Computer Simulation of Flat Plate Solar Collectors

by

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ABSTRACT

The performance of a flat plate solar water heater is predicted by a computer model. This model divides the collector and storage tanks into a finite number of sections and considers an energy balance over each section. Simulation of an actual solar collector was achieved by tracking experimental data with calculated values. The correlation obtained in this simulation resulted in accurate modeling of solar water heater systems.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my advisor, Dr. W. B. Harris, and also to Dr. R. R. Davison for his invaluable computer expertise and assistance.

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INTRODUCTION

To effectively utilize solar energy an accurate prediction of the performance of solar collectors must be achieved. First, computer simulation of a flat plate solar collector is made. This simulation is made by applying energy balances around the solar collector and the storage tank. After a closed loop simulation was completed, simulations of load changes were made. The load changes consisted of taking hot water from the storage tank and replacing it with cold water. This is a practical application of using solar energy. The computer model divides the system into a finite number of sections for simulation. By specifying location, date, and initial conditions, the performance of a flat plate solar collector can be predicted.

MATHEMATICAL CONCEPTS

A computer program that simulates the performance of a flat plate solar collector can, with a few minor changes, predict the collector's performance at any location and under any conditions. The computer subroutines were built in such a manner that predictions could be made by simply changing the main program.

The collector and storage section were modeled as a finite number of sections. The finite sections are numbered in the direction of the water flow. The collector sections are numbered beginning at the bottom of the collector and the storage sections are numbered beginning at the top of the storage tanks.

In section one of the storage tank, hot water is drawn off for use as the load. The water is at the highest temperature at the top of the storage tank. This is a break in the closed loop water flow. Make-up water is fed into the last storage section. In storage section n, the water is at it's coolest temperature in the storage tank and it is the feed point for the collector. Since the make-up water is cooler than the storage tank water, it is fed into section n and then pumped into the collector. In this manner the coldest storage water is always the feed for the solar collector.

COMPUTER PROGRAM

The computer program to simulate a solar collector is based on a pseudo-steady state. This involves iterative heat balances over small time intervals to calculate average water temperatures. The program consisted of five subroutines: SUN, HEATER, STORAGE, EOH, and EFFHTR.

Subroutine SUN (American Society of Heating and Refrigeration Engineers) calculated the total horizontal radiation, solar angle and normal radiation. The input is latitude, longitude, date, and time.

Subroutine HEATER simulates the flat plate solar collector. The major output is the exit water temperature of the collector. The overall heat transfer coefficient is calculated by the Klein equation. (1)

$$U = \left(\frac{NG}{\frac{344}{THAI} \times \left(\frac{THAI - TA}{NG + FZ} \right)^{0.31}} + \frac{1}{HW} \right)^{-1} + \frac{\sigma \left(THAI + TA\right)\left(THAI^2 + TA^2\right)}{\left(EC + 0.0425 \times NG\left(1 - EC\right)\right)^{-1} + \frac{2NG + FZ - 1}{EG} - NG} \quad (1)$$

The Hottel and Woertz equations (2) were used initially but the Klein equations predicted the experimental values more accurately. Next, the heat losses of the top, sides, and bottom are calculated. The total energy absorbed is then calculated by Qabs = (SH x EDH - Q Loss). (2)

Subroutine STORAGE does a heat balance around the water storage tank. The calculated water temperature exiting the bottom of the storage tank is compared to the water temperature entering the solar collector. This comparison yields the error in the iteritation done by the computer.

The next two subroutines, EOH and EFFHTR, calculate the efficiencies of the collector. Subroutine EOH calculates the glazing optical efficiency using the curves determined by Hottel and Woertz (2). Subroutine EFFHTR calculates the overall efficiency of the system. In Figure 2 a flow chart of the computer program is shown.

In subroutine SUN, the solar angle is calculated. Actual solar radiation is inputted when available. Using the solar angle, subroutine EOH determines the optical efficiency of the collector for use in equation(2). Then subroutine HEATER can calculate the outlet water temperature by knowing the energy absorbed and initial temperatures. The solar radiation input is assumed to be constant and equal to the average value of the actual radiation during the time period. The integrated solar radiation is used in this assumption.

