Cumhuriyet Üniversitesi Fen Fakültesi
Fen Bilimleri Dergisi (CFD), Cilt:36, No: 3 Özel Sayı (2015)
ISSN: 1300-1949

Cumhuriyet University Faculty of Science
Science Journal (CSJ), Vol. 36, No: 3 Special Issue (2015)
ISSN: 1300-1949

Study of boundaries equilibrium in a shallow solar pond

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Received: 01.02.2015; Accepted: 05.05.2015

Abstract. One-dimensional mass and heat transfer models have been provided to find salinity and temperature gradients in a gradient layer of a solar pond. Using finite difference method (FDM), heat and mass transfer differential equations were discretized by Crank-Nicolson scheme. The present study is based on the experimental data of a solar pond in Ferdowsi University of Mashhad, obtained in a period of 126 days from May to September 1999. Increase in concentration and temperature gradient, cause increase and decrease in stability, respectively. Time variations of concentration and temperature gradients are affect the dynamic stability and equilibrium of upper and lower boundaries of the solar pond. The equilibrium of the upper and lower boundaries has been compared using Neilson equilibrium boundary criterion. The numerical data of the lower boundary were far from dynamic instability. Those data had good agreement with the Neilson equilibrium boundary criterion. The dynamic stability of the upper boundary was maintained with time, but the numerical data of the upper boundary were not in keeping with the Neilson equilibrium boundary criterion. Therefore the lower boundary has with time, behaved with more equilibrium towards the upper boundary.

Keywords: Boundary equilibrium, Heat and mass transfer, solar pond, Stability

1. INTRODUCTION

A solar pond is composed of a shallow pool, containing salt-water solution whose density and salinity increase with depth from the pool free surface. Three different layers can be recognized in a solar pond, namely, the upper convective zone (UCZ, the top layer), the non-convective zone (NCZ, the gradient layer), and the lower convective zone (LCZ, the bottom layer). The temperature and salinity in the top and bottom layers are almost uniform, but vary linearly in the gradient layer. The thickness of gradient layer is changed with time, because of heat and mass diffusion in this layer. The convective heat transfer in the top and bottom layers and the conductive heat transfer in the gradient layer make one to believe that the solar pond performs like a heat exchanger. Figure 1 shows the schematic diagram of a solar pond and its layers.

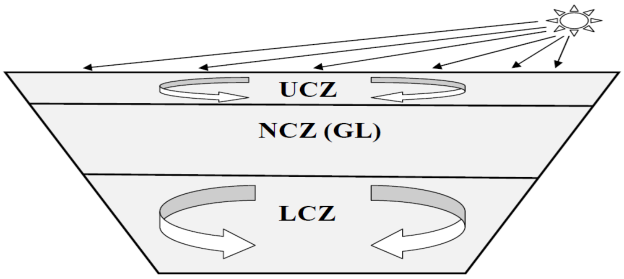

Figure 1. Schematic diagram of a salinity gradient solar pond.

Weinberger [1] studied the physics of solar pond for the first time. He solved the energy equation to obtain the transient temperature distribution, assuming the thickness of top and bottom layers are negligible. Meyer [2] developed a numerical model for predicting the transient performance of the interfaces between the top and bottom layers with the gradient layer. He used empirical correlations to describe the interface heat and mass fluxes. The performance of a

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Special Issue: The Second National Conference on Applied Research in Science and Technology

small solar pond in laboratory scale with salinity gradient was investigated by Jaefarzadeh [3]. The pond was in outdoor air; the history of temperature and salinity distributions, and the top and bottom layer depths were reported at different weather conditions. The numerical study of transient heat and mass transfer and stability in a salinity gradient solar pond were also performed by Mansour et al. [4] using fluent software. They used 3D-model with all properties variable as function of temperature and salt concentration.

Improvements in the development of salt gradient solar ponds have been proposed to reduce the thermal losses from the top to air and to increase the thermal efficiency of the pond. The ideal of using a cover system was proposed by Bezir et al. [5] to reduce the night thermal losses and to increase the daytime performance. They applied this idea successfully for supplying hot water to a leather workshop. Busquets et al. [6] experimentally investigated the thermal analysis and measurement of a solar pond prototype. They studied the non-convective zone salt gradient stability with various salinity gradients based on the Stability Margin Number (SMN) criterion.

