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NUMERICAL HEAT TRANSFER AND FLUID FLOW WITHIN A SALT GRADIENT POND

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ABSTRACT
This paper reports a parametric study of a salt gradient pond. Transfers in a rectangular cavity, translating thermal phenomenon in a pond, are numerically predicted by means of Computational Fluid Dynamics (CFD) in transient regime.
The pond is filled with water, and divided into three zones with different salinity. The heating of the pond is made by a serpentine which covers its bottom. The purpose of this numerical study is to give a good knowledge of the thermal characteristics, to optimize working parameters of the ponds. The parameters considered include the pond length and the lower convective zone (LCZ) thickness.

The Navier-Stokes, energy and mass equations are discredized using finite volume method, and a two-dimensional analysis of the thermal behaviour induced in the cavity is performed. It has been found that, an optimal choice of the pond dimensions can improve the performance of energy storage. This study shows also the importance 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 (NCZ).
Keywords: Salt gradient pond, energy storage, convection, finite volume element analysis.

INTRODUCTION
A shift towards the modular integration of power electronics, resulting in increased power and loss densities [1], have necessitated the development of more effective cooling methods to reduce peak operating temperatures in such applications [2,3]. Due to low thermal conductivities associated with the outer material layers of these integrated power electronic modules [2,3], surface cooling on its own is no longer sufficient as the materials themselves act as major thermal barriers [4]. Internal heat transfer augmentation of these solid-state heat-generating volumes via the creation of low thermal resistance paths to surface regions has become crucial. Through this, restrictions placed upon future development by thermal issues may be made less critical due to the fact that components can be operated at higher power densities and at relatively lower peak temperatures.

Solid state conductive cooling, being a passive cooling scheme and not being dependent on other support systems, exhibits reliability and volumetric advantages. Even though conductive heat transfer may be orders lower than heat transfer associated with convection or evaporation, its reliability aspect justifies in-depth investigations into cooling methods using this heat transfer mode.

NOMENCLATURE
Variables

$\mathcal{C}$	concentration
Cp	specific heat
D	diffusivity
g	gravitational acceleration
$\mathcal{H}$	height of the pond
$\mathcal{H}_0$	height of the LCZ
$\mathcal{J}=\sqrt{g\beta\ \theta_0\ \mathcal{H}}$	characteristic velocity
$\mathcal{L}$	length of the pond
$\mathcal{P}$	pressure
$\mathcal{T}$	temperature
$\mathcal{T}_0$	ambient temperature
$\mathcal{T}_s$	serpentine temperature
t	time
$\mathcal{U}$	horizontal velocity component
$\mathcal{W}$	vertical velocity component
$\mathcal{X}$	horizontal coordinate
$\mathcal{Z}$	vertical coordinate

Dimensionless variables

$C = \mathcal{C}\ \varsigma / \beta\ \theta_0$	dimensionless concentration
$L = \mathcal{L} / \mathcal{H}$	dimensionless length of the pond
$P = \mathcal{P} / (\rho\ g\ \beta\ \theta_0\ \mathcal{H})^2$	dimensionless pressure
$t = t\ \mathcal{J} / \mathcal{H}$	dimensionless time
$U = \mathcal{U} / \mathcal{J}$	dimensionless horizontal velocity component
$W = \mathcal{W} / \mathcal{J}$	dimensionless vertical velocity component
$X = \mathcal{X} / \mathcal{H}$	dimensionless horizontal coordinate
$Z = \mathcal{Z} / \mathcal{H}$	dimensionless vertical coordinate

Grec symbols

ρ	fluid density
μ	cinematic fluid viscosity

β	thermal expansion coefficient
λ	thermal conductivity
$\theta_0 = T_s - T_0$	dimensionless temperature
$\theta = (T - T_0)/\theta_0$	
α	inclination angle
ς	specific expansion coefficient
Dimensionless numbers	
$Gr = g\,\beta\,\rho^2\,\theta_0\,H^3/\mu^2$	Grashof number
$Pr = \mu\,Cp/\lambda$	Prandtl number
$Sc = \mu/(\rho\,D)$	Schmit number
$Ra = Gr\,Pr$	Rayleigh number

The solar pond is an energy trap with the added advantage of built-in long-term heat storage capacity. Solar pond applications include process heat, desalination, refrigeration and power generation. The cost benefit factor of solar ponds has led to a number of experimental projects around the world.

