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On the performance of a salt gradient solar pond

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Abstract

The performance of a laboratory-scale salt-gradient solar pond is described in this paper. Different methods of saline injection to the bottom layer and corresponding temperature and concentration profiles as a function of depth are reviewed and compared with experimental results. A time history of the development of temperatures, salinities and elevations of the lower and upper layers at various climatological situations is reported. The 'dynamic stability' and 'equilibrium boundary criterion' are discussed and verified experimentally for the lower and upper gradient interfaces. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Salt-gradient solar ponds (SGSP) promise to be one of the relatively simple sources of energy collection and thermal storage with a cheap cost per unit area. In these ponds, saline is stored in three layers increasing in density. The surface layer is homogeneous and convective, where the density of saline is close to fresh water. In the middle layer saline density increases in depth, thereby natural convection is stopped. In this layer, mass or thermal energy is transported only by molecular diffusion that is a very low process. The lowest layer is dense and convective, and has a relatively uniform density close to saline saturation. That part of solar irradiation which transmits to this layer increases its temperature. The heat stored there can only be transferred through the middle layer by conduction. Therefore, the middle non-convective layer acts as an insulator. The thermal energy collected in the lowest layer may be utilized later. Research activities on the solar ponds are now widespread in many countries of the world [1].

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2. Description of the experimental apparatus and measuring systems

An experimental 4 m^2–1.08 m depth (SGSP) was built in Ferdowsi University of Mashhad at the north east of Iran (36°16′N, 59°37′E). The pond was double sided and its bottom and sides were thermally insulated by 12 cm thick polystyrene sheets, (Fig. 1). The internal surface of the pond was coated with a thin layer of fiberglass to provide enough protection against corrosion.

Meteorological parameters such as global radiation, wind speed, relative humidity, and ambient temperature were measured by corresponding sensors.

The pond temperature was measured at 15 points spaced 7 cm, in normal direction, by RTD thermal sensors (PT100) with an accuracy of 0.2°C. Five more sensors were installed at the sides and bottom insulating sheets. The monitoring system was fully automatic and the data were recorded hourly by a 32-channel data logger that was built at the University.

Saline concentration was measured by taking samples once a week from at least 75 stations distributed in depth spaced 1 or 2 cm in normal direction, and analyzed up to three digits after decimal in gr/cm^3 by a DMA35 Anton Paar density measurement instrument. The pond was filled on 11 September 1996 by the 'Salinity redistribution method' [2] and since then has been working continuously. The present report covers the period of 20 July 1997–17 March 1998 in which the salinity data were complete and accurate.

3. Concentration and temperature profiles in the gradient zone

Normally, there is a continuous upward flux of salt in a solar pond that reduces the concentration of the lower layer. Pond maintenance requires replenishment of salt to the

