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Exergy variations of the gradient layer in a shallow solar pond

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Abstract. A salinity gradient solar pond can act as a solar thermal energy storage source for all seasons of the year and in all weather conditions. Solar pond layers exergy can be considered as the potential for getting the maximum amount of work done. Exergy in a gradient layer was studied based on the experimental data of the years 1997 and 1998 for 229 days in a solar pond in Ferdowsi university of Mashhad. The research revealed that variations of specific exergy (exergy per unit mass) for gradient layer, is affected by temperature variations of lower and upper convective layers. The specific exergy reached its maximum in mid-August, but the exergy per pond unit area in the early period of that month reached the maximum amount, because in addition to the temperature variations of the lower and upper convective layers, the time variations of the gradient layer thickness also affect exergy variations per unit area.

Keywords: Exergy, Gradient layer, Heat and mass transfer, solar pond

1. INTRODUCTION

A salinity gradient solar pond consists of a shallow pond, with salt-water content whose density and salinity increase along with depth. A solar pond consists of three upper (surface), gradient (insulation) and lower (thermal storage) layers or zones. The convective heat transfer occurs in the upper and lower layers, but the conductive heat transfer happens in the gradient layer. In the upper and lower convective layers, the temperature and salinity are almost constant; but in the gradient layer, temperature and salinity are not constant, and in the depth of the gradient layer they increase by approaching the bottom of the pond. Due to mass and heat diffusion, the thickness of the gradient layer changes with time. Figure 1, shows the schematic diagram of the zones forming a solar pond. The thermal energy stored in the pond can be extracted in different ways and used for power generation.

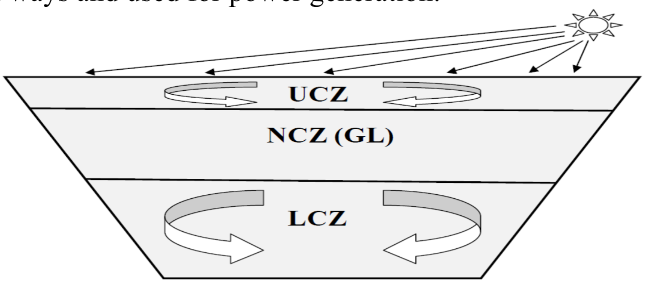

Figure 1. Schematic diagram of a salinity gradient solar pond.

For the first time, Weinberger [1], studied the physics of solar pond. He disregarded the thickness of the upper and lower convective zones, and solved the energy equation to find transient temperature distribution in an analytical method. Meyer [2], offered a numerical model to predict the transient behavior of the interface between the solar pond zones. In this model, some experimental equations have been used to describe heat and mass flux in the interface of the pond zones. The performance of a small solar pond with salinity gradient was investigated in laboratory scale by Jaefarzadeh [3]. This pond was at Mashhad Ferdowsi University under

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open air. The time history of the variation of temperatures, salinities and elevations of the upper and lower layers of the pond under different weather conditions was reported. Karakilcik and Dincer [4] experimentally and theoretically investigated exergetic performance of a solar pond in terms of exergy efficiencies which were then compared with the corresponding energy efficiencies. They revealed that the exergy efficiencies are less than the energy efficiencies for each zone of the solar pond. An experimental investigation of the energetic and exergetic performance of two prototype solar ponds with square and circular cross sections were carried out by Dehghan et al. [5]. They demonstrated that the circular solar pond has better exergetic performance than the square one. Also, they observed that the brine temperature in the lower convective zone of the circular solar pond reaches to a higher value in comparison with the square one. Bozkurt and Karakilcik [6] experimentally and numerically investigated the energetic and exergetic performance of a solar pond integrated with four flat plate solar collectors. They developed an energy and exergy models to study the energetic and exergetic performance of the integrated solar pond. They also compared the energy and exergy performances for the each zone of the solar pond.