In a mass of water of low depth, solar radiation falling on the surface will penetrate and be absorbed at the bottom, raising the water temperature. But the buoyancy will immediately cause this water to the surface and the heat will be rapidly dissipated to the surroundings. If the water in the lower region of the pond could be made heavier than that at the top, then it could stay at the bottom and retain the absorbed heat and thereby yield greater temperature difference between the bottom and the surface layer of the water. Without the difference in concentration of the lower and upper layers of water, the natural convection currents prevent a rise in temperature of more than a few degrees.

A solar pond is an artificially constructed water pond in which significant temperature rises are caused in the lower regions by preventing the occurrence of convection currents. The solar pond, which is actually a large area solar collector, is a simple technology that uses water and salt only. In a solar pond the bottom layer of water is made more saline than the top layer at the surface.

The solar pond possesses a thermal storage capacity spanning the seasons. The surface area of the pond affects the amount of solar energy it can collect. The bottom of the pond is generally lined with a durable black plastic. This dark surface at the bottom of the pond increases the absorption of solar radiation. Salts like magnesium chloride, sodium chloride or sodium nitrate are dissolved in the water, the concentration being densest at the bottom and gradually decreasing to almost zero at the top. Typically, a salt gradient solar pond consists of three zones:

- an upper convective zone of clear fresh water that acts as solar collector/receiver and which is relatively the most shallow in depth and is generally close to ambient temperature,
- a gradient which serves as the non-convective zone which is much thicker and occupies more than half the depth of the pond. Salt concentration and temperature increase with depth,
- a lower convective zone with the densest salt concentration, serving as the heat storage zone. Almost as thick as the middle non-convective zone, salt concentration and temperature are nearly constant in this zone.

The solar pond is filled in stages. To obtain the difference in salt density through this stepped gradient, the pond is filled with at least three successive layers of salt solution, one on top of the other, each less dense than the layer below, so that the top layer is fresh water or nearly so, while the bottom layer contains the most salt. Naturally this kind of stepped concentration cannot remain stable for long, and would eventually disappear due to diffusion and evaporation. In order to maintain the stability, concentrated brine is introduced at the bottom while the top is frequently 'washed' with fresh water.

In the aim of controlling the techniques involvements in the construction of the solar ponds, various numerical models have been developed. Among these works, we can mention those of: Tybout (1966) [1], Hull (1980) [2,3], Sodha and al. (1981) [4], Kishore and Joshi (1984) [5], Srinivasan and Guha (1987) [6], Singh and al. (1994) [7] and Sezai and Tasdemiroglu (1995) [8]. More recently, an analytical approach has been developed by Hussain and al. (2002) [9] to determine the optimal dimension of the NCZ giving a faster maturation phase.

Most of these studies suppose that the temperatures are constant in the LCZ and the UCZ. They also neglect the movement of the fluid in the pond as well as the mass transfer phenomena.

In the present work, we present a numerical two-dimensional modelling relating the thermal behaviour of a storage pond supposed to be used for water desalination. Our objective is to supply by numerical simulation, a fine knowledge of thermal structure developed in the pond. The pond is considered as a rectangular cavity where movements are produced by the natural convection. For this purpose, the resolution of dynamics, heat and mass transfer equations, governing the phenomena occurring in the pond is developed in a cartesian two-dimensional coordinates system. These equations are discretized using finite-volume method.

MATHEMATICAL FORMULATION

In this work, we study the coupled transfers in laminar transient regime into a rectangular cavity. We suppose that the fluid is incompressible and has constant physical properties. The heating of the storage pond is assured by a serpentine which covers its bottom.

The Navier-Stockes, energy and mass transfer equations can be written in dimensionless form as follow:

Continuity equation:

$$\operatorname{div}\vec{V}=0 \tag{1}$$

U – velocity component:

$$\frac{\partial U}{\partial t} = -\operatorname{div}\left(\vec{V}U - \frac{1}{\sqrt{Gr}}\,\overrightarrow{\operatorname{grad}}\,U\right) - \frac{\partial P}{\partial X} \tag{2}$$

W – velocity component:

$$\frac{\partial W}{\partial t} = -\operatorname{div}\left(\vec{V}W - \frac{1}{\sqrt{Gr}}\,\overrightarrow{\operatorname{grad}}\,W\right) - \frac{\partial P}{\partial Z} + \theta - C \tag{3}$$

Energy equation:

$$\frac{\partial \theta}{\partial t} = -\operatorname{div}\left(\vec{V}\theta - \frac{1}{Pr\sqrt{Gr}}\,\overrightarrow{\operatorname{grad}}\,\theta\right) \tag{4}$$

Concentration equation:

$$\frac{\partial C}{\partial t} = -\operatorname{div}\left(\vec{V}C - \frac{1}{Sc\sqrt{Gr}}\,\overrightarrow{\operatorname{grad}}\,C\right) \tag{5}$$

The cavity is filled with water and divided into three zones in which the salinities are different. These concentrations give the initial conditions of mass transfer. Dimensionless temperature, pressure and velocities, have zero initial values.

