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MATHEMATICAL MODELING OF A SALINITY GRADIENT SOLAR POND CONTAINING CARBON NANOTUBES WITH DIFFERENT LEVELS OF TURBIDITY

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ABSTRACT. The mathematical model adopted in this work is based on the discretization of the conservation equations of mass, momentum and energy in 3 dimensions using the finite element method with appropriate initial and boundary conditions. In this numerical simulation work, we are interested in the testing of the influence of carbon nanotubes and in studying the effect of turbidity on solar ponds. The results show that an injection of the carbon nanotubes in a clear salt water solution in the storage zone clearly yields an improvement in thermal performance and generates a higher natural convection

1. INTRODUCTION

The progressive depletion of fossil fuels and their adverse effects on the environment have led scientists to look for other forms of energy in nature, including solar energy. This latter is considered as a major source of energy because of its low cost, its unlimited life and its harmless effect on the environment. Most solar

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energy systems collect this energy for immediate use but do not have the capacity to store it in for a long time under different weather conditions [1]. The technology of solar ponds with salinity gradient is based on the collection and storage of solar energy using salt stratified gradient layers. The solar pond consists of three zones as shown in $\mu m/s$ 1.

FIGURE 1. Real image of a solar pond is an open environment with dimensions (7mx7mx2m)

(1) An upper zone called UCZ where salinity and temperature are relatively low and uniform.
(2) -A zone of temperature gradient and salinity located in the middle of the pond called non convective zone NCZ. The purpose of this zone is to thermally isolate the hot lower convective zone LCZ from the cold upper convective zone UCZ.
(3) -A lower convective zone LCZ or the storage zone whose salinity and temperature are high. The solar radiation reaching the pond bottom heats the LCZ. The density of the latter must therefore decrease because of the thermal expansion. But, because of its high salinity, its density remains quite high compared to those of the upper layers. It remains at the bottom of the pond. Likewise, the salinity gradient existing in the NCZ prevents any natural convection flow. This zone by its transparency allows the radiation to reach the LCZ zone but prevents the upward heat transfer. Thus playing the role of a thermal diode. It is from the LCZ zone that the heat

is extracted by means of hot water while sending it into heat exchangers for different applications such as air conditioning, electricity production, desalination, etc...

It is important to know that one of the reasons that prevent the solar pond from becoming commercial is its low thermal efficiency [[2]] [[3]]. This opinion is shared by many researchers in this field [[6]] [[7]] The explanation of this phenomenon lies in the fact that the saline solution of the LCZ which is composed of a mixture of water and salt has a low thermal conductivity. To improve this conductivity, nanoparticles have been added to the LCZ zone. This yields an improvement in the thermal performance of solar collectors and has made solar ponds better cost effective [[4]].

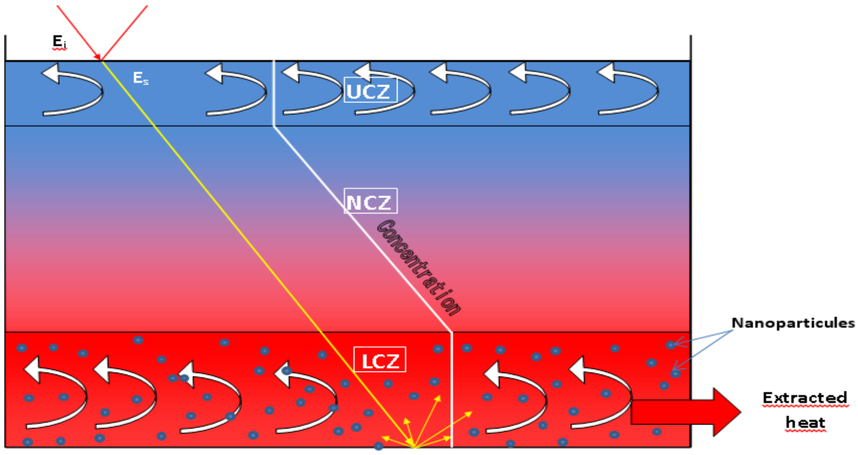


FIGURE 2. The different zones of the solar pond.

Mahian et al.[[5]]. have confirmed that the use of nanoparticles in the solar collectors improves the thermal performance. Milanese et al.[[6]] have succeeded in proving that the nanoparticles of metal oxides could be perfectly suited to a base fluid in solar power plants. Shahmohammadi and Beiki [[7]] have shown that nanofluids have good optical properties. Only industrial fields have seen research advancement. The dispersion of a homogeneous nanosized particle of carbon nanotubes in a liquid greatly increases the liquid temperature and promotes the formation of natural convection currents. Ding et al.[[8]] have shown that the nanoparticles of metals or oxides at low concentrations in the base fluids have a Newtonian behavior whereas the carbon nanotubes react quite differently showing a very high capacity to increase the heat transfer by forced convection. Concerning the introduction of nanofluids in salinity gradient solar ponds, little work has been done in this sense, we can cite, as an example, the study of various geometric shapes for the extraction of hot water from the LCZ layer in solar ponds[[9]]. It is important to know that injection of nanoparticles at the bottom of solar pond increases the temperature and speed up the natural convection in the LCZ, which leads to a shorter time of heating and a wider field of applications. The main objective of this study is to compute the temperature and the velocity distributions of natural convection in the storage area of two solar ponds: one with carbon nanotubes and without in the other. It should be noted that these two solar ponds have the same size (7mx7mx2m), heated by the same heat source and are subject to the same climatic conditions. The sunshine period is 28 days during the month of July. It is known that in solar ponds with a free surface, environmental conditions such as wind and rain have a negative impact because of the introduction of solid particles, algae and microorganisms into the clear water pond causing turbidity. This latter will hinder the penetration of solar radiation, which negatively affects the thermal performance of solar ponds. In order to get closer to the physical reality of the phenomena occurring in the solar ponds, three different levels of turbidity have been taken into account, namely clear, moderately turbid and very turbid water. We opted for the choice of carbon nanoparticles NTC instead of metal or oxides nanoparticles, because these added NTCs in the base fluid behave like thermal nanobridges; thus building a network of connections ensuring quick thermal conduction between the various points. Also, it is important to know that the homogeneous dispersion of carbon nanotubes is difficult. This results in instability and a significant temperature difference between the different points. Hence, it is necessary to use a surfactant to homogenize particle distribution and enhance the stability of the suspension. The finite element method is used to discretize the equations modeling the phenomena. The essential contribution of this work consists, first, in introducing NTC in solar ponds and then studying the temperature and 3D velocity profiles using the meteorological data of the city of Annaba and finally testing the influence of the effects of the presence of carbon nanoparticles on the turbidity. To our knowledge, the convergence, stability and consistency properties of the numerical scheme have been investigated for the first time in a real case solar pond.

