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SOLAR POND CONCEPTS: OLD AND NEW

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ABSTRACT

Different types of solar ponds have been considered from the early 1900s to the present. Salty ponds use salt to create a nonconvecting pond. Shallow solar ponds were investigated by Shuman and Willsie in 1906 and 1907 and are currently being studied by Lawrence Livermore Laboratories. Swedish investigators are studying a combination of solar collectors and water storage in a pond-cover configuration. In addition, there are thermoclines created in large bodies of water, as in large reservoirs.

This paper surveys the various types of solar ponds, classifies and models them, and then tries to combine the best of the ideas to synthesize new concepts. It presents a new solar pond concept which combines the good features of convecting and nonconvecting (salty) ponds.

MOST LOW TEMPERATURE solar thermal systems have collector and storage units as separate components. Storage is usually sufficient to last only a few days. With solar ponds, it is difficult to distinguish the collector unit from the storage unit: the same body of water serves as solar collector and storage medium. This body of water is usually large enough to provide long-term storage spanning seasons.

Solar pond concepts may be classified in two categories: (a) those that reduce heat loss by preventing convection within the water storage medium, and (b) those that reduce heat loss by covering the pond's surface. Combinations are of course possible, but one method is usually the primary determinant of the pond design.

If one objective of the solar pond is to capture and store solar thermal energy, a second objective is to do so cheaply. This means using earth as both the support structure for the body of water and as at least part of the insulation. A large enough body of water embedded in the earth and made usable for thermal storage involves low cost for both support structures and insulation. It can provide sufficient storage to even out short-term temperature and insolation fluctuations and to furnish heat output long after heat collection has taken place.

TYPES OF SOLAR PONDS

NONCONVECTING PONDS - Most studied of the solar ponds is the nonconvecting, salty pond (1*-10). In its simplest form the salty pond is merely a pond with salt dissolved in it. Salts most commonly used are NaCl and $MgCl_2$, although there are numerous other possibilities.

Solar radiation enters the pond, and whatever is not absorbed in the water on the way down is absorbed on the dark bottom (which may be an artificially blackened liner). As a result of this heat collection at the bottom, the deeper waters become warm.

Higher concentrations of salt are established in the lower pond regions than in the upper regions, so the warmer, deep waters contain a higher density of dissolved salt than the colder waters near the surface. This is the opposite of the situation without salt. Pure water, when warmed, becomes less dense. If there were no salt in the pond there would be continuous convection of the warmed water from the bottom of the pond to the cooler layers near the top. However, the increased density created by the salt overcomes the decreased density of pure water with increasing temperature, and thus vertical convection is prevented. Heat transfer to the surface of the pond occurs primarily by conduction, which is slow enough to enable the lower regions of the pond to maintain a high temperature (100°C has been measured in actual ponds).

In practice the salty pond has three layers. In the top layer vertical convection takes place due to the effects of wind and evaporation. This layer serves no useful purpose and is kept as thin as practically possible. The next layer, which may be approximately 1-m thick, contains an increasing concentration of salt with increasing depth and is nonconvecting. The bottom layer is a convecting layer which provides most of the thermal storage and facilitates heat extraction.

Variants on the simplest salty pond design have been proposed to aid in controlling the boundaries of these layers. The so-called "membrane pond" (4) contains a horizontal partition to separate the lower convecting zone from the middle nonconvecting zone and, possibly, a second partition slightly below the surface of the pond to minimize the surface convecting layer.

Salty ponds have been built and operated in such diverse locations as Israel and Canada and in Ohio and New Mexico in the United States.

Proposed alternatives to the salty pond in the nonconvecting pond category are the viscosity-stabilized pond and the gelled pond. Both of them retard internal convection by decreased fluidity of the water in the pond and have not yet advanced significantly beyond the conceptual stage.

