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SOLPOND-A SIMULATION PROGRAM FOR SALINITY GRADIENT SOLAR PONDS

JON HENDERSON
CECILE M. LEBOEUF

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Solar Energy Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

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By
Jon Henderson
Cécile M. Leboeuf

Solar Energy Research Institute
Golden, Colorado

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ABSTRACT

A computer simulation design tool was developed to simulate dynamic thermal performance for salinity gradient solar ponds. Dynamic programming techniques allow the user significant flexibility in analyzing pond performance under realistic load and weather conditions. Finite element techniques describe conduction heat transfer through the pond, earth, and edges. Results illustrate typical thermal performance of salinity gradient ponds. Sensitivity studies of salty pond thermal performance with respect to geometry, load, and optical transmission are included. Experimental validation of the program with an operating pond is also presented.

INTRODUCTION

Salinity gradient solar ponds offer the advantages of relatively high operating temperatures and long-term storage for costs significantly below those of conventional active solar systems. The outlook for greatly increased interest in solar ponds appears favorable, and commercialization may be close at hand. Because development of solar pond engineering is necessary for commercialization, work at the Solar Energy Research Institute (SERI) has addressed many of the engineering problems. This paper discusses a computer simulation program, SOLPOND, for predicting thermal performance of salty ponds. Previous analyses of salty solar ponds have discussed their optical, thermal, and hydrodynamic behavior and developed simplified, closed-form solutions of pond thermal performance [1,2]. SOLPOND offers much greater versatility. Finite element techniques model pond thermal performance, and the program performs discrete time solutions. SOLPOND allows the user considerable flexibility because weather and load profiles are handled as discrete data and optical transmission characteristics of the pond solution are considered as input data.

PROGRAM STRUCTURE

Within SOLPOND the transient thermal performance of a salinity gradient pond is modeled from a lumped-parameter thermal network. For large ponds, edge losses are small in comparison to total energy collection; such ponds are modeled with a one-dimensional finite element geometry (see Fig. 1). Each node of the corresponding thermal network describes the temperature at the related position within the pond. The upper and lower convecting layers are represented by individual finite elements because they are approximately isothermal. Several elements are used to model the thermal profiles within the nonconvecting salinity gradient or the earth below the pond. In the thermal network, the current inputs account for absorption of solar radiation within each finite element. The storage layer current source also accounts for the thermal load delivered by the pond.

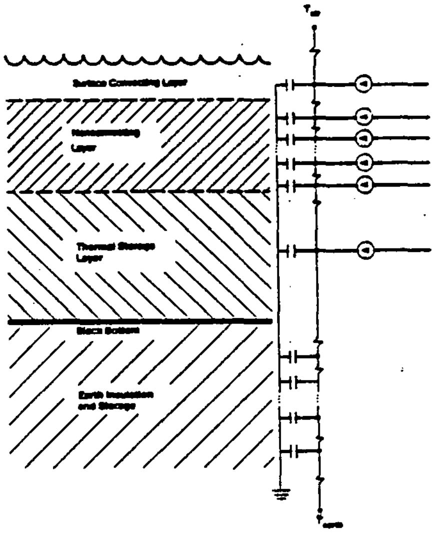

Fig. 1. One-dimensional solar pond thermal network.

The one-dimensional finite element model does not account for heat flow through the pond edges. This assumption is reasonable only for large ponds. The detrimental effects of edge losses become important when the pond perimeter-to-surface-area ratio becomes large (i.e., in a small pond). To account for edge losses, a three-dimensional anaylsis is necessary. For simplicity, SOLPOND models a circular pond. Axial symmetry of temperatures and incident solar radiation are assumed. Thus, the three-dimensional analysis is described by a two-dimensional finite element model revolved around the axis of symmetry. The element geometry is illustrated in Fig. 2.

The computation sequence in SOLPOND first calculates a time invarient discrete state transition matrix from the thermal network and then performs a time solution of the finite element temperatures. Since the discrete state

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transition matrix is computed only once, time-varying factors that may exist in the thermal model are not considered. The major time-varying components that affect thermal performance are the dynamics of the salinity gradient. Because the growth and erosion of the gradient are determined by natural and maintenance effects and are not well understood, modeling of this effect is not practical.