2. Preparation of carbon nanotubes

This method incorporates two steps:

- First, a strong mechanical action is applied using a sonicator to homogenize nanoparticules in the base fluid. It should be noted that too much or prolonged agitation can break these carbon nanotubes.
- The second step is devoted to the dispersion of the CNTs in the LCZ zone. These CNTs tend to agglomerate and sediment in water and in order to ensure that they stay suspended in a stable and homogeneous manner, cetrimonium bromide is used as the surfactant.

These CNTs have very small dimensions: a diameter of 7 nm and a mass concentration equals to 0.06% which amounts to 19.11kg and because of received shocks they are going to be moved up and down and travel some distance in different directions. This overall motion resulting from successive shocks is called Brownian motion.

3. Mathematical formulation of the problem

For the study of convection and the thermal performance analysis of solar ponds, most of the authors consider a one-dimensional or two-dimensional model and assume that the convection movements resulting from buoyancy are negligible and that the distribution of the temperature in these relevant works only varies in one direction or two direction space. These models do not reflect the true physical reality occurring inside the solar pond. In this study, we use a 3D mathematical model based on the three equations taking into account the free convection in NCZ[[10]].

The equation of energy conservation

$$\rho C_P u \cdot \nabla T - k \cdot \nabla^2 T = -\frac{dE(\theta, z, t)}{dz}. \tag{3.1}$$

The equation of the momentum conservation:

$$\rho\frac{\partial u}{\partial t} + (u\cdot\nabla)u = \nabla\cdot\left[-pI + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla\cdot u)I\right] + F + \rho g. \tag{3.2}$$

The equation of mass conservation:

$$rho\frac{\partial u}{\partial t} + \nabla(\rho u) = 0. \tag{3.3}$$

The thermal conductivity, density and heat capacity are given by the following formulas: Thermal conductivity is given by [[11]]:

$$k_{\text{NaCl}} = \exp\left[\ln(0.24 + 0.2s) + \left(2.3 - \frac{343.5 + 370s}{T}\right)\left(1 - \frac{T}{647 + 30s}\right)^{\frac{1}{3}}\right]. \tag{3.4}$$

The density and the heat capacity of NaCl solution base fluid are given respectively by [[12]]:

$$rho_{\text{NaCl}} = 998 - 0.4(T - 293.15) + 650, \tag{3.5}$$

$$C_{P_{\text{NaCl}}} = 0.0048c + 4.396c + 4180. \tag{3.6}$$

The density and the heat capacity of the nanofluid are respectively given by [[9]]:

$$\rho_{\text{nf}} = \rho_f(1 - \phi) + \rho_{\text{np}}\phi, \tag{3.7}$$

$$(\rho C_P)_{\text{nf}} = (\rho C_P)_{\text{f}}(1 - \phi) + (\rho C_P)_{\text{np}}\phi, \tag{3.8}$$

where ϕ is the fractional volume of the nanoparticles and is given by the following formula:

$$\phi = \frac{1}{1 + \frac{\rho_{\text{np}}}{\rho_{\text{fluid}}}\left(\frac{1}{\omega_{\text{np}}} - 1\right)}, \tag{3.9}$$

where ω_{np} is the mass fraction of nanoparticles . The absorption of solar radiation by the pond is given by [[13]]:

$$E(\theta, x, t) = E_s(t)\cdot H(\theta, z), \tag{3.10}$$

$$E_s(t) = E_i(t)\cdot(1 - r), \tag{3.11}$$

$$r = 0.5\left[\frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)} + \frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)}\right], \tag{3.12}$$

where $E_S(t)$ represents the solar radiation reaching the bottom of the pond. $E(t)_i$ gives the radiation reaching the surface of the pond and is recorded every three hours by the weather station. $H(\theta, z)$ is the transmission function (non-dimensional). z is the depth of the pond

$$H(\theta, z) = \psi(0.3, z) \cdot R(\theta, z), \tag{3.13}$$

$$\psi(0.3, z) = 0.58 - 0.076 \ln(100z), \tag{3.14}$$

$$R(\theta, z) = 1 - 0.1975z(\theta - 0.3) + 0.0144z(\theta - 0.3)^2, \tag{3.15}$$

with $0.3 < \theta < 5$ NTU and $0 < z < 2m$, where the NTU is the unit of turbidity. It is important to note that $H(0.3, z)$ represents the reference transmission function based on a turbidity level equals to 0.3 NTU and $R(\theta, z)$ is the ratio of the dimensional function corresponding to a turbidity reference level.

