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Research Paper

Behaviour of a salinity gradient solar pond during two years and the impact of zonal thickness variation on its performance

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HIGHLIGHTS

- The effect of the layer thickness on temperatures of the LCZ and the UCZ has been examined.
- The heat extraction from the salinity gradient solar pond has been investigated.
- The optimal thicknesses of the UCZ and the non-convective zone (NCZ) have been found to be 0.2 and 2 m respectively.
- The SGSP could be deeper with less surface area, and still suitable for applications that require low-grade heat.

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ABSTRACT

The interest in solar energy has increased substantially as a consequence of greenhouse gas emissions that result from the combustion of fossil fuels in power generation processes. Solar energy is likely to be the energy of the future and solar ponds, in particular, salinity gradient solar ponds (SGSP), facilitate simple and cost-effective thermal energy collection and storage. In this study; the influence of varying the thicknesses of the zones present in a salinity gradient solar pond on the temperatures of the upper convective zone (UCZ) and the lower convective zone (LCZ) is investigated. The study finds that thickness variation of the zones within the pond has a considerable impact on the temperature of the LCZ while it has a small effect on the temperature of the UCZ. The optimal thicknesses of the UCZ and the non-convective zone (NCZ) have been found to be 0.2 and 2 m respectively. The results also show that the type of application plays a substantial role in determining the depth of the LCZ, and that temperature of this zone varies with the rate of heat extraction. A period of no heat extraction is required to allow the pond to warm up and the length of this period depends on the depth of the LCZ, the type of application coupled with the pond, and the rate of heat extraction. It was found that the SGSP could be deeper with less surface area, and still suitable for applications that require low-grade heat. These findings could form the basis of future studies regarding the performance and financial viability of the overall depth of SGSPs.

1. Introduction

Interest in reducing pollution levels to create a cleaner environment by exploiting sustainable energy sources has increased noticeably in recent years. One type of sustainable energy source is the solar pond, which absorbs and stores solar thermal energy. The most common form of solar pond is the salinity gradient solar pond (SGSP), a large body of water with a depth of 2–5 m that includes a salinity gradient for absorbing and storing incident solar radiation [1–8]. A typical SGSP consists of three zones: the upper convective zone (UCZ), the non-convective zone (NCZ) and the heat storage zone or the lower convective zone (LCZ). As the LCZ has the highest temperature and salt concentration (density), it is where solar thermal energy is stored. In the NCZ, salinity increases with the depth minimising convection in this zone and the temperature will increase uniformly by absorption of the solar radiation [9–15]. Fig. 1 shows a schematic view of a SGSP and its zones.

As shown in Fig. 1, convection occurs in the UCZ and the LCZ while it is suppressed in the NCZ due to the salinity (density) gradient. The NCZ is a transparent insulating layer; there is no convection in this zone and consequently heat moves upward only by conduction from the LCZ to the UCZ through the NCZ [16–20]. Existence of the NCZ is the key to the operation of a SGSP [21–24].

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Nomenclature

A_{LCZ}	surface area of the LCZ (m^2)
A_{UCZ}	surface area of the UCZ (m^2)
c_{pLCZ}	water heat capacity of the LCZ (J/kg K)
c_{pUCZ}	water heat capacity of the UCZ (J/kg K)
Q_g	heat loss to the ground (W/m^2)
Q_{load}	heat extracted from the LCZ (W/m^2)
Q_{loses}	overall heat loss from the surface of the pond (W/m^2)
Q_{rl}	the solar radiation that is absorbed in the LCZ (W/m^2)
Q_{ru}	solar radiation that is absorbed in the NCZ (W/m^2)
Q_{ub}	conduction heat transfer to the UCZ (W/m^2).
Q_{uc}	convective heat loss from the surface (W/m^2)
Q_{ue}	heat loss due to evaporation from the surface (W/m^2)
Q_{ur}	radiation heat loss from the surface (W/m^2)
Q_w	heat loss through walls of the pond (W/m^2).
T_a	ambient temperature (°C)
T_{LCZ}	temperature of the LCZ (°C)
T_{UCZ}	temperature of the UCZ (°C)
t	time (s)
X_{LCZ}	thickness of the LCZ (m)
X_{UCZ}	thickness of the UCZ (m).
ρ_{LCZ}	density of the LCZ (kg/m^3)
ρ_{UCZ}	density of the UCZ (kg/m^3)

Abbreviations

LCZ	lower convective zone
UCZ	upper convective zone
MED	multi-effect desalination
NCZ	non-convective zone
SGSP	salinity gradient solar pond

