



Research Paper

New comprehensive investigation on the feasibility of the gel solar pond, and a comparison with the salinity gradient solar pond

Asaad H. Sayer^{a,b,*}, Hazim Al-Hussaini^a, Alasdair N. Campbell^a

^a Department of Chemical and Process Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, GU2 7XH, UK

^b University of Thi-Qar, College of Science, Chemistry Department, Thi-Qar, Iraq

HIGHLIGHTS

- The feasibility of the gel solar pond has been investigated.
- The temperature of the LCZ and the UCZ has been calculated.
- The cost of the gel pond was calculated and compared with that of the salinity gradient solar pond (SGSP).
- A gel pond normally costs more than a SGSP.
- Gel ponds can be seen as a viable alternative to SGSPs only if cheap and environmentally friendly polymers are used.

ARTICLE INFO

Article history:

Received 31 January 2017

Revised 8 November 2017

Accepted 11 November 2017

Available online 13 November 2017

Keywords:

Gel ponds

Solar ponds

Solar energy

ABSTRACT

Solar energy is increasingly being exploited to supply energy for many purposes. This paper explores the feasibility of gel solar ponds as a source of renewables, using theoretical evaluation. This could be of critical future utilization in areas such as desalination, where the gel solar pond could in effect be a means to deliver fresh water in the Middle East and other regions where water scarcity is predicted to become an increasingly critical issue to resolve. This study explores all aspects of the gel solar pond's functioning, including optimal thicknesses for its different layers, and explores its strengths and weaknesses. In this study; temperature profiles in the upper convective zone (UCZ) and lower convective zone (LCZ) of a gel pond are investigated. The impact of the thickness of the pond's layers on the temperatures of these zones was also investigated. The cost of the gel pond was calculated and compared with that of the salinity gradient solar pond (SGSP) for a particular application, the multi-effect desalination (MED), which is frequently used to desalinate sea water. The results showed that the gel pond could supply thermal energy to applications requiring low-grade temperatures, and that temperatures in the LCZ of the gel pond could reach values similar to those achieved in the SGSP. Varying the thicknesses of the gel layer and the LCZ affects the temperature of the storage zone. The optimal thickness of the upper water layer and the gel layer was found to be 0.05 and 0.9 m respectively, while the optimal thickness of the storage zone depends on the particular application for which the pond is being used in each case. The results also show that a gel pond normally costs more than a SGSP. This study illustrates that gel solar ponds can offer solutions to some of the challenges posed by the SGSP; however, difficulties relating to cost and labour decrease their potential exploitation. Gel ponds can be seen as a viable alternative to SGSPs only if cheap and environmentally friendly polymers are used to form the gel layer.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Renewables are the solution to many challenges facing the world in the field of energy. Investment in these energies would

minimise reliance on traditional fuels and consequently decrease the impact on the environment. Solar energy is one of the most significant types of renewables, and has been widely and globally exploited in recent years. Among the different applications of solar energy is the solar pond [1–7].

A solar pond is a body of water which can collect and store solar energy. There are several types of solar ponds. These ponds can be divided into two categories: convective and non-convective. A shallow solar pond is the typical type of the convective solar pond:

* Corresponding author at: Department of Chemical and Process Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, GU2 7XH, UK.

E-mail addresses: a.h.sayer@surrey.ac.uk, alimmz5@yahoo.com (A.H. Sayer), h.al-hussaini@surrey.ac.uk (H. Al-Hussaini), a.n.campbell@surrey.ac.uk (A.N. Campbell).

a polyacrylamide polymer layer has been suggested instead of the NCZ [24].

The first gel pond was constructed at New Mexico University with a surface area of 18 m². In this pond, the gel layer floats on the storage zone (LCZ) and works as an insulator, much like the non-convective zone (NCZ). Salt concentration in the LCZ beneath the gel can be 2–7% or higher [25]. A thin water layer of about 5 cm was used to catch dust and dirt, and it is evident that the upper water layer is small when compared with the 25–50 cm (UCZ) freshwater layer in the SGSP [23]. Yogev and Mahlab [26] implied that the gel used in the gel pond must be stable at high temperatures, even at 100 °C or greater. They pointed out that for such a large gel pond, such as 10,000 m², the gel solution required to build a 50 cm thick layer is approximately 5000 m³. As a consequence of the high polymer cost, the insulating layer needs to be as thin as possible to reduce the cost of the pond.

Wilkins and Michael [27] identified that polyacrylamide polymer has a relatively small molecular weight and can be utilised to construct the gel layer. The prepared polymer floated on the salt water surface and insulated the storage layer (LCZ). The polymer solution could be added to the salt water with stirring because there is no gradient zone to be disturbed when mixing occurs. Economically, Garg [28] considered the gel pond not competitive to the SGSP.

Matsumoto et al. [29] claimed that the insulating layer in salinity gradient solar ponds is constructed from salt water and the density of layers varies with height. Therefore, convection phenomena will be prevented by the gradient layer. They introduced several difficulties for the application of the SGSP; it is a source of pollution and maintaining the concentration gradient is not simple. Consequently, they consider the gel pond as the best alternative to the SGSP. A polymer of SPR-402 was tested using a range of thicknesses (1–15 cm) and of concentrations (0.1–0.5 wt%). It was found that SPR-402 is a suitable polymer to act as an insulator for the lower convective zone (LCZ).

Sozhan et al. [30] considered the gel pond to be an inventive method to eliminate the challenges of the conventional gradient solar pond, with low maintenance requirements. A polymer gel (Carbowax) has been used to construct the insulating layer (gel layer) since it has some positive properties. It is claimed that Carbowax has suitable characteristics such as solubility, uniformity, transitivity, cost and resistance to corrosion. A solution of 3–8% NaCl was used to construct the storage zone (LCZ). Several specifications for a suitable polymer were mentioned by the researchers: it should have high viscosity, and be inexpensive, inert and non-toxic. It should also be soluble in cold water before polymerisation and insoluble afterwards: if it dissolves in water after polymerisation, the polymer layer might disappear after a period. Its stability should be high physically and chemically, and non-opaque with high solar insolation absorptivity. A glass pool with dimensions 0.5 × 0.5 × 0.5 m was used as the small experimental gel solar pond in the study [30]. The walls and bottom of the pool were insulated using two insulators: sawdust and polystyrene. Carbowax was dissolved in cold water. Different concentrations were used to form a gel layer with a thickness of 1 cm. The transmissivity of 1 cm of the polymer was measured as 97.43%. It was suggested that the Carbowax polymer was promising because there was no reaction with the salt solution of sodium chloride (NaCl). The average temperature difference between the storage and gel zones was 10 °C. This is an indication of the future potential of the gel pond. However, the thickness of the gel layer was small at only 1 cm; consequently, heat transfer by conduction and convection will be high, and this will affect the performance of the pond.

The gel solar pond has attracted much less interest than the SGSP over the past 35 years, and there is a lack of scientific research on this subject. To address the gap, this paper seeks to

investigate this type of solar pond and its feasibility, using theoretical evaluation. Many issues have been considered, such as performance, cost (the actual and theoretical), maintenance and the availability of materials. These factors have been compared with the SGSP to draw fully researched conclusions about the feasibility of the gel pond, and to assess whether it can compete with the SGSP.

2. Previous theoretical models

In 1981, Wilkins et al. [31] suggested a one-dimensional model to predict the performance of the gel pond. Many assumptions were adopted in this model: (i) that there is no edge effect and no fresh water layer on top of the gel layer, (ii) that there is no heat loss to the ground and (iii) that the temperature gradient in the pond is linear.

In 1982, Wilkins et al. [32] developed a steady state model to describe the behaviour of the gel pond. Temperature profiles in the gel pond were computed. Meanwhile, temperatures in the NCZ of the SGSP were calculated to compare them with the temperatures in the gel pond. Heat loss from the surface of both the gel pond and the SGSP was also calculated. It was concluded [32] that heat loss from the surface of the SGSP is higher than that from the gel pond. Wilkins et al. (1986) [22] used three different analytical models which previously described the thermal behaviour of the SGSP to describe the gel pond. A slight modification was made to these models to make them suitable for the gel pond description. These models were Kooi's model [33], Wang and Akbarzadeh's model [34] and Bansal and Kaushik's model [35]. Table 1 shows some properties of polyacrylamide polymer which was suggested to construct the gel layer of the gel solar pond.

In recent years, most research has focused on the SGSP and many new models have been suggested for analysis of this type of solar pond.

3. Proposed model

To calculate temperatures in the UCZ and LCZ in the gel pond, the model developed by Sayer et al. [36] has been used. It is proposed that the pond has a surface area of 1 m² and has vertical walls. It is comprised of three layers: the storage layer (LCZ), a gel layer and finally a water layer to protect the gel layer from the environment. A cross-section of the proposed gel pond is illustrated in Fig. 1.

The process began with establishing a heat balance of the upper water layer (UCZ); the process is demonstrated in Fig. 2.

