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Michael F. Bregar

William E. Stewart Jr.

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COMPUTER MODELING OF A
SOLAR HOT WATER COLLECTOR SYSTEM

Michael F. Bregar
Black & Veatch Consulting Engineers
Kansas City, Missouri

Dr. William E. Stewart, Jr.
University of Missouri, Kansas City
Kansas City, Missouri

Abstract

Computer modeling of a solar collector system can facilitate the selection of design paths and produce the optimal orientation and layout of the system for its intended location and seasonal usage patterns. Application of economic criteria to modeling also enables the analysis of alternate designs in terms of their installed and operating costs, as well as allowing calculation of payback periods for the various system configurations.

This program was intended to aid in the design of solar hot water collector systems. Design parameters of the system are used as inputs to the program. System configuration and design can then be varied to study the effect of these parameters on overall system performance. The object is to optimize the design of the system around those system parameters which are fixed.

1. INTRODUCTION

This paper describes a Fortran computer modeling approach to the optimization of design of a solar collector system using water as the working fluid. The desired output form of the energy is hot water at a specific temperature. The outlet temperature is one of the input variables that is fixed at the beginning of the program by the user, according to the required usage temperature of the water.

2. THE PROGRAM

2.1 PROGRAM SEQUENCES

The program's approach can be best described in four logical sequences. The first of which consists of the calculation of the solar flux into the collector. This is accomplished from equations relating the flux at the collector to the peak solar flux at the site by variables of: latitude of the collector site, time from solar noon, day of the year, altitude of the collector site, angle at which the collector is inclined, and the orientation angle of the collector with respect to the east-west movement of the sun.(1)

The second of the four sequences consists of an iterative approach to the solution of the heat inputs and outputs to the solar collector as suggested in Meinel and Meinel. (1) The iterative approach used in Meinel and Meinel for solution of the solar collector heat transfer equations was modified by linearizing the four sets of log equations relating the Nusselt Number and the Rayleigh Number for various arrangements of heat flow between parallel surfaces. This was done to allow direct computation of convection and wind losses upward from the absorber surface, thus eliminating the necessity of hand calculating the Rayleigh Number and then using the correct curve for the collector configuration considered to find the value of the Nusselt Number to be read into the program. The program, instead, determines the proper linearized Rayleigh-Nusselt equation to use from the value read into the program for the angle at which the collector is inclined. The program then utilizes the iterative approach, described in detail in Meinel and Meinel, to solve for the net heat into the absorber for the desired outlet temperature, collector parameters specified, and particular time of day and of the year for which it is calculated.

The third sequence consists of calculation of the heat losses, heat inputs, and the net heat delivered by the system as well as the number of square meters of collector required to meet heating needs. Utilizing the absorber outlet temperature, the heat input from the collector, and various parameters of the piping associated with the collector, the net heat loss from piping is determined. Heat loss from the storage facility, if any is used, is computed also along with the power usage necessitated by the system's pumping requirements. Economic evaluation is then performed to relate all the costs associated with the solar system, and compare them to the cost of conventional fuels saved over the sample period. This value is computed to determine a net savings or loss figure for the solar system for that iteration.

The fourth sequence essentially consists of double nested "do loops". The inner "do loop" repeats the above described calculations for a given day for incremental time periods of one hour beginning at solar noon and preceeding until sundown (i.e. until the calculated incremental zenith angle exceeds 90 degrees). Once the inner "do loop" has satisified its requirements, the outer "do loop" then increments the day of the year by any given constant integer value read into the program, and then returns control to the inner "do loop" to repeat its function. This preceeds as long as the incremental value for the day does not exceed 365, at which time the program terminates. The result is a printout of design parameters on an hourly basis from solar noon for specified intervals (days) during the year. The net solar insolation and the net savings or losses of the system for each incremental interval examined is algrebraically summed to determine the system's net yearly savings or losses. If a solar system is to function only for a particular season rather than for the whole year, the program also has provisions for examination of seasonal savings or losses of the proposed system configuration. This cost analysis, of course, is highly speculative due to the uncertain future cost of the input variables used for the price of natural gas and electricity. The user may wish to run the program for an expected minimum and maximum cost of these conventional sources to determine their effect on net savings or losses of the system.

