An experimental and theoretical investigation of novel configurations of solar ponds for use in Iraq

by

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Declaration

The work in this thesis was carried out in the Department of Chemical and Process Engineering at the University of Surrey, between January 2014 and June 2017. The work is accomplished by the author alone, except where specifically acknowledged in the text. It has not been submitted for a degree to any other university.

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# Table of contents

Declaration .................................................. i  
Acknowledgements .......................................... ii  
Table of contents ........................................... iii  
List of figures ............................................... vi  
List of tables ............................................... xiv  
Nomenclatures ............................................... xvi  
Abstract ..................................................... xii  
Chapter 1  
1.1 General introduction ................................... 2  
1.2 Solar energy ............................................ 3  
1.3 Types of solar energy applications ...................... 5  
1.3.1 Water and space heating applications ............... 6  
1.3.1.1 Flat plate solar collectors ....................... 6  
1.3.1.2 Evacuated tube solar collectors .................. 6  
1.3.1.3 Solar ponds ..................................... 7  
1.3.2 Electricity generating applications .................. 8  
1.3.2.1 Photovoltaic panels ............................... 8  
1.3.2.2 Concentrating solar power ....................... 9  
1.4 Iraqi challenges ........................................ 10  
1.4.1 Renewable energy in Iraq ........................... 10  
1.4.1.1 Solar energy for Iraq ............................ 11  
1.5 Salinity gradient solar pond ........................... 12  
1.6 Aims and objectives of the study ....................... 14  
1.7 Structure of the thesis ................................ 15  
1.8 Publications Arising from this Work ................... 16  
Chapter 2  
2.1 Introduction ........................................... 18  
2.2 Applications of solar ponds ............................ 19  
2.2.1 Power production .................................. 19  
2.2.2 Desalination ...................................... 20  
2.3 Classification of solar ponds ........................... 21  
2.3.1 Convective solar ponds ............................. 21  
2.3.2 Non-convective solar ponds ......................... 23  
2.3.2.1 Salinity gradient solar ponds (SGSP) .......... 23  
2.3.2.2 The gel pond .................................. 49  
2.3.2.3 Membrane solar pond ........................... 52  
2.4 Heat extraction ....................................... 56  
2.5 Summary ............................................... 61  
Chapter 3  
3.1 Introduction ........................................... 62  
3.2 Previous theoretical models ........................... 63  
3.3 Proposed model ....................................... 66
3.3.1 Upper convective zone (UCZ) 66
3.3.2 Lower convective zone (LCZ) 69
3.4 Results and discussions 72
3.4.1 Validation of the model 74
3.4.1.1 Kuwait city 74
3.4.1.2 El Paso 74
3.4.2 Effect of ground heat loss 76
3.4.3 Temperature distributions in suggested model pond 79
3.4.3.1 Temperature profiles in the UCZ and LCZ 79
3.4.3.2 Non-convective zone 80
3.5 Surface heat loss 81
3.6 Effect of layer thicknesses 84
3.6.1 Effect the thickness of the UCZ 84
3.6.2 Effect the thickness of the NCZ 86
3.6.3 Effect the thickness of the LCZ 88
3.7 Loading 90
3.7.1 Loading with constant LCZ thickness 90
3.7.2 Loading with different thicknesses of the LCZ 93
3.8 Summary 101
Chapter 4 The Gel pond 102
4.1 Introduction 103
4.2 Previous theoretical models 103
4.3 Proposed model 103
4.4 Results and discussions 106
4.4.1 Validation of the model for the gel pond 106
4.4.2 Temperature distributions in the suggested model gel pond 109
4.4.3 Effect of the layer thicknesses of the gel pond 110
4.4.3.1 Effect of the thicknesses of the UCZ 110
4.4.3.2 Effect of the thickness of the gel layer 111
4.4.3.3 Effect of the thickness of the LCZ 112
4.5 Comparison with the SGSP 113
4.6 Cost calculations 117
4.6.1 The cost of the SGSP 117
4.6.2 Cost of the gel pond 119
4.7 Summary 124
Chapter 5 Experimental design and method 125
5.1 Experimental unit, general description 126
5.2 Water body construction 129
5.3 Temperature measurements 131
5.4 Concentration 133
5.5 Algae growth 133
Chapter 6 Experimental Results and Discussions 134
6 Introduction 135
List of figures

Figure 1.1 Shares of energy sources in total global primary energy supply in 2008 (IPCC report, 2012) 3