The energy conservation equation for this layer can be written as:

$$M_u C_p \frac{dT_u}{dt} = Q_{r_{in}} + Q_b - Q_{o1} - Q_{uc} - Q_{ur} - Q_{ue} - Q_w \quad (1)$$

$$M_u = \rho_u v_u \quad (2)$$

$$M_u = \rho_u h_{UCZ} A_u \quad (3)$$

Table 1
Some physical properties of polyacrylamide [27].

| Polyacrylamide Homopolymer | |
|----------------------------|--------------|
| Appearance | White powder |
| Viscosity 0.1% solution | 1.8–2.2 cps |
| Volatiles % by weight | 14 maximum |
| pH 1% solution | 6–6.5 |

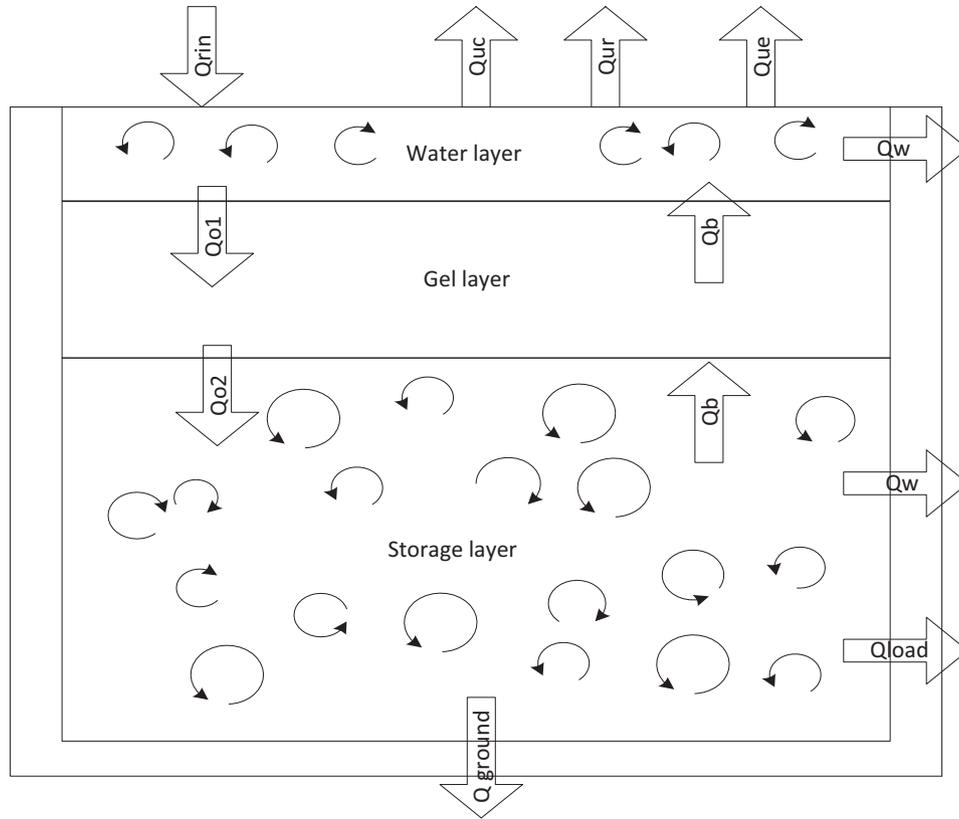


Fig. 1. Schematic of the suggested gel pond.

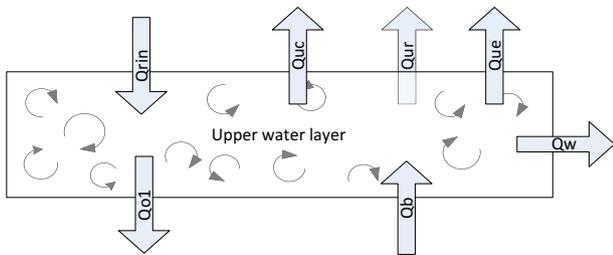


Fig. 2. Heat flows through the UCZ of the gel pond.

$$\frac{dT_u}{dt} = \frac{1}{M_u C_{p_u}} [Q_{r_{in}} + Q_b - Q_{o1} - Q_{uc} - Q_{ur} - Q_{ue}] - \frac{1}{M_u C_{p_u}} [Q_w] \quad (4)$$

where M_u is the mass of the UCZ in kg, C_{p_u} is the heat capacity of the UCZ in J/kg K, ρ_u is the density of the UCZ in kg/m³, v_u is the volume of the UCZ in m³. The symbol $Q_{r_{in}}$ represents the penetrated solar radiation to the UCZ of the pond (data from NASA is considered to calculate this term); and Q_{o1} is the solar radiation coming out of the UCZ. The term Q_{o1} is calculated using Brayant and Colbeck's formula [37] as below:

$$Q_{o1} = H[0.36 - 0.08 \ln h_{UCZ}] \quad (5)$$

where H is the solar insolation on the surface of the pond in W/m², and h_{UCZ} is the depth of the UCZ in meters. The terms of Eq. (4) Q_b , Q_{uc} , Q_{ur} , Q_{ue} are respectively the conduction heat transfer to the UCZ, the convection heat loss from the surface, the radiation heat loss from the surface, and the evaporation heat loss, they are in W/m². They are given by the following equations (Sayer et al. [36]) as follows:

$$Q_b = U_{ge} A_u [T_L - T_u] \quad (6)$$

Here, A_u is the surface area of the UCZ, T_u and T_L are the temperatures of the UCZ and the LCZ respectively, and U_{ge} is the overall heat transfer coefficient in the gel pond which can be computed as:

$$U_{ge} = \frac{1}{\frac{1}{h_1} + \frac{X_{ge}}{K_{ge}} + \frac{1}{h_2}} \quad (7)$$

Eq. (6) will be:

$$Q_b = \frac{A_u [T_L - T_u]}{\frac{1}{h_1} + \frac{X_{ge}}{K_{ge}} + \frac{1}{h_2}} \quad (8)$$

where h_1 and h_2 are respectively the convective heat transfer coefficient between the gel layer and the UCZ, and between the LCZ and the gel layer. Their values are 56.58 and 48.279 W/m² K respectively [35]; X_{ge} is the thickness of the gel layer in meters, and K_{ge} is the thermal conductivity of the gel layer in W/m K.

The convection heat loss is computed as:

$$Q_{uc} = h_c A_u [T_u - T_a] \quad (9)$$

where T_a is the average ambient temperature in °C, h_c is the convective heat transfer coefficient from the surface of the UCZ to the air in W/m² K and is calculated using a formula which was introduced by McAdams [38] as:

$$h_c = 5.7 + 3.8 v \quad (10)$$

where v is the monthly average wind speed.

Radiation heat loss is computed as:

$$Q_{ur} = \sigma A_u (T_u^4 - T_k^4) \quad (11)$$

where σ is the Stefan-Boltzmann constant = 5.673 × 10⁻⁸ W/m² K⁴, ϵ is the emissivity of water = 0.83 [45], and T_k is the sky temperature in °C. It is computed as:

$$T_k = 0.0552T_a^{1.5} \quad (12)$$

The evaporation heat loss is calculated by Kishore and Joshi [9] as:

$$Q_{ue} = \left\{ \frac{[\lambda h_c (p_u - p_a)]}{[(1.6C_s p_{atm})]} \right\} A_u \quad (13)$$

Here λ is the latent heat of vaporisation in kJ/kg, p_u is the water vapour pressure at the upper layer temperature, p_a is the partial pressure of water vapour in the ambient temperature, p_{atm} is the atmospheric pressure, all pressures are in mmHg, and C_s is the humid heat capacity of air in kJ/kg K. All the parameters of Eq. (13) are given in Sayer et al. [36]. The walls of the gel pond are considered to be well insulated, and therefore heat loss from them (Q_w) is neglected. Eq. (4), which represents energy conservation in the UCZ, will be rewritten as:

$$\begin{aligned} \frac{dT_u}{dt} = \frac{A_u}{M_u C_{p_u}} \left[Q_{r_{in}} + \frac{[T_L - T_u]}{\frac{1}{h_1} + \frac{x_{ge}}{k_{ge}} + \frac{1}{h_2}} - H[0.36 - 0.08 \ln h_{UCZ}] \right. \\ \left. - \left\{ (5.7 + 3.8\nu)[T_u - T_a] \right\} - 4.708 \times 10^{-8} \{ T_u^4 - [0.0552(T_a)^{1.5}]^4 \} \right. \\ \left. - \frac{[\lambda h_c (p_u - p_a)]}{[(1.6C_s p_{atm})]} \right] \quad (14) \end{aligned}$$

The heat balance of the storage zone (LCZ) is shown in Fig. 3.

The heat conservation equation of the LCZ can be written as follows:

$$M_l C_{p_l} \frac{dT_L}{dt} = Q_{o2} - Q_b - Q_{ground} - Q_{load} - Q_w \quad (15)$$

$$M_l = \rho_l v_l \quad (16)$$

$$\frac{dT_L}{dt} = \frac{1}{M_l C_{p_l}} [Q_{o2} - Q_b - Q_{ground} - Q_{load}] - \frac{1}{M_l C_{p_l}} [Q_w] \quad (17)$$

where M_l is the mass of the LCZ in kg, C_{p_l} is the heat capacity of the LCZ in J/kg K, v_l is the volume of the LCZ in m^3 , Q_{ground} is the heat loss to the ground in W/m^2 , and Q_{load} represents the heat extracted from the LCZ in W/m^2 . The parameter Q_{o2} represents the solar radiation which enters and is absorbed into the LCZ. In 1986, Wilkins et al. [22] claimed that the transmissivity of 15–40 cm gel thickness is very close to the transmissivity of 10–60 cm fresh and 16% salt water. Accordingly, Q_{o2} can be calculated using Eq. (5) as follows:

$$Q_{o2} = H[0.36 - 0.08 \ln(h_{UCZ} + x_{ge})] \quad (18)$$

where x_{ge} is the thickness of the gel layer in meters.

