Conference Proceedings

EuroSun 2016

Palma de Mallorca (Spain), 11 – 14 October 2016

CFD modeling of a small case Solar Pond

M. C. Giestas[a], J. P. Milhazes[b], P. J. Coelho[b], A. M. Joyce[a] and D. Loureiro[a]

[a]*LNEG, Estrada do Paço do Lumiar, 1649-038 Lisboa, Portugal*
[b]*IDMEC/IST, Avenida Rovisco Pais, 1049-001 Lisboa, Portugal*

Abstract

A Salt Gradient Solar Pond (SGSP) is a basin of water where solar energy is trapped due to an artificially imposed salinity gradient. Three main zones can be identified: the surface and bottom zones that are both convective and an intermediate zone in between intended to be non-convective. This zone acts as a transparent insulation allowing the storage of thermal energy at the bottom, where it is available for later use. A numerical model where the SGSP dynamics is described in terms of velocity, pressure, temperature and salt concentration is presented. This model is based on the Navier-Stokes equations for an incompressible fluid, coupled to two advection-diffusion equations: one for temperature and another one for salt concentration. The fluid density ρ depends on temperature and salinity and the Boussinesq hypothesis is adopted. The variation of the daily solar radiation and its attenuation along the depth of the pond are also considered.

The objective of this work is to reproduce existing experimental data with a model robust enough to describe the physical phenomena involved for a long period of time. A transient computation with the finite element *deal.II* library and a finite volume model in *ANSYS Fluent* account for the dynamic behavior of the pond. This way it will be possible to contribute to the correct design and operation of these long thermal storage energy devices.

Keywords: Solar ponds, thermal storage, numerical modeling, finite elements, double advection-diffusion.

doi:10.18086/eurosun.2016.03.02 Available at http://proceedings.ises.org

1. **Introduction**

Tab. 1: Nomenclature

A	Thermal diffusivity (m^2/s)	α	Thermal expansion coefficient (K^{-1})
B	Salt diffusivity (m^2/s)	β	Salt contraction coefficient
b	Buoyancy		Kinematic viscosity (m^2/s)
$\mathbf{C_p}$	Specific heat of the fluid (J/kg °C)		Angle of declination (º)
g	Gravity acceleration (m/s^2)	ρ	Fluid density (kg/m^3)
h	Convection coefficient (W/m^2 K)		Incident and refracted angle (º)
I, I_R	Incident solar radiation (W/m^2)		Hour angle
L_1, L_2	Domain length and height (m)		Salt concentration (%)
n	Unit normal vector	Ω, ∂Ω	Domain, boundary
p	Pressure (Pa)		
k	Transparency coefficient	*Operators*	
T	Temperature (K)	∇	Gradient
t	Time (s)	∇.	Divergence
u	Velocity field (m/s)	Δ	Laplacian
x	Space coordinates (m)		
R	Reflection coefficient		
Subscripts		*Superscripts*	
0, *f*	Initial, final	$\dot{z}$	Time derivative
r	Reference values	*n*	Time instants
a	Ambient values		
1, 2, 3, 4	Left, right, bottom, top		

A Salt Gradient Solar Pond (SGSP) is a basin of water that collects and stores solar thermal energy. A temperature gradient is established in a natural way induced by solar radiation absorption at the pond surface. Three distinct zones are present in the SGSP: A upper convective zone (UCZ), a lower convective zone (LCZ) and an intermediate zone intended to be non-convective (NCZ). A salt concentration gradient (denser at the bottom and lighter at the top) is established to prevent convective motions. These motions would promote the return of the stored energy to the outside ambient destroying the SGSP very purpose. Thus a double advection-diffusion process occurs in the SGPS with the temperature and salinity fields making opposite contributions to the fluid density.

Studies of Solar Ponds have been performed since 1902, Kalecsinsky (1902). The experimental, analytical and numerical studies of SGSP pursued with Stommel et al. (1956), Weinberger (1964), Turner (1974), Tabor (1969) and Veronis (1968). A significant number of Solar Ponds were constructed with different characteristics: coupled to desalination units; as low cost seasonal thermal energy storage reservoirs for solar thermal energy production agricultural applications as greenhouse heating Joyce et al (2001) or heating aquaculture ponds especially if constructed near coastal zones.