Figure 1.2 Energy generation from solar energy, 2004-2012 (Source: Statistical review of world energy, 2015) 4

Figure 1.3 Solar power generation in TWh in some developed countries (inhabitat.com) 5

Figure 1.4 Types of solar applications according to their utilisation 6

Figure 1.5 Images of flat plate solar collectors showing (a) photo of installation on rooftop; (b) photo of external appearance; (c) cross-section of components 7

Figure 1.6 Images of evacuated tube solar collectors showing (a) and (b) photos of tubes connected to a tank or pipe to exchange heat with cold water; (c) cross-section of tube; (d) photo of collectors installed on roofs (www.siliconsolar.com; interestingenergyfacts.blogspot.co.uk; www.sunmaxxsolar.com) 8

Figure 1.7 Images of solar panels showing (a) photo of solar panels on a roof; (b) photo of a field of solar panels; (c) schematic of power generation and electrical current flow through the load (solarenergyxpert.com; www.scienceabc.com) 9

Figure 1.8 Photos of concentrating solar power technologies showing (a) field of parabolic troughs; (b) field of solar dishes; (c) solar tower in Seville, Spain 10

Figure 1.9 Zones of the SGSP - the UCZ, which loses heat from the surface by convection, evaporation and radiation; the NCZ, with concentration and temperature gradients, and no convection currents; and the LCZ, the hottest layer with the highest salt concentration 11

Figure 2.1 Alice Spring SGSP; (a) the pond which had a surface area of 0.5 hectare; (b) the ORC engine installed to generate 15 kW electricity (http://members.optusnet.com.au) 12

Figure 2.2 Diagram showing the different types of solar ponds. 13

Figure 2.3 Two schematic diagrams of the Shallow pond, (a) a simple shallow pond (batch process), (b) a shallow pond has a heat exchanger to circulate water for the heat extraction (closed process) 14

Figure 2.4 Photos of the El-Paso solar pond; (a) the pond and the facilities; (b) the top surface of the pond; it shows tubes use for the heat extraction (Leblanc et al., 2011). 15

Figure 2.5(a) A schematic diagram of a salinity gradient solar pond (SGSP). The pond surrounded by an insulator to minimize the heat loss, particularly from the bottom, the pond zones are the UCZ, the NCZ and the bottom layer (LCZ), convection currents only in the top and bottom layers. 16
The change in the density of sodium chloride brine with the salinity and temperature (Perry, 1999)

The most common shape of solar pond (trapezoidal) (Leblanc et al., 2011)

Solubility variation with temperature for some salts

Solubility of some salts in water with temperature (kentchemistry.com)

Installation of lining system of El Paso solar pond (Leblanc et al., 2011)

Picture and scheme of the diffuser used in the formation of the salinity gradient of the 50 m² experimental solar pond at Solvay-Martorell facilities, Catalonia (Spain) (Valderrama et al., 2011)

Photos of the RMIT experimental salinity gradient solar pond, (a) the external appearance of the pond showing it full of water and built on the ground, (b) the salt charger, and showing also the floating rings to reduce the impact of wind, (c) the diffuser used to setup the salinity gradient

A schematic of a solar pond and the units used for the water body formation (Aizaz and Yousaf, 2013)

Solar pond with: (a) complete coverage with continuous transparent cover, (b) partial (60%) coverage with continuous transparent cover, (c) complete (88%) coverage with floating discs, and (d) complete (97%) coverage with floating hemispheres (Ruskowitz et al., 2014).

Results of Ruskowitz et al. (2014) regarding of evaporation rates and temperatures, (a) Evaporation rate from the solar pond surface as a function of percent coverage for the continuous cover, floating discs, and floating hemispheres during daylight operation, (b) Highest recorded LCZ temperatures for maximum percent coverage of the continuous cover, floating discs, and floating hemispheres and the average temperature of the LCZ in the uncovered pond

A schematic and photo of the pond in Solvay-Martorell, facilities, Catalonia in Spain (a) Schematic view of the pond showing the distribution of the three zones, and (b) photo of the 50 m² experimental salinity gradient solar pond.

Photos of Nie et al.’s pond, (a) The experimental SGSP in operation, (b) The pond after operation.