3.1. **Assumptions.** Our model is based on the following assumptions: In this work, we consider that the turbidity is uniform and that the numerical simulation is carried out for three different levels of turbidity namely: relatively clear water corresponding to ($\theta = 0.5NTU$), moderately turbid water for ($\theta = 1.5NTU$) and very turbid water for ($\theta = 4NTU$). The flow regime is assumed to be laminar. The physical and thermodynamic parameters change from one layer to another. The fluid is supposed to be weakly compressible. The period of sunshine is 28 days from 01/07 to 28/07 and the meteorological data is provided by our university station.

3.2. **Initial and Boundary conditions.** The initial condition is given by:

$$T(x, y, z, 0) = T_a. \tag{3.16}$$

This condition means that the initial temperature at each point of the pond is the same and is equal to the ambient temperature.

The Boundary Conditions: Z_1, Z_2, and Z_3 are given in $\mu m/s$ 1.

- At the surface when $z = z_1$:

$$T(x, y, z, t) = T_a. \tag{3.17}$$

- At the bottom of the pond, the energy is given by the formula (10).
- On the side walls:

$$T(x = 0, y, z, t) \quad \text{and} \quad T(x = L_1, y, z, t) \quad \text{where} \quad Q_{LW} = h(T - T_a) \quad (18).$$

- At the walls of the pond, we have $U = V = W = 0$ because of the condition of non-permeability.

In this work, we assume that the heat transfer coefficient of free convection, h, is 20 W/m°C [[14]].

3.3. **Discretization of the problem.** In order to study the dynamic behavior of the solar pond, the discretization method used in this work is the finite elements method which aims to look for the approximate numerical solution by transforming the infinite dimensional space into a finite dimensional space. Our pond geometry is a parallelepiped of 98 m3. This method consists of cutting the volume space of the solar pond into small tetrahedral elements. The finer the mesh the more the numerical solution approaches the exact solution. The approximate solutions are computed at each nodal point of the mesh and the numerical values in the other points will be deduced by polynomial interpolation. The computation using the software has several steps: Transformation of the system of equations governing the model of heat transfer and the fluid dynamics in the pond into a system of linear equations. Matrix representation of each system of linear equations. The formation of a large matrix which is carried out by an assembly option. The numerical resolution of the global system of equations. The numerical stability of the numerical scheme depends always on the discretization and convergence properties. The existence and uniqueness of the solution are guaranteed used by the method. The software display developed of the numerical results indicates the convergence properties.

3.4. **Numerical Details.** Comsol software uses a geometric multigrid solver which is defined as an iterative, fast, memory-efficient method and can be easily used in the numerical resolution of mathematical models used in the solar ponds . Several multi-level grids will be used and each level is a well-defined mesh with chosen shape functions. At each time, we refine the mesh, the order of the shape functions and the number of degrees of freedom will be automatically increased; therefore, the resulting mesh will be rebuilt automatically. An iterative magnifying algorithm working with Galerkin's projection method will be used to obtain a non-aligned mesh. For successive refinements, the Comsol software transforms an aligned mesh into an aligned. One similarly, it should be noted that the advantage of the geometric multigrid solver is that it does not show any results if the convergence will not be guaranteed and fast.

4. Results and discussions

4.1. **Choice of meshes.** The choice of the mesh has a direct influence on the accuracy of the numerical solutions. No software can do everything for the user that is why one should be very careful with the displayer approximate solutions. The refinement of the mesh reduces the difference between the approximate and the exact solutions and hence minimizes the computational errors. But however, this leads to a high computational cost. Thus, the necessity to use a super powerful computed.

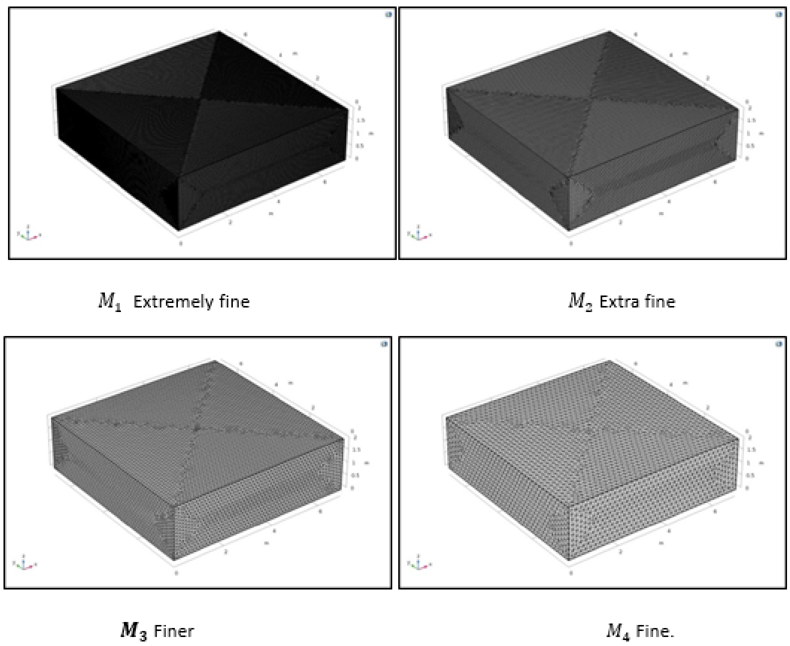


FIGURE 3. The Different mesh discretizations used in the simulation

Element size	**Domain elements**	**Boudary elements**	**Edge elements**
Mesh M_1: Extremely fine	3959184	151652	1316
Mesh M_2: Extra fine	892865	49168	752
Mesh M_3: Finer	271030	19208	468
Mesh M_4: Fine	97437	9544	328

