have nearly constant COP of the energy conversion components between the storage tank and the loads.

C. Students from the Laboratory

The work of this laboratory is largely carried out by graduate students in Mechanical and Chemical Engineering. They not only produce interesting and useful research results, but they are trained and are in demand in the solar energy industry. In the last two years 11 students have finished M.S. programs and are now working on solar energy or closely related matters in the following industries; The Trane Company, Engineering Associates (an A and E firm), Honeywell, Lennox Industries,

Science Associates Inc., Atlas Corporation, Thermol Electron Engineering, Johnson Controls and others. Thus, the experience gained as a result of this research program carries over into industrial employment in the field.

D. Instruction and Public Service

In addition to the graduate students who work on the research program in our laboratory, the staff at the laboratory offers instruction to resident students in engineering and is active in lecturing at seminars, short courses, and workshops all which serve as mechanisms for the dissemination of the results of our research.

The staff of the Solar Energy Laboratory has also been active in professional societies. W. A. Beckman is technical program chairman for the 1979 International meeting of the International Solar Energy Society. (In 1978 he received the C. G. Abbot Award of the American Section of ISES for his contribution to the solar energy field.)

III. TRNSYS AND FCHART

As noted above, the TRNSYS and FCHART programs are made available to the public through sale by the University at costs designed to cover the direct costs of their reproduction and shipping. The two programs are widely distributed, with more than 300 copies of FCHART and over 500 copies of TRNSYS (approximately 300 copies of Version 9.2, the current version) shipped to other laboratories, industries and government agencies.

Each of these programs is extensively and carefully documented (13,14). The TRNSYS manual constitutes a book on modeling and solar processes (and has been distributed in moderate numbers for use as a text). Each of the programs goes through major and minor revisions, to improve their capabilities and to eliminate "bugs" which occur in programs of this magnitude. TRNSYS Version 9.2 and FCHART Version 3.0 are being distributed in December 1978. A new Version 10 of TRNSYS and a new Version 4 of FCHART are in preparation.

Wide distribution of these programs inevitably leads to questions and problems regarding their use. Engineers at the Solar Energy Laboratory provide user services through answering inquiries, preparing updates, keeping documentation up to date, assessing the experience of users, preparation of new versions, and working with Research Assistants in the laboratory who are developing new components. FCHART services are carried out in cooperation with the Solar Energy Research Institute.

IV. PROGRESS SINCE THE AUGUST 20 REPORT

Here we briefly state what has been accomplished in the last four months on three of the major projects within the program.

A. The Arlington House

The contract has supported the operation of an experimental solar heating system on the Arlington (Wisconsin) solar house. This experiment serves both as a source of information for comparisons of the results of physical experiments and simulations (which are necessary to gain confidence and better knowledge of how to use simulations) and also evaluate experiments as a means of evaluating a unique solar heating system. The system is an air system using evacuated tubular collectors and off-peak electric auxiliary. The experiment has been done in cooperation with the Wisconsin Electric Utilities who have an obvious interest in the impact of solar heating on electric load distribution.

We have now developed a very good picture of four months of operation of the Arlington system during the 1977-78 winter (23). This has been summarized in a paper presented at the solar heating workshop in Colorado Springs (paper in the Appendix).

The Arlington system has also been used in a comparative study of the performance of rock bed energy storage units and the correlations used in TRNSYS. The result of this study indicates that the rock bed model formulated by Hughes, Klein, and Close appears to represent the long term performance of the pebble bed very well and also does remarkably well at predicting temperature gradients within beds (24).

B. Absorption Cooling

Work is essentially complete on a model of the Arkla Solaire 3-ton LiBr-H₂O absorption cooler designed for solar operation. This model includes start-up and shut-down transients; the steady state operation of the model is based on measured operating data from Arkla. Time constants for the model were determined from experiments on the Colorado State University House I installation. A thesis and paper on this work (25) are now in preparation, and the model has been programmed in TRNSYS-compatible format and will be included in Version 10 of TRNSYS. It is being used in studies of absorption cooling by several outside organizations who have need of a current model.

C. Passive Components

The very strong upsurge of interest in passive solar heating has lead us to develop passive components for TRNSYS. We now have

storage walls, windows (direct gains), and shading components which now allow TRNSYS modeling of the range of passive buildings. These have been programmed in TRNSYS-compatible format, are being exercised and will be included in Version 10 of TRNSYS. A presentation will be made () on these developments at the Passive Heating Conference in early January, 1979. And, a general method for calculating monthly average shading factors for overhangs, wingwalls and similar architectural features has been worked out.

V. PUBLICATIONS

Publications are a major output of a research program of this type. For purposes of this report we have divided our publications into three categories. The first includes those which have been published in refereed Journals or accepted for publication in those Journals, plus several publications which are available in the form of Engineering Experiment Station reports. Thus these all are or will be readily available to the interested user. The second category includes workshop presentations and papers which have been submitted for publication and are in the reviewing process. Many of these papers are available in workshop proceedings. The third category includes papers which are in preparation and which soon will be submitted to appropriate Journals for publication.