$Q_w = 0$ (walls are well insulated)

Eq. (17) can be rewritten as:

$$\frac{dT_L}{dt} = \frac{1}{M_l C_{p_l}} [Q_{o2} - Q_b - Q_{ground} - Q_{load}] \quad (19)$$

The term Q_{ground} is calculated [36] as:

$$Q_{ground} = \frac{A_b (T_L - T_g)}{\frac{1}{h_3} + \frac{x_g}{k_g} + \frac{1}{h_4}} \quad (20)$$

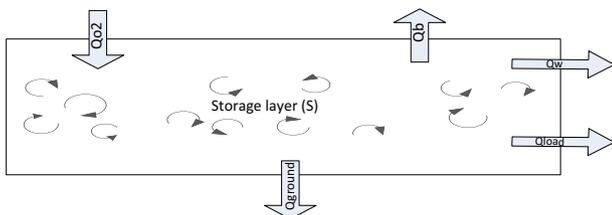


Fig. 3. Heat flows through the LCZ of the gel pond.

where T_g is the temperature of the water table under the pond and A_b is the area of the bottom surface of the pond. Symbols of h_3 and h_4 represent the convective heat transfer coefficient at the boundary between the LCZ and the bottom surface of the pond and the convective heat transfer coefficient at the surface of the ground water sink in $W/m^2 K$ respectively. Their values are given in Sayer et al. [36]. The distance of the water table from the bottom of the pond in meters, it depends on the pond's location, and it is shown by x_g , and k_g is the thermal conductivity of the soil under the pond in $W/m K$.

The case of no load is considered, so the term Q_{load} in Eq. (19) is neglected and it can be re-written as:

$$\begin{aligned} \frac{dT_L}{dt} = \frac{A_l}{M_l C_{p_l}} \left[H[0.36 - 0.08 \ln(h_{UCZ} + x_{ge})] - \frac{[T_L - T_u]}{\frac{1}{h_1} + \frac{x_{ge}}{k_{ge}} + \frac{1}{h_2}} \right] \\ - \frac{A_b (T_L - T_g)}{\frac{1}{h_3} + \frac{x_g}{k_g} + \frac{1}{h_4}} \quad (21) \end{aligned}$$

4. Results and discussions

Eqs. (14) and (21) have been solved using the model developed by Sayer et al. [36]; they utilised the ode45 MATLAB function to solve the first order ordinary differential equations. These two equations can be solved using initial values to the T_L and T_u ; these initial values depend on the area of the study and the time when the pond commences working. The values of the constants which are used in the model (ρ_u , ρ_l , C_{p_u} , C_{p_l} , h_1 , h_2 , h_3 , h_4 , and k_g) are given in Sayer et al. [36].

4.1. Validation of the model for the gel pond

To verify the model for the gel pond, the results are compared with the available experimental results of the Albuquerque pond which was constructed at New Mexico University in 1981. The pond had a diameter of 4.8 m and a depth of 1.22 m [31]. The physical properties of the gel used are listed in Table 2.

The ground thermal conductivity under the pond was considered to be 1.279 $W/m K$ and the ground temperature at a depth of 5 m was considered to be equal to the yearly average ambient temperature, and it was 14.1 °C [22]. The climatic conditions of the Albuquerque City are given in the Table 3.

The available published experimental data was for the temperature in the LCZ of the Albuquerque gel pond for three weeks (15 March–6 April 1981), with a gel thickness of 5 cm. The properties of the gel are given in Table 2 (Wilkins et al. [31]). The comparison is illustrated in Fig. 4.

Fig. 4 shows that the agreement with the experimental results is reasonable. Wilkins and Lee [23] pointed out that the Albuquerque gel pond reached a maximum temperature of 57 °C with a 0.25 m gel layer and a thickness of 0.92 m for the LCZ. They stated that the performance of the pond was acceptable because its size was small. Moreover, they reported three temperatures at different times while the pond was warming up; these temperatures are illustrated in Table 4.

The temperatures in Table 4 are also compared with the theoretical temperatures of the LCZ which were calculated by the

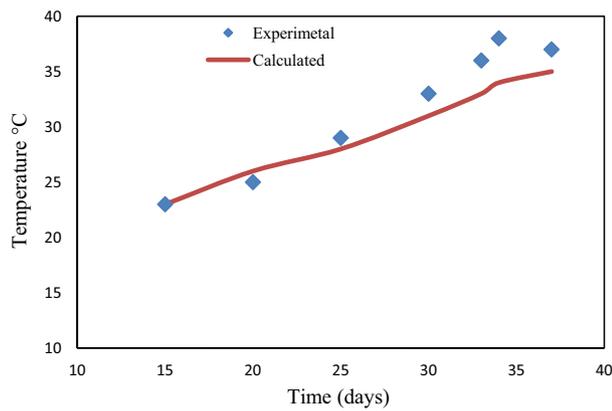
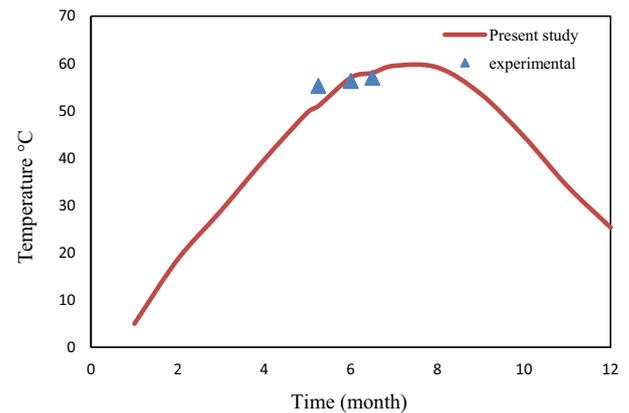
Table 2
Physical properties of the gel used in the Albuquerque pond [31].

| Specific heat kJ/kg K | Density Kg/m ³ | Thermal conductivity W/m K | Viscosity at 25 °C (cp) |
|-----------------------|---------------------------|----------------------------|-------------------------|
| 4.284 | 1166 | 0.556 | 3×10^4 |

Table 3

The climatic conditions of the Albuquerque City.

| Month | Solar radiation measured MJ/m ² .month (Wilkins et al. [22]) | Ambient temperature measured °C (Wilkins et al. [22]) | Relative humidity %(eosweb. larc.nasa.gov) [40] | Wind speed m/s (eosweb. larc.nasa.gov) [40] |
|-----------|---|---|---|---|
| January | 347.3 | 2 | 70 | 3.9 |
| February | 456.19 | 4.8 | 66.8 | 4.1 |
| March | 601.3 | 8 | 64.3 | 4.4 |
| April | 759.4 | 13.6 | 55.8 | 4.4 |
| May | 865.7 | 18.8 | 53 | 4.1 |
| June | 912.3 | 24 | 55.2 | 4 |
| July | 847.5 | 26.5 | 62.7 | 3.7 |
| August | 780.1 | 25 | 69.7 | 3.7 |
| September | 671.3 | 21.5 | 73.8 | 3.8 |
| October | 526.1 | 15 | 76.2 | 3.8 |
| November | 386.2 | 7.3 | 72.8 | 4 |
| December | 316.2 | 2.7 | 69.5 | 4 |
| Average | 622.4 | 14.1 | 65.8 | 4 |

**Fig. 4.** A comparison between the present calculation and the experimental data of Wilkins et al. [31] (from 15 of March to 6 of April 1981).**Fig. 5.** The comparison of the calculated temperature distribution of the LCZ for the Albuquerque gel pond with three experimental temperatures (depths of the gel pond are 0.05, 0.25 and 0.92 m for the UCZ, gel layer and the LCZ respectively [23]).**Table 4**

Changes in temperature of the Albuquerque gel pond [23].

| Date | 7/5/1981 | 31/5/1981 | 14/6/1981 |
|----------------|----------|-----------|--------------|
| Temperature °C | 55.25 | 56.31 | 57 (maximum) |

model for a one-year period. According to the model used, the maximum temperature was around 59 °C in July (using the same depths); the comparison is demonstrated in Fig. 5.

It is evident from Figs. 4 and 5 that there is a good agreement between the experimental data and the theoretical results of the current study. The maximum theoretical temperature of the LCZ (59 °C) is not far from the maximum experimental temperature (57 °C). Consequently, the model of Sayer et al. [36] can be used to describe the temperature behaviours of the UCZ and the LCZ in the gel pond.

4.2. Temperature distributions in the suggested model gel pond

The temperatures of both the UCZ and the LCZ are calculated, plotted against time. The results are demonstrated in Fig. 6 for a proposed pond with dimensions of 1 × 1 × 1.5 m and depths of 0.05, 0.35 and 1.1 m for the UCZ, gel layer and LCZ respectively. The pond is considered to be in the city of Nasiriyah in Iraq, thermal conductivity of the gel (k_{ge}) is taken as 0.556 W/m K [31], thermal conductivity of the ground (k_g) as 2.15 and temperature of the ground (T_g) as 23.1 °C [39]. The climatic conditions of Nasiriyah City are given in Table 5.