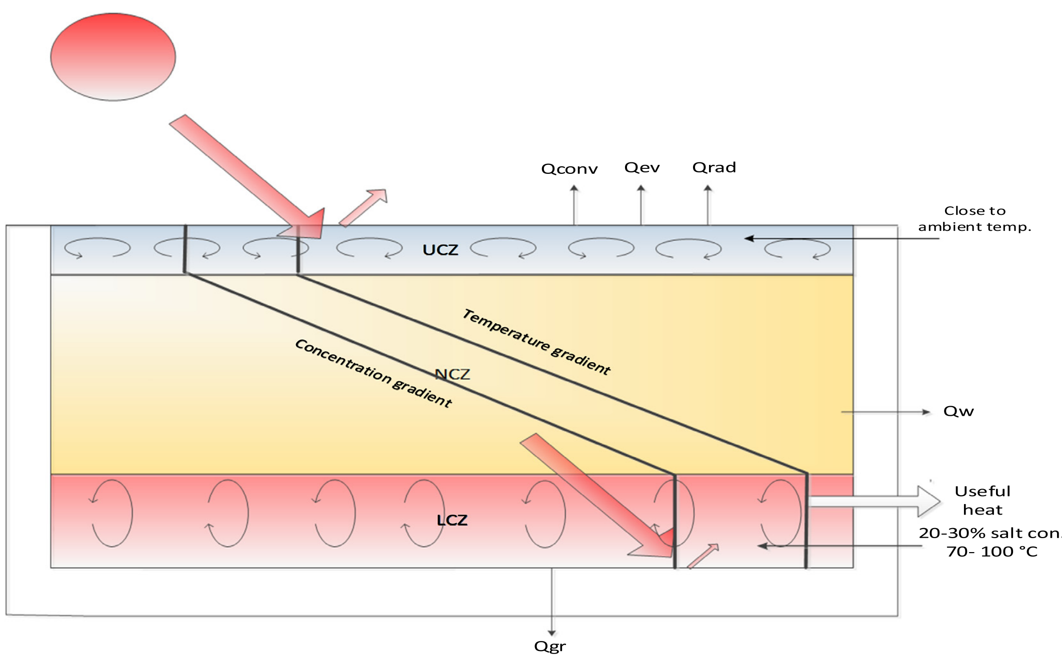

Fig. 1. Schematic view of a salinity gradient solar pond.

Jaefarzadeh pointed out that thermal capacity, maintenance and construction costs of a solar pond determine its viability [25]. Thermal storage capacity can be changed by varying the thickness of the storage zone (LCZ). Recently, many theoretical and experimental studies have aimed to investigate ways to enhance the performance of the SGSPs [26–32]. Thickness of the different zones of the SGSP has a substantial effect on its performance. This issue has been discussed by several researchers in the past [33–35]. However, further investigation on the relationship between zone thickness variation and heat extraction is needed to understand the influence of zone thickness on temperatures of the LCZ. For some applications, instead of increasing the surface area of the pond, the depth of the LCZ could be increased, and the same performance could be achieved. This method of pond construction will reduce the surface area and, consequently, could decrease the capital cost of the pond. However, further research is required to estimate the cost of the pond when it is deeper with less surface area.

In the present study, the influence of the thickness variation of all three zones on the performance of the SGSP in terms of the temperature achieved in the LCZ is assessed. Moreover, the impact of heat extraction from the LCZ on its temperature is investigated. The effect of the depth of the LCZ is studied for a particular load to examine the suitability of the deep SGSP for continuous power supply for applications that require low-grade heat such as multi-effect desalination (MED), requiring 60 °C, and domestic heating, requiring 40–45 °C.

2. Results and discussion

2.1. Effect of zonal thicknesses

This study considers a SGSP in Nasiriyah City, south of Iraq (Latitude: 31.05799, Longitude: 46.25726), with a surface area of 1 m^2. The experimentally validated model developed by Sayer et al. has been utilised to determine the temperatures in the UCZ and the LCZ for different cases [36]. Many assumptions have been made in this model; firstly, the pond is considered to comprise three zones; the UCZ, NCZ and the LCZ. Secondly, the UCZ and LCZ are well mixed, and the temperatures are uniform in these zones. Finally, the solar radiation that reaches the LCZ is entirely absorbed and stored in this zone, and there is no heat loss from the side walls of pond. The heat conservation equations of the UCZ and LCZ were given respectively by Sayer et al. as follows [36]:

$$\rho_{UCZ} c_{pUCZ} A_{UCZ} X_{UCZ} \frac{dT_{UCZ}}{dt} = Q_{ru} + Q_{ub} - Q_{uc} - Q_{ur} - Q_{ue} - Q_w \quad (1)$$

$$\rho_{LCZ} c_{pLCZ} A_{LCZ} X_{LCZ} \frac{dT_{LCZ}}{dt} = Q_{rl} - Q_{ub} - Q_g - Q_{load} - Q_w \quad (2)$$

where Q_w is the heat loss through walls of the pond (Q_w is neglected, it is assumed that walls are well insulated), Q_{ru} is the solar radiation that is absorbed in the UCZ, Q_{ub} represents the heat transfer to the UCZ by conduction from the LCZ. The symbols Q_{uc}, Q_{ur} and Q_{ue} represent heat which is lost from the surface of the pond which is written as [36].