2. MASS AND HEAT TRANSFER IN THE SOLAR POND

The mass transfer phenomenon in the gradient layer takes place because of the molecular diffusion of salt. Heat conduction occurs within the gradient layer. The conservation form of mass and heat transfer equations for the gradient layer looks like:

$$\frac{\partial C}{\partial t} = \vec{\nabla}.\left(d\vec{\nabla}C\right) \tag{1}$$

$$\frac{\partial(\rho c_p T)}{\partial t} = \vec{\nabla}.(k\vec{\nabla}T) + H \tag{2}$$

In the above equations, C, T and H are concentration, temperature and heat source generating from the solar absorption in the gradient layer respectively. Also, *k* is the thermal conductivity, *d* is the saline diffusivity, *ρ* is density, c_p is the specific heat at constant pressure.

The Crank-Nicolson finite difference scheme is used to solve the one dimensional mass and heat transfer equations. The gradient layer is divided into F parts, when *i* vary from 1(a node located at upper boundary of NCZ) to F+1(a node located at lower boundary of NCZ). Equations 3 and 4, are discretized:

$$\frac{C_i^{n+1}-C_i^n}{\Delta t} = \frac{1}{2(\Delta y)^2}\left\{d_{i+\frac{1}{2}}\left[\left(C_{i+1}^{n+1}-C_i^{n+1}\right)+\left(C_{i+1}^{n}-C_i^{n}\right)\right]+d_{i-\frac{1}{2}}\left[\left(C_{i-1}^{n+1}-C_i^{n+1}\right)+\left(C_{i-1}^{n}-C_i^{n}\right)\right]\right\} \tag{3}$$

where $\Delta y = y_{i+1}-y_i = y_i-y_{i-1}$ and $\Delta t = t_{n+1}-t_n$

$$\frac{T_i^{n+1}-T_i^n}{\Delta t} = \frac{1}{2(\Delta y)^2}\left\{k_{i+\frac{1}{2}}\left[\left(T_{i+1}^{n+1}-T_i^{n+1}\right)+\left(T_{i+1}^{n}-T_i^{n}\right)\right]+k_{i-\frac{1}{2}}\left[\left(T_{i-1}^{n+1}-T_i^{n+1}\right)+\left(T_{i-1}^{n}-T_i^{n}\right)\right]\right\}+H_i^{n+\frac{1}{2}} \tag{4}$$

The initial conditions are C^0_i and T^0_i for all *i*. also, the boundary conditions for above equations are as follows:

$$C_1^n = C_{UCZ}^n,\ C_{F+1}^n = C_{LCZ}^n,\ T_1^n = T_{UCZ}^n,\ T_{F+1}^n = T_{UCZ}^n \tag{5}$$

4. IMPORTANT PARAMETERS

The value of solar radiation at the depth *y* in the solar pond is as follows [7]:

$$I = 0.6 I_0 \exp[-\mu(2.2 - y)] \tag{6}$$

Where I_0 and μ are the solar radiation at the water free surface of pond and the extinction coefficient of saline solution respectively. The solar heat source is absorbed from the solution per unit time and volume as follow [7]:

$$H = \frac{\partial I}{\partial y} = 0.6 \mu I_0 \exp[-\mu(2.2 - y)] \tag{7}$$

The saline diffusivity d (m^2/s) for the brine in the temperature range $5^{\circ}C$ to $20^{\circ}C$ and the salinity range 0% to 20% is [8]:

$$d(T,S) = (8.16 + 0.255T + 0.00254T^2 - 0.28S + 0.0147S^2) \times 10^{-10} \tag{8}$$

where *S* is the salinity in wt% ($S = 100C/\rho$)

The thermal conductivity, density and specific heat for the salt-water solution are given as [9]:

$$k = 0.5553 - 0.0000813C + 0.0008(T - 20) \tag{9}$$

$$\rho = 998 + 0.65C - 0.4(T - 20) \tag{10}$$

$$c_P = 4180 - 4.396C + 0.0048C^2 \tag{11}$$

where T is in $^{\circ}C$ and C (salt concentration of salt water) is in kgm^{-3}.