The computer we used in this work is: (Intel Core Processor (TM) i5- 2400S CPU 2.5 GHZ 6.00 GB RAM). To ensure the convergence of the numerical results, our problem was solved w.r.t four meshes: extremely fine M_1, extra fine M_2, finer M_3 and fine M_4.

4.2. **Discussion.**

4.2.1. *The temperature profile and velocity.* Figure 4 and Figure 5 represent respectively the numerical results of two solar ponds heated by the same heat source over a period of 28 days in the month of July, One of the ponds (see Figure 4) contains in its storage zone a mixture (water + salt + carbon nanotubes) and the other (see Figure 5) just salty water. The pond of the nanofluide records the highest temperature compared to the ordinary pond because of the presence of particles of carbon nanotubes in the LCZ. Temperature difference is of the order of 7.69 ° C when the water is clear, 5.98 ° C for water moderately turbid and 5.13 ° C for very turbid water (see Figure 6). This difference in temperature is explained by the high thermal conductivity of the CNTs and its conversion into heat in the liquid of the LCZ zone. Turbidity also appears to have a negative effect on thermal performance. This is predictable because the higher the effect of the turbidity level the more difficult is the solar beam path. Consequently this will have a decrease in temperature and natural convection speed due to the absorption of a portion of this solar radiation by the minerals and plants or in suspension. It is also interesting to note that the LCZ zone records the highest temperature and the heat is dispersed within this zone due to convective movements and to the buoyancy. Also, the hottest points are located at the ends of the storage zone LCZ despite the presence of heat loss. This can be explained by the absorption of solar radiation by the walls and its transformation into heat. The temperature profile as a function of time within the NCZ zone is almost linear and the salinity temperature gradient is obtained. This will allow us to conclude that the pond is physically stable because of the non-deterioration of its stratified layers at the intermediate zone NCZ because it has resisted to the small convection movements generated by the convection velocity. It is known that in a solar pond there is a dynamics that is created between the heat transfer decreasing the density and the salt concentration increasing it. As long as the density of the adjacent lower layer is greater than that of the layer immediately above, the pond maintains its physical equilibrium and thus stratification will be kept.

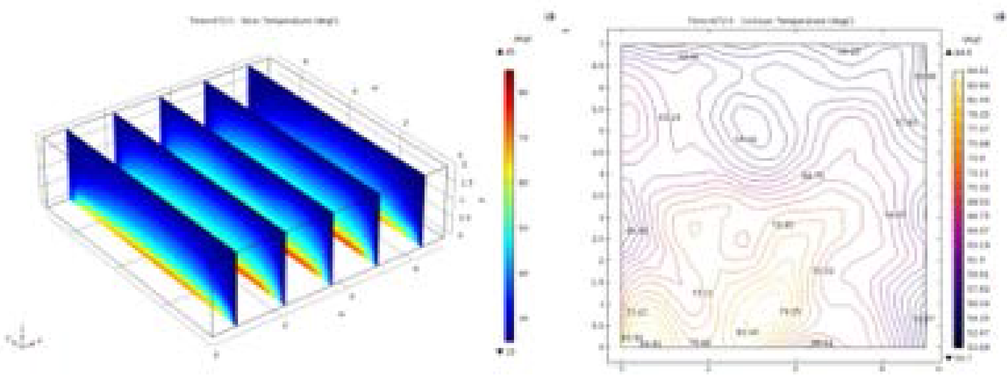


Figure 4a: relatively clear water (corresponding to θ = 0.5 NTU)

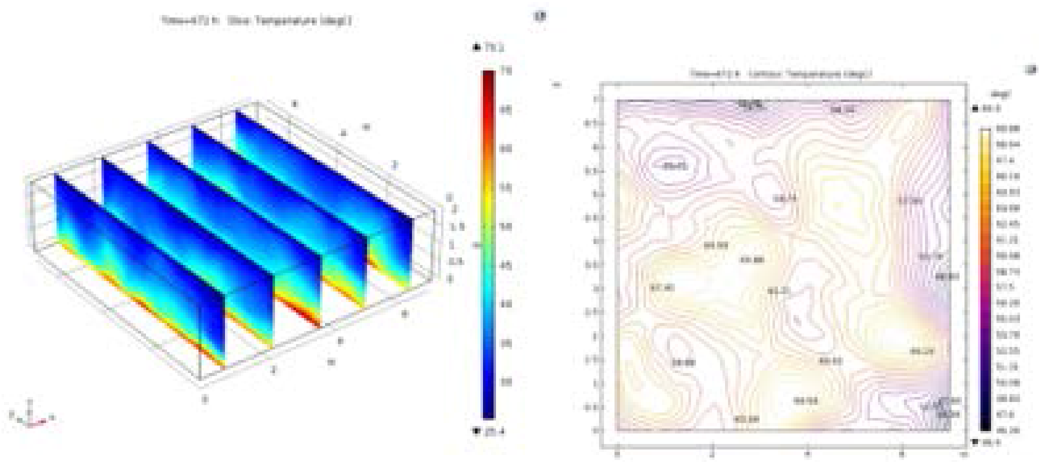


Figure 4b: Moderately turbid water(corresponding to θ = 1.5 NTU)