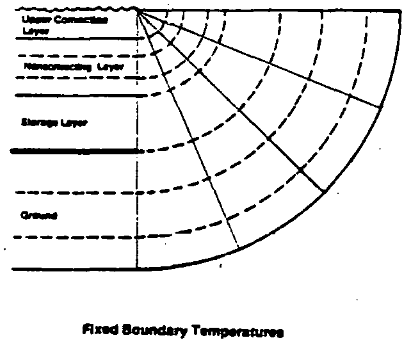

Fig. 2. Three-dimensional finite element geometry.

Additional aspects of the simulation program are as follows:

- Depths for the upper convection layer, nonconvecting layer, storage layer, load data, optical transmission, simulation time step, thermal conductivities, and heat capacities are user-selected inputs.
- Weather data that include daily averages for dry bulb temperature and modified solar radiation that accounts for reflected losses from the pond surface are available for Typical Meteorological Year (TMY) sites.
- The number of finite elements used to model the gradient layer and ground are user selected.
- To avoid numerical overstability, implicit finite difference equations compute the time solution.
- The pond storage temperature never exceeds 100° C. It is assumed that excess energy is extracted when necessary to avoid overheating.

SIMULATION RESULTS

Knowledge of the thermal performance of salty solar ponds is of fundamental importance in assessing their market potential. For any salty pond, local weather, predicted load, geometry, and optical properties will greatly affect thermal performance. The potential combinations of these properties are limitless, but a general understanding of salty solar pond thermal performance is possible by examining several simulation results. The presented results focus on aspects of pond thermal performance that would be difficult to investigate with previous simpler solar pond thermal models. From these simulations, several significant design factors affecting thermal performance are investigated. The stationary parameters used for these simulations are listed in Table 1.

Table 1. **ASSUMED PARAMETER VALUES**

Thermal conductivity of salt solution	0.65 (W/m° C)
Thermal conductivity of ground	1.0 (W/m° C)
Heat capacity of salt solution	3.98 x 10^6 (J/m^{3}° C)
Heat capacity of ground	2.0 x 10^6 (J/m^{3}° C)
Ground temperature 10 m below pond bottom	10 (° C)
Depth of upper convection layer	0.1 (m)
Simulation time step	14 (days)

For all the following simulations (except where noted), optimistic optical transmission properties for the pond saline solution are assumed. Transmission is computed from Nielsen's lumped representation of the solar spectrum and the associated exponential decay terms [2].

All simulation results are based on pond thermal performance after initial heating is completed. Thus, the pond thermal response results are steady-state, periodic solutions. This approach is convenient and appropriate for initial study because the pond warm-up transient is usually short-lived and of minor importance after the first summer of operation.

Effect of Load Profile

Temperature and load matching between a particular application and solar pond thermal performance is of obvious design importance. The seasonal thermal performance of the pond is sensitive to total energy extraction and the time that this extraction occurs. To illustrate this effect, three simulation results are drawn in Fig. 3. For these runs, total annual energy extraction, pond geometry, and weather data were identical. The time of year when the load was applied to the pond was the only variable in these simulations.

The summer-peaking and winter-peaking loads continuously extracted 70 W/m^2 for 22 weeks beginning in May and November, respectively. The continuous load extracted 29.6 W/m^2 throughout the entire year.

As can be seen in Fig. 3, this pond could provide the summer-peaking load at temperatures above 65° C. The same pond would have a minimum storage temperature below 25° C if it were used for the winter-peaking load.

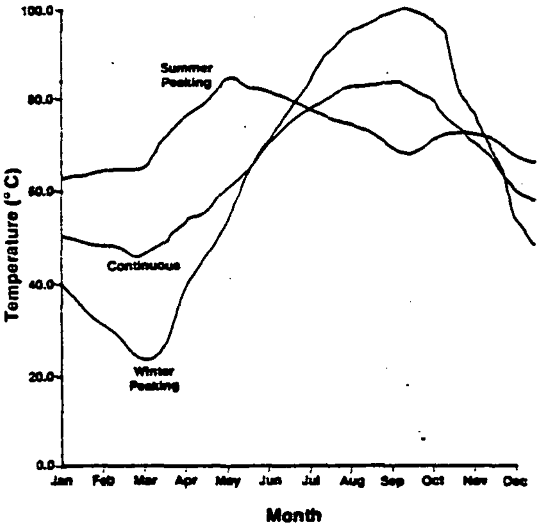

Fig. 3. Effect of seasonal load profile.