A linear temperature profile is assumed in the solar collector while a thoroughly mixed section is assumed in the storage tank. The bulk average temperature is used in calculation of the heat losses from both the collector and the storage sections. In the collector, a plug flow type model is used. As the plug moves through the collector it is heated by the radiation. When the plug moves from one section to the next section, the temperature of the plug is used and not the bulk average temperature of the previous section. This has proved to be an appropriate model because of the smooth flow of water from the bottom to the top of the collector.

In subroutine STORAGE, thoroughly mixed sections are used in the temperature calculations. The bulk average temperature is used in the heat loss calculations and as the inlet temperature into the next section. Because of the nature of the fluid flow in the storage tank, this is a practical model for these sections. As the height and volume of the storage tank increases, the number of storage sections must also increase to accurately simulate the storage tank.

Complex iterations are used in solving for the temperatures of the storage and collector sections. Initially, in the collector, two outlet water temperatures are assumed.

After an iteration has solved for the outlet water temperature, an iteration over the complete collector must be done. Next, the storage temperatures are calculated. The outlet water temperature from the storage tank is then compared to the initial inlet water temperature of the collector. Again an iteration is done to determine these values within a tolerance.

APPARATUS

The experimental apparatus consisted of a flat plate solar collector, a water storage tank, a water manometer, an Eppley pyrheliometer and a strip chart recorder.

The collecting surface was a rubber bag supported on a plywood board by hardware cloth and metal banding. The entire surface was painted black and placed inside a wooden frame. This surface was then covered by plexiglas glazings that added a greenhouse effect and greatly reduced convective and radiative heat losses.

As shown in Figure 1, the system was a closed loop process. Water was pumped into the bottom of the solar collector where it was heated by solar radiation. The water then flowed out the top collector and into the top of the storage tank. Water was then taken from the bottom of the storage and pumped into the collector, completing the closed cycle.

The mass water flow rate was determined by measuring manometer readings across an orifice plate. Water temperature entering and exiting the collector along with ambient temperatures were recorded. Wind speed and direction were also measured and recorded at each time interval.

The actual solar radiation was measured by a phrheliometer on a horizontal surface. These continuous measurements were recorded and integrated by a strip chart recorder.

In the computer program, the solar radiation was corrected to the incidence angle of the collector.