$$Q_{loses} = Q_{uc} + Q_{ur} + Q_{ue} \quad (3)$$

Here Q_{uc} is the loss by convection, Q_{ur} represents radiation heat loss, and Q_{ue} is the heat loss from the surface by evaporation. In Equation (2), Q_{load} is the heat extracted from the pond, the solar radiation which is absorbed in the LCZ is represented by Q_{rl} and finally, Q_g is the heat loss to the ground. Symbols T_{UCZ}, T_{LCZ} X_{UCZ} and X_{LCZ} are the temperature of the UCZ, the temperature of the LCZ, the thickness of the UCZ, and the thickness of the LCZ respectively. Values of $\rho_{UCZ}, c_{pUCZ}, \rho_{LCZ}$ and c_{pLCZ} are given in Sayer et al. [36]. The terms of Eqs. (1) and (2) ($Q_{ru}, Q_{ub}, Q_{uc}, Q_{ur}, Q_{ue}, Q_{rl}, Q_g$ and Q_{load}) are in W/m^2, they are given and calculated in Sayer et al. [36].

In their model [36] equations of heat transfer are solved using the MATLAB ode45 function and the results are validated by experimental data.

2.1.1. Effect of the UCZ

Thicknesses of the NCZ and the LCZ are set to be 1.25 and 1.5 m respectively while the depth of the UCZ is changed from 0.1 to 0.5 m with an interval of 0.1 m. Temperatures of the LCZ are plotted with time throughout a year for these proposed thicknesses as illustrated in Fig. 2.

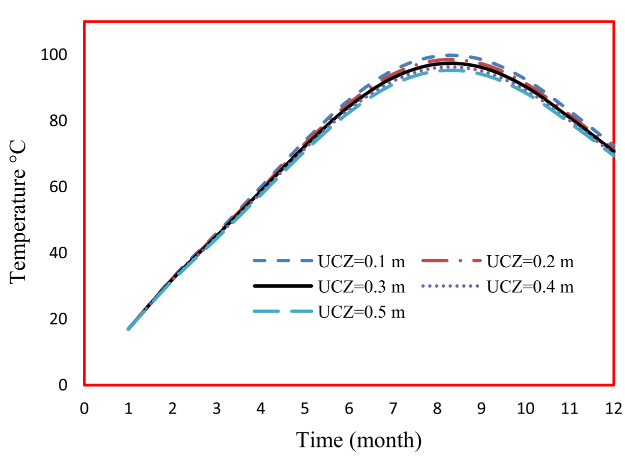

Fig. 2. The temperature profiles in the LCZ for various thicknesses of the UCZ (month 1 is January, initial temperatures of the UCZ and LCZ are 15 and 17 °C respectively).

Fig. 2 shows that temperature of the LCZ decreases as the thickness of the UCZ is increased. With 0.1 m thickness, the maximum temperature (August) is approximately 100 °C while it is 94 °C for a 0.5 m thickness. It is observed that with a further increase in the depth of the UCZ, there is a uniform decrease in the temperature of the LCZ. When the thickness is 0.2 m, the temperature in the LCZ is approximately 97 °C. Additional thickness to the UCZ can decrease the probability of layers mixing due to the effect of wind, but this increase in thickness will reduce the temperature in the LCZ and is an additional cost as the evaporated freshwater would need to be replaced on a regular basis. On the other hand, the thickness can be increased in arid and windy areas to avoid disturbance of the NCZ and subsequently the LCZ which might reduce the efficiency of the pond. Jaeferzadeh emphasised that the thickness of the UCZ should be kept as thin as possible [33]. He recommended a thickness of 0.2 m as this thickness not only should protect the NCZ below the UCZ, but also permits solar radiation to easily penetrate into the pond. Given the small effect (3 °C) of changing the thickness of the UCZ from 0.1 m to 0.2 m on the LCZ as well as the previously mentioned advantages of having a deeper UCZ in terms of the stability of salinity gradient, it is concluded that 0.2 m is the optimum thickness for the UCZ.

It is also observed that changing the thickness of the UCZ has an insignificant effect on its temperature. Table 1 shows temperatures of the UCZ during a year for different thicknesses (0.1, 0.2, 0.3, 0.4 and 0.5 m) as well as the corresponding ambient temperatures.

Table 1 illustrates that there is no significant change in the temperature of the UCZ with variation of its thickness throughout the year. It is also apparent that the temperatures of the UCZ for all the different thicknesses are lower than the ambient temperatures during the entire 12 months of the year.

2.1.2. Effect of the NCZ

Thickness of the NCZ is changed from 0.5 to 2.5 m with an interval of 0.5 m and simultaneously, thicknesses of the UCZ and LCZ are considered to be 0.2 and 1.5 m respectively. Temperature profiles of the LCZ are plotted against time (month) as shown in Fig. 3.