Effect of Storage Layer Depth for Winter Peaking Loads

The pond in Fig. 3 is poorly designed for a winter-peaking heating load requiring thermal energy above 35° C because the delivered energy temperature is too low during part of the operating season. One approach toward raising the minimum delivered energy temperature is to increase the thickness of the storage layer.

Figure 4 illustrates this effect for a pond used for continuously supplying a 55 W/m^2 heating load from November through March in Madison, Wis. A 5-m storage depth would be required to maintain the storage temperature above 40° C. A 3.0-m storage layer would have a minimum storage temperature near 30° C, and a pond with a 1.5-m storage layer would drop to about 15° C by the end of the heating season. If salty ponds are to be used for winter heating applications, they will have to be deeper than ponds yet constructed.

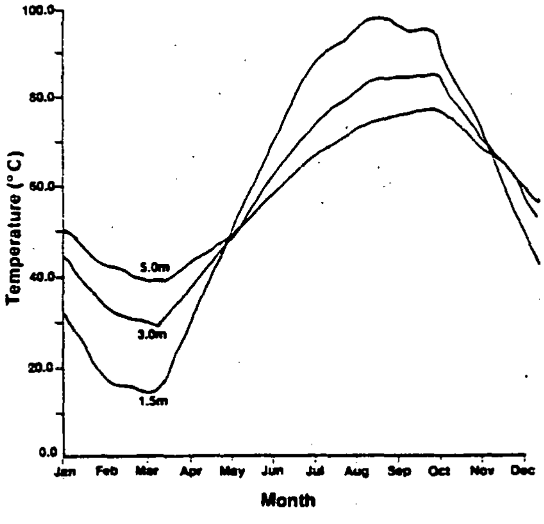

Fig. 4. Effect of storage depth.

Effect of Optical Transmission

The variation in pond thermal performance because of variation in optical transmission of the salt solution is great. Pond thermal performance is sensitive to the amount of solar radiation absorbed in the nonconvecting layer and the amount that penetrates into the storage layer. Also, the solution optical transmission can vary greatly because of salt impurities that inexpensive salts contain.

The optical transmission characteristics of the pond saline solution vary with the salt purity. Pure water characteristics establish an upper bound on optical transmission, with the dissolved salt and impurities further degrading transmission. The thermal performance of a pond using transmission properties of distilled water and Nielsen's data of a clear solution has been simulated with SOLPOND. The resulting seasonal temperature profiles are drawn in Fig. 5.

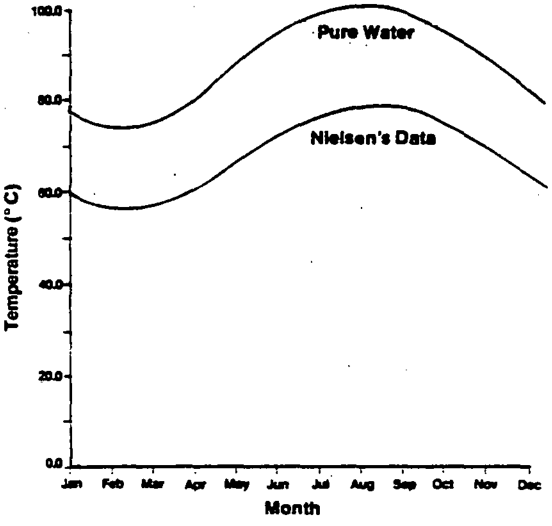

Fig. 5. Effect of optical transmission.

Nielsen's transmission data is for a highly clear salt solution. For applications using less pure salt, such as industrial byproducts, the transmission may be further degraded with a corresponding drop in pond performance. The need for high optical transmission is a major consideration in salt selection and pond maintenance.

Edge Loss Analysis

A convenient parameter for approximating average annual thermal losses through the pond edges is a perimeter heat-loss coefficient. This parameter relates the edge loss per length of perimeter to the temperature difference between the pond storage layer and the ambient air.