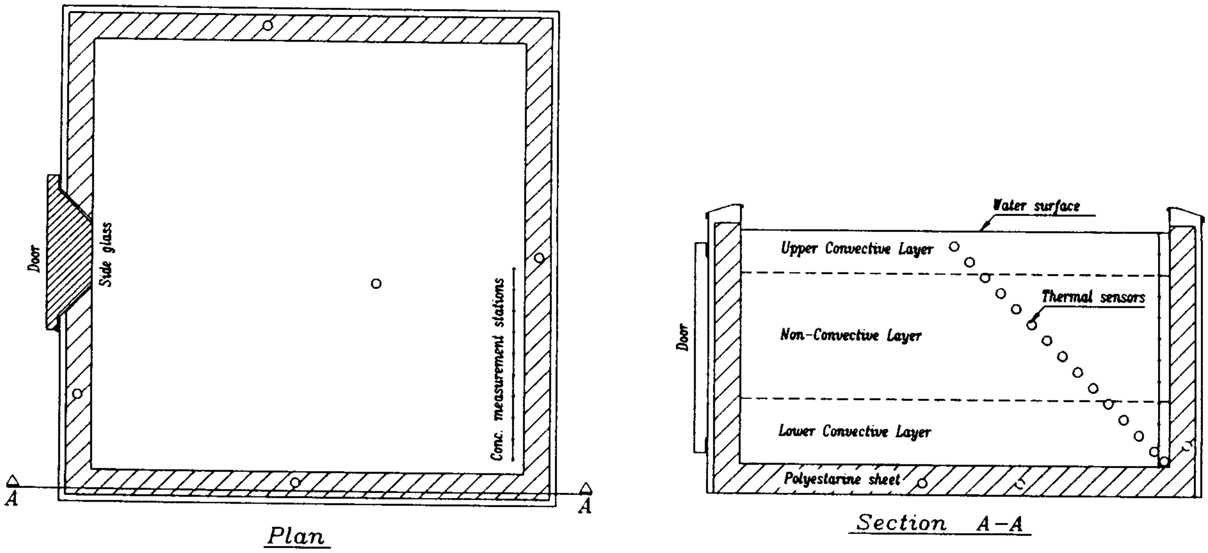

Fig. 1. Schematic view of experimental set up.

bottom layer to compensate for reduction in concentration. In order to predict the mass flux of salt the concentration profile as a function of depth should be determined.

In a vertical system of coordinates with Z measured as positive upward and $Z = 0$ at the bottom of the pond it can be written

$$C = C_L \quad 0 < Z < Z_L \tag{1}$$

$$C = C(Z) \quad Z_L < Z < Z_U \tag{2}$$

$$C = C_U \quad Z_U < Z < H \tag{3}$$

where C_L and C_U are the average concentrations of the lower and upper layers, Z_L and Z_U are the lower and upper levels of the boundaries of the gradient zone and H is the water surface elevation. The mass flux of salt, q, across a unit area is given by [3]

$$q = WC - D_C \, \mathrm{d}C/\mathrm{d}Z \tag{4}$$

where W is the upward velocity and D_C is the molecular diffusivity coefficient. It is assumed that the system is in a steady state condition (q = cte.) and the boundaries remain at fixed levels. Provided that D_C, C_L and C_U are known Eq. (4) can be integrated, first from Z_L to Z_U to determine q and then from Z_L *to* Z to obtain the concentration profile $C(Z)$.

At the start of operation, the pond is cool and D_C is constant. The solution of Eq. (4), for $W = 0$, is

$$q = -D_C(C_U - C_L)/(Z_U - Z_L) \tag{5}$$

$$C(Z) = C_L - q(Z - Z_L)/D_C \quad Z_L < Z < Z_U \tag{6}$$

where, the concentration profile is a linear function of height above the bed.

For a warm pond with temperature between the range of 20°C to 90°C, the molecular diffusivity of NaCl is strongly dependent on temperature and weakly on salinity; therefore, with a good approximation it can be assumed [3]

$$D_C = 1.39(1 + 0.029(T - 20))10^{-9} \tag{7}$$

where D_C is in m^2/s and T is in °C.

For the purpose of solving Eq. (4), Hull and Nielsen [4] assumed a parabolic temperature profile, in the gradient zone, in the form of

$$T(Z) = T_L - aZ_1^2 \quad Z_1 = Z - Z_L \quad 0 < Z_1 < Z_U - Z_L \tag{8}$$

where a is constant and T_L is the average temperature of the lower layer. Substituting for T from Eq. (8) into Eq. (7), the diffusion coefficient is given by

$$D_C(Z) = D_L(1 - b^2 Z_1^2) \tag{9}$$

where D_L and b are constants. Knowing the variation of D_C in depth, Eq. (4) may be solved and the flux and concentration profiles be obtained for the following two cases.

1. Warm pond without upward flow ($W = 0$)

$$q = -2bD_L \frac{C_U - C_L}{\ln\left[\dfrac{1+b(Z_U - Z_L)}{1-b(Z_U - Z_L)}\right]} \tag{10}$$

$$C(Z) = C_L - \frac{q}{2bD_L} \ln\left[\frac{1+b(Z - Z_L)}{1-b(Z - Z_L)}\right] \tag{11}$$

2. Warm pond with upward flow

$$q = W(C_U - F_U C_L)/(1 - F_U) \tag{12}$$

$$C(Z) = (C_L - q/W)F + q/W \tag{13}$$

where,

$$F = \left[\frac{1+b(Z - Z_L)}{1-b(Z - Z_L)}\right]^{W/2bD_L} \tag{14}$$

and F_U is obtained for $Z = Z_U$.

Fig. 2 shows the concentration and temperature profiles at the beginning of the pond operation. It is clear that the concentration profile is linear as given by Eq. (6) and the temperature profile is nearly uniform.

