NUMERICAL SIMULATION OF HEAT TRANSFER AND FLUID FLOW IN A SALT GRADIENT POND

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ABSTRACT

In this paper, transfer phenomena generated in a rectangular Salt Gradient Pond (SGP) are numerically predicted by means of CFD. The purpose of this study is to give a good knowledge of the hydrodynamic and thermal characteristics, and to optimize and control different parameters or techniques in the construction of the ponds. The pond is filled with water and salt to constitute three zones with different salinity, and heated by the bottom. The Navier-Stokes, energy and concentration equations are discretized using finite volume method, and a two-dimensional analysis of the hydrodynamic and thermal characteristics of the flow in the pond are performed. The mathematical modelling has allowed us to predict the performances of ponds by developing parametrical studies which are of paramount importance such as the NCZ zone dimension and the buoyancy ratio influences. The great impact of the salinity in the preservation of the high temperature in the bottom of the pond, and the important reduction of the phenomenon of thermal transfer by convection in the non convective zone, are also shown.

Keywords: finite volume method, heat and mass transfer, numerical simulation, salt gradient pond

INTRODUCTION

A Salinity Gradient Solar Pond (SGSP) is a simple and low cost mean to collect and store solar energy in the high-density salt water. Therefore, in practice, a typical solar pond consists of three distinct zones. Two convective zones where the first is at the top (Upper Convective Zone, UCZ) and the second is at the bottom (Lower Convective Zone, LCZ). These two layers are separated by a salinity gradient (Non Convective Zone, NCZ). Although the diffusion flux tends to homogenize the system, the maintenance of the salinity profile in the solar pond can be obtained by addition of brine at the LCZ and fresh water in the UCZ.

Because of its potential applications in thermal and solar energy systems, such as in heating and desalination, the salt Gradient Solar Pond (SGSP), has received much attention from researchers. So far, many experimental solar ponds were constructed and operated around the world; see in particular Nielsen & Rabl (1975), Nielsen (1976), Badger *et al*. (1977) and Rajput (2005). Many anterior analytical and numerical works have been developed to study the Salt Gradient Solar Pond behaviour (Weinberger, 1964; Kaushika *et al*., 1980;

Bansal & Kaushika, 1981). In these works, the approach consist of solving the one dimensional heat conduction equation with a heat source term (due to volume absorption of solar radiation) and with a constant salinity profile along the pond depth. Kurt *et al*. (2000 ; 2006) have developed a one dimensional unsteady state heat conduction model, and they have solved analytically as well as numerically energy and mass balance equations for the UCZ, the NCZ and the LCZ zones in a solar pond. Angeli & Leonardi (2004) have investigated a one dimensional finite difference semi implicit model to study the transient behaviour of a solar pond with brine injection. A transient, double diffusive convection in a horizontal enclosure is investigated numerically and analytically by Bennacer *et al*. (2001). The enclosure is heated and cooled along the vertical walls and solutal gradient is imposed vertically. In their work, these authors have identified the flow regime for thermal and solutal dominated flows. Jubran *et al*. (2004) have presented a prediction of convective cells generated in solar ponds with sloping walls.

More recently, the two and three dimensional character of the solar pond has been considered for studying the heat diffusion. Ben Mansour *et al.* (2004; 2006) have studied respectively three and two dimensional numerical study of transient heat and mass transfer. The solar radiation absorption as well as the heat losses through the pond free surface and the pond stability has been taken into consideration.

In the present work, a numerical analysis of the Salt Gradient Pond (SGP) behaviour is conducted in two dimensional coordinates to predict the convective cells generated in the system. A parametric study is developed to provide the influence of the buoyancy ratio and the effect of the dimension of the NCZ layer on the performances of the pond. Particularly, we have studied the difference between the two models of pond: convective and non convective pond.

Nomenclature

A	aspect ratio $= L/H$
C	dimensionless concentration $= (C_{ini} - C_{ref})/(C_{max} - C_{ref})$
C_{ini}	initial concentration
C_{max}	maximal concentration
C_{ref}	reference concentration
D	mass diffusivity
H, L	height and length of the solar pond
g	gravitational acceleration
Le	Lewis number $= \alpha / D$
N	buoyancy ratio $= Ra_C / (Ra_T . Le)$
Pr	Prandtl numbers
T	dimensional temperature
t_0	reference time $= H/U_0$
T_a	ambient temperature
T_p	bottom temperature
U , W	dimensionless velocity
U_0 , W_0	horizontal and vertical reference velocity $= \alpha/H$
x , z	dimensionless coordinates system