Fig. 3 illustrates that with a small NCZ thickness (0.5 m), the temperature of the LCZ is the lowest, maximum temperature (August) is around 80 °C and minimum temperature (December) is around 50 °C. Changing the thickness of the NCZ from 0.5 to 1 m increases the temperature of the LCZ significantly. Maximum and minimum temperatures increase by approximately 16 °C to be 96 °C and 66 °C respectively. Extending the thickness to 1.5 m adds approximately an extra 5 °C to the maximum temperature and around 8 °C to the minimum temperature (Fig. 3). Further increase of the thickness to 2 m enhances the maximum temperature by approximately 2 °C and shifts it from August to September. It also adds 6 °C to the minimum temperature. At 2.5 m thickness, it can be observed that there is a drop in the temperatures of the LCZ during most months of the year (Fig. 3). It is evident (Fig. 3) that any increase in the thickness of the NCZ past 2 m will likely be unprofitable, and it will reduce the efficiency of the pond. Therefore, the optimum thickness of the NCZ is 2 m. The financial implications of increasing the thickness of the NCZ from 1.5 m to 2 m must be evaluated in order to justify 2 m as the optimum. As mentioned, such increase only results in 2–6 °C rise in the temperature for 4–5 months of the year but leads to higher capital and operating expenditure.

These changes in temperature of the LCZ are due to the function of the NCZ as a transparent thermal insulator. Therefore, an increase in its thickness can improve the efficiency of the thermal insulation by reducing the upward heat loss from the LCZ. However, this increase in the thickness will influence the quantity of solar radiation that reaches the LCZ and will lead to a lowering of the temperature in this zone. German and Muntasser studied a

Table 1
The temperatures of the UCZ and the corresponding ambient temperatures in °C during a year with various thicknesses of the UCZ (month 1 is January).

Month	1	2	3	4	5	6	7	8	9	10	11	12
T_a	15	16.26	20.7	25.74	32.96	36.5	38.6	39.9	36.3	27.6	19.6	13.6
0.1	15	13.88	16.94	20.42	22.99	24.31	24.72	24.61	23.70	21.22	17.01	12.01
0.2	15	14.09	17.17	20.65	23.21	24.54	24.94	24.81	23.84	21.36	17.08	12.03
0.3	15	14.2	17.27	20.77	23.35	24.67	25.07	24.94	23.98	21.49	17.23	12.24
0.4	15	14.28	17.35	20.86	23.45	24.76	25.16	25.02	24.05	21.56	17.33	12.35
0.5	15	14.34	17.41	20.91	23.50	24.84	25.25	25.08	24.12	21.63	17.40	12.47

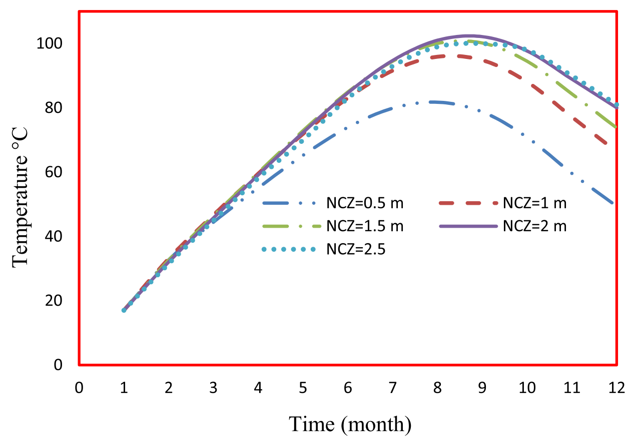

Fig. 3. The temperature profiles of the LCZ for various thicknesses of the NCZ, (month 1 is January, the initial temperatures of the UCZ and the LCZ are 15 and 17 °C respectively).

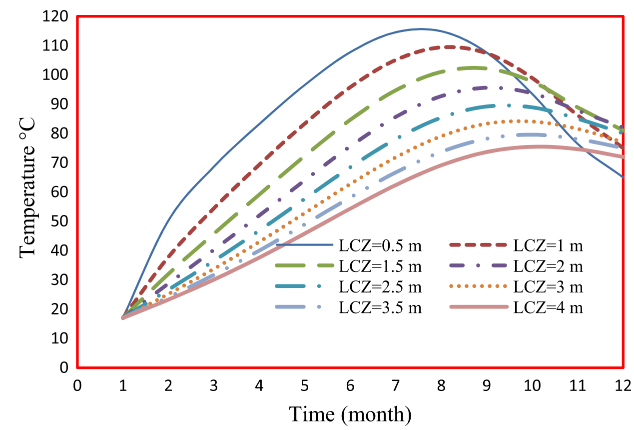

Fig. 4. The temperature profiles of the LCZ for various thicknesses of the LCZ, (month 1 is January, the initial temperatures of the UCZ and the LCZ are 15 and 17 °C respectively).