Concerning boundary conditions, the vertical walls are supposed impermeable and thermally isolated. In the bottom of the pond, we imposed a fixed temperature (θ=1) and a zero flux of mass. The free surface of the pond is supposed impermeable and has the ambient temperature.

NUMERICAL METHOD

The resolution of momentum, energy and mass transfer equations, is based on the finite-volume method. The cavity domain is subdivided in elementary volumes surrounding every point of the meshing. The equation of transport to be resolved is then integrated on each of these volumes so expressing the balance of flux 'J' of the transport parameter 'Φ' which stand for components of velocity vector, temperature scalar or concentration scalar :

$$\iiint_{\Omega} \frac{\partial \Phi}{\partial t}\, dv = -\iiint_{\Omega} div\, \vec{J}_{\Phi}\, dv + \iiint_{\Omega} S_{\Phi} \cdot dv \qquad (6)$$

with $\vec{J}_{\Phi} = \Phi \vec{V} \quad \Gamma_{\Phi} \vec{grad}\, \Phi$ is the flux term of Φ,

Γ_{Φ} is the corresponding diffusivity coefficient,

S_{Φ} is the corresponding source/sink term.

The spatial discretization is obtained using a hybrid scheme interpolation. Concerning temporal discretization, an implicit formulation was adopted. The integration in the time is begun by using the implicit scheme of alternated directions of Douglass-Gunn [10]. The pressure-velocity coupling is handled by the SIMPLE algorithm of Patankar [11].

Table 1: Flux term, diffusivity coefficient and source term of the transport parameter 'Φ'.

Φ	$\vec{J}_{\Phi}$	Γ_{Φ}	S_{Φ}
U	$\vec{V}U - \frac{1}{\sqrt{Gr}}\overrightarrow{grad}\,U$	$\frac{1}{\sqrt{Gr}}$	$-\ \partial P/\partial X$
W	$\vec{V}W - \frac{1}{\sqrt{Gr}}\overrightarrow{grad}\,W$	$\frac{1}{\sqrt{Gr}}$	$-\partial P/\partial Z + (\theta - C)$
1	$\vec{V}$	0	0
C	$\vec{V}C - \frac{1}{Sc\sqrt{Gr}}\overrightarrow{grad}\,C$	$\frac{1}{Sc\sqrt{Gr}}$	0
θ	$\vec{V}\theta - \frac{1}{Pr\sqrt{Gr}}\overrightarrow{grad}\,\theta$	$\frac{1}{Pr\sqrt{Gr}}$	0

Results

In this part, we will present numerical results to illustrate the importance of the water salinity and the influence of the pond length, the Grashof number and the height of the LCZ on the performance of the pond. These results are given for a fixed values of Prandt and Schmit numbers (Pr = 7, Sc = 1000).

Importance of salt gradient

When the serpentine heats the pond, the temperature of the dense salt layer therefore increases. If the pond contained no salt, the bottom layer would be less dense than the top layer as the heated water expands. The less dense layer would then rise up and the layers would mix.

Figures 1 and 2 show the dimensionless concentration at t = 0 and t = 7 10^5. Grashof number is equal to 2 10^6 and the ratio $\mathcal{L}/\mathcal{H}$ is equal to 10.

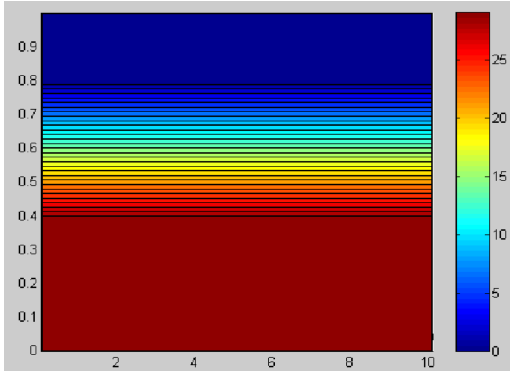


Figure 1: Dimensionless concentration distribution at t=0.