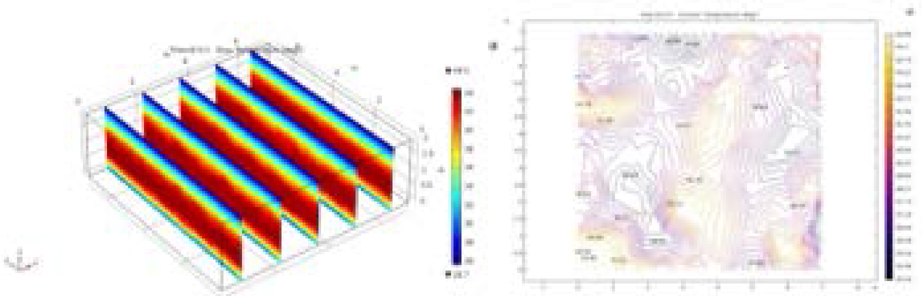


Figure 4c: Very turbid water (corresponding to θ = 4 NTU)

FIGURE 4. The temperature fields (on the left) and the isotherms (on the right) of a solar pond with a salinity gradient comprising carbon nanotubes in its storage zone corresponding to three turbidity levels, namely clear water, moderately turbid water, and very turbid water .

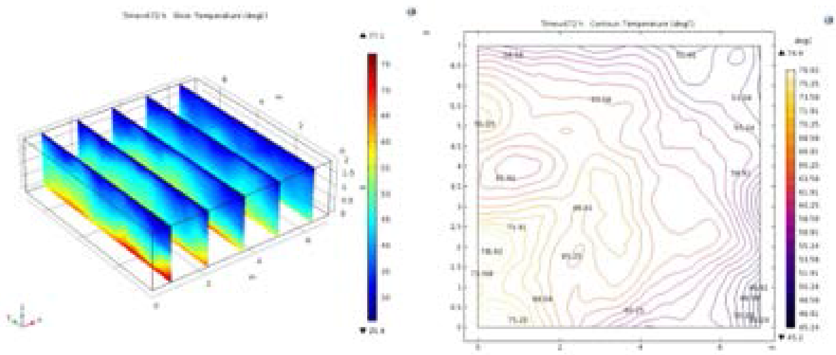


Figure 5a: Relatively clear water (corresponding to θ = 0 .5 NTU)

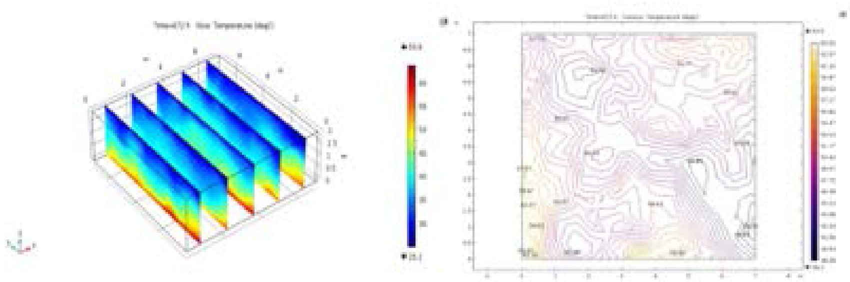


Figure 5b: Moderately turbid water (corresponding to θ = 1.5 NTU)

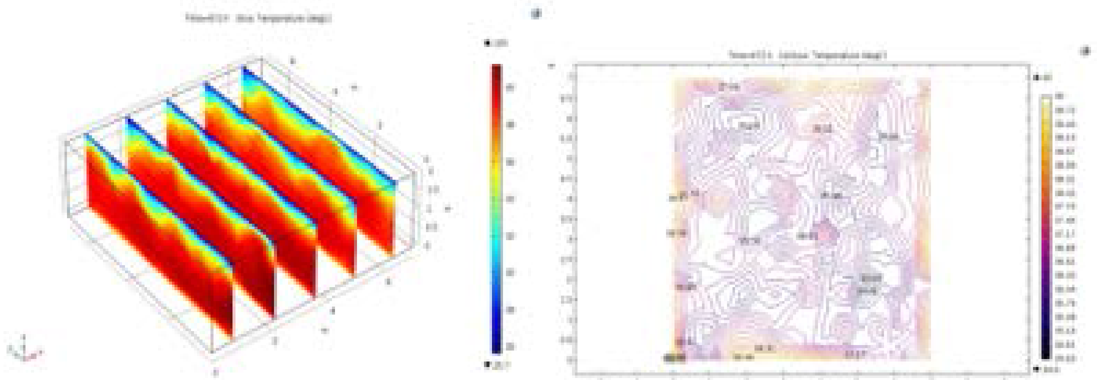


Figure 5c: Very turbid water (corresponding to θ = 4 NTU)

FIGURE 5. The temperature fields (left) and isotherms (right) of a solar pond with salinity gradient not having in its storage area carbon nanotubes corresponding to the three levels of turbidity namely relatively clear water, moderately turbid water and very turbid water.