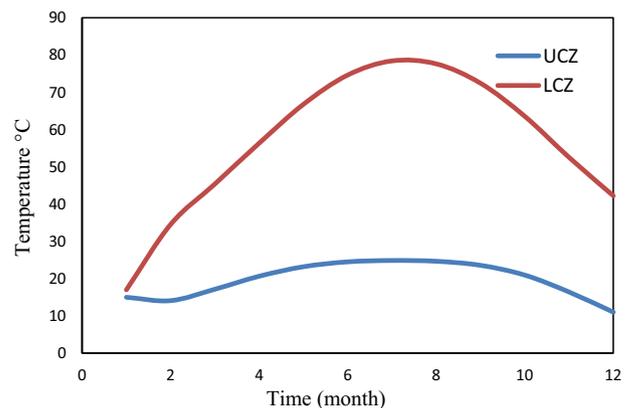
**Fig. 6.** Temperature distributions of both the UCZ and the LCZ of the gel pond in Nasiriyah city (initial temperature for the UCZ and the LCZ are 15 and 17 °C respectively).

Fig. 6 shows that the temperature of the LCZ increases progressively with time to reach its maximum in July (78 °C). The temperature then decreases to around 42 °C in December. It can be concluded from Fig. 6 that the gel pond (with thicknesses of 0.05, 0.35 and 1.1 m for the UCZ, gel layer and LCZ respectively) can reach a maximum temperature of more than 70 °C. This temperature might change by varying the thickness of the pond's layers, and that will be discussed in the following sections of this paper.

Table 5
Climatic conditions of Nasiriyah City (eosweb.larc.nasa.gov, 2015 [40]).

| Month | Solar radiation MJ/m ² .month | Ambient temp °C | Relative humidity % | Wind speed m/s |
|-----------|--|-----------------|---------------------|----------------|
| January | 349.92 | 11.7 | 57.3 | 3.77 |
| February | 451.44 | 13.6 | 46.4 | 4.08 |
| March | 527.04 | 18.3 | 38.5 | 4.42 |
| April | 608.04 | 25.1 | 29.9 | 4.57 |
| May | 717.12 | 31.3 | 20.7 | 4.87 |
| June | 825.12 | 35.3 | 15.5 | 5.16 |
| July | 784.08 | 37.4 | 15.5 | 4.83 |
| August | 741.96 | 37.1 | 16.5 | 4.7 |
| September | 624.24 | 33.3 | 19.4 | 4.38 |
| October | 448.2 | 27.6 | 28.6 | 4.16 |
| November | 334.8 | 19.6 | 43.4 | 3.85 |
| December | 304.56 | 13.6 | 53.7 | 3.82 |
| Average | 559.44 | 25.4 | 32.1 | 4.38 |

4.3. Effect of the layer thicknesses of the gel pond

4.3.1. Effect of the thickness of the UCZ

The depth of the UCZ is considered at 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 m, while the thickness of the gel layer and the LCZ are fixed at 0.6 and 1.25 m respectively. The temperature distribution of the LCZ is shown in Fig. 7.

It is evident from Fig. 7 that there is a small decrease in the temperature of the LCZ as the depth of the UCZ increases. Temperatures at the end of the year (December) are very similar in all cases: the temperature decreases from 56 °C with a 0.05 m thickness, to 53 °C with a 0.5 m thickness. The temperature in the LCZ declines as a result of the attenuation of the solar radiation in the upper water layer when it becomes deeper. The reduction in the temperature of the LCZ when the thickness is changed from 0.05 to 0.1 m is slight, at about 1 °C (Fig. 7). Increasing the thickness of the UCZ to 0.2 m reduces the temperature of the LCZ by 2 °C. It can be observed from Fig. 7 that for thicknesses between 0.2 and 0.5 m, each further 0.1 m increase reduces the temperature of the LCZ by about 2 °C.

In the gel pond, the presence of the UCZ helps to protect the gel layer beneath it from environmental effects. Its function here is different from that in the SGSP, where its significance lies in decreasing the mixing of layers caused by the impact of wind speed; it is also essential to the stability of the SGSP. However, in the gel pond there is no layer mixing or diffusion through layers, and consequently, the UCZ can be thinner than that in the SGSP. It might be that the optimum thickness of the UCZ is 0.05 m and that this is sufficient to deal with any dust or impurities which come from the surrounding environment. Wilkins et al. [22] suggested that a suitable thickness for this layer is 0.05 m, because this enables

users to occasionally flush away any dirt from the surface of the pond. Additionally, changing the thickness of the UCZ does not have a substantial influence on its temperature.

4.3.2. Effect of the gel layer

For this section, it is proposed that the thickness of the UCZ and the LCZ should be fixed and the thickness of the gel layer varied. Accordingly, the thickness of the two layers is set respectively at 0.05 m (as previously concluded) and 1.25 m, and the thickness of the gel layer was variously considered at 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1 m. The temperature profiles of the LCZ are shown in Fig. 8.

It is shown from Fig. 8 that the temperature increases with the increase in the thickness of the gel layer. There is also an increase in the temperature at the end of the year (December). With the smallest thickness of 0.05 m, the maximum temperature is around 40 °C, and in December it is around 20 °C (the lowest temperature profile). With a 0.9 m gel thickness, the temperature reaches around 115 °C, and it is around 80 °C in December (the highest temperature profile). When the gel thickness is increased to 1 m, there is a decrease in the temperature of the LCZ across the whole year, and therefore any further increase after 0.9 m will negatively affect the temperature of the LCZ.

Other observations can also be made from Fig. 8. Firstly, when the thickness of the gel layer is increased from 0.2 to 0.3 m, there is a significant increase in the LCZ temperature throughout the year. The temperature jumps about 10 °C, with the maximum temperature increasing from 67 to 78 °C, and the minimum temperature (December) increasing from 33 to 43 °C. Similar behaviour can also be seen when the thickness is increased from 0.3 to 0.4 m.

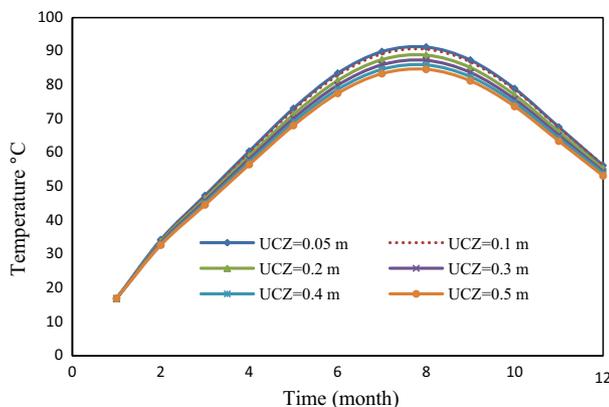


Fig. 7. Temperature distributions of the LCZ with different depths of the UCZ and constant depths of the gel and the LCZ (the initial temperature of the UCZ and the LCZ are 15 and 17 °C respectively).

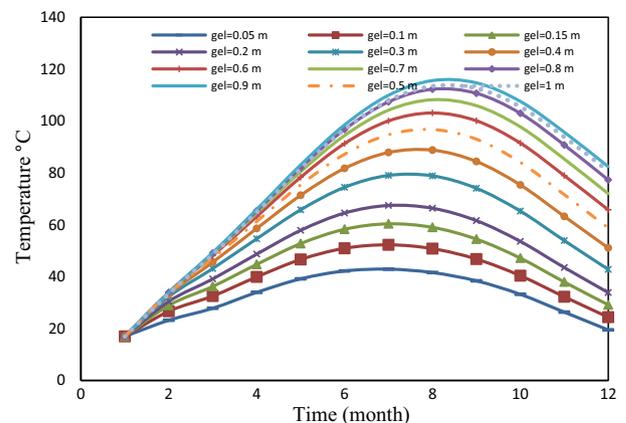


Fig. 8. Temperature distributions in the LCZ for many gel thicknesses with constant thickness of the UCZ and the LCZ on 0.05 and 1.25 m respectively.

Secondly, between the thicknesses of 0.5 and 0.9 m, each further 0.1 m increase in thickness adds about 5, 4, 3 and 2 °C to the temperature for the thicknesses 0.6, 0.7, 0.8 and 0.9 m respectively; when the thickness becomes 1 m the temperature drops. It is important to consider that the cost of the gel is the determinant of the gel thickness, because this is relatively high and it is difficult to recycle the polymer after expiry.

It is observed that changes in the gel thickness make no significant impact on the temperature of the UCZ.

4.3.3. Effect of the thickness of the LCZ

In this part of the investigation, the effect of the thickness of the LCZ has been considered. The thicknesses of the upper and gel layers are set respectively at 0.05 and 0.9 m (as previously concluded), while the thickness of the LCZ changes between 0.5 and 6 m at intervals of 0.5 m. The temperature profiles of the LCZ are illustrated in Fig. 9.