FIGURE 1 EXPERIMENTAL APPARATUS

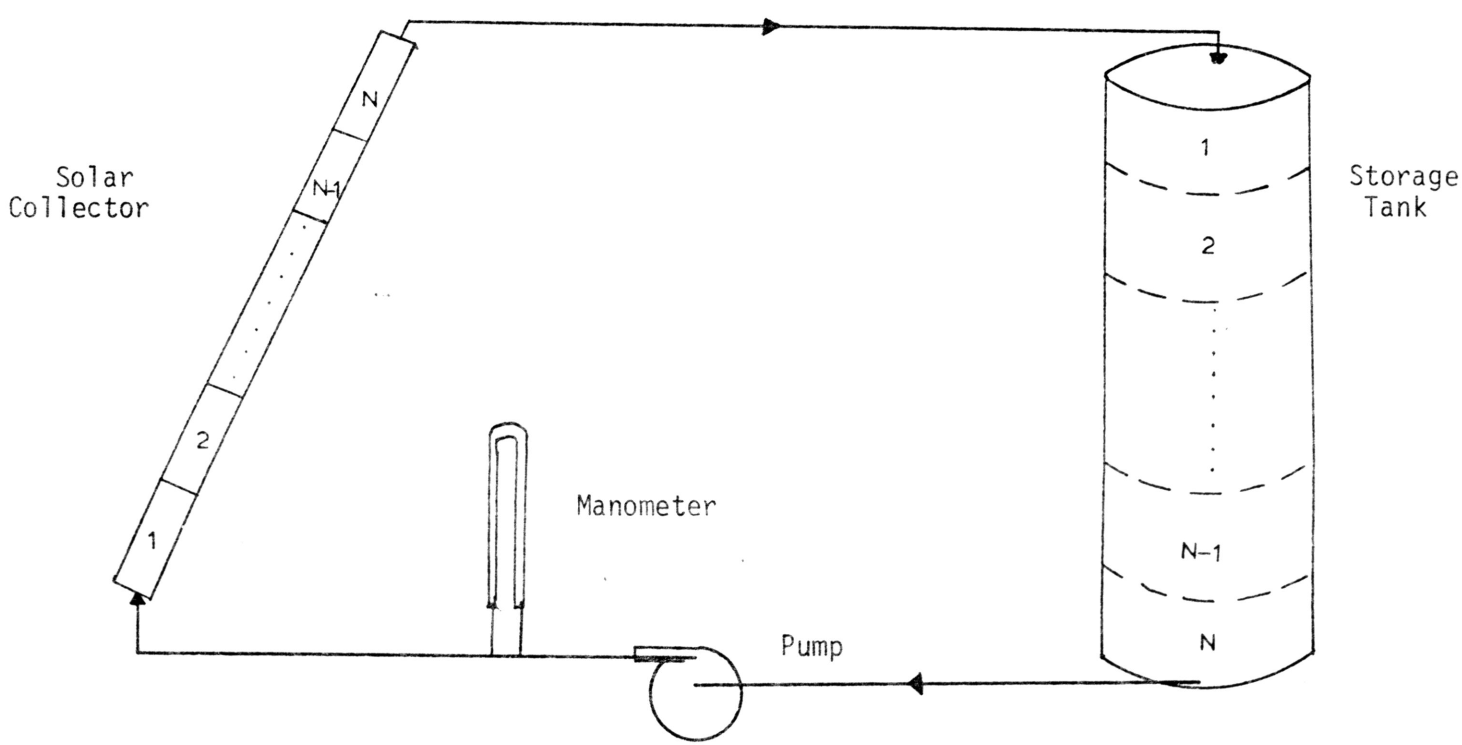


FIGURE 2 COMPUTER FLOW CHART