CONVECTING PONDS - The single well-researched example of the convecting pond is the shallow solar pond proposed and designed by Lawrence Livermore Laboratories (11,12). The shallow solar pond is about a 10-cm depth of pure water enclosed in a large water bag (typically 5 m by 60 m) with a blackened bottom, insulated below with foam insulation and on top with glazings. The water from many such ponds is pumped into a large storage tank for night storage and back into the water bags each morning, in an operating method called the "batch" mode. The shallow solar pond may also be operated in the "flow through" mode, in which the water flows continuously through the water bags in such a way as to maintain control over the outlet temperature.

Especially when operated in the flow-through mode, the shallow solar pond is almost the same as a flat-plate collector with water storage, the main difference being that the solar pond collector is fixed in a horizontal position and is less costly than the usual flat-plate collector. For this reason the shallow solar pond is classified in the collector-pond storage category described below.

A second type of convecting pond will be introduced in more detail in later sections of this paper. This type of pond is more similar to the salty pond than to the shallow solar pond in that it will be embedded in the ground and will have a similar depth.

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*Numbers in parentheses designate references at end of paper.

To compensate for the losses prevented by the nonconvecting layer in the salty pond, the convecting pond will have glazings and special night insulation.

COLLECTOR-POND STORAGE COMBINATIONS - Several collector-storage combinations have been suggested in which the thermal storage is provided by a large pond embedded in the ground.

In a Swedish design (13), a bank of tilted collectors is floated on a raft of insulation on top of a large pond. The heated water is drained into the pond and the collectors are fed with cooler water pumped back up from the pond.

A pond tested at the University of Virginia (14) had a trickle collector mounted just above the surface of a square pond. Between the pond surface and the collector was a layer of foam insulation "beads" through which the heated water trickled into the pond.

An Italian proposal (15) calls for focusing collectors to heat water to a high temperature and deposit it in a pond of several square kilometers surface area. According to the proposal, this water can then be transported long distances in underground pipes to heat a city.

When the shallow solar pond concept is compared with the collector-pond storage designs, it is apparent that the shallow pond is analogous to the collector, and the night storage tank is analogous to the thermal storage.

Fig. 1 shows the classification of the different solar pond concepts.

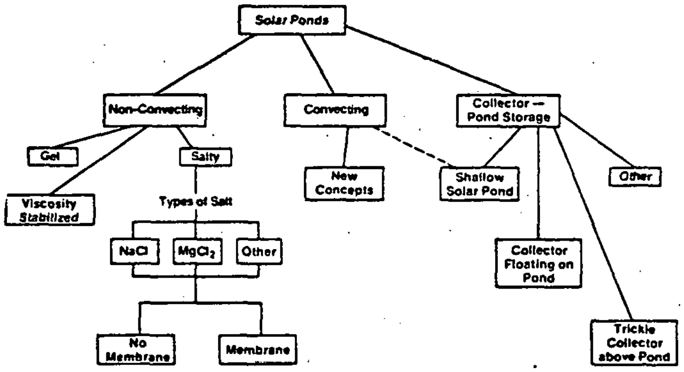

Fig. 1. - Solar pond taxonomy

A GENERIC MODEL

Whatever their differences, the various solar pond designs have in common a very large body of thermal storage. It may be assumed that this storage is so large that daily fluctuations in ambient temperature and insolation have a negligible effect on the temperature of storage, and that only seasonal variations in the environment need be considered.

It is assumed also that the heat loss from storage is related linearly to the difference between the temperature of storage and the temperature of the ambient air and to the difference between the temperature of storage and the temperature of the ground. This means there must be effective heat loss coefficients U_a and U_g such that the rate of heat loss is $U_a(T-T_a) + U_g(T-T_g)$, where T_a is ambient temperature, T_g is ground temperature (presumably equal to $\overline{T}_a$, the average annual ambient temperature), and T is the temperature of the lower convecting layer. In the convecting pond, T is assumed to be the temperature at any point.

It is reasonable to model the insolation and the ambient temperature as sine waves, and for simplicity it can also be assumed that the load can be represented as a sine wave.