Later, on the following days, a certain amount of saline (60 l) was extracted from the bottom layer and the same volume with a higher concentration injected in to that layer once a week. Thereby, reduction of concentration in the bottom layer was compensated, whereas upward velocity was not allowed. In Fig. 3 the profiles of pond concentration and temperature as a function of depth together with Eqs. (11), (6) and (8) are plotted. The theory is in agreement with the experimental results.

In another series of experiments a certain volume of concentrated saline (~6 l) was injected into the bottom layer weekly. It is usually called the 'rising pond' and an upward velocity is contributed to the normal process of diffusion. Fig. 4 shows the profiles of concentration and temperature together with the results obtained from Eqs. (13) and (8).

4. Variation of physical characteristics of convective layers

All the physical characteristics of the upper convective layer (UCL) and the lower convective layer (LCL) such as salinity (in percentage of weight), temperature and elevation, change with time depending on the climatological conditions.

In Fig. 5 temperature and salinity variation for the lower and upper layers were plotted

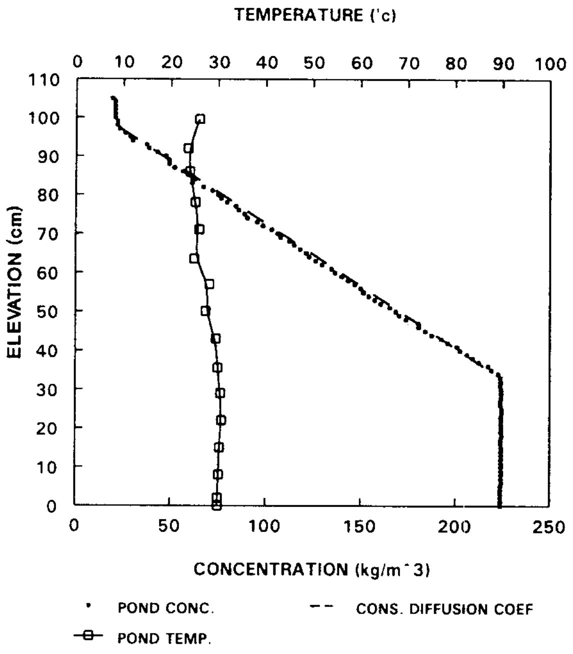

Fig. 2. 20 July 1997—Start of pond operation.

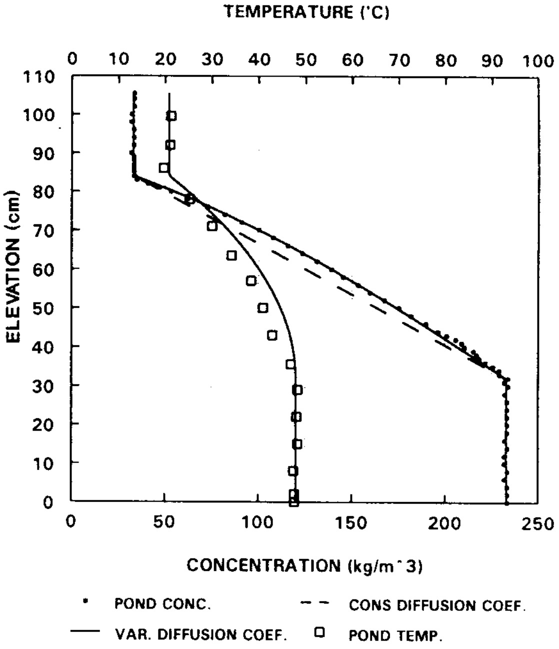

Fig. 3. 30 September 1997—Warm pond ($W = 0$).

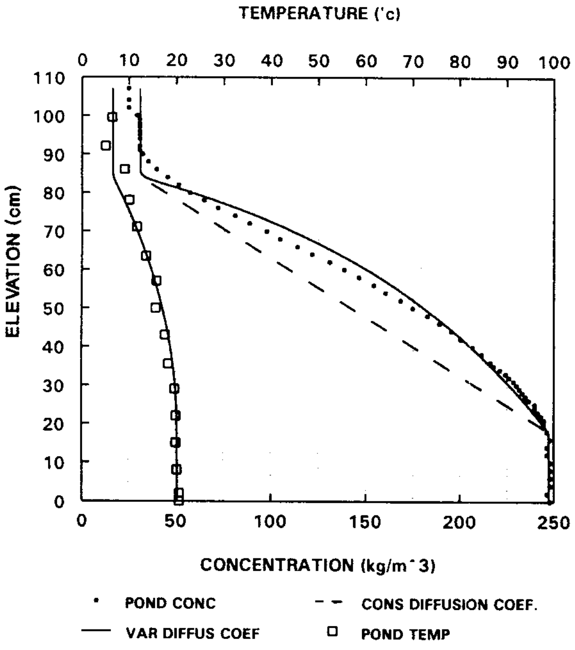

Fig. 4. 9 December 1997—Rising pond $W = 0.1$ cm/week.