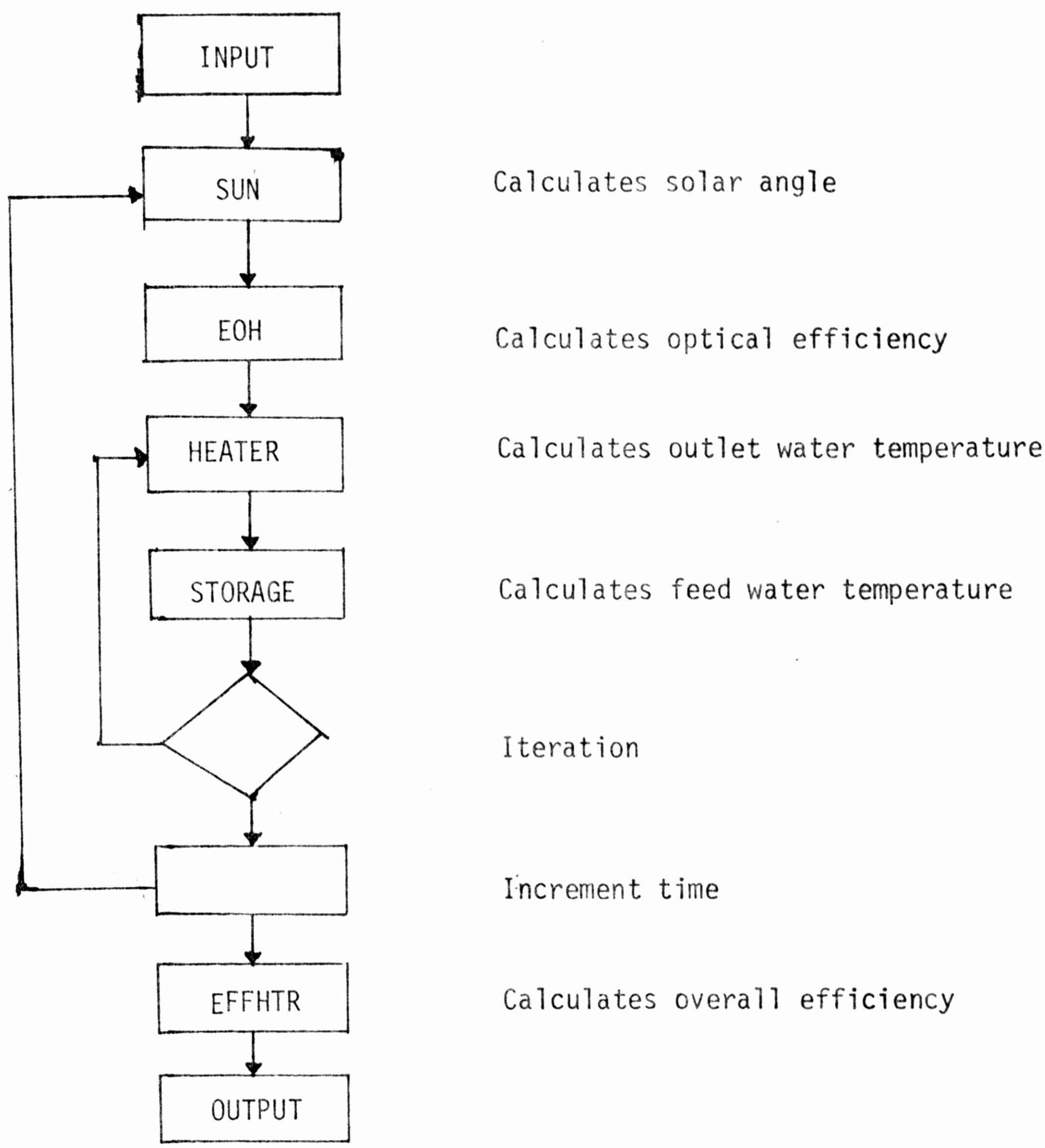


FIGURE 3 PERFORMANCE CURVE OF EXPERIMENTAL AND CALCULATED OUTLET WATER TEMPERATURES