Thus, let

$$T_a(t) = \overline{T}_a + \widetilde{T}_a \sin 2\pi(t-\phi_T)$$

$$I(t) = \overline{I} + \widetilde{I} \sin 2\pi(t-\phi_I)$$

$$L(t) = \overline{L} + \widetilde{L} \sin 2\pi(t-\phi_L)$$

The time t and the phase angles ϕ_T, ϕ_I, ϕ_L are measured in years. If insolation peaks in June, then ϕ_I is approximately 0.22; if ambient temperature peaks about a month afterward, then ϕ_T is approximately 0.30.

Let A signify the solar collection area, $\tau\alpha$ the fraction of insolation transmitted to the storage area of the pond, and dVc_p the total heat capacity of storage (where d is the water density, V is the volume of storage, and c_p is its heat capacity per unit mass).

An energy balance yields

$$\tau\alpha AI(t) = L(t) + U_a[T(t) - T_a(t)] + U_g[T(t) - \overline{T}_a]$$
$$+ dVc_p\dot{T}(t)$$

or

$$\dot{T}(t) + \frac{U_a+U_g}{dVc_p} T(t) = \frac{1}{dVc_p} [\tau\alpha A\overline{I} + (U_a+U_g)\, \overline{T}_a - \overline{L}$$
$$+ \tau\alpha A\widetilde{I} \sin 2\pi(t-\phi_I)$$
$$+ U_a\widetilde{T}_a \sin 2\pi(t-\phi_T)$$
$$- \widetilde{L} \sin 2\pi(t-\phi_L)]$$

The solution to this differential equation is

$$T(t) = \overline{T} + \psi(t) - C(t_o)\, e^{-\sigma t} \qquad (1)$$

where

$$\overline{T} = \overline{T}_a + \frac{\tau\alpha A\overline{I}-\overline{L}}{U_a+U_g}$$

$$\psi(t) = \frac{S}{dVc_p} [\tau\alpha A\widetilde{I}\, h(t-\phi_I) + U_a\widetilde{T}_a\, h(t-\phi_T)$$
$$- \widetilde{L}\, h(t-\phi_L)]$$

$$h(t-\phi) = [\sigma \sin 2\pi(t-\phi) - 2\pi \cos 2\pi(t-\phi)]/[(2\pi)^2+\sigma^2]$$

$$\sigma = S(U_a+U_g)/dVc_p$$

$$C(t_o) = \overline{T} - \overline{T}_a + \psi(t_o)\, e^{\sigma t_o}$$

and t_o is the startup date for the pond (in years from January 1), at which time it is assumed $T = \overline{T}_a$. S is the number of seconds in a year, if I and L are expressed in watts.

Note that Eq. 1 expresses the pond storage temperature as the sum of the long term average temperature $\overline{T}$, a periodic temperature deviation $\psi(t)$, and a transient term $C(t_o)e^{-\sigma t}$.

Setting the derivative of Eq. 1 equal to zero, one finds that in the steady state, extreme temperatures occur at times $(1/2\pi)\tan^{-1}[\psi(0.25)/\psi(0)]$; by plugging these times into Eq. 1 one can find the maximum and minimum temperatures.

EXAMPLE

For a circular salty pond simulated by Nielsen (5), of 12-m radius and 2-m depth, wall losses were 3573 W and floor losses were 2920 W when the pond temperature was 50°C and ambient temperature was 10°C. (Note that only earth insulation was used in this simulation). Assuming that the coefficient of heat loss to ambient is $U_a = 3573/(50°-10°)$ or $U_a = 89.3$ W/°C, and the coefficient of heat loss to ground is $U_g = 2920/(50°-10°) = 73$ W/°C, the projected pond temperatures shown in Table 1 are obtained with the formulas just developed. (The pond is assumed to have been started on April 1. Transmission through the nonconvective layer is assumed to be 25%, ambient temperatures are 10 ± 15°C, and insolation is 200 ± 50 W/m^2.)

A DEEP CONVECTING POND CONCEPT

Although the shallow convecting pond develops high temperature water in a fairly short time, it requires pipes and plumbing to shuttle water out of the "ponds" each evening and storage tanks to hold the water at night. It also requires insulation under the water bags because the ground is allowed to cool off each night after the water is removed from the bags.