The construction of Yu et al.’s G-SGSP and the constructed pond

Schematic diagram of lithium extraction by G-SGSP and a picture showing the heat exchanger submerged in the LCZ of the experimental pond and connected with the geothermal water simulation system to form a semi-enclosed hot-water circulation system (Yu et al., 2015)
Figure 2.18  Schematic of Yogev and Mahlab (1984) for a power generation project using a gel solar pond.

Figure 2.19  Sozhan et al.’s (2013) prototype model showing the polymer layer had a thickness of 1 cm, and floats on the storage zone; the figure also shows the used thermocouples, and the two layers of insulation, the polystyrene and sawdust.

Figure 2.20  A cross suction of a membrane solar pond (Anderson, 1980).

Figure 2.21  Conventional in-pond closed heat extraction system (Leblanc et al., 2011).

Figure 2.22  In-pond heat exchanger at Pyramid Hill salinity gradient solar pond in Australia, it shows heat extraction tubes and inlet manifold (Leblanc et al., 2011).

Figure 2.23  Second conventional method of heat extraction (Leblanc et al., 2011).

Figure 2.24  Heat extraction system which was used by Jaefarzadeh (2006).

Figure 2.25  A schematic of the heat extraction approach suggested by Andrews and Akbarzadeh, 2005, showing that the heat exchanger is installed in the NCZ.

Figure 2.26  A schematic of the heat extraction approach suggested by Date et al. (2013), 2005, showing that the heat exchanger is installed along the NCZ and LCZ of the pond, the hot fluid (water) leaves the LCZ to exchange heat with the cold air and return to the pond and enters the NCZ.

Figure 3.1  Schematic diagram of the Kooi’s solar pond for the steady state case (1979).

Figure 3.2  Schematic diagram showing heat flows through the upper convective zone.

Figure 3.3  Schematic diagram showing heat flows through the lower convective zone (storage zone).

Figure 3.4  The profile of solar radiation of Kuwait City during one year.

Figure 3.5  Validation of temperature distribution of the LCZ of the present model with experimental data for Kuwait City (initial temperatures are 14 and 23 °C for UCZ and LCZ respectively).

Figure 3.6  Comparison profiles of the LCZ temperature of the present model with El Paso pond experimental data (1999) (initial temperatures are 6 and 70 °C for the UCZ and the LCZ respectively).

Figure 3.7  Comparison of the experimental temperature distribution of the lower layer LCZ of the Kuwait pond with unburied and Hull et al. (1988) formulae for heat loss to the ground.

Figure 3.8  Comparison of the temperature distribution of the LCZ between small and large pond when formula of Hull et al. (1988) is used.

Figure 3.9  The profile of temperature in LCZ and UCZ during one year (initial temperatures are 12.6 °C for both layers and month 1 is January).

Figure 3.10  The NCZ section of the pond which shows the suggested partitions.
Figure 3.11  The distribution of temperature in the pond for four selected months, February, April July and November 81
Figure 3.12  The temperature of the LCZ with different cases of heat loss from the surface. 82
Figure 3.13  The temperature of the UCZ with different cases of heat loss from the surface. 82
Figure 3.14  Profiles of both the ambient and the calculated temperatures of UCZ 83
Figure 3.15  Profiles of both measured ambient and UCZ temperatures for El-Paso pond (1999), extracted from (Lu et al., 2001). 83
Figure 3.16  The temperature profiles in the LCZ for various thicknesses of the UCZ (NCZ = 1.25 m, LCZ = 1.5 m, month 1 is January, initial temperatures for the UCZ and LCZ are 15 and 17 °C respectively) 85
Figure 3.17  The temperature profiles of the LCZ for various thicknesses of the NCZ, (UCZ = 0.2 m and LCZ = 1.5 m, month 1 is January, the initial temperatures of the UCZ and the LCZ are 15 and 17 °C respectively) 86
Figure 3.18  The temperature profiles of the LCZ for various thicknesses of the LCZ, (UCZ = 0.2 m and NCZ = 2 m, month 1 is January, the initial temperatures of the UCZ and the LCZ are 15 and 17 °C respectively) 88
Figure 3.19  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, the initial temperatures of the UCZ and LCZ are 15 and 17 °C respectively). 91
Figure 3.20  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, the initial temperatures of the UCZ and the LCZ are 15 and 17 °C respectively) 92
Figure 3.21  The temperature of the LCZ with various thicknesses and 30 W/m2 load for one year (month 1 is January and initial temperatures of the UCZ and LCZ are 15 °C and 17 °C respectively, thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively). 93
Figure 3.22  The temperature of the LCZ with various thicknesses and 30 W/m2 load over two years (month 1 is January and initial temperatures of the UCZ and LCZ are 15 °C and 17 °C respectively, thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively). 94
Figure 4.1  Schematic of the suggested gel pond 104
Figure 4.2  Heat flows through the UCZ of the gel pond. 104
Figure 4.3  A schematic of heat flows through the LCZ of the gel pond 105
Figure 4.4  A comparison between the present calculation and the experimental data of Wilkins et al. (1981) (from 15 of March to 6 of April 1981) 107
Figure 4.5  The comparison of the 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). 108
Figure 4.6  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).