2. THE GROWTH AND EROSION OF THE GRADIENT LAYER IN THE SOLAR POND

Since salt diffusion in the gradient layer, happens slower than the thermal diffusion, the distribution of the concentration in the gradient layer has a higher stability compared to temperature distribution and therefore temperature profiles change faster than concentration profiles. Salt concentration and temperature gradients in the upper and lower boundaries of the gradient layer, move the boundaries and consequently result in the growth or erosion of the gradient layer. It should be noticed that the upper and lower boundaries can move upwards or downwards independently from each other, but there's a possibility for the growth of the gradient layer to a certain thickness according to the boundary conditions.

3. MASS AND HEAT TRANSFER IN THE SOLAR POND

The phenomenon of mass transfer in the gradient layer of the solar pond normally happens due to the effect of salt molecular diffusion process, because the density is not constant and the natural convection cannot occur in the gradient layer. The gradient layer is also called the non-convective layer. The absence of convection flows make the gradient layer, act as a transparent and insulating layer and pass the sunlight to heat the lower convective layer, but it doesn't waste the heat of the lower convective layer through convection, yet inevitably, it loses some less energy through thermal conduction. The conservative form of the heat and mass transfer equations for the gradient layer is as follows:

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

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

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

4. GRADIENT LAYER EXERGY

Mr. Hull and Nielsen, have offered temperature variation in the depth of the gradient layer according to the temperature of the upper and lower layers as below [7]:

$$T_{GL} = T_L - \left(\frac{T_L - T_U}{\Delta Z^2}\right)Z^2 \qquad 0 \le Z \le t_{GL} \tag{3}$$

In this equation, the indexes of L, U and GL, belong to the lower, upper and gradient layers, respectively. Therefore, by integration, the mean temperature of the gradient layer according to the above equation becomes:

$$T_{AG} = \frac{2T_L + T_U}{3} \tag{4}$$

The flow exergy of a fluid, by disregarding potential and kinetic energy is as follows:

$$Ex = (H - H_0) - T_0(S - S_0) \tag{5}$$

In above equation, H and S are the enthalpy and entropy respectively. The index 0, is related to the equilibrium condition of the fluid with the environment. The exergy stored in the gradient layer, is expressed with the equation below:

$$Ex_{GL} = M_{GL}[c_p(T_{AG} - T_U) - c_p T_U Ln(\frac{T_{AG}}{T_U})] = M_{GL}c_p\left[\frac{2(T_L - T_U)}{3} - T_U Ln\left(\frac{2T_L + T_U}{3T_U}\right)\right] \tag{6}$$

Therefore the specific exergy of the gradient layer becomes:

$$ex_{GL} = \frac{Ex_{GL}}{M_{GL}} = c_p\left[\frac{2(T_L - T_U)}{3} - T_U Ln\left(\frac{2T_L + T_U}{3T_U}\right)\right] \tag{7}$$

Also, the exergy of the gradient layer per pond unit area is:

$$Exa_{GL} = \frac{Ex_{GL}}{A} = \rho_{GL} t_{GL} c_p\left[\frac{2(T_L - T_U)}{3} - T_U Ln\left(\frac{2T_L + T_U}{3T_U}\right)\right] \tag{8}$$

In this equation, M is mass, c_p is specific heat, ρ is density and t is the thickness of the gradient layer. In the above equations, the temperatures should be based on Kelvin degree. It should be pointed out, that in order to calculate the exergy of the gradient layer, the original temperature (which is usually the temperature of the free air or environment) is exactly the same as the temperature of the upper convective layer which is very close to the environment temperature. This means that the exergy of the gradient layer is measured according to the upper convective layer exergy which is considered to be zero.

5. CHARACTERISTICS OF THE SOLAR POND BEING STUDIED

The solar pond in Mashhad Ferdowsi University, started to operate on the 20th of July 1997 after the creation of profile with proper concentration in it, and started to absorb solar energy. During different months, the pond with a cross section of $4m^2$ and depth of 1.08m was continuously operating. All the experimental data related to this solar pond, are taken from reference [3]. Time variations of the temperature in the upper and lower convective layers of the solar pond for the years 1997 and 1998 for a period of 229 days, are shown in figure 2.