Fig. 9 shows that the temperature of the LCZ decreases as its depth increases. The highest maximum temperature is with a 0.5 m thickness (≈120 °C, unphysical), whereas the lowest is with a 6 m thickness (≈66 °C); this means that the deeper the LCZ, the lower its temperature. In general, further increases in the thickness of the LCZ affect the increases in temperature, which become progressively slower. For example, with a 0.5 m thickness, the maximum temperature is in July; at 1 m it moves to August; and at 2 m, it moves to September. Moreover, it can be observed from Fig. 9 that the gaps between the profiles become smaller and smaller with further increases in the thickness.

The behaviour of the gel pond in this case appears similar to that of the SGSP, and it might be that there is a particular optimal thickness for a specific application; consequently the type of application coupled with the gel pond may determine the thickness of the LCZ. When the thickness of the LCZ is 3.5 m or more, the profile of the temperature in this layer tends to be approximately linear with the time progress (Fig. 9).

It is noticed that the change in the thickness of the LCZ has no significant effect on the temperature of the UCZ of the gel pond.

5. Comparison with the SGSP

A theoretical comparison between the temperatures of the LCZ in the gel pond and the SGSP has been performed; the optimum thicknesses for both ponds (optimum layer depths) have been considered for a particular application, that of multi-effect desalination (MED), which requires about 60 °C. Accordingly, for the gel pond, the thicknesses are taken as 0.05, 0.9 and 3 m for the UCZ, gel layer, and the LCZ respectively,

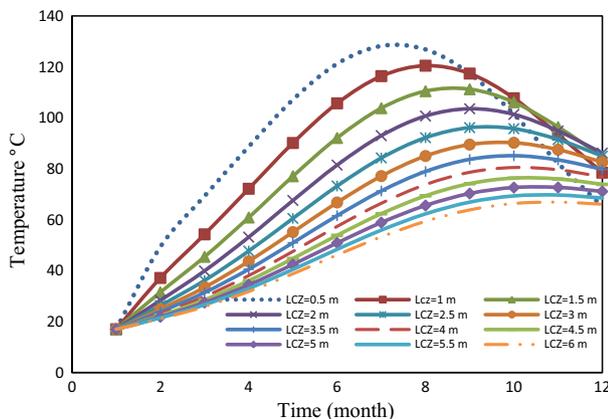


Fig. 9. Temperature profiles of the LCZ with different thicknesses of the layer with constant thicknesses for the UCZ and gel layer on 0.05 and 0.9 m respectively.

For this gel pond, the maximum temperature is 90 °C in October, and about 82 °C in December; it reaches more than 70 °C in July, at which point heat extraction can be commenced (Fig. 9). For the SGSP, the thicknesses are considered to be 0.2 and 2 m for the UCZ and NCZ respectively [41]. The thickness of the LCZ is taken as 2.5 m because at this thickness the pond will give a suitable temperature for the MED. The SGSP with these thicknesses (0.2, 2 and 2.5 m for the UCZ, NCZ and LCZ respectively) can supply sufficient heat for the MED. The maximum temperature (calculated by the model of Sayer et al. [36]) in this SGSP is 90 °C in September, about 80 °C in December, and around 70 °C in June, at which point heat extraction can be started efficiently. Both ponds with these thicknesses are suitable for multi-effect desalination (MED) which requires about 60 °C, but heat extraction can be commenced in June with the SGSP, a month earlier than the gel pond, and this therefore results in a cost. The comparison is demonstrated in Fig. 10.

Fig. 10 illustrates that for the whole year, the difference between the temperatures in the LCZ in both ponds is small. The increase in temperature in the SGSP is slightly faster than in the gel pond. This behaviour might result from the high thickness of the NCZ (2 m), and that means it insulates the LCZ more efficiently than the gel layer (0.9 m) in the gel pond. Moreover, the thickness of the LCZ in the SGSP is 2.5 m, compared with 3 m in the gel pond, and that means the water volume is smaller in the case of the SGSP and might increase its temperature faster. After September, the temperature in the SGSP becomes a bit lower than in the gel pond for the rest of the year.

It is necessary for users to weigh up which pond is suitable for their applications. The gap in temperatures between the two ponds is small. The heat stored in the LCZ for both ponds has been computed according to the following equation:

$$Q = M_l C_p \Delta T \tag{22}$$

The results are illustrated in Fig. 11.

Fig. 11 illustrates that the heat capacity of the LCZ in the gel pond is mostly higher than that of the LCZ in the SGSP for the chosen thicknesses; and the trend in Fig. 11 is similar to the temperature trend seen in Fig. 10. The difference between the two heat capacities increases over time, reaching its maximum in October. This indicates that although the temperatures of the LCZ in the SGSP are slightly higher than those of the gel pond LCZ, the LCZ heat capacity is greater in the gel pond, as a result of the difference in water volume between the two ponds. Interestingly, the heat capacity of the gel pond might vary with changes in the concentra-

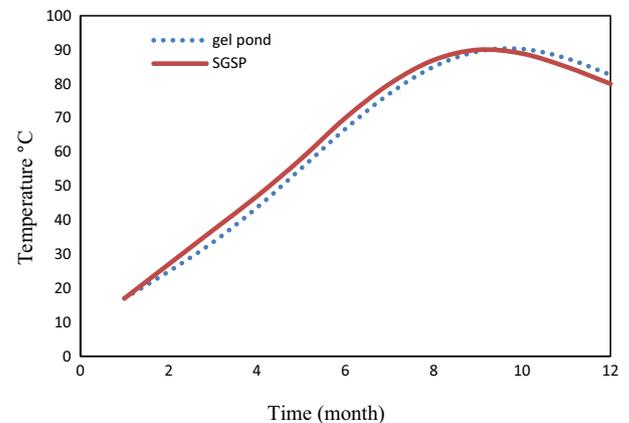


Fig. 10. Temperature profiles of the LCZ of the gel pond and the SGSP, the layer depths of the gel ponds are 0.05, 0.9, and 3 m for the UCZ, gel layer, and the LCZ respectively, the SGSP has a layer's depth of 0.2, 2, and 2.5 for the UCZ, NCZ, and the LCZ respectively.

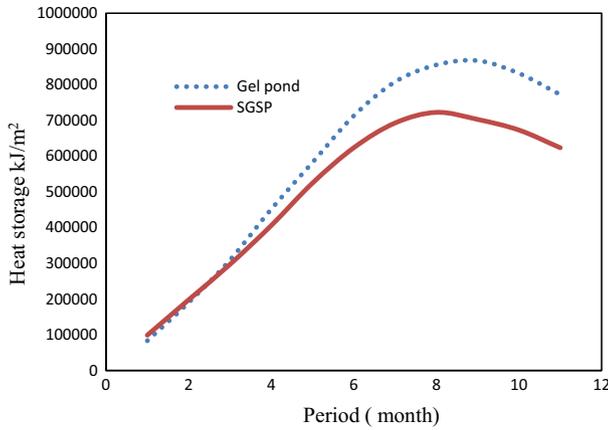


Fig. 11. Heat capacities of the LCZ of the SGSP and the gel pond.

tion of the LCZ; for the results in Fig. 11, it is considered that the concentration of the salt water of the LCZ is 0.25 kg/l for both ponds. The impact of the concentration of the LCZ on its heat capacity in the gel pond has also been investigated. The density and specific heat capacity of water vary with its concentration, and they affect the temperature and heat capacity of water in the LCZ. Their variations with different salt concentrations are shown in Figs. 12 and 13.

The gel layer in the gel pond must have an intermediate density between the fresh water and the brine densities. According to Wilkins et al. [22], the gel used in the gel layer construction can float on a 7% salt solution. Using this idea, the concentration of the LCZ was changed between 10 and 25%, because the gel can float on these brine solutions. The results are illustrated in Fig. 14.

It can be concluded (Fig. 14) that the concentration of the salty water in the LCZ has only a small effect on its heat capacity in the gel pond. The highest capacity is with the lowest concentration (10%). It might be that the variation in the heat capacity of the pond does not depend only on the specific heat capacity; it may also depend on the density of water. Figs. 12 and 13 clarify that the change in the density of water with the variations in the salt concentration is entirely opposite to the variation in the specific heat. While the density increases with the concentration, the

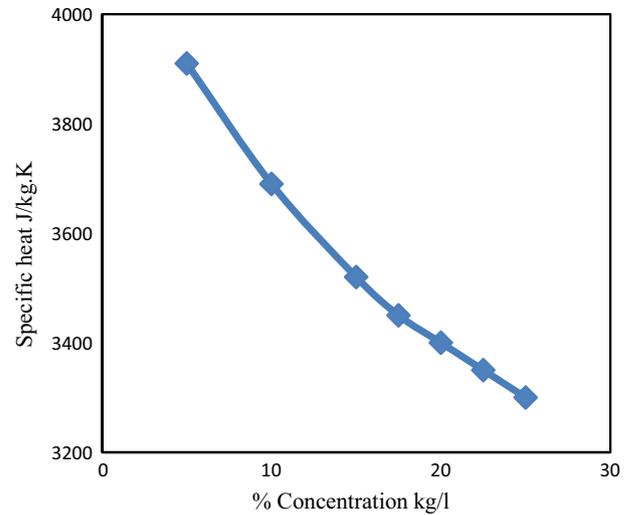


Fig. 13. Change of water specific heat with the sodium chloride concentration (engineeringtoolbox.com [42]).