Concerning modeling, Weinberger (1964) was the first to give a mathematical formulation of a SGSP behavior. The numerical solution of the governing equations that describes a SGSP was firstly reported by Hull (1980), and Hawlader and Brinkworth (1981). Rubin et al. (1988) applied a finite difference method to discretize the governing equations, while Jayadev and Henderson (1979) used a finite element method (FEM). Meyer et al. (1982) developed a numerical model to predict the time dependent behavior of the interface between the convective and the non-convective regions. Panahi et al. (1983) used a one-dimensional model. A SGSP year control operation was successful obtained with a one-dimensional model by Ouni et al (2003).

One of the critical factors in SGPS performance is the stability of the non-convective zone. Stability has been studied by researchers like Da Costa et al. (1981), Schechter et al. (1981), Dake et al. (1969), Akbarzadeh et al. (1980), Cha al. (1982), Meyer et al. (1982) and Giestas et al. (1996, 1997). They resorted in most cases to a linear perturbation theory. The results obtained provided important information regarding the onset of the instabilities, as well as the existence of several possible stable or unstable states that may arise (see Jin et al. (1996) and Mambole et al. (2004)). In Pina et al. (2005), a 2D numerical model that considers the viscosity dependent on both temperature and salt concentration was presented.

Mansour et al. (2006) solved numerically the problem of transient heat and mass transfer through a two-dimensional finite volume method. Angeli and Leonardi (2004, 2005) analyzed the evolution of salt concentration profiles in a SGSP.

Ould Dah et al. (2010) studied experimentally the transient evolution of profiles in a small Solar Pond in Tunisia. Boudhiaf and Baccar (2014) payed special attention to the hydrodynamic behavior of a two dimensional SGSP model in transient regime. Results have shown that the buoyancy ratio and the aspect ratio have an important effect in the thermal performance of the SGSP. Boudhiaf (2015) analyzed those effects using a finite volume technique in transient regime with a fixed salt concentration profile. Those authors used *ANSYS Fluent* to better understand ponds performance. With the development of this kind of finite volume analysis, a new way of visualization of SP behavior was possible.

This work presents a 2D CFD model for the described mathematical problem. Density is assumed to vary acording to the Boussinesq hypothesis, heat conduction is treated according to Fourier´s law and salt diffusion obeys Fick´s law. Initial and boundary condition are given in Section 2.2 and Section 2.4. To validate this model, comparisons with available experimental data, namely with the results of Ould Dah et al. (2010) are presented. These authors studied experimentally the time evolution of profiles in a small Solar Pond in Tunisia and presented results for temperature profiles. The cylindrical tank considered was insulated, the area of the surface is 0.64 m^2 and the depth is 0.90 m. In that small tank the temperature and salinity profiles were measured through a set of 27 thermocouples each of 6mm diameter. The obtained results give a special contribution to the validation of the model proposed here.

The solution of the time-dependent coupled system of equations of a SGSP is a difficult numerical task. To perform equally well the solution with respect to the several physical phenomena, a sequence of simpler sub-problems in correspondence with the underlying physics was performed. The study involves the splitting of the temperature, salinity and Navier-Stokes equations the later employing a pressure correction approach leading itself also to a decoupling of velocity and pressure. A general introduction to operator splitting techniques can be seen in Farago and Havasiy (2009). A computer code was developed using the finite element (FE) library *deal.II* (Bangerth et al. 2007) with some parallelization achieved in the assembling of element matrices and vectors and the solver of the linear system.

A 2D pressure based ANSYS Fluent simulation was also performed based on the same model hypothesis.

2. Physical and Mathematical Formulation

2.1 Physical model and simplifying assumptions

A numerical model for the SGSP dynamics of the fluid flow and heat and mass transfer was developed. The SGSP prototype is modeled as a rectangular cavity of height

We present below the governing partial differential equations as well as the boundary conditions adopted for the studied case. These governing equations are the standard conservation laws for continuum media.

Heat equation:

Therefore the domain in study is

Where

A bounded second order implicit scheme was chosen for the time marching solution. The time step was constant and equal to 0.8 seconds.