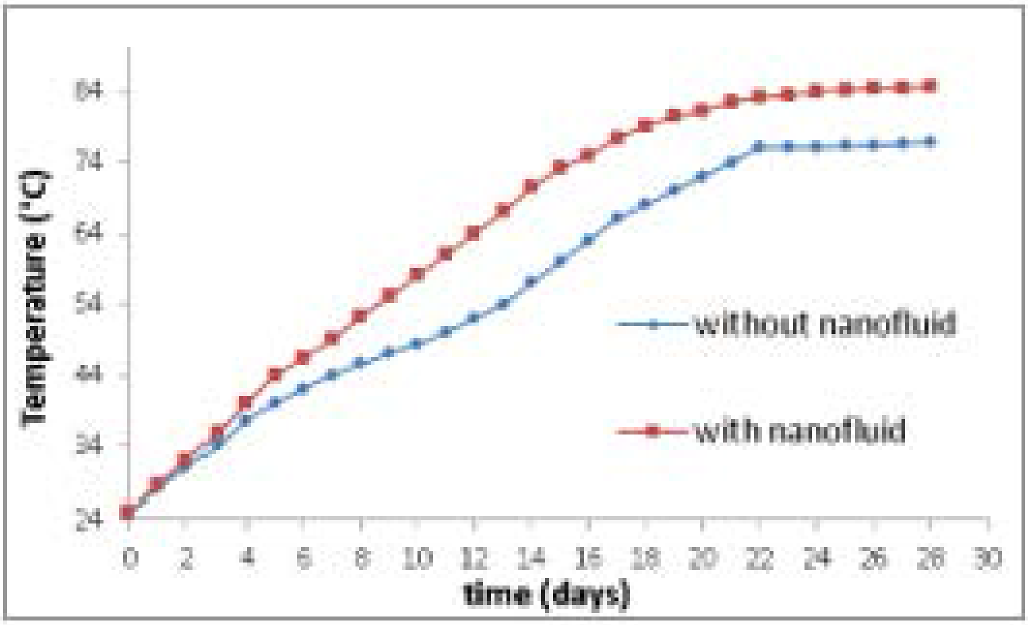


Figure 6a: Relatively clear water

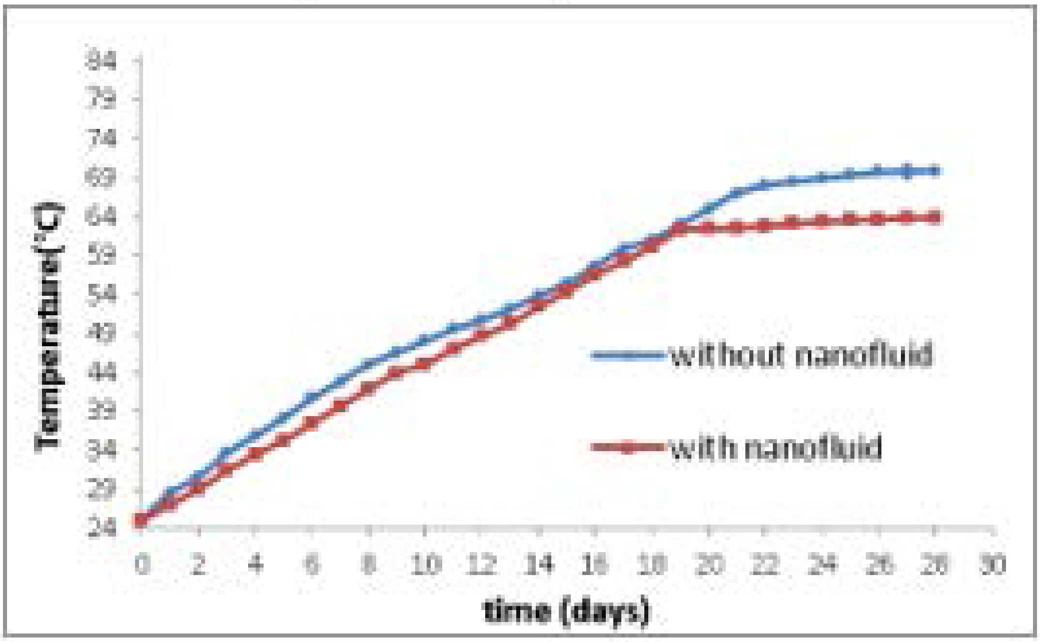


Figure 6b: Moderately turbid water

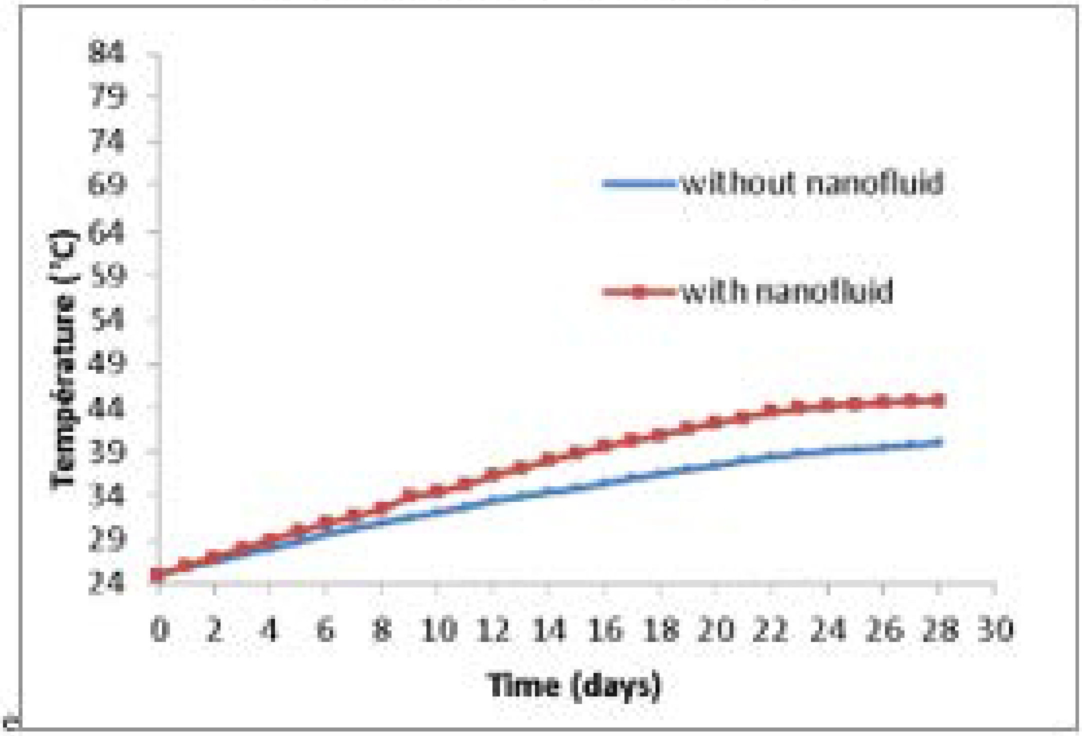
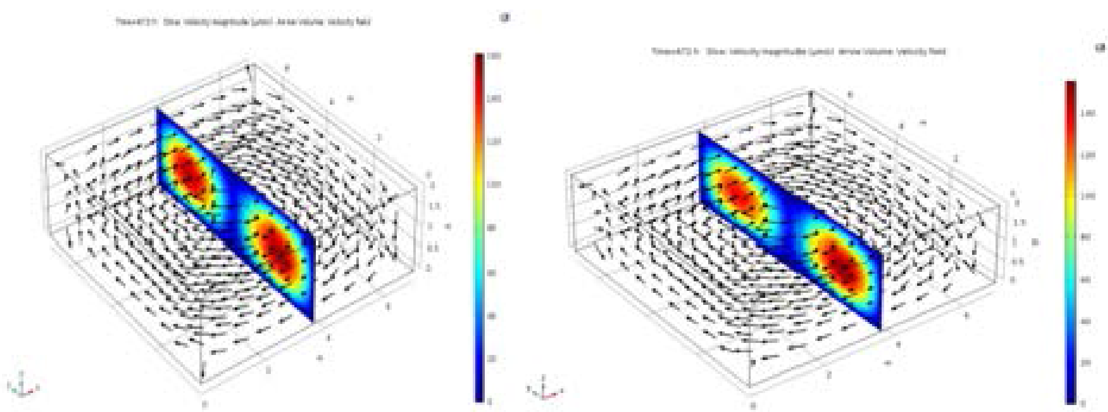


Figure 6c: Very turbid water

FIGURE 6. Comparison of heating rates between the two ponds

The pond with the nanofluid can become operational in a very short time compared to the ordinary pond. The concentration of the CNTs in the LCZ storage layer can certainly contribute to the increase of the thermal performance but, in return, its excess wile allow the liquid of the LCZ to easily reach the boiling temperature which will result in an increase of the rate of natural convection and hence a deterioration of the layers stratified from the NCZ zone as a thermal stabilizer. It is also interesting to note that the high salt concentration of the LCZ layer will increase the liquid density and weaken the convection which is an important advantage for the NCZ layers to maintain their stable levels of salt concentration. It is interesting to note that the convection velocities (see Figure 7) are strong in the pond with nanofluid compared to the pond without nanofluid: this difference is of the order of 20 $\mu m/s$ for an environment where the water is clear, 23$\mu m/s$ for a moderately turbid medium and 50 $\mu m/s$ for a very turbid environment. This difference in velocity is due to the rise in temperature recorded at the LCZ zone, that is to say, that the increase in temperature leads to an acceleration of the convection velocities. Also, we note that the convective motions increase at the extremities and weaken at the midpoints because of the rise in the temperature. But, in general, we estimate that this velocity remains low enough so that it cannot deteriorate the stratified layers of the solar pond.