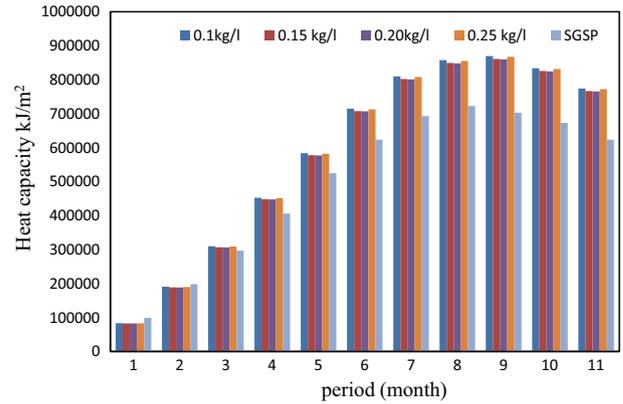


Fig. 14. Change of the heat capacity of the gel pond throughout one year and a comparison with the SGSP.

specific heat capacity decreases. It might be that the variance in the two behaviours established a balance and kept the heat capacity with a low variation with the concentration. The heat capacity of the SGSP is also compared with the capacities of the gel pond (Fig. 14). It is evident from Fig. 14 that the heat capacity of the SGSP is almost always lower than the heat capacity of the gel pond, except in the first two months.

6. Cost calculations

6.1. The cost of the SGSP

The essential parameter in any industrial application is the cost. Srinivasan [43] claimed that the cost of a SGSP was much less than the cost of a flat plate collector. He also concluded that the initial cost of the SGSP was high and strongly depended on the site of the pond. Site factors such as the local cost of excavation and salt availability have a significant effect on cost. On the other hand, the performance of the solar pond depends heavily on site properties such as the ground thermal conductivity, the depth of the water table below the pond and the solar radiation intensity, which is the source of energy. Depending on these properties, it is expected that a pond in a dry, sunny and hot area will perform differently from a pond in an area with wet, cloudy and cold

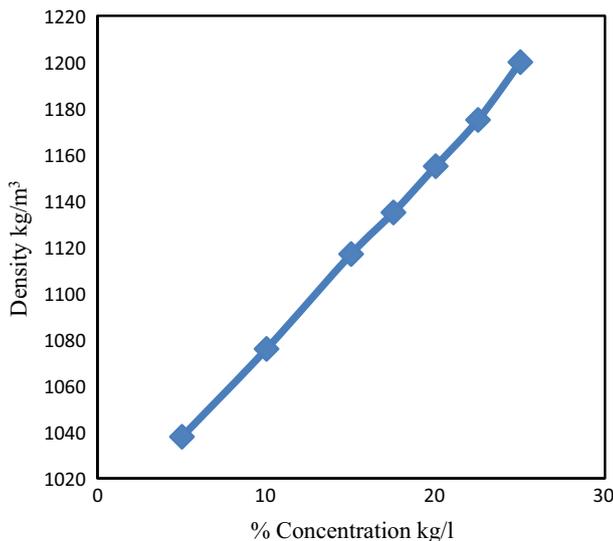


Fig. 12. Change of water density with the sodium chloride concentration (engineeringtoolbox.com [42]).

conditions. Rao and Kishore [44] have published the following equation to calculate the capital cost of the SGSP per square metre:

$$C_p = 2.546(C_1 + C_2) + 0.675C_3 + 1.3C_4 + 0.456C_5 + 0.0415C_6 + 0.124C_7 + 0.021C_8 + 0.085C_9 + C_{10} \quad (23)$$

where C_1 is the excavation charge/m³, C_2 is the water charge/m³, C_3 is the salt cost/tonne, C_4 the liner cost/m², C_5 is the clay cost/tonne, C_6 is the cost of bricks/1000 bricks, C_7 the cost of cement/bag, C_8 is the cost of sand/m³, C_9 the cost of the brick lining/m³ and C_{10} is the cost of the wave suppressor/m². Hull et al. [45] published some of these costs using experimental data which was collected from ponds constructed in Israel and the USA: some of these costs are shown below.

The cost of excavation is \$5/m³ for small ponds, decreasing to \$1/m³ for large ponds. The cost of the lining is typically \$10–15/m², even for small ponds. The cost of salt depends on the site: for example, Hull et al. [45] put it at \$0.04/kg, while the price recently reached around \$0.4/kg. The cost of the wave suppressor is \$1/m², decreasing to \$0.35/m² for a large pond.

If it is proposed that a SGSP is constructed in the city of Nasiriyah in Iraq, the cost of the parameters for Eq. (23) can be set out as follows:

The cost of excavation is \$17.5/m³ (wisconsinlpr.com, 2015 [46]). The cost of cement in Iraq is around \$100/tonne, or \$5 per 50 kg bag for the salt-resistant type (southern-cement.com, 2015 [47]). Sand is not expensive, costing around \$20/m³; while the cost of bricks has recently been put at around \$90 per 1000 bricks [48]. To calculate the cost of 1 m³ of bricks, modern brick dimensions are 10 × 10 × 20 cm, so the number of bricks required is 500. Consequently, the cost of bricks is around \$45/m³. The cost of water is around \$4/m³, and the cost of the NaCl salt in Iraq is around \$0.25/kg or even less. Considering these costs and applying Eq. (23), the cost of a SGSP with a 1 m² surface area in Iraq will be approximately \$304 and this is of years 2016/2017.

The actual cost of the SGSP at varying depths has been calculated per 1 m², and has been compared with the cost which has been computed by using Rao and Kishore's equation [44]. Layer thicknesses of the SGSP are taken as UCZ = 0.2 m, LCZ = 2 × NCZ and the concentration of the LCZ is considered to be 0.25 kg/l. The results are listed in Table 6.

Table 6 demonstrates that the Rao and Kishore equation can provide a reasonable estimation of the cost of the SGSP in the depth range 2–3.5 m. Most of the constructed salt gradient solar ponds around the world are in this depth range. For example, the El Paso solar pond in Texas in the USA, a 3000 m² pond with a depth of 3.25 m; Pyramid Hill solar pond in Australia, a 3000 m² pond with a 2.3 m depth [49]; a 6000 m² SGSP at Bhuj in India with a 3.5 m depth [50]; Bet Ha-Arava 4000 m² pond in Israel, which has

a 2.5 m depth; and Ein Boqeq, also in Israel, a 7500 m² pond with a depth of 2.6 m [45].

According to William and Tolbert [51] and Hull et al. [45], the cost of the salt alone represents more than one-third of the total construction cost of the SGSP. In this study, it is concluded that this cost represents from 34 to 42% of the total cost. It increases with the pond's depth, confirming the findings of previous studies. The results are shown in Table 7.

6.2. The cost of the gel pond

The cost of the gel pond depends on many parameters: the thickness of the gel layer, the gel concentration, the depth of the LCZ and its salt concentration. The effect of the gel concentration on the actual cost of the gel pond for many gel thicknesses has been investigated; a particular depth (2.5 m) is considered with a thickness of 0.05 m for the UCZ and concentration of 0.25 kg/l in the storage zone. The polymer used to construct the gel layer is deemed to be polyacrylamide; the results are demonstrated in Fig. 15. Once again the gel pond is considered to be in the Iraqi city of Nasiriyah.

Fig. 15 illustrates that the cost of the gel pond increases linearly with the gel concentration for all chosen depths of the gel layer. Furthermore, the cost also increases as the gel thickness becomes larger; the cost with a 0.5 m gel thickness is much higher than the cost with a 0.1 m thickness.

The impact of both the salt concentration of the LCZ, and of its depth, on the cost of the gel pond are also considered; the thick-

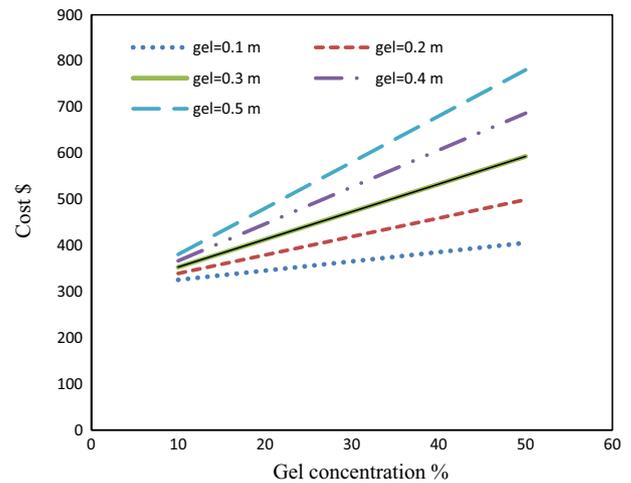


Fig. 15. The effect of the gel concentration on the actual cost of the gel pond for many gel's thicknesses, the total depth is 2.5 m and the UCZ's depth is 0.05 m.