4. Results and discussion

Tab. 3: Constants values used to obtain the results

Symbol	Value	Unit
A	10.52 x 10^{-7}	$m^2\ s^{-1}$
B	1.72 x 10^{-9}	$m^2\ s^{-1}$
	110.0	$W\ m^{-2}\ K^{-1}$
	930.0	$W\ m^{-2}$
L_1	0.9	m
L_2	0.86	m
	1.068 x 10^3	$kg\ m^{-3}$
	3.8 x 10^{-4}	K^{-1}
	6.3 x 10^{-4}	$m^3\ kg^{-1}$
	36.42	
	21.95	ºC
	0.0	$g\ kg^{-1}$
	0.99 x 10^{-6}	$m^2\ s^{-1}$
	8.2505 x_2 + 25.6418	ºC
	0.8	S

We present the results for computations in a transient regime in order to better describe and understand the inherent dynamics of a SGSP. A particular interest of this work is the long term simulation of the physical SGSP phenomena with heating of the fluid due to the absorption of solar radiation.

An important issue one should answer at this time is whether the model simplifications and the numerical methods for solving this problem are robust enough for a long term simulation (in order of days or even months) or not. The comparison of the numerical data with the available experimental data should provide some insight on this question and verify the respective limitations. Prior to this, it could in theory, be refined to model larger times and larger or different geometries.

The incident solar radiation

Fig. 4 also shows a good accordance with ED. Although, comparing Fig 3 with Fig.4, it can be observed that the F-ND differs mainly in the UCZ and NCZ. On the F-ND it can be observed a larger temperature gradient on the NCZ and a less sharp transition from the NCZ to the UCZ.

One important feature that is implemented in the present model is the time evolution of the LCZ, NCN and UCZ's. The dynamics of these zones are very important to the stability of the SGSP, thus it should not be neglected. Fig. 5 represents the salt concentration profiles, where the three zones can be identified. As expected, both UCZ, LCZ and salt concentration gradient increase with time.

Fig. 6 shows a visual representation of temperature and velocity taken for day 5 with *Ansys Fluent* post processing software. It is patent in this figure the two convective zones that separate the NCZ. Fig. 7 is a Schlieren representation, taken from *deal.II* data for the same day as the case of Fig. 6. Comparing Figs. 6 and 7, becomes clear that the UCZ is greater in Fig. 6 which corresponds to the F-ND.

6. Conclusions

The results presented here comprise a subset which is considered representative of the results available. Although, the validation of the results are for a small scale prototype, it is believed that the information gathered can be useful for the full scale SGPS dynamics.

The developed model seems to be able to predict the main features of the physics involved in a SGSP. Particularly, it was possible to get a good prediction for temperature in the three main zones of the SGSP with either the *deal.II FEM* code or with the *Ansys Fluent* software.

It is intended in future work to include the wall shading effect, heat extraction and long term SGSP simulation.

Fig. 3: Temperature profiles for experimental (ED) and *deal.II* numerical data (D-ND)

Fig. 4: Temperature profiles for experimental (ED) and *Ansys Fluent* numerical data (F-ND)

Fig. 5: Salt concentration profiles for experimental (ED) and *deal.II* numerical data (D-ND)