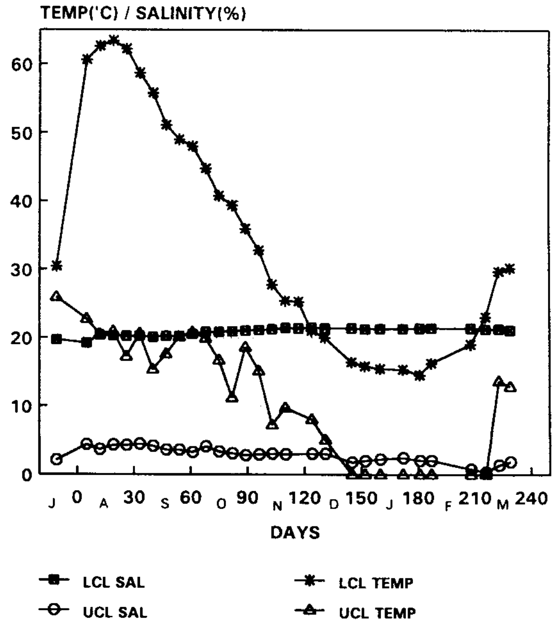

Fig. 5. Temperature and salinity of LCL–UCL vs time.

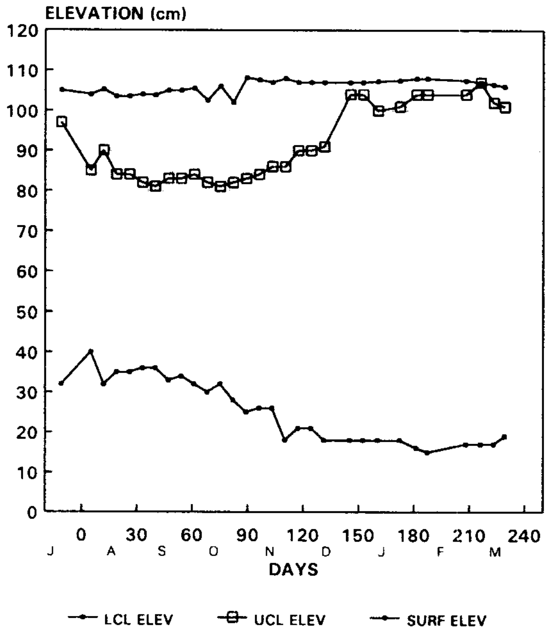

Fig. 6. LCL, UCL and surface elevation vs time.

starting from 20 July, 1997. The minimum temperature of the LCL was 15°C in February 1998 and the maximum of 64°C occurred in August 1997. The maximum temperature of the UCL was 27°C in July 1997. For nearly two months during the winter, the surface of the pond was frozen. While temperature of the LCL decreased monotonically from summer to winter, temperature of the UCL was fluctuating, in conformity with the ambient temperature.

The salinities of the LCL and UCL were uniform except for the salinity of the UCL which was stratified after rainy days and during the frozen period.

The surface elevation together with the elevations of the UCL and the LCL interfaces with the gradient zone are plotted in Fig. 6. It can be seen that the depth of upper and lower layers decreased during the cold months. In fact ice cover had stopped the circulation caused by the wind in the upper layer, and low temperature diminished natural convection in the lower layer. Therefore, diffusional process was responsible for the growth of the gradient zone in the normal direction.

5. Dynamic stability and equilibrium boundaries

While increasing concentration with depth enhances the stability of a solar pond, increase in temperature has a reverse effect on it. The dynamic stability criterion given by Weinberger [5] establishes a relationship between the concentration and temperature gradients as

$$\frac{\mathrm{d}C}{\mathrm{d}Z} \geq -\frac{\nu + D_\mathrm{T}}{\nu + D_\mathrm{C}} \frac{\partial\rho/\partial T}{\partial\rho/\partial C} \frac{\mathrm{d}T}{\mathrm{d}Z} \tag{15}$$

where ρ, ν and D_T are the density, kinematic viscosity, and thermal diffusivity coefficient of saline. It can be shown that a salt gradient solar pond is stable within a large range of operational situations.