Figure 4.7  Temperature evolution of the LCZ with different depths of the UCZ and constant depths of the gel and the LCZ at 0.6 and 1.25 m respectively (the initial temperature of the UCZ and the LCZ are 15 and 17 °C respectively).

Figure 4.8  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 (the initial temperature of the UCZ and the LCZ are 15 and 17 °C respectively).

Figure 4.9  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 (the initial temperature of the UCZ and the LCZ are 15 and 17 °C respectively).

Figure 4.10  Temperature profiles of the LCZ in the gel pond and the SGSP, the two pond have a surface area of 1m2, 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.

Figure 4.11  Heat capacities of the LCZ of the SGSP and gel pond

Figure 4.12  Change of water density with the sodium chloride concentration (engineeringtoolbox.com)

Figure 4.13  Change of water specific heat with the sodium chloride concentration (engineeringtoolbox.com)

Figure 4.14  Change of the heat capacity of the gel pond throughout one year and a comparison with the SGSP

Figure 4.15  The effect of the gel concentration on the actual cost of the proposed gel pond for many gel’s thicknesses, the total depth is 2.5 m and the UCZ’s depth is 0.05 m.

Figure 4.16  The effect of concentration of the LCZ on the actual cost of the proposed gel pond.

Figure 4.17  The proposed costs of the gel pond and the costs calculated by the modified Rao and Kishore’s equation.

Figure 5.1  Pictures of the experimental SGSP, (a) the external appearance of the pond, (b) the water body of the pond.

Figure 5.2  Schematic diagram showing the cross section through the experimental salinity gradient solar pond. The distribution of the thermocouples which monitor the spatio-temporal evolution of the temperature field within the pond is also shown. The dashed horizontal lines in the NCZ show the layers that were used to construct the salinity gradient.

Figure 5.3  The schematic of the system used for the water body formation
Figure 5.4  The paraffin layer floats on the water surface due to the difference in their densities.

Figure 5.5  The control board, showing the buttons and the digital reader.

Figure 5.6  Gray Wolf devices which were used to measure the relative humidity, ambient temperature and wind speed.

Figure 5.7  HANNA (HI2300) device which was used for concentration measurements.

Figure 5.8  (a) Daily average measurements of evaporation rate, relative humidity and the ambient temperature for the experimental pond for 12 days from 29/7-9/8/2015, (b) Scatter plot of daily evaporation rate versus average temperature. (c) Scatter plot of the evaporation rate versus average relative humidity.

Figure 5.9  The results when all parameters affecting evaporation are considered, (a) the predicted results against the measured values, (b) the predicted evaporation against the residuals.
Figure 6.10  The residuals against the four meteorological parameters, (a) the solar radiation with the residuals, (b) the ambient temperature with the residuals, (c) the relative humidity against the residuals, and (d) the wind speed against the residuals.

Figure 6.11  The results when the solar radiation is excluded, (a) the predicted results against the measured values, (b) the predicted evaporation against the residuals.

Figure 6.12  Points distribution of the three meteorological parameters (the solar radiation is excluded) around the horizontal line, (a) the solar radiation with the residuals, (b) the ambient temperature with the residuals, (c) the relative humidity against the residuals, and (d) the wind speed against the residuals.

Figure 6.13  The results when the solar radiation is excluded and the interaction between the ambient temperature and the relative humidity is considered, (a) the predicted results against the measured values, (b) the predicted evaporation against the residuals.

Figure 6.14  The residuals against with the independent variables, (a) the residuals against the ambient temperature, (b) the residuals against the wind speed, (c) the residuals against the relative humidity, (d) the residuals against the ambient temperatures * the relative humidity.

Figure 6.15  (a) Evolution of the daytime temperature (2 p.m.) in the UCZ, LCZ and ambient over the first 12 days of operation (29/7-9/8/2015), (b) evolution of the night-time temperature (2 a.m.) in the UCZ, LCZ and ambient over the first 12 days of operation (29/7-9/8/2015).