2.2 PROGRAM INPUT PARAMETERS

Input variables to the program are structured to provide the user with the maximum flexibility to model a proposed or existing configuration for determination of its efficiencies, cost, and other design parameters. The program uses such input variables as: site solar flux, site position coordinates, altitude, weather data, air temperature, the desired usage temperature of the water, as well as data on the type of collector, piping, storage (if any) associated with the system. These input variables detailing process and economic criteria are manipulated by the program to yield design data on: collector and system efficiencies, heat outputs, solar flux distribution during the day (modified for season), heat losses in the system, modeling of storage systems including cost trade-offs of various system configurations, as well as comparisons of cost to conventional energy supplies over the life of the solar water heating installation.

The primary input to the computer program is the peak solar insolation, adjusted for use in desert or urban atmospheres and consisting of direct or direct plus scattered components of the insolation depending on the type of collector used. Concentrating collectors use only the direct component of the solar insolation since it alone can be focused on an absorber, whereas non-concentrating collectors, such as flat plate types, can accept both direct and scattered sunlight.

The program modifies the peak flux for locational, seasonal, and daily variations, to determine the flux at the collector site. Details of this modeling are described in the following paragraphs.

The tilt in the axis of rotation of the Earth causes the relative north-south position of the sun in the sky, during its daily east-west movement, to vary with the time of year (that is, it is dependent on the position of the Earth in its orbit around the sun). This defines the declination angle of the sun which is the north-south angle from vertical, at the equator, that the sun would take during its relative daily east-west movement, for a given time of year.

This declination angle, along with the latitude of the collector site, and the time from solar noon defines the position of the sun in the sky for a given time of year and at a particular time of day.* From this information and the altitude of the collector site, as well as weather data, the solar insolation available at the location is computed for a given point in time.

This value of solar insolation defines solar flux at a non-inclined flat plate collector, alligned parallel with east-west movement of the sun. If an inclined flat plate collector is used and/or the collector is not alligned parallel with the east-west movement, this value is modified by calculation to define the insolation at the collector. The value for solar insolation at the collector is then corrected for the reflection losses of the particular collector under consideration giving the net flux into the collector.

Heat balance equations are then used to describe the conditions at the absorber and, if applicable, the collector cover glass. The desired output temperature and therefore absorber temperature, is known and is used as an input variable. The temperature of the cover glass is not know. This temperature is solved for by an iterative technique. (1) A first guess approximation is used to select a value of cover glass temperature. This value is then used to solve the heat balance equations developed for the collector cover glass. The total heat input into the cover glass minus the total heat loss of the cover glass is computed. If this value is negative, the "first guess" approximation of the temperature of the cover glass is modified downward by a fixed increment. This new guess of the temperature is then used to reevaluate the cover glass heat equations. If the value initially obtained was instead positive, the "first guess" would be modified upward by a fixed increment and the new guess then used to reevaluate the cover glass heat equations. This iterative process continues until the absolute value of the mismatch between the heat into and the heat out of the cover glass falls within an acceptable target value. When this value is reached, the heat equations for the absorber are solved to determine the net heat out of the collector. These computed values are also utilized in the economic evaluation of the solar collector system.

Heat loss of piping associated with the collector is also evaluated from input variables of pipe diameter, length, insulation thickness, and the thermal conductivity of pipe insulation.

From these input parameters of the piping, along with the specified heat to be delivered, and the heat

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* solar noon is defined as the time of daily peak solar insolation, i.e. when the sun is directly overhead.

carrying capacity of water, the required flow rate of water through the piping can be computed. With this value and the frictional coefficient of the pipe used, a pressure drop across the pipe can be determined. This figure is used to determine pumping power required for the system utilizing an inputed variable of pump efficiency. The input variables of capital cost of the pump in dollars plus the cost of electricity in dollars per kilowatt-hour and the expected life of the installation are then used to determine the cost of operating the pump over the life of the installation.

Provision for heat storage capability of the system is also made in the program. The heat required to be delivered each day, the number of consecutive storage days required, the percent of storage heat loss each day (assuming non-perfect storage means), and the cost of the heat storage facility are input variables required for modeling of the storage system.