Using the material properties and ground temperature listed in Table 1 and a 0.3-m upper convection layer, several perimeter heat-loss coefficients have been calculated. These are presented in the graph in Fig. 6, which illustrates the dependence between pond depth profile and the perimeter heat-loss coefficient. Significant variation in the perimeter heat-loss coefficient will result if the ground conductivity differs from the 1.0 W/m°C value typical of dry ground used in the simulations; wet ground can have a thermal conductivity more than five times greater than dry ground. Other factors, such as operating temperature and load profile, affect the value of the perimeter edge loss coefficient but to a much lesser degree.

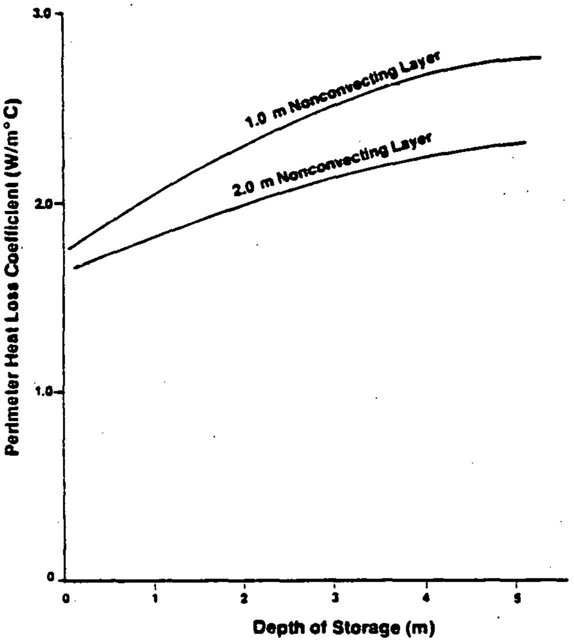

Fig. 6. Typical perimeter heat-loss coefficients for dry ground.

The importance of accounting for thermal losses through the pond edges can be highlighted by considering the degradation in delivered energy for several pond sizes. Table 2 lists the approximate load per unit surface area lost through the pond edges for three ponds having a 2.0 W/m°C perimeter heat-loss coefficient and operating 50°C above ambient. The small pond, typical in size of research ponds in the United States, loses over 3 kW through the edges, which is equivalent to a 40 W/m^2 load on a pond with negligible edge losses. This is most of the potential load. The second pond has the same surface area-to-perimeter ratio as the Miamisburg pond* and, consequently, suffers similar thermal degradation that is more than 10/Wm^2 of pond surface for these operating assumptions. The 100-m diameter pond is large in comparison with ponds constructed in the United States and loses 4 W/m^2, which is about 10% of the delivered energy. The performance degradation from edge losses is significant for small ponds, and insulation may be desirable. SOLPOND may be used to simulate small ponds with insulation along the perimeter.

SOLPOND COMPARISON TO ACTUAL POND PERFORMANCE

It is desirable to test the validity of a computer modeling code by comparing simulation predictions with measured performance of a full-scale system. Only a handful of solar ponds are located within the United States, and all except the Miamisburg, Ohio pond are used for experimental purposes. About 1/2 acre in surface area, the pond in Miamisburg is significantly larger and of a more practical size than the experimental ponds. Additionally, thermal performance data have been collected for over a year. Based on data availability, size, and the ready cooperation of the associated personnel, the Miamisburg Pond was selected for this evaluation of the accuracy of SOLPOND predictions.

Thermal performance and weather data taken at the Miamisburg Pond during the period from 23 July through 5 November 1979 were used for this validation exercise. Temperature values from July 23 established the necessary initial conditions for SOLPOND. Because SOLPOND models circular ponds and the Miamisburg pond is rectangular, a circular pond with a surface-area-to-perimeter ratio equivalent to that of the Miamisburg pond was simulated.

Figure 7 shows SOLPOND predictions and measured values for storage temperatures. The lower curve was developed using a ground thermal conductivity of 5.0 W/m-°C (wet ground). SOLPOND default values were used for the remainder of the material properties. Close agreement between measured and predicted values is apparent. In the upper simulation, all of the SOLPOND default values, including ground thermal conductivity of 1.0 W/m-°C (dry ground), were used. This illustrates the degradation in performance of the Miamisburg pond caused by the greater thermal conductivity of wet earth.