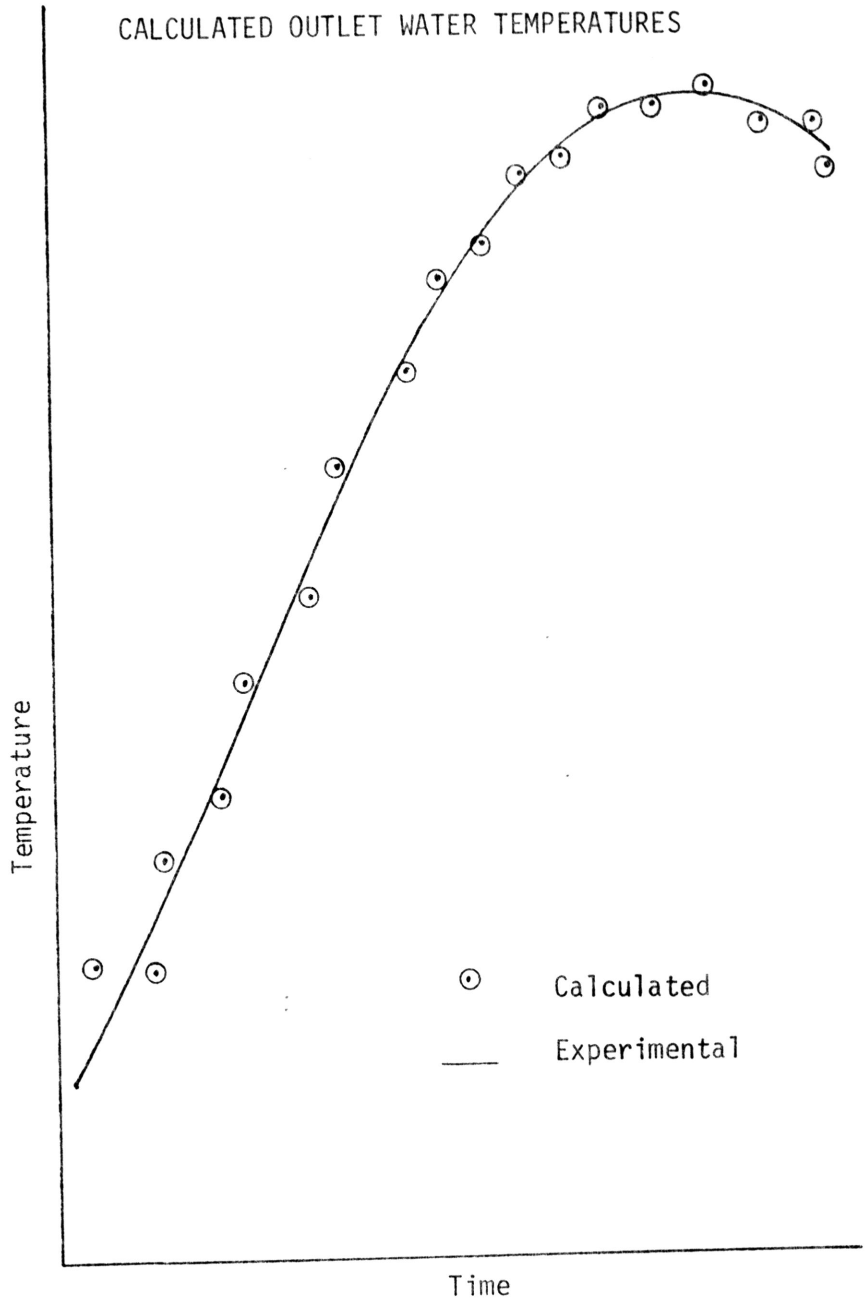


FIGURE 4 PERFORMANCE CURVE OF EXPERIMENTAL AND CALCULATED