The cost of the solar collector is calculated by determining the total heat required to meet specific heat loads to be delivered, piping heat losses, and supply heat storage losses (if storage is used). This total, and the net heat out of the absorber per square meter of collector, as determined by the computer solution yields the number of square meters of collector required. The calculated cost per square meter of collector is then used as an input variable in the determination of the net collector cost.

The total cost of the solar collector installation is determined by summing the cost of the collector, total pumping costs, piping and installation cost, and the cost of the storage unit (if any is used).

To determine the net savings or losses of the solar installation, the savings in natural gas or electricity required for heating/hot water usage must be determined. To accomplish this, the gas heat or electricity cost saved is calculated from input variables of heat required on a daily basis, the percent of sunny days each year, the average number of hours per day that the solar system is operating, the life of the installation, the conversion efficiency of natural gas or electricity, and the cost per 1,000 cubic feet of natural gas, or the cost in mills per kilowatt-hour for electric usage. If the system has heat storage capability, the amount of natural gas or electric usage saved from the use of the storage facility on cloudy days is determined.

The net savings in energy costs over the life of the installation is calculated, and the difference between this cost savings and the total cost of the solar installation yields the net savings or losses over the life of the system.

Determination of the net savings or losses of the system is accomplished by a summation process of the individual program iterations. The program is designed to vary by increments the time from solar noon for a given day of the year, repeating the calculation of the heat loss equations for each increment. The program further repeats this iteration process for any number of intervals (days) during the year starting with January 1st. The number of intervals chosen is an input parameter, and can be varied as the user desires. The results of the program then yield data for collector efficiency, heat losses, heat flows, and other design parameters as they vary with time from solar noon for various times of the year, as well as providing for an overall summation of the heat inputs and outputs and an evaluation of the economics of the system's operation.

3. CONCLUSION

The results obtained can be used to examine cost trade-offs of collector and overall system design, such as: water outlet temperature, percent of total load solar is to supply, piping size and insulation, pumping requirements, advisability of storage, days of continuous storage desired, number of hours per day solar is to operate, the effect of escalation of the cost of conventional sources on net savings or losses of the solar system, and optimization of the collector orientation for maximum output and best seasonal performance for peak load.

These are some, but by no means all, of the system design parameters that are accessible to the program user, which may be varied as inputs to determine their effects on system design.

It is the intent of this program to allow as much flexibility as to the type of system that can be modeled, and the maximum of freedom to the user to manipulate the design variables he controls to obtain the optimum system configuration.

The results obtained from the program are intended as a design aid for the design of a solar hot water collector system. The best results, in terms of the cost savings or losses of the system, will be obtained from a good initial choice of collector parameters based on seasonal demand requirements on the unit.

Cost data obtained is highly dependent on the price per square meter of collector and the values used for the cost of conventional sources it is to replace.

This program is essentially in its first iteration. Several refinements such as further expansion of the scope of the program will improve its usability.

REFERENCES

(1) Aden B. and Majorie P. Meinel, Applied Solar Energy - An Introduction. Tucson: Addison-Wesley Publishing Company, 1977.

4. BIOGRAPHIES

Michael F. Bregar

He is a graduate of the University of Illinois - Urbana with a BS in Electrical Engineering (1976) and the University of Missouri - Columbia with a MS in Electrical Engineering (1978). He has worked for Black & Veatch Consulting Engineers in Kansas City for approximately three years in the control and electrical departments of the Power Division.

Dr. William E. Stewart, Jr.

As an assistant professor of Mechanical Engineering at the University of Missouri - Kansas City, Dr. Stewart teaches both undergraduate and graduate level courses in heat transfer, thermal dynamics, and solar energy. He played an integral role in initiating the UMKC solar energy program and in acquiring necessary laboratory equipment, including an experimental solar collector.

He has had industrial experience as a research and development engineer in the area of fluid dynamics and environmental control, and consulting experience in cost and efficiency analysis of energy systems.

Dr. Stewart was graduated from the University of Missouri - Rolla in 1968, and received a Ph.D. in Mechanical Engineering from UMR in 1972.