A. Papers Published, Accepted for Publication and Experiment Station Reports

1. Nelson, J.S., W.A. Beckman, J.W. Mitchell and D.J. Close, "Simulations of the Performance of Open Cycle Desiccant Systems Using Solar Energy," Solar Energy, Vol. 21, No. 4 (1978).
2. Klein, S.A., "Calculation of Flat Plate Collector Utilizability," Solar Energy, Vol. 21, No. 5 (1978).
3. Jurinak, J.J. and S.I. Abdel-Khalik, "Properties Optimization for Phase-Change Energy Storage in Air-based Solar Heating Systems," Solar Energy, Vol. 21, No. 5 (1978).
4. Freeman, T.L., J.W. Mitchell, and T.E. Audit, "Performance of Combined Solar-Heat Pump Systems," accepted by Solar Energy, (1978).
5. Morrison, D.J. and S.I. Abdel-Khalik, "Effects of Phase-Change Energy Storage on the Performance of Air-Based and Liquid-Based Solar Heating Systems," Solar Energy, 20, 57 (1978).
6. Klein, S.A., W.A. Beckman and J.A. Duffie, "A Design Procedure for Solar Air Heating Systems," Solar Energy, 19, 509 (1977).

7. Klein, S.A., "Calculation of Monthly Average Insolation on Tilted Surfaces," Solar Energy, 19, 325 (1978).

8. Hughes, P.J., J.A. Duffie, and W.A. Beckman, "Simulation Study of Several Solar Heating Systems With Offpeak Auxiliary," Solar Energy, 19, 317 (1978).

9. Beckman, W.A., "Duct and Pipe Losses in Solar Energy Systems," Solar Energy, 21, (1978).

10. Klein, S.A. and W.A. Beckman, "A General Design Method for Closed-Loop Solar Energy Systems," accepted for Solar Energy

11. Brandemuehl, M.J. and W.A. Beckman, "Economic Evaluation and Optimization of Solar Heating Systems," accepted for Solar Energy.

12. Beckman, W.A., et al., "Units and Symbols in Solar Energy," Solar Energy, 21, 65 (1978).

13. "TRNSYS Users Manual," Engineering Experiment Station Report #38-9, University of Wisconsin-Madison (February 1978).

14. "FCHART Users Manual," Engineering Experiment Station Report #49-3, University of Wisconsin-Madison (June 1978).

15. "Monthly Average Radiation on Inclined Surfaces for 261 North American Cities," (revised), Engineering Experiment Station Report 44-2, University of Wisconsin-Madison (August 1978).

B. Papers Delivered at Workshops, and Being Reviewed by Journals

16. Pawelski, M.J., J.W. Mitchell, and W.A. Beckman, "Transfer Functions for Combined Walls and Pitched Roofs," paper to be submitted to ASHRAE, 1978.

17. Olson, T.J., D.M. Beckman, W.A. Beckman and J.W. Mitchell, "Performance of Solar Source Rankine Cycle Engine Cooling Systems," paper presented at Orlando ISES meeting, June 1977.

18. Hughes, P.J., "FCHART Version 3.0: Current Status of the University of Wisconsin Computer Program for Solar Heating Design," abstract of discussion at San Diego SS/EA, June 1978.

19. Klein, S.A. and J.A. Duffie, "Estimation of Monthly Average Diffuse Radiation," paper for presentation at Denver ISES meeting, August 1978.

20. Mitchell, J.W., W.A. Beckman, and M.J. Pawelski, "Comparisons of Measured and Simulated Performance for CSU House I," paper submitted to ASHRAE, 1978.

21. Freeman, T.L., M.W. Maybaum and S. Chandra, "A Comparison of Four Solar System Simulation Programs in Solving a Solar Heating Problem," abstract of a presentation at San Diego SS/EA Conference, June 1978.

22. Klein, S.A., J.W. Mitchell, J.A. Duffie and W.A. Beckman, "Computers in the Design of Solar Energy Systems," accepted for Energy.

23. Persons, R.W. and R.D. Erdmann, "The Arlington Solar House of the University of Wisconsin-Madison," paper presented at Solar Heating and Cooling Systems Operational Results Conference, Colorado Springs, Colorado, November 1978.

C. Manuscripts in Preparation

24. Persons, R.W. and Mitchell, J.W., "Comparison of Rock-Bed Model and Experiment."

25. Blinn, J.S., Mitchell, J.W. and Duffie, J.A., "Modeling of Transient Performance of Residential Solar Absorption Air Conditioning Systems."

26. Utzinger, D.M. and Klein, S.A., "A Method of Estimating Monthly Average Solar Radiation on Shaded Surfaces."

27. Jurmak, J.J. and Abdel-Khalik, S.I., "Economics of Phase Change Energy Storage in Air-Based Solar Heating Systems."

28. Abdel-Khalik, S.I. and Jurmak, J.J., "Sizing Phase-Change Energy Storage Units for Air-Based Solar Heating Systems."

29. Buckles, W.E., Klein, S.A., Beckman, W.A. and Duffie, J.A., "Analysis of Solar Water Heating Systems."

30. Anderson, J.V., Mitchell, J.W. and Beckman, W.A., "A Design Method for Parallel Solar-Heat Pump Systems."

VI. ACKNOWLEDGEMENT

The staff of the University of Wisconsin-Madison Solar Energy Laboratory acknowledges with thanks the support provided by the Department of Energy for this research program. We feel that we have made very substantial progress and see this reflected in the many references to the work of this contract in the reports and publications of others. This support has enabled us to offer unique educational opportunities for our students, and they in turn are making their contributions to developments of the solar energy field. The cooperation we have had from the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, United States Department of Energy, has been very much appreciated.

VII. APPENDICES

Attached are copies of papers and manuscripts not previously included in reports to the Department of Energy.

Items 1-3 are papers which were previously included in our report of August 20th in manuscript form and which have been now published. The balance of the items included here are new papers which have been accepted for publication but which have not yet appeared, new manuscripts, and workshop papers.

Enclosures: Bibliography items as follows:

Published Papers: 1, 2, 3, 12
 Manuscripts Accepted: 9, 10, 11
 Workshop Manuscripts: 23

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