It was proved that the gradient zone boundaries did not remain at fixed levels. Nielsen [6] defined a stationary boundary level between a convective zone and a non-convective gradient zone as a position where a dynamic balance exists between diffusion, which tends to enlarge the gradient zone, and convective circulation, which tends to erode the gradient zone. The diffusion rate is proportional to the concentration gradient ($\mathrm{d}C/\mathrm{d}Z$) and the convective circulation is the result of convective heat transport, which is proportional to the temperature gradient ($\mathrm{d}T/\mathrm{d}Z$). Nielsen's empirical equation is given by

$$\mathrm{d}C/\mathrm{d}Z = 28(\mathrm{d}T/\mathrm{d}Z)^{0.63} \tag{16}$$

where C is in kg/m^3 and T is in °C. In Fig. 7 samples of the concentration and temperature gradient data for the upper and lower gradient boundaries are plotted together with Eqs. (15) and (16).

The lower gradient boundary data are quite far from dynamic instability. They are in accordance with Nielsen equilibrium criterion. In other words, lower interface is always

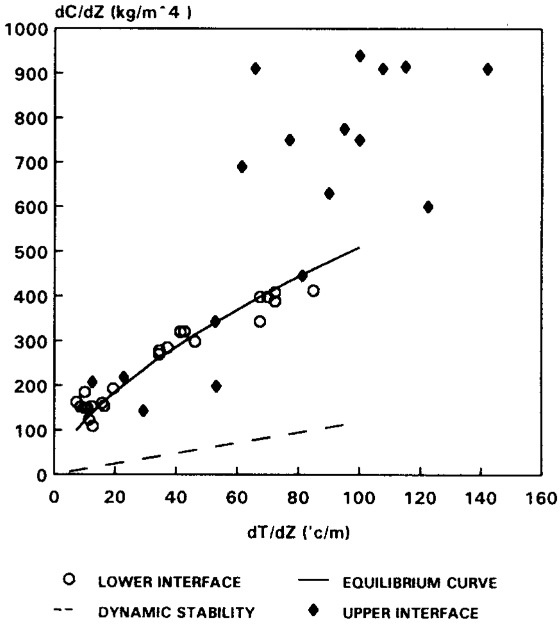

Fig. 7. Stability and boundary equilibrium.

looking for an equilibrium position compatible with the conditions (e.g. radiation, salinity, temperature, etc.) that are imposed upon it.

The upper gradient boundary data are so much scattered that no meaningful relationship can be deduced. However, it is noteworthy that the data which are above the equilibrium curve, were obtained when a single uniform upper convective layer was formed and the concentration gradient at the interface was high enough to resist the shear stresses caused by wind circulation. The data which are very near or on the equilibrium curve were taken a few days after each rainfall, when the upper layer had been divided into at least two convective parts, separated by a subsidiary thin gradient zone. Therefore, the main upper gradient interface was far from the surface effects and behaved similar to the lower gradient boundary in following the equilibrium curve. The data which are below the curve belong to the frozen period, when the gradient zone had moved up to the surface and the superficial gradient was very weak.

6. Summary and conclusions

The performance of a laboratory-scale outdoor salt-gradient solar pond was studied in this paper. The concentration and temperature profiles in the gradient zone for two cases of a warm pond with and without upward flow was obtained experimentally and compared with the corresponding theoretical profiles. The agreement was quite satisfactory. Therefore, as a first approximation, the assumptions of parabolic temperature profile in depth and linear dependence of molecular diffusion coefficient on temperature give relatively accurate concentration profile and mass flux.

The physical characteristics of the lower and upper convective layers changed with time. For example, the temperature of the lower layer decreased uniformly from summer to winter and the temperature of the upper layer followed closely the ambient temperature. It was also observed that the elevations of the upper and lower interfaces varied considerably during a year.

The solar pond was stable within a large range of its operational situations and the dynamic stability condition was normally satisfied. Nielsen equilibrium boundary criterion was successful in explaining the position of the lower interface. However, it was shown that the circulation process was so complex in the surface layer that the position of the upper interface could not be easily described by this very simple empirical equation.

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