Figure 6.16  Temperature variation with depth for Days 2, 6 and 12, measured at 2 p.m.

Figure 6.17  (a) Measurements of the UCZ, and ambient temperature from 29/7-7/10/2015 (daytime 2 p.m), (b) Measurements of the UCZ and ambient temperature from 29/7-7/10/2015 (night-time 2 a.m)

Figure 6.18  Change in LCZ, UCZ and ambient temperature in daytime (2 p.m) from 29/7-7/10/2015

Figure 6.19  Temperature distribution in the experimental pond on different days before and after coverage

Figure 6.20  Measurements of day and night temperatures of the LCZ and UCZ

Figure 6.21  Salinity gradient of the experimental SGSP for four different days.

Figure 6.22  Schematic of the injection system (Date and Akbarzadeh, 2013)

Figure 6.23  Change in concentrations of the LCZ with its depth during 50 days. The depths considered are, 0.05, 0.15, and 0.35 m; 8 litres of brine was injected to the bottom of the LCZ through 8 days (from Day 31-Day 39 with an injection rate of 11/day)

Figure 6.24  Concentrations of the UCZ and the top measured point of the NCZ; pond dimensions of the experimental pond were 1x1x1 m and had
depths of 0.1, 0.5 and 0.4 m for the UCZ, NCZ and the LCZ respectively.

Figure 6.25 Comparisons between theoretical and experimental results before the pond covering. The pond had dimensions of 1×1×1 m and a layer thickness of 0.1, 0.5 and 0.4 m respectively for the UCZ, NCZ, and the LCZ.

Figure 6.26 Comparison between theoretical and experimental results after the pond covering. The pond had dimensions of 1×1×1 m and a layer thickness of 0.1, 0.5 and 0.4 m respectively for the UCZ, NCZ, and the LCZ.

Figure 6.27 Theoretical temperature distributions of the LCZ and UCZ of the covered and uncovered ponds. The pond had dimensions of 1×1×1 m and a layer thickness of 0.1, 0.5 and 0.4 m respectively for the UCZ, NCZ, and the LCZ.

Figure 6.28 The comparison between the experimental and calculated temperatures in the NCZ for the experimental pond, (a) the comparison for days 30 and 50 (UCZ = 0.1 m, NCZ = 0.5 m and LCZ = 0.4 m), (b) the comparison for day 12 before the pond coverage.

Figure 6.29 The comparison between the experimental measurements and the theoretical evaporation (calculated by the Kishore and Joshi’s equation, Equation 6.1, and Equation 6.3) levels (month 1 is January).

Figure 6.30 The theoretical evaporation rates during one year calculated by Kishore and Joshi’s equation (1984), Equation 6.1, and equation 6.3 in the site of the experiment (Nasiriyah City) (month 1 is January).

Figure 6.31 Comparison of the experimental pond concentration profiles with profiles computed using the analytical equations for three different days, the pond had a surface area 1 m², depth 1 m, and zone depths of 0.1, 0.5 and 0.4 for the UCZ, NCZ and LCZ respectively.

Figure 6.32 Theoretical concentration profiles of the pond over time, estimated using Equations (6.16) and (6.17) in a pond with surface area of 1 m², depth of 1 m, and zone depths of 0.1, 0.5 and 0.4 for the UCZ, NCZ and LCZ respectively.

Figure 6.33 Change in UCZ and LCZ concentrations over time, in a pond with surface area 1 m², depth of 1 m, and zone depths of 0.1, 0.5 and 0.4 for the UCZ, NCZ and LCZ respectively.

Figure 6.34 Experimental and computed concentrations of Karakilcik et al. 2006’s pond, with zone depths of 0.10, 0.6 and 0.8 m for the UCZ, NCZ and LCZ respectively, where (a) shows comparisons between experimental results and calculated concentrations for May and August and (b) shows the UCZ and LCZ profiles over time.

Figure 6.35 Theoretical and computed concentrations of Kanan et al. (2014), for a pond with zone depths of 0.3, 1 and 0.7 m for the UCZ, NCZ and LCZ respectively, where (a) shows current computed concentrations.
compared with the theoretical results of Kanan et al. and (b) shows the UCZ and LCZ profiles over time.

Figure 6.36  Schematic of a pond with a trapezoidal shape.