SGSP connected to a multi-effect desalination (MED) unit [37]. Based on their model, they suggested that the appropriate depth of the NCZ is 1.1 m. However, this depth is optimal for a solar pond coupled to a desalination unit as it requires the brine temperature of the LCZ to be around 60 °C. In 1995, Al-Jamal and Khashan suggested a mathematical model to include many parameters affecting the performance of the SGSP [38]. They suggested that the optimal depth of the NCZ is 1 m. Jaefarzadeh explains that the increase in the thickness of the NCZ can enhance the pond's performance (LCZ temperature) significantly [33]. He concluded that raising thickness of the NCZ from 0.5 to 1 m added a 30 °C increase in the maximum temperature of the LCZ while extension from 1 to 1.5 m and then 2 m rose the maximum temperature 15 °C and only 6.5 °C respectively. Additionally, it is observed that varying the thickness of the NCZ will result in no significant impact on the temperature of the UCZ.

2.1.3. Effect of the LCZ

In this part of the investigation, the influence of varying the thickness of the LCZ on its temperature and the UCZ temperatures is studied. Thickness of this zone (LCZ) is changed from 0.5 to 4 m with an interval of 0.5 m and meanwhile, the thicknesses of the UCZ and NCZ are kept at 0.2 and 2 m respectively. The results are illustrated in Fig. 4.

As shown in Fig. 4 that there is a decrease in the temperature of the LCZ as it becomes deeper. The highest temperatures are obtained with 0.5 m thickness whereas the lowest temperatures are at a 4 m thickness. Considering the thickness of 0.5 m, its maximum temperature (July) is about 115 °C (above boiling), and the minimum temperature is around 65 °C (the lowest minimum temperature). This behaviour is due to the variation of volume in the LCZ. For a thickness of 0.5 m, the water volume of the LCZ is small and consequently heat accumulation in the LCZ is increased noticeably. With 4 m thickness the temperature in the LCZ rises slowly to reach a maximum of 75 °C (in October) and the minimum temperature of 72 °C (in December). The previous explanation applies here again as the depth of 4 m results in the volume of the brine being 8 times higher than the volume with a 0.5 m thickness, and therefore the rise in the temperature will occur over a longer period of time. However, the heat capacity using a thickness of 4 m will be much higher which can be suitable for applications which require heat in relatively low temperatures of around 70

Table 2
Minimum and maximum temperatures in the LCZ for various thicknesses of this zone (UCZ = 0.2 m, NCZ = 2 m).

LCZ's thickness (meter)	Maximum temperature °C	Minimum temperature °C (December)	Observation
0.5	115 (July)	65	Temperature of the LCZ increases quickly, it reaches 69 °C in March and 83 °C in April, and heat extraction can commence early
1	109 (August)	75	Temperature of the LCZ reaches 70 ° in April
1.5	102 (September)	81	Temperature of the LCZ reaches 73 °C in May
2	96 (September)	82	Temperature of the LCZ reaches 64 °C in May and 76 °C in June
2.5	89 (September)	80	Temperature of the LCZ reaches 70 °C in June
3	84 (October)	77	Temperature of the LCZ reaches 63 °C in June and 72 °C in July
3.5	80 (October)	75	Temperature of the LCZ reaches 67 ° in July
4	75 (October)	72	Temperature of the LCZ reaches 62 °C in July and 70 °C in August

°C. Such applications will therefore benefit from increasing the depth of the LCZ rather than the surface area of the pond. Table 2 corresponds to the results shown in Fig. 4 to provide a better understanding of the impact of the LCZ thickness variation on the temperatures obtained in this zone.

Generally, each industrial application coupled to a solar pond requires heat at its own particular temperature which is different to other applications. For example, power generation requires approximately 80 °C for the turbine to operate with an organic fluid in the Rankine cycle. Hence, given the information in Table 2, if the pond is implemented for power generation purposes, the depth of the LCZ cannot be higher than 2 m to provide the suitable temperature. Some desalination processes (except thermal desalination) such as multi-effect desalination (MED) require heat at 60 °C to produce distilled water. In this case, thickness of the LCZ of 0.5–3 m can be employed efficiently since they can comfortably provide temperatures above 60 °C. In addition, depths of 3.5–4 m can also be implemented, but with lower rates of heat extraction. The reduction of the temperature in the LCZ with heat extraction will be investigated in this paper to study the relationship of loading with the depth of the LCZ.

Moreover, domestic heating requires heat at about 40 °C and that means all thicknesses mentioned in Table 2 can be used for this purpose. On the other hand, the capital cost and the availability of land to establish the pond are the major parameters to determine the optimum surface area and depth of the pond in terms of financial viability. Hence, the economic analysis that are required to be carried out to establish the financial viability of a solar pond will be specific to the location being considered since land prices and construction costs vary in different places.

Another observation that can be made from Table 2 is the warming up period of the pond for the various thicknesses of the LCZ. It is evident that for a 0.5 m thickness, heat extraction can efficiently commence in April or even in March for applications that require low temperatures. However, when the thickness increases, the pond takes longer to warm up. For example, for a 1 m thickness, the LCZ takes 4 months to reach 70 °C while with 2.5 m it reaches 70 °C in June requiring 6 months for warming up (Table 2).