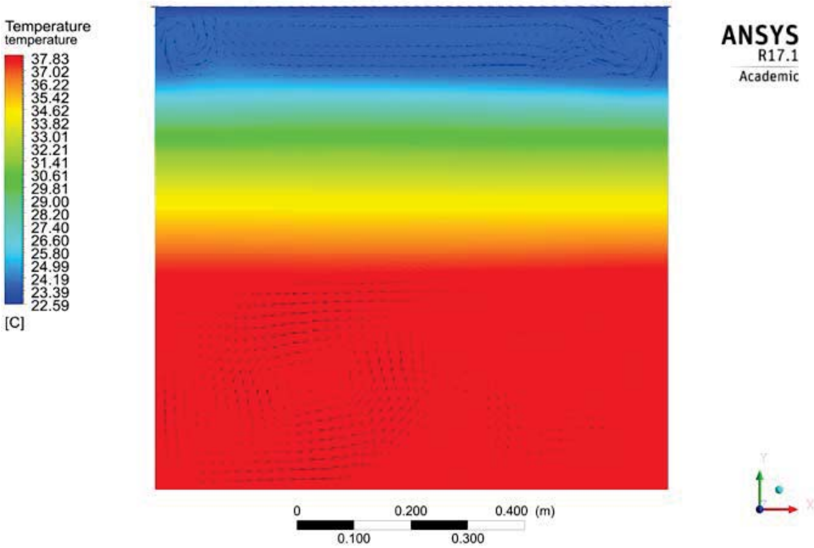

Fig. 6: *Ansys Fluent* visual representation of temperature and velocity taken for day 5.

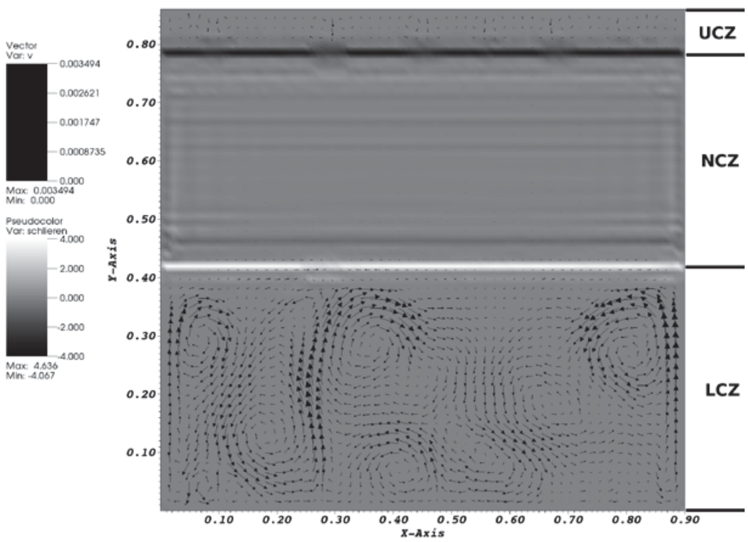

Fig. 7: Schlieren representation taken from *deal.II* data for day 5.

Acknowledgments

The present work was possible due to the help of Professor Dah, who kindly provided the experimental data for the solar pond prototype.

References

Angeli C. and Leonardi E. 2004. A one-dimensional numerical study of the salt diffusion in a salinity gradient solar pond. Int. J. Heat Mass Transfer.47, 1–10.

Angeli C. and Leonardi E. 2005. The effect of thermo-diffusion on the stability of a salinity gradient solar pond. Int. J. Heat Mass Transfer. 48, 21-22.

Akbarzadeh A. and Ahmadi G. 1980. Computer simulation of the performance of a solar pond in the southern part of Iran. Solar Energy. 24.

Bangerth W., Hartmann R. and Kanschat G. 2007 deal.II — a general-purpose object-oriented finite element library. ACM Trans. Math. Softw. 33, 4.

Boudhiaf R. 2003. Numerical Temperature and Concentration distributions in an insulated salinity gradient solar pond. Renewables: Wind, Water and Solar. 2, 10

Boudhiaf R. and Baccar. 2014. Transient hydrodynamic heat and mass transfer in a gradient solar pond study. Energy Conversion and Management. 79, 568-580.

Da Costa L. N.., Knobloch E. and Weiss N. O. 1981. Oscillations in double-diffusive convection. J. Fluid Mech. 109, 257, 25–43.

Dake J. M. K. and. Harleman D. R. F. 1969. Thermal stratification in lakes: analytical and laboratory studies. Water Resources Res. 5.

Duffie J. A., Beckman, 1980 Solar Engineering of Thermal Processes. John Wiley and Sons.

Farago I. and Havasiy A. 2009. Operator Splitting and their Applications. Nova Science Publishers.

Giestas M., Joyce A, and Pina H. 1996. The influence of radiation absorption on solar ponds stability. J. Heat Mass Transfer. 39, 18.3873–3885.

Giestas M., Joyce A., and Pina H.1997. The influence of non-constant diffusivities on solar ponds stability. J. Heat Mass Transfer. 40, 18.4379–4391.