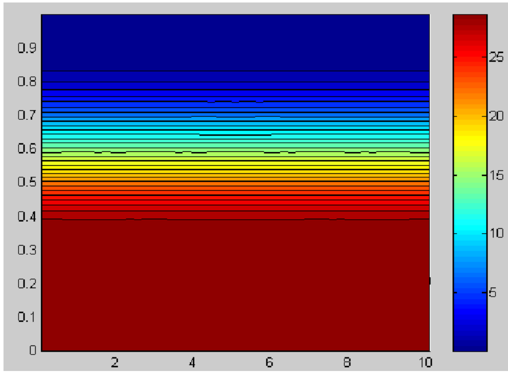
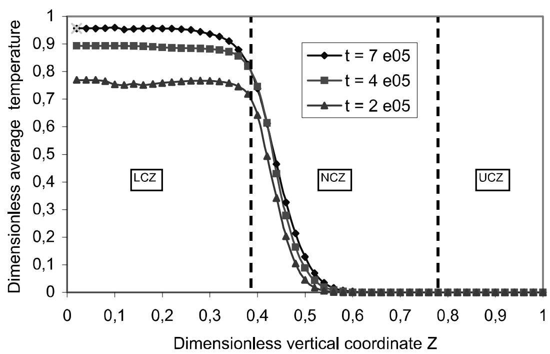


Figure 2: Dimensionless concentration distribution at t=7 10^5.

The salt density difference keeps the 'layers' of the solar pond separate. The denser salt water at the bottom prevents the heat being transferred to the top layer of fresh water by natural convection, due to which the dimensionless average temperature of the lower layer may rise to as much as θ = 0,96 (Fig. 3).



The temperature distribution in the pond is represented in figures 4, 5 and 6 at t = 7 10^5, for a Grashof number Gr = 2 10^6 and for different ratio $\mathcal{L}/\mathcal{H}$ 60, 40 and 2.

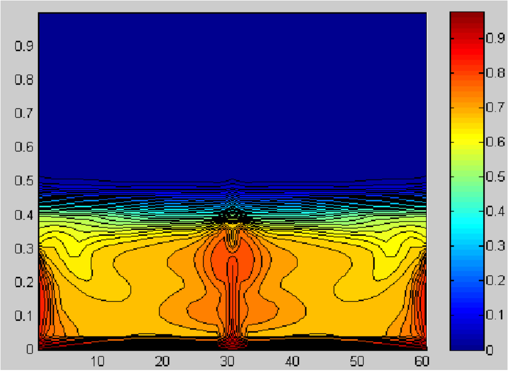


Figure 4: Dimensionless temperature distribution for $\mathcal{L}/\mathcal{H}$ = 60.

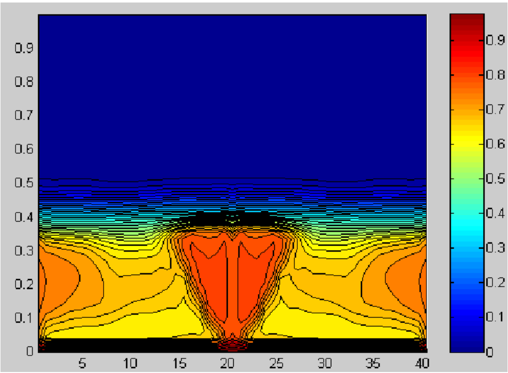


Figure 5: Dimensionless temperature distribution for $\mathcal{L}/\mathcal{H}$ = 40.

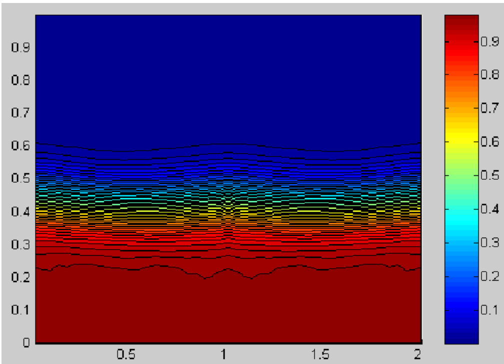


Figure 6: Dimensionless temperature distribution for $\mathcal{L}/\mathcal{H}$ = 2.

We notice that the reduction in the dimensionless length permits a fast increase in temperature of the storage zone. Consequently, for a large given pond, it's recommended to divide it into several compartments, to get smaller lengths. Therefore, there is a compromise between the heat gain and the number of compartments.

In this part, we intend to fix the quantity of heated water (to fix the volume of the LCZ), to look for the optimal LCZ height giving the more important energy storage.

On the figures 7 and 8, we represent the dimensionless temperature distribution at t=7 10^5 for different $\mathcal{L}/\mathcal{H}$ ratios ($\mathcal{H}0/\mathcal{H}$= 40%), with the hypothesis of a constant water volume in the LCZ.