Greek symbols

α	thermal diffusivity
ν	cinematic viscosity
β_C	coefficient of salt expansion

P	dimensionless pressure	β_T	coefficient of thermal expansion
Ra_T	thermal Rayleigh numbers $= \frac{g \cdot \beta_T \cdot H^3}{\nu \cdot \alpha}$	ρ	density
		Θ	dimensionless temperature $= (T - T_a)/\Delta T$
Ra_C	solutal Rayleigh numbers $= \frac{g \cdot \beta_C \cdot H^3}{\nu \cdot D}$	ΔT	reference temperature $= T_p - T_a$
t	dimensionless time	ΔC	reference species concentration $= C_{max} - C_{ref}$

MATHEMATICAL MODEL FOR THE SGP

In this investigation, a numerical model of transient hydrodynamic, heat and mass transfers in a SGP is developped. The conservation equations for a laminar incompressible buoyancy-driven flow in a rectangular configuration pond are established in 2D coordinates system. The pond's solution properties are assumed to be constant, except for density in the buoyancy term, which depends linearly on both the local temperature and concentration (Boussinesq approximation). Furthermore, we suppose that the pond's liquid is heated at constant temperature by heating-coil covering the entire of the bottom of the pond.

Governing equations

The height of the cavity H is taken as a reference length for the spatial coordinates. The velocity, pressure, temperature and species concentration scales are, respectively:

$$t_0 = \frac{H}{U_0}, \; U_0 = \frac{\alpha}{H}, \; P_0 = \rho \, U_0^2, \; \Delta T = T_p - T_a, \; \Delta C = C_{max} - C_{ref}.$$

The resulting continuity, momentum, mass and energy coupled equations can be written in dimensionless form as follow:

- Continuity equation:

$$\frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} = 0 \tag{1}$$

- Navier-Stockes equations:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + W\frac{\partial U}{\partial z} = \Pr\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial z^2}\right) - \frac{\partial P}{\partial x} \tag{2}$$

$$\frac{\partial W}{\partial t} + U\frac{\partial W}{\partial x} + W\frac{\partial W}{\partial z} = \Pr\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial z^2}\right) + Ra_T \Pr[\Theta - N \cdot C] - \frac{\partial P}{\partial z} \tag{3}$$

- Energy equation:

$$\frac{\partial \Theta}{\partial t} + U\frac{\partial \Theta}{\partial x} + W\frac{\partial \Theta}{\partial z} = \frac{\partial^2 \Theta}{\partial x^2} + \frac{\partial^2 \Theta}{\partial z^2} \tag{4}$$

- Concentration equation:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + W\frac{\partial C}{\partial z} = \frac{1}{Le}\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}\right) \tag{5}$$

Boundary and initial conditions

The cavity is initially filled with water and subdivided into three zones in which the salinities are as follows:
- The first zone (LCZ) is the deepest zone and it is salt-saturated. In this study, it occupies 40 % of the total volume of the pond,
- The second zone (NCZ) is an intermediate zone in which the concentration of salt increases with the depth. This zone occupies 40 % of the total volume,
- The third zone (UCZ) is situated above the NCZ, is a salt-free zone and occupies 20% of the total volume.

The pond is initially supposed at the ambient temperature. Boundary conditions include no slip condition for the velocity at the rigid walls u=0 and W=0, All walls are impermeable and the vertical walls are well insulated. In the bottom of the pond, we imposed a fixed temperature (Θ=1) and the free surface is supposed to have an ambient temperature.

Resolution method

A finite volume method, Patankar (1980) is used to solve the equation system with the specified boundaries conditions. The SIMPLER algorithm is employed to solve the equations in primitive variables. The governing equations are converted into a system of algebraic equations by integration over each control volume. The algebraic equations are solved by a line-by-line iterative algorithm using an Alterning Direction Implicit method. The calculations are performed by adopting non uniform 100*50 grids, and fine grids are utilized near boundaries.

RESULTS AND DISCUSSIONS

In this part, numerical results will be present in transient regime to give a fine knowledge of the temporal evolution of thermal and concentration behaviours of a storage pond starting with a stratified initial salinity condition. A particular interest is devoted to the study of influences of the buoyancy ratio and the NCZ thickness on the performances of the pond. These results are obtained for an aspect ratio equal to three, a thermal Rayleigh number $Ra_T= 10^6$, and fixed values of Prandtl and Lewis numbers (Pr=4.34 and Le =230) which correspond to the averaged salt-water characteristics.

Buoyancy ratio effect

Figures 1 and 2 show the results giving respectively the thermal and concentration distributions for different value of buoyancy ratios N.