From the above discussion, it can be concluded that the depth of the LCZ must correspond to the type of application the SGSP is coupled with. However, the thickness of 1–1.5 m is suitable for most applications. The rationale behind this claim is that firstly, the period of warm up is around 4 months. Secondly, the maximum temperature reaches 102–109 °C and the minimum temperatures are 75–81 °C. Further increase in thickness does not enhance the minimum temperature and causes a decrease in the maximum temperature. On the other hand, a higher thickness means increasing the heat capacity of the pond, but that requires a considerable addition to the capital cost of the SGSP. In 2005, Jaefarzadeh claimed that the appropriate thickness of the LCZ depends on the design conditions and the required operating temperatures [33]. German and Muntasser pointed out that the thickness of the LCZ can be 4 m [37]. However, this value is obtained as it results in the lowest surface area. The pond considered in their study was designed for desalination purposes by the MED process, and the operating temperature for this process is around 60 °C. Wang and Akbarzadeh concluded that depth of the LCZ should vary depending on the desired operating temperature, to accomplish the maximum efficiency [34]. Sayer et al. implied that the type of application coupled with the gel pond may determine the thickness of the LCZ, they claimed that this pond behaviour is similar to that of the SGSP [39].

In addition, varying the thickness of the LCZ has no considerable impact on the temperatures of the UCZ.

2.2. Loading

2.2.1. Loading with constant LCZ thickness

The behaviour of the SGSP is examined with heat extractions of 10, 20, 25, 30 and 40 W/m^2 load and these values are compared with the case of no load. Once again, the pond is considered to be in the city of Nasiriyah with a 1 m^2 surface area and with zonal thicknesses of 0.2, 2 and 1.5 m for the UCZ, NCZ and LCZ respectively. Thicknesses of the UCZ and the NCZ are the optimum and 1.5 m thickness for the LCZ is suitable for most applications (previously concluded). The obtained results are shown in Fig. 5.

As indicated in Fig. 5, heat extraction cannot take place for the first five months in order to allow the pond to warm up. The temperature of the LCZ reaches around 73 °C in May (depending on the application, heat extraction can be started in April because the temperature in the LCZ is around 60 °C in this month). It is also evident that the temperature in the LCZ varies depending on the load. With a 10 W/m^2 load, the temperature of the LCZ continuously rises to reach the maximum of 93 °C (about 9 °C below the case with no load) in August, and then decreases to be 69 °C (12 °C below the case of no load) in December. A similar behaviour is observed with a load of 20 W/m^2 but with lower values of maximum and minimum temperatures. With loads of 30 and 40 W/m^2, it is shown that there is a slight sudden decrease in temperatures during June. However, the temperature rises again for two month and then starts declining; in case of the 30 W/m^2 it decreases to around 47 °C and for 40 W/m^2 it is around 35 °C. The reason for this behaviour is that when heat is extracted from the pond it causes a reduction in the temperature, but with time the incident radiation on the pond substitutes the heat loss as it rises towards the middle of the summer. Consequently, a slight increase in the temperature reappears.

To elaborate further on the loading impact, the seasonal variation of the temperature in the LCZ with loading over two years has been studied and the results are illustrated in Fig. 6.

As mentioned previously for the heat extraction over one year, extraction can start in May. The temperature rises slowly in the second year as a consequence of solar radiation absorption even with continuous heat extraction. It is highlighted by Fig. 6 that heat extraction should be stopped after a period and this period depends on the load and also on the type of application. For example, in the case of 10 W/m^2, the minimum temperature of the LCZ is around 69 °C in the end of the first year and it increases again in the second year. That means if this load (10 W/m^2) is implemented for domestic heating or certain types of desalination that require

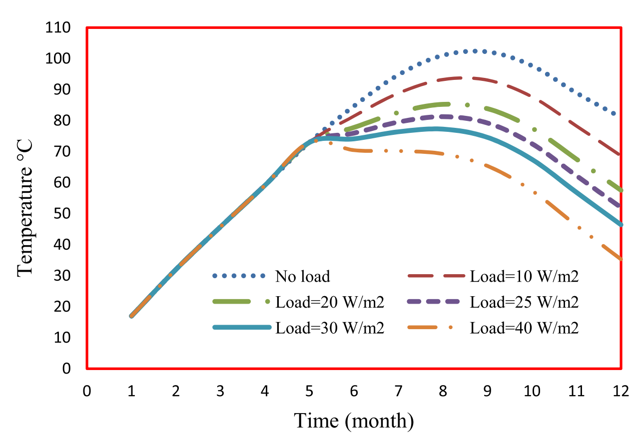

Fig. 5. The behaviour of the salinity gradient solar pond during one year with different loads and no load (month 1 is January, UCZ = 0.2, NCZ = 2 and LCZ = 1.5 m, load in W/m^2).