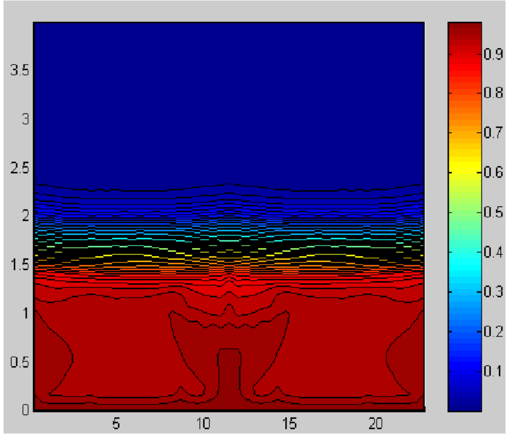


Figure 7: Dimensionless temperature distribution for $\mathcal{L}$ x $\mathcal{H}$ = 22,5m x 4m.

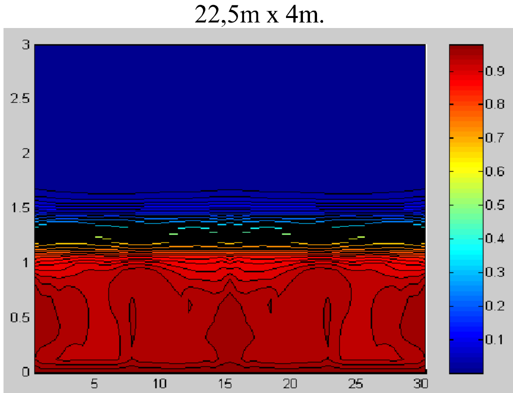


Figure 8: Dimensionless temperature distribution for $\mathcal{L}$ x $\mathcal{H}$ = 30m x 3m.

In spite of the difference between the temperature distributions for $\mathcal{L}$ x $\mathcal{H}$ = 22,5m x 4m and $\mathcal{L}$ x $\mathcal{H}$ = 30m x 3m, the average temperature in the storage zone is the same ($\theta \approx$ 0.93). This permits to choose the measurements of the LCZ according to the nature of soil and the space devoted to the pond, since we obtained nearly the same energy quantity.

1. Conclusion

This study has been developed in two-dimensional numerical modelling of the transfer thermosolutal in rectangular cavity. It has been allowed to predict the performances of ponds by developing parametrical studies which are for importance to search the maximal temperature and the influence of the length and height of the lower convective zone (LCZ) on the performance of the pond.

The resolution of coupled momentum, heat and mass transfer equations give interesting local information concerning the hydrodynamic and the thermal behaviours of the pond. We put in evidence the importance of the salinity gradient in the accumulation of energy and in the reduction of the thermal losses by convection. The $\mathcal{L}/\mathcal{H}$ ratio appears as a determining parameter to increase the temperature fluid in the lower convective zone, and an optimal choice of $\mathcal{L}/\mathcal{H}$ ratio can improve the performance of energy storage.

REFERENCES

[1] R.A. Tybout, (1966), A recursive alternate to Weinberger's model of the solar pond, Solar Energy, Vol. 11, p.109-119.

[2] J.R. Hull (1980), Computer simulation of solar pond thermal behaviour, Solar Energy, Vol. 25, p.33-40.

[3] J.R. Hull (1982), Calculation of solar pond thermal efficiency with diffusively reflecting bottom, Solar Energy, Vol. 29 (2), p.385-389.

[4] M.S. Sodah, N.D. Kaushik, , S.K. Rao, (1981), Thermal analysis of three zone solar pond, Int. J. Energy Res., Vol. 5, p.321-340.

[5] V.V.N. Kishore, V. Joshi, (1984), A practical collector efficiency equation for non-convecting solar ponds, Solar Energy, Vol. 33 (5), p.391-395.

[6] J. Srinivasan, A. Guha, (1987), The effect of bottom reflectivity on the performance of a solar pond, Solar Energy, Vol. 39 (4), p.361-367.

[7] T.P. Singh, A.K. Singh, N.D. Kaushik, (1994), Investigations of thermodynamic instabilities and ground storage in a solar pond by simulation model, Heat Recovery Systems, CHP. 14 (2), p.401-407.

[8] I. Sezai, E. Tasdemiroglu, (1995), Effect of bottom reflectivity on ground heat losses for solar ponds, Solar Energy, Vol. 55 (4), p.311-319.

[9] M. Husain, P.S. Patil, S.R. Patil, S.K. Samdarshi, (2002), Optimum size of non-convective zone for improved thermal performance of salt gradient solar pond, ELSEVIER.

[10] J. Douglass, J.E. Gunn, (1964), A general formulation of alternating-direction implicit methods, Num Math 6, 428.

[11] S.V. Patankar, (1980), Numerical heat transfer and fluid flow, Series in Computational Methods in Mechanics and Thermal Sciences, McGraw Hill, New York.