Without salt gradient (Figure 1-a), the convective movements prevent accumulation of energy in the bottom of the pond. In fact, the warmer fluid becomes lighter, rises to the surface where it loses some of its heat due to the difference between the warm surface temperature and the ambient and through evaporation from the surface. As the surface fluid cools, it gets heavier and sinks to the bottom again. This way, convection currents occur in the fluid due to the buoyancy effect. Because of this continuous mixing and, thus, the loss of heat, it is impossible to capture and store heat in the bottom of the pond. Imposing salinity profile suppresses this convection effect and allows accumulation energy (Figures 1-b, 1-c and 1-d). Hence, salinity has a considerable role in maintaining hot temperature in the bottom of the pond, and in reducing the thermal transfer phenomenon by convection in the NCZ.

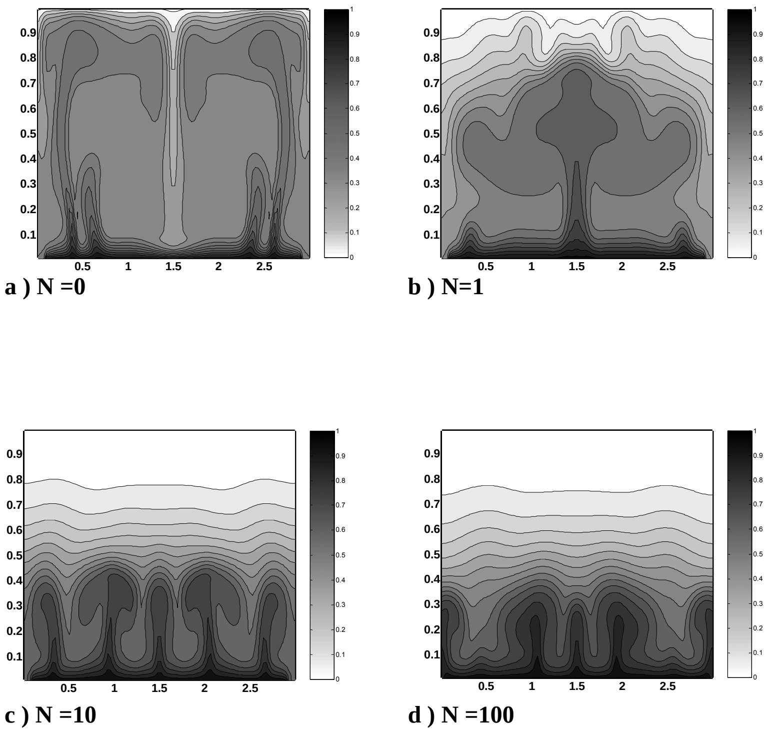
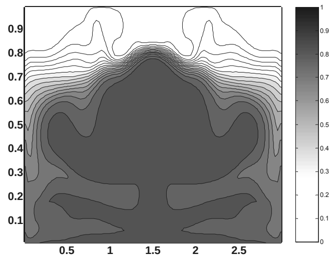
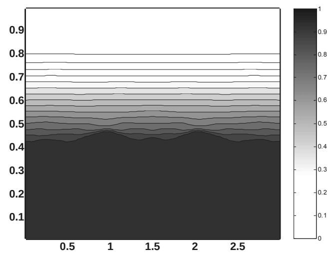


Figure 1. Effect of the buoyancy ratio on the temperature behaviour at t=0.023.

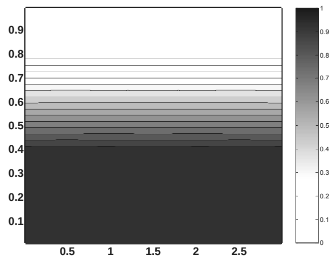
Figure 2 shows the concentration distribution at the same time t=0.023 and for different buoyancy ratio. We can easily verify that the initial concentration profile is disturbed when N is less then or equal to 10 (Figure 2-a and 2-b). However, for N=100 (figure 2-c) we can note that the concentration profiles remain invariable, which indicates that the stratified pond is still stable.



a) N=1



b) N=10



c) N=100

Figure 2. Effect of the buoyancy ratio on the concentration behaviour at t=0.023.

Transient temperature behaviour

Figures 3-a to 3-f show the evolution with time of the temperature distribution in the pond for thermal Rayleigh number $Ra_T=10^6$ and buoyancy ratio N=100. These figures demonstrate the role of the NCZ layer in the reduction of the heat transfer phenomenon, which yield an elevation of temperature in the storage zone. Without salt gradient, the convective movements prevent accumulation of energy in the bottom of the pond.