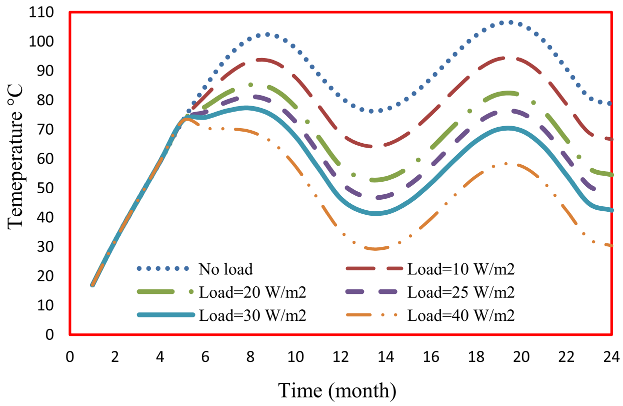

Fig. 6. The behaviour of the salinity gradient solar pond over two years with different loads and no load (month 1 is January, UCZ = 0.2, NCZ = 2 and LCZ = 1.5 m, load in w/m^2).

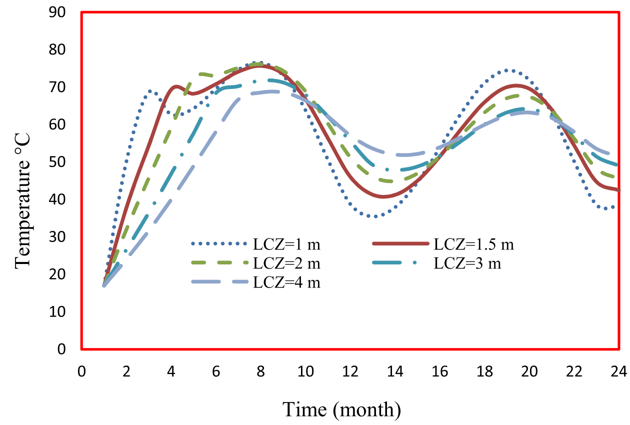

Fig. 8. The temperature of the LCZ with various thicknesses and 30 W/m^2 load over two years (month 1 is January and thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively).

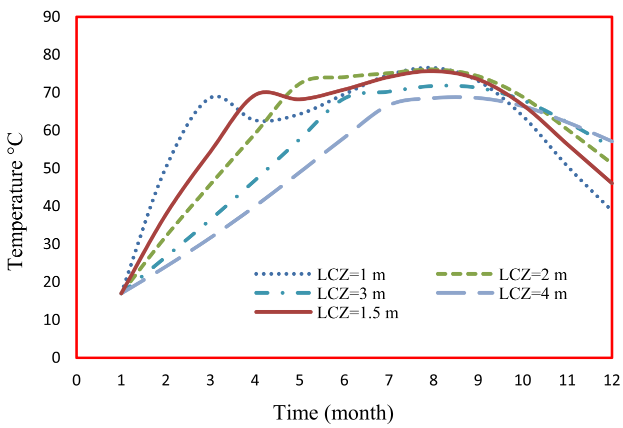

Fig. 7. The temperature of the LCZ with various thicknesses and 30 W/m^2 load for one year (month 1 is January and thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively).

60 °C, there is no need to stop heat extraction. However, if the desired temperature is higher than 60 °C, heat extraction must be stopped in December and started again in February. The same explanation can be applied to the other loads. It should be noted that these procedures would only apply to a SGSP with zonal thicknesses of 0.2, 2 and 1.5 m for the UCZ, NCZ and LCZ respectively).

The behaviour of the UCZ is totally different. It is observed that there is no significant impact on temperatures of the UCZ for all loads even over two years.

2.2.2. Loading with different thicknesses of the LCZ

As previously observed, the thickness of the LCZ has an effect on its temperature because changing the thickness will change the capacity of the zone and consequently its temperature. Therefore, the behaviour of the pond with constant load (30 W/m^2) and various depths of the LCZ are investigated. The results are demonstrated in Fig. 7.

Table 3
Variation of the LCZ thickness and the load throughout one year.

In this table, it is considered that thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively, and depth of the LCZ is changed from 0.5 to 4 m

Total depth m	LCZ m	Max. temperature of the LCZ °C (no load)	Load W/m^2	Max. temperature after heat extraction °C	T_{LCZ} in December (after heat extraction)	Comment
2.7	0.5	115 (July)	10	103	53	Heat extraction can be started from March. In April the temperature in the LCZ is 84 °C and in May 89 °C
			20	91	41	
			30	80	28	
			40	69	16	
			50	57	5	
3.2	1	109 (Aug)	10	100	63	The temperature of the LCZ in April is 70 °C. It can be used for power generation and other applications that require low temperatures
			20	90	51	
			30	80	40	
			40	71	27	
			50	61	16	
3.7	1.5	102 (Sep)	10	93	69	In May, the temperature of the LCZ reaches 71 °C, and it can be used for power generation with low rates of heat extraction taking into account the time to warm up. It can also be used for domestic heating continuously with loads of 10, 20, 30 W/m^2 and with a short stoppage with 40 and 50 W/m^2
			20	84	58	
			30	74	46	
			40	65	35	
			50	56	24	
4.2	2	96 (Sep)	10	90	71	The temperature of the LCZ reaches around 76 °C in June, and it can be used for different applications with some rates of heat extraction
			20	82	62	
			30	78	52	
			40	69	42	
			50	62	33	