Giestas M.C, Milhazes M. P., and Pina H.L.2014. Numerical Modeling of Solar Ponds. Energy Procedia. 57, 2416-2425.

Guermond J.L., Minev P., and Jie Shen. 2006. An overview of projection methods for incompressible flow. Comput. Methods Appl. Mech. Eng.195, 6011–6045.

Hairer E. and Wanner G. 1991. Solving Ordinary Differential Equations II – Stiff and Differential-Algebraic Problems. Springer-Verlag.

Hawlader M.N.A .and Brinkworth B. J.1981. An analysis of the non-convecting solar pond. Solar Energy. 27, 195–204.

Hull. J. R.1980. Computer simulation of solar pond thermal behavior. Solar Energy. 25, 33–40, 1.

Hundsdorfer W.and Verwer J. G. 2003. Numerical Solution of Time-Dependent Advection-Diffusion-Reaction Equation*s*. Springer - Verlag.

Jayadev T. S.and J. Henderson. S. 1979. Salt concentration gradient solar ponds. Modeling and optimization.

Jaefarzadeh M.R.2004.Solar Energy. Thermal behavior of a small salinity gradient solar pond with wall shading effect.77.281-290.

Joyce, A., Giestas, M., Loureiro, D., Tavares, C. 2001. The Portuguese Experience on Salt Gradient Solar Ponds. Workshop on Solar Ponds. Tunis.

Kalecsinsky A. V. 1902. Ueber die ungarischen warmen und heissen kochsalzseen als natuerlich waermeaccumulatoren. Ann. Physik IV, 7, 408. Cited by Nielsen C. 1979 in Dickinson W.C. and Cheremisinoff P.N. (Eds.) Solar Energy Handbook.

Knopp,T G. Lube G., and Rapin.G 2002. Stabilized finite element methods with shock capturing for advection–diffusion problems, Comput. Methods Appl. Mech. Engen. 191, 2997–3013.

Kurt H. F, Halicir, and Binark A. 2000. Solar pond conception - experimental and theoretical studies. Energy Conv. Manag. 41, 9.

Mansour R., Nguyen C., and Galanis N.2006. Transient heat and mass transfer and long-term stability of a salt-gradient solar pond. Mech. Research Communications. 33, 233–249.

Meyer K. A., Grimmer D. P., and Jones G. F.1982. An experimental and theoretical study of salt-gradient pond interface behavior. Progress in Solar Energy.

Ould Dah M. M, Ouni. M, Guizani, A. and Belghith A. 2010. Study of temperature and salinity profiles development of Solar Pond in laboratory. Dessalination.183, 179-185.
Panahi Z., Batty J. C. and Riley J. P.1983. Numerical simulation of the performance of a salt gradient solar pond. Trans. of ASME. J. of Solar Energy Eng.. 105, 361–374.
Pina H., Giestas M., Joyce A. 2005.Modelação tridimensional de Lagos Solares Congresso de Métodos Numéricos en Ingenieria. Granada, Espanha.
Rabl, A. Nielson, C.E 1975. Solar ponds for space heating Solar Energy.17, 1-12
Rubin H., Benedict B. A. and Bachu S. 1988 Modeling the performance of a solar pond as a source of thermal energy. Solar Energy. 32, 771–778.
Schechter R.S., Velarde M. G. and Platten J. K. 1981.The two-component Bénard problem. Wiley.
Stommel H., Arons B. and Blanchard D. 1956. An oceanographical curiosity: the perpetual salt fountain. Deep Sea Res. 3, 152–153.
Tabor H. 1969. Solar Ponds. Solar Energy. 12, 549–552.
Turner J. S. 1974. Double-diffusive phenomena. Ann. Rev. Fluid Mech.6, 37–56.
Wang Y.F. and Akbarzadeh, A.A 1983. Solar Energy. A parametric study on solar ponds.30, 555-562.
Washburn, E. W 1929 ed. McGraw Hill Book Co., Ina; NY 10036 Vol V.
Weinberger H. 1964. The Physics of the solar pond. Solar Energy. 8, 2.
Veronis G. 1968. Effect of a stabilizing gradient of solute on thermal convection. J Fluid Mech.34, 315–336.