OUTLET WATER TEMPERATURES

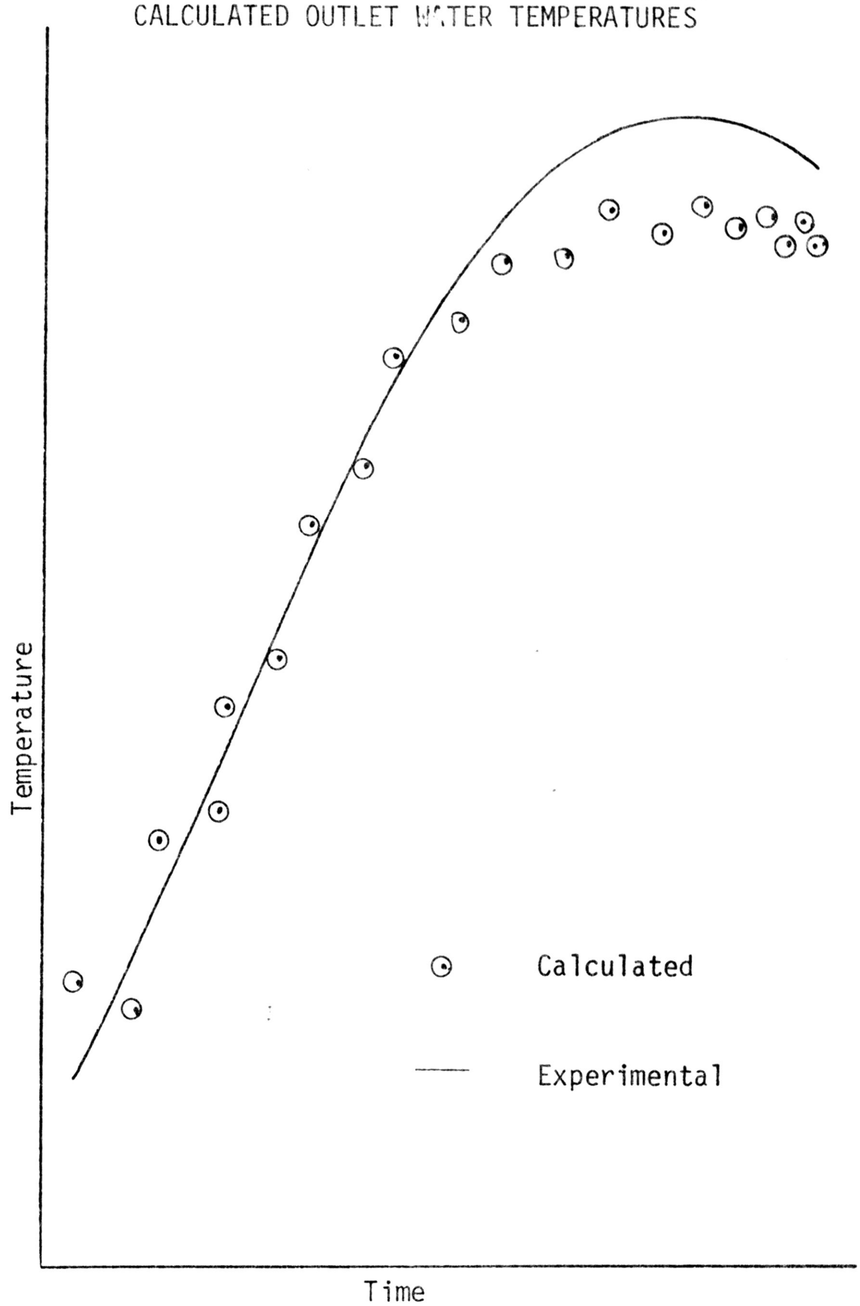
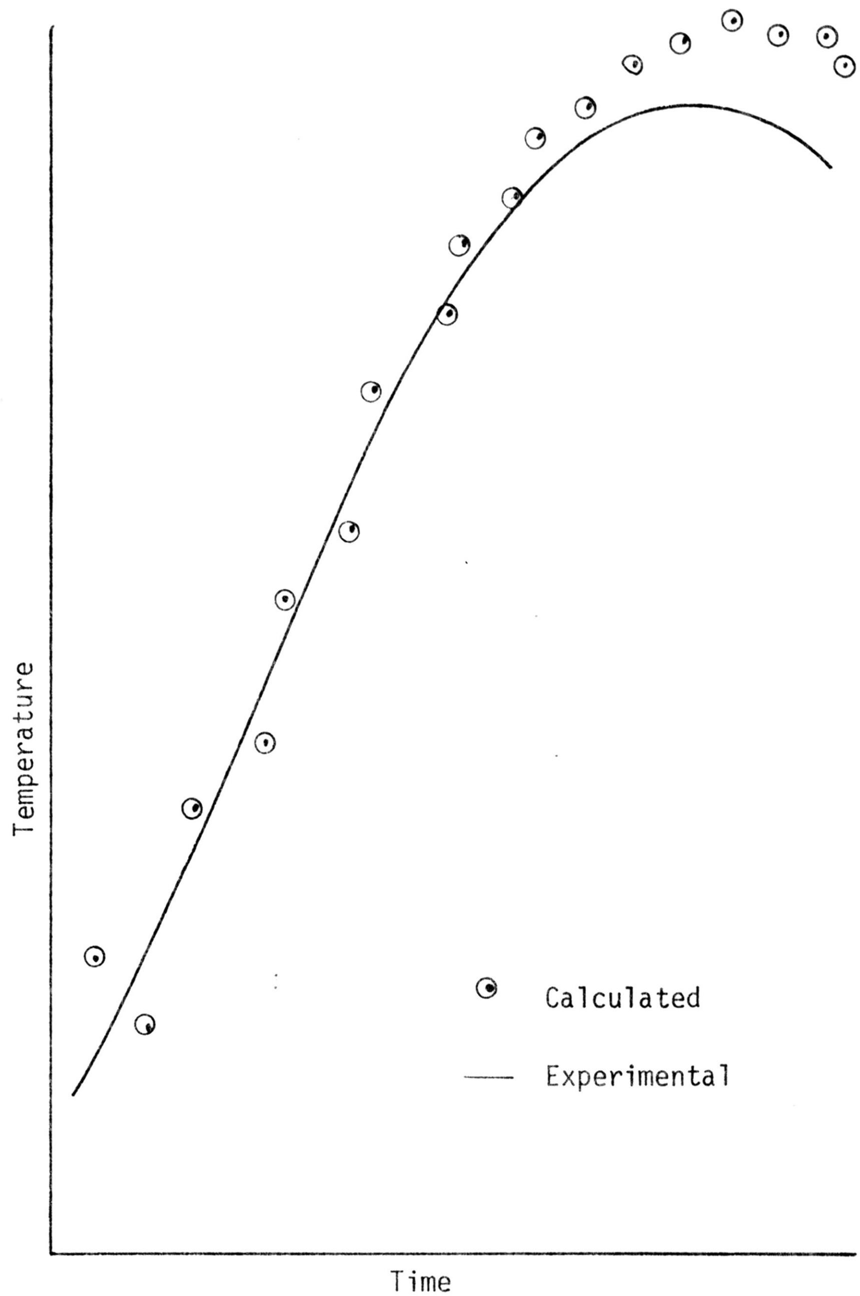