5. STABILITY CRITERIA IN SOLAR POND

While increase in salt concentration along with depth in gradient layer, increases stability of solar pond; increased temperature along with depth has the opposite effect on it. Dynamic stability criterion is formed by Mr. Weinberger [1] by establishing a relationship between concentration and temperature gradient:

$$\frac{dC}{dy} \geq -\frac{\nu + \alpha}{\nu + d} \frac{\frac{\partial \rho}{\partial T}}{\frac{\partial \rho}{\partial C}} \frac{dT}{dy} \tag{12}$$

Were ν and α are the Kinematic viscosity and thermal diffusivity coefficient of saline, respectively.

We know that gradient layer boundaries do not remain in a constant level. Salt concentration gradients have stabilizing affects in the upper and lower boundaries of the gradient layer but temperature gradients have destabilizing affects in the boundaries. Neilson's experimental equation is as follows [10]:

$$\frac{dC}{dy} = 28\left(\frac{dT}{dy}\right)^{0.63} \tag{13}$$

Where T is in $^{\circ}C$ and C is in kgm^{-3}.

6. CHARACTERISTICS OF THE SHALLOW SOLAR POND

The experimental pond, $4m^2$ in area and $1.08m$ deep was built in outdoor air [11]. The floor and side walls were insulated using 12cm thick poly styrene plates. The internal surface of the pool was covered by a thin sheet of fiber glass on top of styrene plates to avoid corrosion. Temperatures were measured at 15 equidistant points in vertical direction. Temperature sensors with an accuracy of 0.2 $^{\circ}C$ were used. Data acquisition system automatically operated and the experimental data were recorded on an hourly basis using a logger having 32 channels. In order to measure the concentration of salt-water solution, sampling from 75 points inside the pool was carried out on a weekly basis. The data points were selected in a vertical direction 1 or 2 cm away from each other. The concentration was measured to three decimals using calibrated densimeters. High-density salt-water solution was injected to the bottom layer of the pool to improve the salt concentration in LCZ, when it was reduced after a long period of operation. The injection of make-up solution was performed only when equal amount of brine was already removed from the pond. Fresh water was added to the upper surface of the pond once a week in order to compensate for the surface evaporation. The simulation period lasted 126 days starting from 1 May until 3 September 1999 [9], in which the pond was continuously and stably in active operation. The measured data were used to validate the model.

7. BOUNDARY AND INITIAL CONDITIONS

Transient temperature distributions of top and bottom layers of the solar pond are shown in Figure 2. The scattered points in the figure are experimental data [11], over which the fifth order least squares are fitted to determine the boundary conditions.

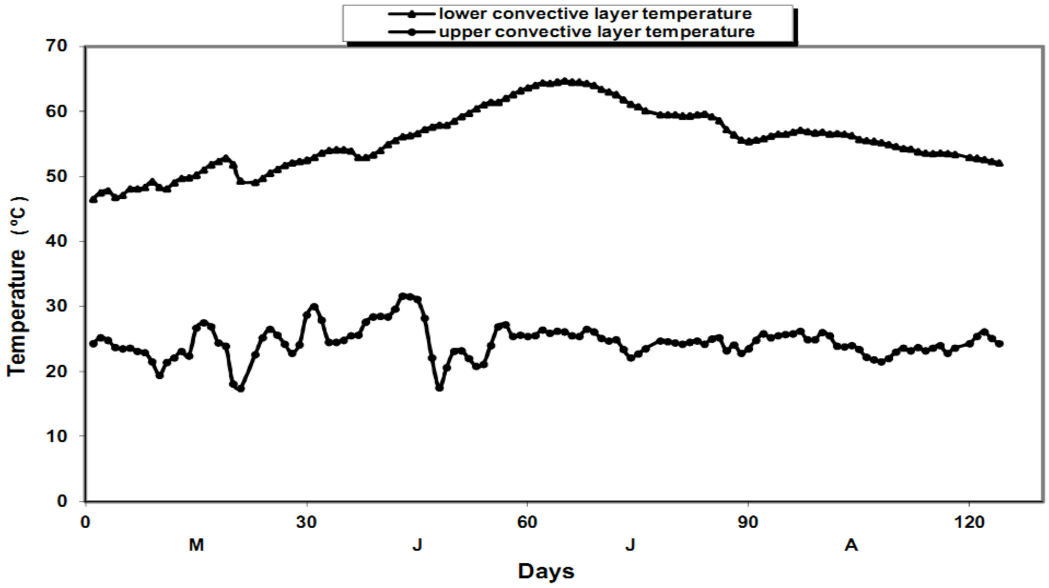

Figure 2. Time variations of the temperature in the upper and lower convective layers