Table 3 (*continued*)

In this table, it is considered that thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively, and depth of the LCZ is changed from 0.5 to 4 m

Total depth m	LCZ m	Max. temperature of the LCZ °C (no load)	Load W/m²	Max. temperature after heat extraction °C	T_{LCZ} in December (after heat extraction)	Comment
4.7	2.5	89 (Sep)	10	83	71	Similar to the LCZ depth of 2 m. The temperature in June reaches around 70 °C. It cannot be used for power generation
			20	78	62	
			30	72	54	
			40	66	45	
			50	60	36	
5.2	3	84 (Oct)	10	79	71	The temperature in July reaches around 69 °C; it is suitable for desalination or domestic heating because it can provide heat for an extended period and a short period of warming up is needed. It cannot be used for applications that require temperatures higher than 70 °C
			20	74	64	
			30	70	57	
			40	64	49	
			50	59	42	
5.7	3.5	80 (Oct)	10	75	70	Similar to the LCZ depth of 3 m, in July the temperature of the LCZ is 67 °C. The pond can be implemented for applications with low temperatures between 40 and 60 °C, and it can supply heat continuously for all loads with a short period of warming up in the case of 40 and 50 W/m²
			20	71	62	
			30	66	56	
			40	62	50	
			50	57	43	
6.2	4	75 (Oct)	10	72	67	The temperature in July reaches 62 °C; this depth is suitable for applications requiring low temperatures from 40 to 60 °C with the continuous and low rate of heat extractions (10–30 W/m²) and with a short period to warm up for loads 40–50 W/m²
			20	68	62	
			30	64	55	
			40	60	50	
			50	56	44	

Fig. 7 demonstrates that with a 1 m thickness, heat extraction (30 W/m²) can start from March when the temperature in the LCZ is 69 °C. It is also indicated that due to the small heat capacity of the LCZ there is a decline in its temperature when heat extraction begins and it increases again after heat accumulation. Furthermore, the temperature in December reaches 39 °C. With a thickness of 1.5 m, heat extraction (30 W/m²) starts in April with the similar temperature of the LCZ at 69 °C and the temperature in December reaches 46 °C. With a 2 m thickness, heat extraction (30 W/m²) starts in May (temperature of the LCZ is 72 °C) and that means 5 months are dedicated to warming up. The temperature in December is around 51 °C. With thicknesses 3 and 4 m, heat extraction (30 W/m²) can commence in June and July when the temperatures of the LCZ are 68 and 67 °C respectively. In December, temperatures in the LCZ for both thicknesses are around 55 and 57 °C respectively.

The same procedure is carried out for the results over two years as shown in Fig. 8.

Fig. 8 clearly illustrates that for thicknesses of 1, 1.5 and 2 m, heat extraction has to be stopped from November to February (around 4 months) if the required temperature is above 50 °C. Moreover, heat extraction should be stopped from October to February if the temperature is to be supplied at above 60 °C. When the thickness is 3 or 4 m, heat extraction can be continued to December and then stopped to February (3 months) if the desired temperature is above 50 °C (suitable for domestic heating and some industrial applications such as dairy and food industries). However, if the pond is to be implemented for yielding temperatures above 60 °C, it is inevitable to stop heat extraction in October to February. It is shown in Figs. 7 and 8 that the purpose of construction of the pond will have a vital role in the determination of the optimum thickness of the LCZ. Based on these results Table 3 is provided.

3. Conclusions

In this paper, the optimum thickness of the three zones present in a SGSP has been examined. A model of Sayer et al. [36] was utilised in the temperature calculations in the UCZ and the LCZ. The results show that the optimum thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively. On the other hand, thickness of the LCZ depends mainly on the type of the application coupled with the SGSP. Thickness variation of the UCZ and NCZ has a considerable impact on the LCZ temperature. Simultaneously, the thickness variation of the NCZ and the LCZ on the temperature of the UCZ is minimal. The results illustrate that the temperature of the LCZ varies with the heat extraction rate and its thickness. For applications that require low-grade heat in a range of 40–60 °C, there are possible cost-effective benefits to constructing a deeper pond by increasing the thickness of the LCZ rather than its surface area. However, construction costs and land prices must be assessed. Therefore, comprehensive financial studies carried out for the particular application of solar ponds are recommended to evaluate further the optimum thicknesses of the three zones in a SGSP introduced in this study.

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