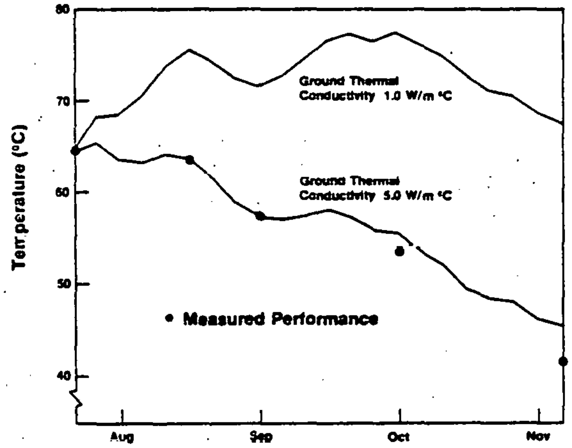

Fig. 7. Comparison of SOLPOND simulations to measured performance for the Miamisburg Pond.

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*An existing salinity gradient pond, 55 m by 37 m in size.

Software/hardware validations are inherently limited in their accuracy for several reasons. Material anisotropies, data collection limitations, and model approximations contribute to prediction error. These general problems as they relate to this simulation are detailed next.

A precise knowledge of material properties is important for an accurate solar pond simulation. Ground properties such as thermal conductivity and specific heat vary according to the type of soil and the moisture content. Because variations may be found both regionally and locally, if one assumes constant properties throughout, the pond may introduce errors. Currently, however, ground property measurements do not exist, and values are estimates.

The optical transmission of the pond solution is another unknown. For the SOLPOND simulations, Nielsen [2] coefficients for clear water were used. A study of the optical properties of the Miamisburg solution currently underway at SERI indicates little deviation from Nielsen's data.

A third unmeasured characteristic of the pond is the surface heat-loss coefficient. However, as long as evaporation is not suppressed (by means of a cover or other device) performance is fairly insensitive to this parameter. A large value is used to provide close tracking of the pond surface temperature to the ambient temperature.

Data collection at an experimental facility is determined by a balance among hardware, design, and data reduction costs. The Miamisburg pond is well instrumented with thermocouples in the salt solution and in the ground to 1.5 m below the pond bottom. SOLPOND required initial temperatures for the salt solution and the ground around and below the pond. Many of these beginning conditions were necessarily estimated.

Also, during early 1979, a leak developed in the pond liner, causing significant losses of solution from the storage layer. Three hundred tons of salt and the associated water were lost from May to mid-October, when the leak was repaired. This fluid loss translates into a unmeasured heat loss from storage, but the loss also caused shifting in the depths of all three layers. For example, the depth of the upper convecting layer went from 0.5 m in July to 1.3 m in November. Also, the ground beneath the pond became wet, thereby raising the ground thermal conductivity.

SOLPOND was developed as a design tool to help the modeler examine the sensitivity of a variety of external parameters on solar pond behavior. SOLPOND was also designed to give maximum system information with minimum computer time, thus allowing multiple runs for a parametric study. To keep computational time small, several simplifying assumptions were used in the model.

For example, SOLPOND does not allow for changes in layer depths during a run; thus, it was necessary to interrupt the Miamisburg simulation to update the layer depth values. Material properties are also assumed to be constant, thereby discounting variation in optical transmission or ground thermal properties with time or location. However, the close agreement shown in this exercise demonstrates the viability of SOLPOND for future use.

CONCLUSIONS

A simulation program, SOLPOND, has been developed to analyze solar pond thermal performance under realistic weather and energy extraction conditions. This program was used for several illustrative examples. Simulation results highlight a pond sensitivity to seasonal load profile, storage layer depth, and optical transmission through the salt solution. Thermal losses through the pond edges were evaluated for several pond sizes and were shown to be significant for ponds as large as 100 m. A validation exercise showed close agreement between predicted thermal performance and measured data for an operating pond.

ACKNOWLEDGMENTS

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