The initial temperature and concentration distributions are shown in Figure 3. As the figure shows, the initial distributions are nonlinear. The initial thickness of bottom layer, gradient layer and top layer are 13 cm, 76 cm, and 16cm respectively. The initial height of the free surface area is therefore 105cm; while 3cm remains unfilled (the total depth is 108cm). It is assumed that this level remains constant during the test period.

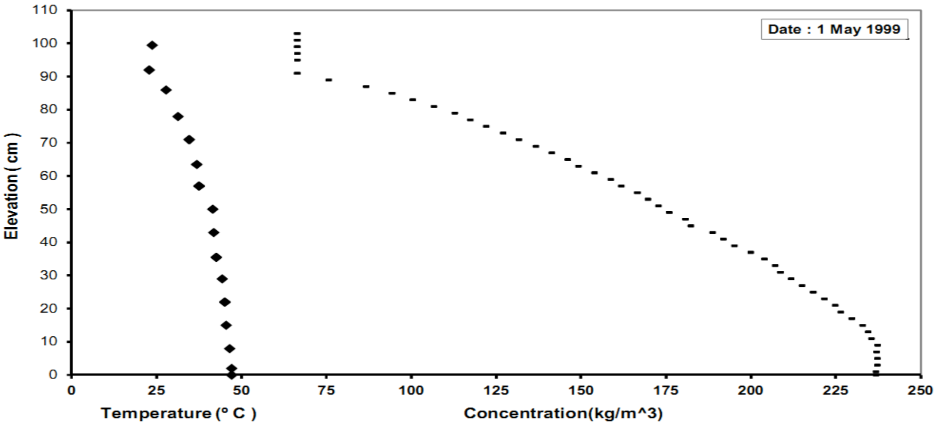

Figure 3. The initial temperature and concentration distributions

8. NUMERICAL RESULTS

Often the value of the extinction coefficient of saline solution (μ) considered in an experimental solar pond for the numerical solution is 0.8m^{-1}. Now we want to investigate the equilibrium of the upper and lower boundaries (gradient layer interface with upper and lower layers). In figure 4, some samples of data for concentration and temperature gradient for the lower boundary are drawn. The dynamic stability curve and Neilson boundary equilibrium curve are drawn with equations 12 and 13, respectively. From the beginning of the simulation period, sparse data in figure 4 are related to some days with time intervals of 5 days from each other.