Table 6

The calculated actual costs of the SGSP and the comparison with the cost computed using Rao and Kishore's equation [44].

| Depth (m) | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 |
|--|-----|-----|-----|-----|-----|-----|-----|-----|
| Actual cost \$ | 191 | 246 | 300 | 353 | 407 | 461 | 514 | 568 |
| Cost using the Rao and Kishore equation (\$) | 304 | 304 | 304 | 304 | 304 | 304 | 304 | 304 |
| Relative difference % | 59 | 23 | 1 | 13 | 25 | 34 | 40 | 46 |

Table 7

Change of the salt's cost with the depth of the pond and its percentage to the total cost.

| Depth (m) | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5 | 5 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Pond's cost \$ | 191 | 246 | 300 | 353 | 407 | 461 | 514 | 568 |
| Salt's cost \$ | 66 | 91 | 116 | 140 | 165 | 191 | 215 | 240 |
| The salt cost % | 34 | 36 | 38 | 39 | 40 | 41 | 42 | 42 |

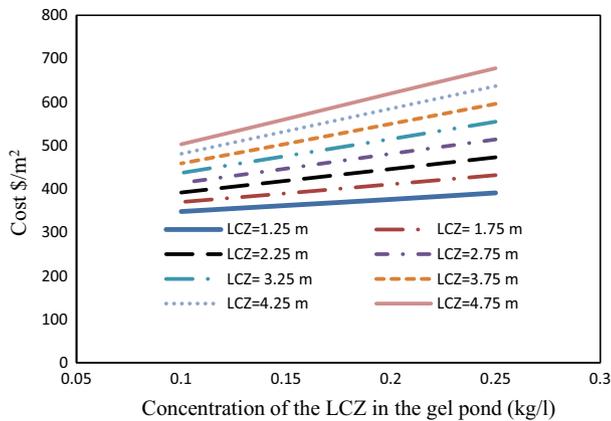


Fig. 16. The effect of concentration of the LCZ on the actual cost of the gel pond.

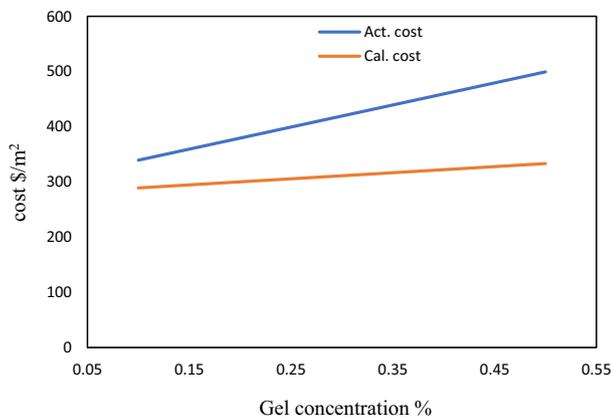


Fig. 17. The actual costs of the gel pond and the costs calculated by the modified Rao and Kishore's equation. The pond had a thickness of 0.05, 0.2 and 2.25 m for the UCZ, gel layer, and the LCZ respectively.

ness and the concentration of the gel are fixed at 0.2 m and 30% respectively. The results are demonstrated in Fig. 16 for different depths of the gel pond.

It can be observed from Fig. 16 that the cost of the gel pond increases with higher salt concentrations in the LCZ, for all depths. Moreover, Fig. 16 illustrates clearly that the depth of the LCZ in the gel pond has a significant influence on cost: the cost of an LCZ with a 4.75 m depth is approximately double the cost where the depth is 1.25 m.

A slight modification to Eq. (23) might be beneficial to estimate the capital cost (C_p) of the gel pond. The parameter C_3 (cost of the salt) in the equation could be modified to be $C_3 = C'_3 + C''_3$, where C'_3 and C''_3 are the costs of the salt and the gel materials respectively. Once again, polyacrylamide is considered as the gel, and its cost is taken from alibaba.com [52]. For the gel pond, most con-

struction costs are similar to those of the SGSP, except the cost of the salt, because in the gel pond a gel layer has been used instead of the NCZ in the SGSP.

For an approximate estimate of the capital cost of the gel pond, Eq. (23) can be rewritten as:

$$C_p = 2.546(C_1 + C_2) + 0.675(a * C'_3 + (b * b' * C''_3)) + 1.3C_4 + 0.456C_5 + 0.0415C_6 + 0.124C_7 + 0.021C_8 + 0.085C_9 + C_{10} \quad (24)$$

where a and b are the percentages of the LCZ and the gel layer thicknesses to the total thickness ($LCZ + gel$), b' is the concentration of the gel material in the gel solution, the solvent used for the gel is mostly water, so the additional cost of the new chemicals is neglected, and water is considered to be the solvent in the present calculation. Eq. (24) illustrates that the capital cost of the gel pond depends on four factors: the salt concentration of the LCZ and its thickness as a percentage (represented by $a = LCZ/(LCZ + gel)$), the percentage of the gel thickness (represented by $b = gel/(LCZ + gel)$) and the gel concentration. For example, if the gel pond of Wilkins and Lee [23] is considered with the same thicknesses of 0.05, 0.2 and 2.25 m for the UCZ, gel layer and LCZ respectively, with a range of gel concentrations 10%, 20%, 30%, 40% and 50%. The results are shown in Fig. 17.

Fig. 17 shows that Eq. (24) gives a reasonable approximation for the cost of the gel pond; that means if a gel pond is proposed with a particular depth, gel thickness and gel concentration, Eq. (24) could give a realistic estimation of the capital costs.

To elucidate further whether a SGSP or gel pond should be chosen for a particular application, depending on the cost, the actual expenditures of the two ponds selected for the MED process have been calculated. The thickness of the SGSP's layers for MED is 0.2, 2 and 2.5 m for the UCZ, NCZ and LCZ respectively, with an actual cost of \$493/m²; while the gel pond layers had thicknesses of 0.05, 0.9 and 3 m respectively, with an actual cost of \$600/m²; the gel concentration is considered to be 30%. The cost of the two ponds (\$493/m² and \$600/m²) gives an indication that the SGSP is cheaper than the gel pond; in both ponds the concentration of the LCZ is considered to be 0.25 kg/l.

On the other hand, the cost might decrease in both ponds by changing the depth of the layers or the concentrations of the gel and the salt water in the LCZ. For example, in the SGSP, if the depth of the NCZ is 1.5 m it can supply energy to the MED comfortably. Simultaneously, in the gel pond, the concentration of the LCZ can be lower than 0.25 kg/l and the gel thickness can be decreased to less than 0.9 m (the optimal thickness), and it is still suitable for the MED process, but with lower capacity. Some of these choices are given in Table 8.

Table 8 illustrates that there are many choices suitable to supply thermal energy to the MED unit, but with different heat capacities and accordingly different costs. The user can evaluate which pond is appropriate for the job depending on the performance and the cost.

Table 8
Cost of some gel and salinity gradient solar ponds.

| Pond type | Layer's thickness (m) | Cost (\$) | |
|-----------|--|-----------|---|
| SGSP | UCZ = 0.2, NCZ = 2, LCZ = 2.5 (concentration of LCZ = 0.25 kg/l) | 493 | Optimal thicknesses |
| SGSP | UCZ = 0.2, NCZ = 1.5, LCZ = 2.5 (concentration of LCZ = 0.25 kg/l) | 476 | Thickness of the NCZ is decreased (1.5 m) |
| SGSP | UCZ = 0.2, NCZ = 2.5, LCZ = 2.0 (concentration of LCZ = 0.25 kg/l) | 444 | Thickness of the LCZ is decreased (2 m) |
| Gel pond | UCZ = 0.05, gel = 0.9, LCZ = 3 (concentration of LCZ = 0.25 kg/l) | 600 | Optimal thicknesses |
| Gel pond | UCZ = 0.05, gel = 0.9, LCZ = 3 (concentration of LCZ = 0.2 kg/l) | 584 | Concentration of the LCZ is decreased (0.2 kg/l) |
| Gel pond | UCZ = 0.05, gel = 0.9, LCZ = 3 (concentration of LCZ = 0.15 kg/l) | 568 | Concentration of the LCZ is decreased (0.15 kg/l) |
| Gel pond | UCZ = 0.05, gel = 0.7, LCZ = 3 (concentration of LCZ = 0.15 kg/l) | 505 | Gel thickness is decreased (0.7 m) |
| Gel pond | UCZ = 0.05, gel = 0.6, LCZ = 3 (concentration of LCZ = 0.25 kg/l) | 469 | Gel thickness is decreased (0.6 m) |

7. Conclusion

This paper has fully researched the gel pond and its feasibility as a source of renewable energy. Its performance and costs have been compared with those of the SGSP. The gel solar pond does address some of the difficulties encountered with the SGSP; however, challenges relating to cost and labour decrease its potential. To construct a large pond, massive amounts of chemicals would be needed, and after a period these would have to be disposed of safely. This issue therefore confines the gel pond's applications, and it is clear that cheap and environmentally friendly polymers will be required if the gel pond is to become a viable alternative to the SGSP.

A number of findings have been made in this study:

- A gel pond can supply thermal energy to applications requiring only low temperatures such as multi-effect desalination (MED).
- The cost of a gel pond is normally higher than that of a salinity gradient solar pond (SGSP)
- Operational costs are similar for both types of pond; nevertheless, with the gel pond, there will be a need to employ some people experienced at working with chemicals, and this will increase the cost.

New types of gel polymers with low densities (lower than water density) and with low thermal conductivities could substantially improve the gel pond, increase the temperature in the LCZ and consequently enhance its performance.