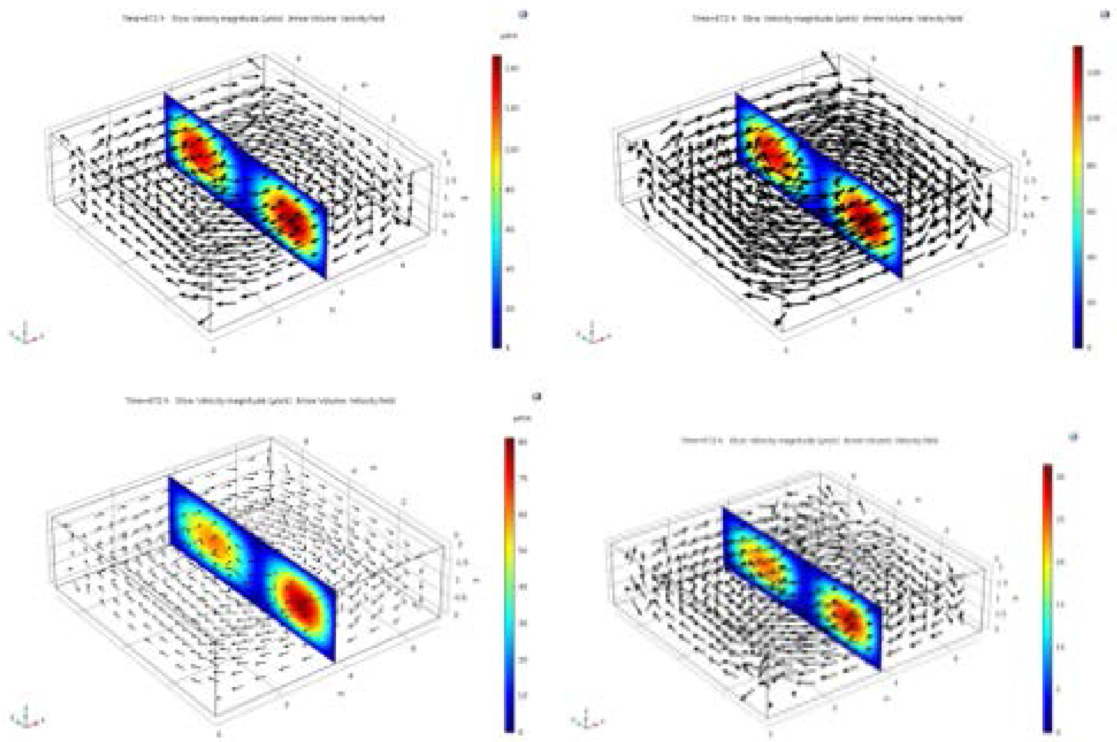


FIGURE 7. Natural convection velocities: On the right (the nanofluid pond) and on the left (the pond without nanofluid)

4.2.2. *Error analysis.* It is clear that the numerical solutions are iteratively computed with finite precision and subject to rounding errors. We notice that these errors are decreasing with decreasing steps w.r.t time and space. This confirms that the errors in numerical solutions was not amplified during the iterations, hence, the iterative scheme is stable. It should be noted that when we go from the mesh M1 to the mesh M2 , the absolute error is of the order of 0.45°C, and from M2 to M3 the absolute error decreases and will be of the order of 0.11 ° C. On the other hand, we note that this error will be very small when we go from mesh M3 to mesh M4 and is close to 0.02 ° C (table 1).

This significant decrease of the relative error is proportional to the density of the mesh showing that the finite element scheme is consistent. So, there is a convergence of the approximate solutions to the exact solution as the scheme is consistent and stable.

TABLE 1. Absolute errors for different mesh's for the pond with nanofluid and clear water

Coordinates			**Ref solution (°C)**	**Numerical Solution (° C) for the 2nd, 3rd and 4thmesh**			**Absolute Error**		
x	y	z	Mesh1	Mesh2	Mesh3	Mesh4	M_2 -M_1	M_3 -M_2	M_4 -M_3
1.75	1.75	1.00	76.87698	76.37061	76.25706	76.24520	0.50637	0.11355	0.01186
1.75	3.50	1.00	67.56509	67.09286	66.96898	66.94774	0.47223	0.12388	0.02124
1.75	5.25	1.00	63.84871	63.33541	63.23760	63.20164	0.51330	0.09781	0.03596
3.50	1.75	1.00	74.77823	74.29341	74.14716	74.12211	0.48482	0.14625	0.02505
3.50	3.50	1.00	65.64367	65.17590	65.06635	65.04979	0.46777	0.10955	0.01656
3.50	5.25	1.00	63.58656	63.14312	63.02531	63.00109	0.44344	0.11781	0.02422
5.25	1.75	1.00	72.75787	72.30512	72.19323	72.16901	0.45275	0.11189	0.02353
5.25	3.50	1.00	64.85476	64.41213	64.29225	64.26747	0.44263	0.11988	0.02478
5.25	5.25	1.00	59.77622	59.33211	59.22322	59.19710	0.44411	0.10889	0.02612

5. CONCLUSION

The behavior of two solar ponds under the same climatic conditions and to the same solar radiation, one containing a saline solution of sodium chloride and the other containing a mixture of carbon nanotubes inserted into a saline solution was numerically studied for a 28 day period based on a transient three-dimensional model using the COMSOL software taking into account the influence of the physical and thermodynamic properties such as the thermal conductivity K, the density, the specific heat Cp and solar radiation E. This helps drawing the following conclusions:

- The pond with the nanofluid records a highest temperature and the higher convection rate compared to the ordinary pond;
- The concentration of carbon nanotubes in the nanofluid should be watched, that is, in the case of a high concentration, the liquid could reach boiling point and therefore the stratification may be deteriorated.
- The performance of the solar pond is very sensitive to the degree of turbidity in the water because it directly affects the radiation arriving at storage

zone because the presence of solid particles and the growth of microorganisms is harmful and they drastically reduce the transparency of the pond water and consequently its performance.

- The numerical results show that the temperature difference between the exact values and the simulated values decreases as the temporal and spatial discretization steps tend towards zero.

Nomenclature

C_p: Specific heat $[kJ/kg°C]$
E: Radiation intensity $[w/m^2]$
h: Heat Transfer Coefficient $[w/m^{2}°C]$
k: Heat Conductivity Coefficient $[w/m°C]$
q or Q: Heat transfer rate $[w/m^2]$
s: Salinity of the brine $[\%]$
T: Temperature $[°C]$
t: Time [sec]
μ: Extinction Coefficient of Transmission Function $[m-1]$
ρ: Density $[kg/m^3]$. μ: The extinction coefficient of the transmission function $[m^{-1}]$

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