In fact, as it can be seen in Figures 3-a to 3-f, at the beginning the pond's liquid warms up and develops thermal gradient in the bottom of the pond giving a growing up of multicellular thermal patterns. Temperature level increases with time and cells tend to be collapsed to form a uniform temperature in the LCZ. We can see that the temperature in the UCZ remains nearly equal to the initial temperature.

NCZ thickness effect

The NCZ of the pond serves as being an insulating layer because water is a poor conductor of heat. Also, to limit the diffusion of salt, it is important to consider a big thickness of the NCZ.

In this case, the heat loss by conduction across the NCZ is reduced and the LCZ region of the pond attains high temperature while the UCZ remains at a temperature close to that of ambient air (Figure 4-a). However, when the NCZ layer becomes thinner (Figure 4-b and 4-c), we can note a tendency of homogeneity of the pond and subsequently an increasing of loss of heat to the environment. This is due to the improvement of the heat flux across the thin NCZ.

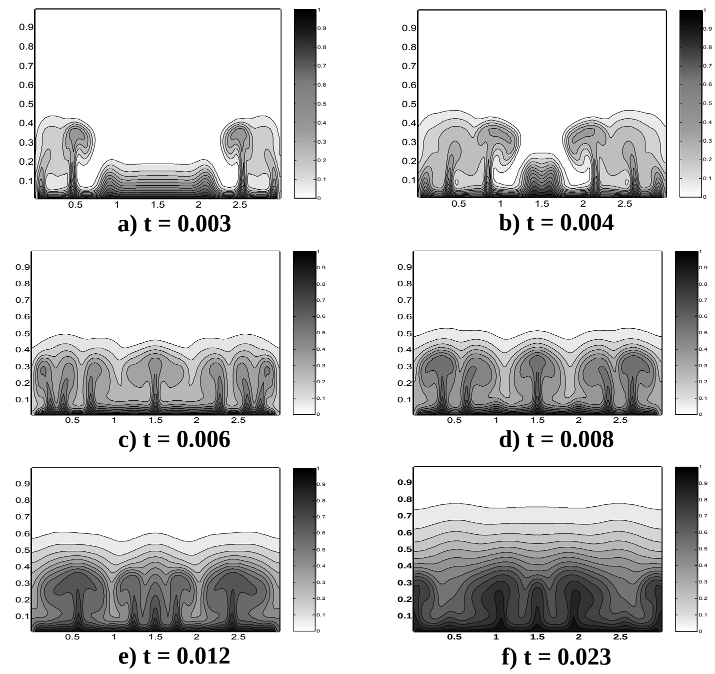


Figure 3. Transient temperature behaviour for N=100.

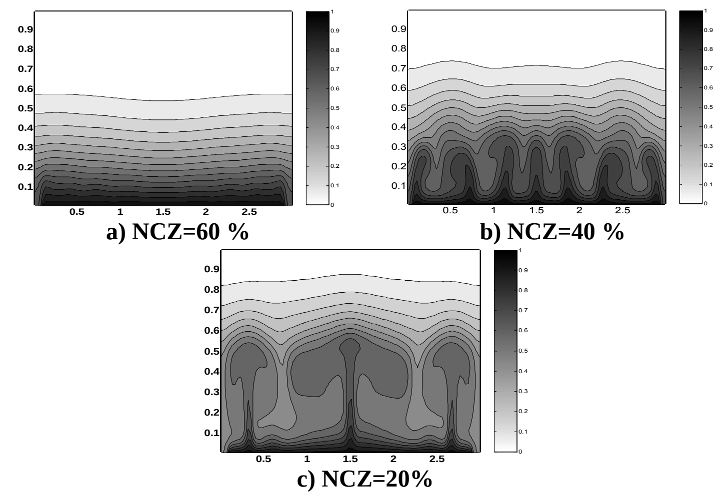


Figure 4. NCZ thickness effect for N = 100 at t = 0.02.

CONCLUSION

In this paper, two dimensional numerical simulation concerning the stability of a rectangular SGP has permitted to get a good knowledge of the hydrodynamic and thermal characteristics in the three different salinity zones constituting the pond. The parametric study put in evidence the importance of the buoyancy ratio on the stability of the pond layers and in the reduction of the thermal losses by convection. Also, the transient temperature behaviour demonstrates the role of the NCZ layer in the reduction of the heat transfer convection phenomenon which yields in this case, a temperature elevation in the storage zone. Finally, a reduction of the NCZ layer thickness has led to a good homogenization pond, as well as an increase of the thermal transfer loss.

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