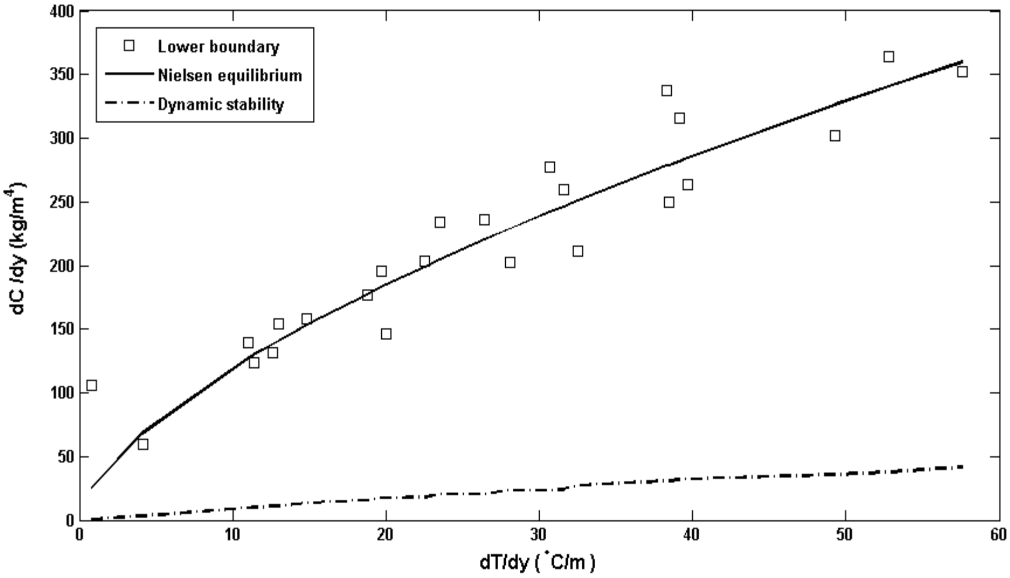

Figure 4. Dynamic stability and Neilson boundary equilibrium criterion compared to numerical data for the lower boundary

The data for the lower gradient boundary are fully away from the dynamic instability. They have a good agreement with Neilson equilibrium criterion. In other words, the lower interface always follows an equilibrium condition consistent with the imposed conditions. The mean relative error of the numerical data of the lower boundary, compared to Neilson equilibrium criterion is 6%. Figure 5, shows the stability and boundary equilibrium criterion compared with the upper boundary's numerical data.

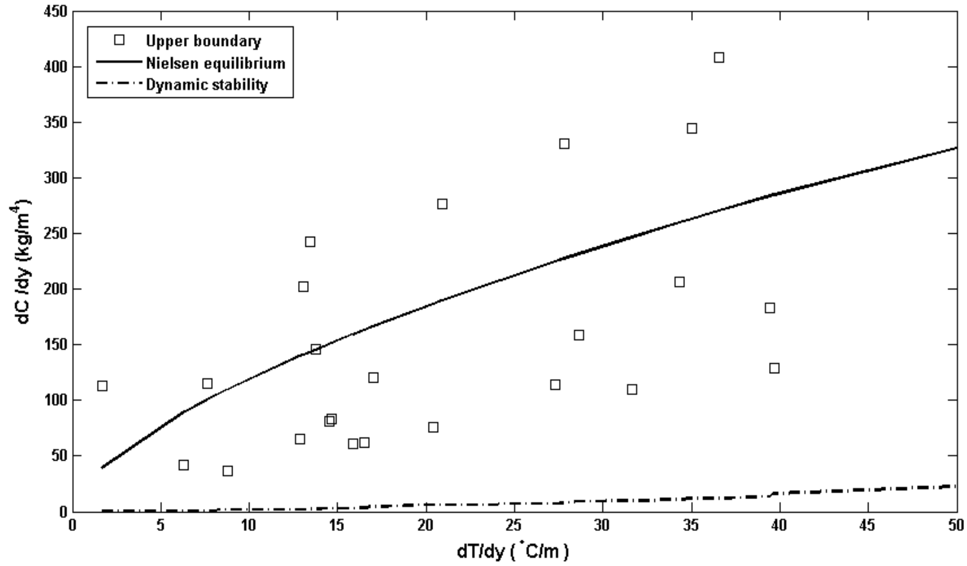

Figure 5. Dynamic stability and Neilson boundary equilibrium criterion compared to numerical data for the upper boundary

The sparse data of the upper boundary are between the dynamic stability curve and Neilson boundary equilibrium curve. As a result, the stability of the upper boundary is guaranteed, but its equilibrium is questionable. Neilson equilibrium criterion, does not confirm the equilibrium of the upper boundary. The data near to the dynamic stability curve, belong to cool days, when the gradient layer has an upward movement towards the surface and the concentration gradient in the upper boundary (located near the surface) is very weak.

7. CONCLUSION

Time variations of concentration and temperature gradients affect solar pond stability. Increased gradient of concentration and temperature, will increase and decrease stability, respectively. The upper and lower interfaces in a solar pond, are more susceptible to instability. With regular cleaning of the pond surface and injection of salt-water with high salinity to the lower convective layer, it's possible to increase the stability of the interfaces. The equilibrium of the upper and lower boundaries compared to Neilson boundary equilibrium criterion, was investigated. The numerical data of the lower boundary were far from dynamic instability. Those data had a good agreement with Neilson boundary equilibrium criterion. The dynamic stability of the upper boundary was maintained with time, but the numerical data of the upper boundary were not in agreement with the Neilson boundary equilibrium criterion. So the lower boundary had more equilibrium compared to the upper boundary with time.

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