A more economical approach is to leave the water in the pond at night and to provide as much extra insulation as possible on top of the pond. During the daytime, when insolation must be received through the top of the pond, there is a limit as to how much top insulation can be used, and double glazing similar to that used in the shallow solar pond would be employed. But at night or during periods of low insolation additional insulation could be provided. An obvious and simple method would be to lay extra insulation over the top of the pond, either automatically or manually, whenever insolation falls below a prescribed level.

A more interesting and economical technique is to spray foam insulation between the glazings and between glazing and pond when insolation drops below the prescribed level (Fig. 2). A spray foam has been used successfully to provide night insulation for greenhouses (16). It has been found in practice to reduce the heat loss by at least 50%, although in theory an 85% reduction should be attainable. It should be noted that the spray foam used in greenhouse experiments is a material normally used for firefighting. It seems likely that improvements could be made in the material for purposes of pond insulation.

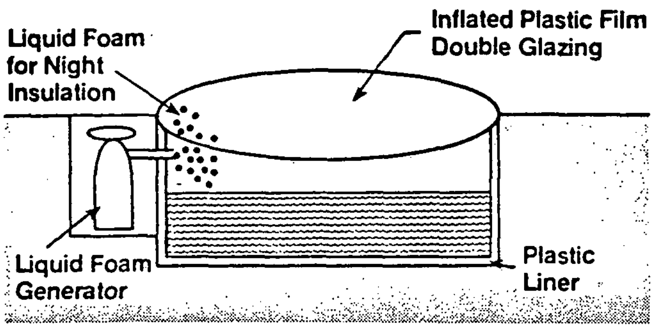

Fig. 2. - Example of deep saltless pond design

In the morning, the spray foam insulation would be allowed to settle and run off, leaving a negligible residue. The capital cost of using spray foam to provide supplemental night insulation amounts to less than \$1/m^2 of pond.

Besides eliminating the need for pipes, pumps, and plumbing to transport the water to nighttime storage, this "stationary" pond would not require bottom insulation. After a warmup period the temperature of the ground would approach that of the pond water, providing good insulation. The only additional insulation that might be desired would be along the sides of the pond to prevent edge losses.

To provide sufficient storage to even out daily and seasonal temperature fluctuations, the stationary convecting pond would be a deep pond, not a shallow one.

SUMMARY AND CONCLUSIONS

The salty nonconvecting pond is a viable and economical way of collecting and storing large quantities

Table 1 - Projected Pond Temperatures Obtained Using Developed Formulas

		Projected Temperature (°C)			
Year	Month	No Load	5 kW Constant Load	5±3 kW Summer Peaking	5±3 kW Winter Peaking
	July 1	51.0	44.1	40.8	47.4
	Oct. 1	66.3	56.7	53.7	59.7
Year 1					
	Jan. 1	53.7	43.0	45.1	40.9
	Apr. 1	49.8	38.7	41.2	36.1
	July 1	67.1	55.7	53.4	58.0
	Oct. 1	72.8	61.4	58.7	64.0
Year 2					
	Jan. 1	56.3	44.9	47.1	42.6
	Apr. 1	50.9	39.4	42.0	36.8
	July 1	67.5	56.0	53.7	58.3
	Oct. 1	73.0	61.5	58.9	64.1
Year 3					
	Jan. 1	56.4	44.9	47.2	42.7
	Apr. 1	50.9	39.4	42.0	36.8
	Average	62.0	50.5	50.5	50.5
Steady	Minimum	49.6	38.1	41.4	34.8
State	Maximum	74.4	62.9	59.6	66.2

of solar energy, especially where salt is free or inexpensive. Other techniques may be more desirable where salt is not so readily available. The membrane pond may eliminate the need for high salt concentration in the convecting layer. The shallow solar pond uses no salt but requires considerable expense for plumbing and night storage. Combinations of collectors with pond storage are appropriate for some applications and can provide water of higher temperature, but they enter the realm of higher and more expensive technology. Where salt is not free or inexpensive the deep convecting pond may be an economically viable and environmentally acceptable alternative and deserves further investigation.

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