FIGURE 5 PERFORMANCE CURVE OF EXPERIMENTAL AND CALCULATED OUTLET WATER TEMPERATURES



RESULTS

Nineteen days were simulated by the computer program. Figures 3, 4, and 5 are representative of the results obtained. The values plotted are the actual and calculated exit water temperatures of the collector at the end of the time period. As shown in Figure 3, the calculated values oscillate around the actual temperatures. Figures 4 and 5 show deviations around the peak water temperatures. However, one plot predicts higher temperatures and one predicts lower temperatures. These deviations are probably caused by weather conditions. Peak water temperatures recorded ranged from 140^{o} F to 145^{o} F. The peak temperature occurred around 15:00 to 17:00 hours. The total efficiency of the system is around 50%.

DISCUSSION OF RESULTS

Simulation of the solar collector was calculated by using one-half hour time increments. This corresponds to the time interval used in recording the experimental data. The calculated values for any one time period is an average value over that time period. The oscillatory effect (Figure 3) shows that a simulation has been achieved. Values above and below the actual values result in the calculating of average values. The oscillating is greatly dependent on the time interval used.

The time at which the prediction started was important. The solar collector reached an even temperature distribution after running a few hours. After this pseudo-steady state has been reached the simulation was readily accomplished. By varying the starting time, the actual water temperatures were tracked by the Klein equations.

The calculated efficiencies of 30% to 50% were expected for this type of collector.

CONCLUSIONS

Our computer program does simulate a flat plate solar collector. Of course, this program is only as accurate as the prediction of weather conditions. Therefore, the values of output of this program is only an average calculation and safety factors should be considered for practical use. Solar collectors can now be sized given the location and the amount of hot water required.

NOMENCLATURE

EC	-	emissivity and absorptivity of collector
EG	-	emissivity and absorptivity of glazings
EOH	-	optical efficiency of collector
FZ	-	effective thermal resistance of glazings
HW	-	forced convection coefficient
NG	-	number of glazings
QAB	-	energy absorbed
Q Loss	-	energy losses
SH	-	total energy available
TA	-	ambient temperature
THAI	-	bulk average temperature
U	-	overall heat transfer coefficient
σ	-	Boltzman Constant

REFERENCES

1. J. A. Duffie and W. A. Beckman, *Solar Energy Thermal Processes*, John Wiley & Sons, Inc., New York (1974).

2. H. C. Hottel and B. B. Woertz, "The performance of flat plate solar heat collectors", *Trans.* ASME 64, 91 (1942).

APPENDIX

Computer Input

Latitude, Longitude, time zone number, day, days in month, area of heater, number of heater sections, number of storage sections, capacity of storage, actual initial inlet and outlet water temperatures at time and time increments, number of time periods, wind speed, time of day, ambient temperature, mass flow rate, solar radiation, angle from horizontal, angle from south, load changes, and time increment.

Computer Output

Calculated inlet and outlet water temperature, Q absorbed, Q loss, overall heat transfer coefficient, efficiency of heater, and optical efficiency