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

Also, figure 3, shows the recorded variations in the thickness of the gradient layer in the same time period. The initial thickness of the gradient layer, on the 20th of July 1997, equals 65cm.

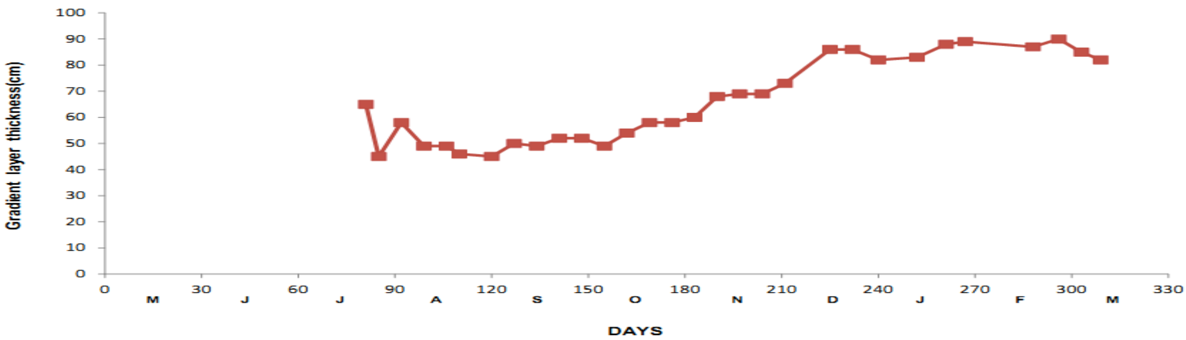

Figure 3. Time variations in the thickness of the gradient layer

6. RESULTS

With increased salinity of salt-water solution in the depth of the gradient layer, the density of the solution increases but its specific heat decreases. Therefore, the average values of 1110 kg/m^3 and 3710 J/kg°C are considered for the density and specific heat of the gradient layer, respectively. Figure 4, shows the specific exergy variations of the gradient layer in different days. It's observed that the process of time variations of the specific exergy in the gradient layer is affected by the process of time variations in the lower and upper convective layers. In mid-August 1997, the specific exergy reached the maximum amount of 5382J/kg. On the first day of the pond's operation on the 20th of July, because the temperatures of the lower and upper convective layers were very close to each other, we observe a minimum amount for the specific exergy.