References

- [1] A. Alcaraz, C. Valderrama, J.L. Cortina, A. Akbarzadeh, A. Farran, Enhancing the efficiency of solar pond heat extraction by using both lateral and bottom heat exchangers, *Sol. Energy* 134 (2016) 82–94.
- [2] B.M. Ziapour, M. Shokrnia, M. Naseri, Comparatively study between single-phase and two-phase modes of energy extraction in a salinity-gradient solar pond power plant, *Energy* 111 (2016) 126–136.
- [3] M. Karakilcik, I. Dincer, A.R. Marc, Performance investigation of a solar pond, *Appl. Therm. Eng.* 26 (2006) 727–735.
- [4] O. Edenhofer, R. PichsMadruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. Stechow, IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011, reprinted with corrections in 2012.
- [5] S. Keles, S. Bilgen, Renewable energy sources in Turkey for climate change mitigation and energy sustainability, *Renew. Sustain. Energy Rev.* 16 (2012) 5199–5206.
- [6] V.G. Gude, Energy storage for desalination processes powered by renewable energy and waste heat sources, *Appl. Energy* 137 (2015) 877–898.
- [7] A.H. Sayer, H. Al-Hussaini, A.N. Campbell, An analytical estimation of salt concentration in the upper and lower convective zones of a salinity gradient solar pond with either a pond with vertical walls or trapezoidal cross section, *Sol. Energy* 158 (2017) 207–217.
- [8] A.H. Sayer, H. Al-Hussaini, A.N. Campbell, Experimental analysis of the temperature and concentration profiles in a salinity gradient solar pond with, and without a liquid cover to suppress evaporation, *Sol. Energy* 155 (2017) 1354–1365.
- [9] V.V.N. Kishore, V. Joshi, A practical collector efficiency equation for non-convecting solar ponds, *Sol. Energy* 33 (5) (1984) 391–395.
- [10] A.L. Anderson, Solar pond what are they? Second Industrial Energy Technology Conference Houston, TX, 13–16 April 1980.
- [11] A.V. Spyridonos, A.A. Argiriou, J.K. Niokeletatos, Thermal storage efficiencies of two solar saltless water ponds, *Sol. Energy* 75 (2003) 207–216.
- [12] J. Andrews, A. Akbarzadeh, Enhancing the thermal efficiency of solar ponds by extracting heat from the gradient layer, *Sol. Energy* 78 (6) (2005) 704–716.
- [13] M.R. Jaferzadeh, Heat extraction from a salinity-gradient solar pond using in pond heat exchanger, *Appl. Therm. Eng.* 26 (2006) 1858–1865.
- [14] Y. Yaakob, An innovative approach to heat extraction from a salinity gradient solar pond to enhance overall efficiency, PhD's Thesis, RMIT University, 2013.
- [15] A. Alrowaished, I. Azni, A. Mohamed Thamer, A. Amimul, The development and applications of solar pond: a review, *Desalination Water Treat.* 10 (2013) 1–13.
- [16] A.A. El-Sebaili, M.R. Ramadan, S. Aboul-Enein, A.M. Khallaf, History of the solar ponds: A review study, *Renew. Sustain. Energy Rev.* 15 (2011) 3319–3325.
- [17] A. Date, A. Akbarzadeh, Salinity gradient solar ponds, in: E. Napoleon, A. Akbarzadeh (Eds.), *Energy Sciences and Engineering Applications*, CRC Press, E. Book, 2013.
- [18] A. Date, A. Akbarzadeh, Theoretical study of a new thermodynamic power cycle for thermal water pumping application and its prospects when coupled to a solar pond, *Appl. Therm. Eng.* 58 (2013) 511–521.
- [19] A. Date, Y. Yaakob, Ashwin Date, S. Krishnapillai, A. Akbarzadeh, Heat extraction from non-convective and lower convective zones of the solar pond: a transient study, *Solar Energy* 97 (2013) 517–528.
- [20] A. Abbassi Monjezi, A.N. Campbell, A comprehensive transient model for the prediction of the temperature distribution in a solar pond under Mediterranean conditions, *Sol. Energy* 135 (2016) 297–307.
- [21] C. Silva, D. Gonzalez, F. Suarez, An experimental and numerical study of evaporation reduction in a salt-gradient solar pond using floating discs, *Sol. Energy* 142 (2017) 204–214.
- [22] E. Wilkins, T.K. Lee, S. Chakraborti, Optimization of the gel solar pond parameters: Comparison of analytical models, *Energy Convers. Mgmt.* 26 (1) (1986) 123–134.
- [23] E. Wilkins, T.K. Lee, Design and optimization of the gel solar pond, *Can. J. Chem. Eng.* 65 (1987).
- [24] L.H. Shaffer, B. Dorothy, Viscosity stabilized solar ponds, United States Patent No.4, 138, 992 February 13, 1979. Available at: <<http://www.google.com/patents/US4241724>> (accessed: 15 May 2014).
- [25] E. Wilkins, Operation of a commercial solar gel pond, *Sol. Energy* 46 (6) (1991) 383–388.
- [26] A. Yogev, D. Mahlab, Aqueous gel for heat storage pond and method for making the gel, United States Patent, 1984, No. 4, 461, 276. <<https://www.google.ch/patents/US4461276>> (accessed 20 May 2014).
- [27] E. Wilkins, G. Michael, Polymer-gel covered solar energy collector and storage unit, United States Patent, No. 4, 537, 179, 1985. <<http://www.google.com/patents/US4537179>> (accessed 15 May 2014).
- [28] H.P. Garg, *Advance in Solar Energy Technology, Collection and Storage Systems*, Springer, Holland, 1987.
- [29] T. Matsumoto, N. Kato, M. Taga, On the polymer thickener for viscosity-stabilized solar pond, *J. Appl. Phys.* 37 (1998) 5088–5093.
- [30] N. Sozhan, T. Senthilvelan, T. Kaliyappan, E. Vijayakrishna, Experimental investigation on a 0.25 m² solar gel pond, *Int. J. Innovat. Res. Sci., Eng. Technol.* 2 (8) (2013) 3384–3396.
- [31] E. Wilkins, E. Yang, C. Kim, The gel pond. Report, University of New Mexico, Albuquerque, New Mexico 87131, USA, 1981.
- [32] E. Wilkins, M. El-Genk, K. El-Husseini, D. Thakur, An Evaluation of the Gel Pond Performance, *The American Society of Mechanical Engineers* 345 E. 47, St., New York, N.Y. 10017, 1982.
- [33] C.F. Kooi, The steady state salt gradient solar pond, *Sol. Energy* 23 (1979) 37–45.
- [34] Y.F. Wang, A. Akbarzadeh, A parametric study on solar ponds, *Sol. Energy* 30 (6) (1983) 555–562.
- [35] P.K. Bansal, N.D. Kaushik, Salt gradient stabilized solar pond collector, *Energy Convers. Manage* 21 (1981) 81–95.
- [36] A.H. Sayer, H. Al-Hussaini, A.N. Campbell, New theoretical modelling of heat transfer in solar ponds, *Sol. Energy* 125 (2016) 207–218.
- [37] H.C. Bryant, I. Colbeck, A solar pond for London?, *Sol Energy* 19 (3) (1977) 321–322.
- [38] W.H. McAdams, *Heat Transmission*, third ed., McGraw-Hill Kogakusha, Tokyo, Japan, 1954.
- [39] S. Kanan, D. Jonathan, L. Gregory, A simple heat and mass transfer model for salt gradient solar ponds, *Int. J. Mech., Indust. Sci. Eng.* 8 (1) (2014) 27–33.
- [40] <https://eosweb.larc.nasa.gov/cgi> (date accessed 8-6-2015).
- [41] M.R. Jaferzadeh, Thermal behaviour of a large salinity-gradient solar pond in the city of Mashhad, Iran. *J. Sci. Technol., Trans. Eng.* 29 (2005) (B2).
- [42] <https://www.engineeringtoolbox.com> (date accessed 8/6/2015).
- [43] J. Srinivasan, *Solar Pond Technology*, Sadhana 18(1) (1993) (March) 39–55 Printed in India.
- [44] K.S. Rao, V.V.N. Kishore, Power generation from solar ponds, *Techno-economics of renewable energy power generation system*, 1989, (cited in J. Srinivasan, 1993).
- [45] J.R. Hull, C.E. Nielsen, P. Golding, *Salinity Gradient Solar Ponds*, CRC Press, Florida, 1988.
- [46] <http://www.wisconsinlpr.com/much-pond-cost-wisconsin-lake-pond-resource> (date accessed 18/05/2015).
- [47] <https://www.southern-cement.com> (date accessed 12/5/2015).
- [48] <http://www.cosit.gov.iq/en/> (date accessed 18/5/2015).
- [49] J. Leblanc, A. Akbarzadeh, J. Andrews, Lu. Huanmin, P. Golding, Heat extraction methods from salinity-gradient solar ponds and introduction of a novel system of heat extraction for improved efficiency, *Sol. Energy* 85 (2011) 3103–3142.
- [50] A. Kumar, V.V.N. Kishore, Construction and operational experience of A 6000 m² solar pond at Kutch India, *Sol. Energy* 65 (4) (1999) 237–249.
- [51] A. William, P.E. Tolbert, State of the art review of solar ponds, Final report prepared in cooperation with U.S. department of energy, Seri site office, 1981.
- [52] <http://www.alibaba.com/showroom/polyacrylamide-flocculant-price.html> (date accessed 18/5/2015).