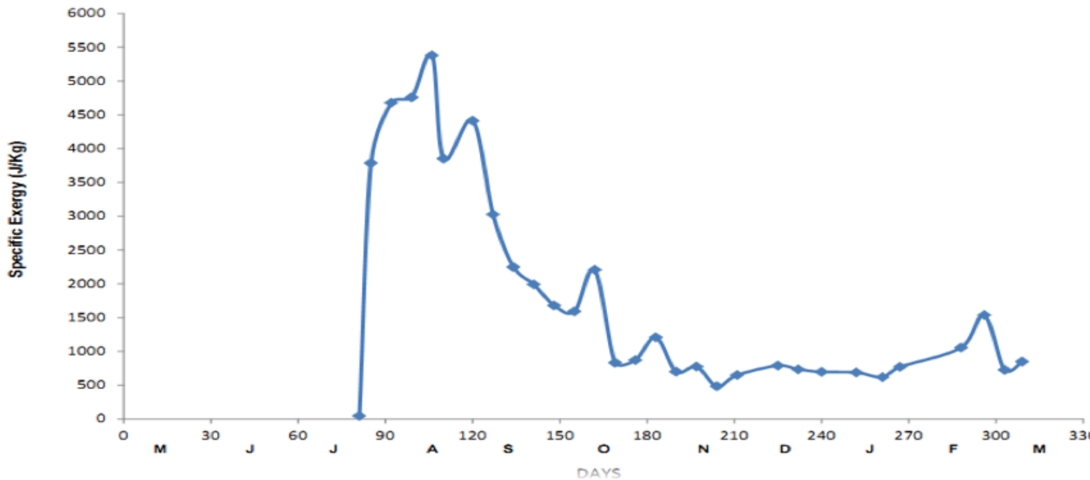

Figure 4. Time variations of the specific exergy in the gradient layer

In figure 5, the time variations of the exergy of the gradient layer per pond unit area is shown. It's seen that in mid-August 1997, the amount of exergy in pond unit area reaches the maximum amount of 2.7 MK/m^2, and the starting day of the pond has still taken the lowest amount, because the pond has not yet received energy from the sun and has not found any opportunity to increase its exergy. The exergy per unit area in the gradient layer, is affected by the lower and upper convective layers as well as the thickness of the gradient layer; therefore, the growth of the gradient layer in mid-August 1997 (according to figure 3) maximizes the exergy per unit area in the gradient layer, whereas the specific exergy reached its maximum in mid-August. Also, in the last ten days of November in which the upper and lower convective layers, are closer than ever to each other, we observe the relative minimum amount for the specific exergy and the exergy per unit area of the gradient layer, with the values of 486 J/kg and 0.335 MJ/m^2, respectively.

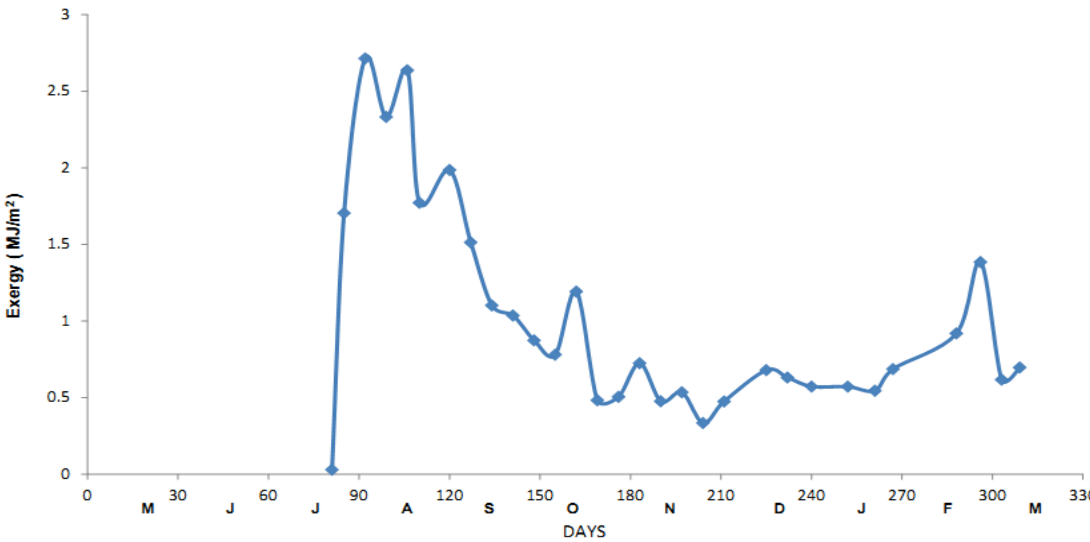

Figure 5. Time variations of the exergy of the gradient layer per pond unit area

7. CONCLUSION

A solar pond can be considered a solar thermal energy storage source. The flow exergy is a criterion to estimate the system potential to reach maximum Available Work. The gradient layer like the lower convective layer has the potential to store solar energy; therefore in ponds with extensive area, the energy stored in the gradient layer can be considered. The time variations of the upper and lower convective layers temperatures in the solar pond and also the variations of the thickness of the gradient layer due to heat and mass transfer phenomena, affect the exergy stored in that layer. The exergetic analysis of the gradient layer revealed that given the environmental conditions, in addition to hot days, in mild and even cold days, the amount of the gradient layer exergy is noticeable for the small and shallow pond. To control the thickness of the gradient layer, salt or salt-saturated water should be added to the lower convective layer according to the area and depth of the pond and also by adding freshwater in the upper convective layer, water deficit due to surface evaporation is compensated and also the salinity in the upper convective layer is controlled.

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