Figure 6.37  Trapezoidal experimental pond of Karim et al. (2010)

Figure 6.38  Comparison of computed results with the experimental results of Karim et al. (2010) on (a) Day 10 and (b) Day 20, for a pond with surface area of 3.6 m$^2$ and layer depths of 0.15, 0.5 and 0.35 for the UCZ, NCZ and LCZ respectively.

Figure 6.39  Calculated concentration profiles of the UCZ and LCZ for the pond used by Karim et al. (2010) for vertical and many different inclined walls, where zone depths of the pond are 0.15, 0.5, and 0.35 for the UCZ, NCZ and LCZ respectively.

Figure 6.40  Change temperatures of the UCZ and the LCZ with time to reach equilibrium when no heat loss or addition is considered after the LCZ reaches the maximum.

Figure 6.41  Comparisons of the calculated temperature using the analytical equation with the experimental results and temperatures calculated by the model for the LCZ.

Figure 6.42  Comparisons of the calculated temperature using the analytical equation with the experimental results and temperatures calculated by the model for the UCZ.

Figure 6.43  The comparisons of the UCZ and LCZ temperatures calculated by the model with the temperatures computed using Equations 6.59 and 6.61.

List of tables

Table 2.1  Some artificial salinity gradient solar ponds around the world

Table 2.2  Information given by Rabl and Nielsen (1975)

Table 2.3  Detail of ponds of Jayaprakash and Perumal (1998), Karakilcik et al. (2006), Bezir et al. (2009), and Sakhrieh and Al-Salaymeh (2013)

Table 2.4  Some physical properties of polyacrylamide (Wilkins and Michael, 1985)

Table 2.5  Advantages and disadvantages of the convective (Shallow pond) and non-convective solar ponds (SGSP, gel and membrane ponds)

Table 3.1  Climatic conditions of Kuwait City (NASA, 2014)

Table 3.2  Climatic conditions of El Paso, Texas (1999), (Lu et al., 2001)

Table 3.3  Small and large suggested pond specifications

Table 3.4  Climatic conditions of Nasiriyah City (NASA, 2015)
Table 3.5  The temperatures of the UCZ and ambient temperatures in °C during a year with various thicknesses of the UCZ (month 1 is January)

Table 3.6  Minimum and maximum temperatures in the LCZ for various thicknesses of this zone (UCZ = 0.2 m, NCZ = 2 m).

Table 3.7  Variation of the LCZ thickness and the load throughout one year (NCZ = 1.5 m); in this table it is considered that depths of the UCZ and NCZ are 0.2 and 1.5 m respectively, and the depth of the LCZ is changed from 0.5-4 m.

Table 3.8  Variation of the LCZ thickness and the load throughout one year (NCZ = 2 m); in this table it is considered that depths of the UCZ and NCZ are 0.2 and 2 m respectively, and the depth of the LCZ is changed from 0.5-4 m.

Table 4.1  Physical properties of the gel used in the construction of the Albuquerque pond (Wilkins et al. 1981)

Table 4.2  The climatic conditions of the Albuquerque City

Table 4.3  Relative errors of the theoretical results from the previous experimental results of Wilkins et al. (1981)

Table 4.4  The change in the temperature of the Albuquerque gel pond with time (Wilkins and Lee, 1987)

Table 4.5  The calculated real costs of the proposed SGSP and the comparison with the cost computed using Rao and Kishore’s equation (1989).

Table 4.6  Change of the salt’s cost with the depth of the pond and its percentage to the total cost

Table 4.7  Cost of some gel and salinity gradient solar ponds

Table 5.1  Some physical properties of paraffin used in the experimental pond

Table 6.1  The correlation coefficients of the different parameters affecting the evaporation from a solar pond

Table 6.2  Statistical data of multiple regression analysis

Table 6.3  Statistical data of multiple regression analysis (incident solar radiation is excluded)

Table 6.4  Statistical data of multiple regression analysis (interaction between the ambient temperature and the relative humidity is taken into account)

Table 6.5  The relative errors between the theoretical calculations and the experimental measurements of the evaporation for 9 months (January-September); the theoretical values were calculated using Kishore and Joshi’s equation, Equation 6.1, and Equation 6.3.
Nomenclatures

\(A_\text{bp}\) Area of the bottom surface of the pond (m\(^2\))
\(A_{cL}\) The cross sectional area of the LCZ (m\(^2\))
\(\text{Adj} R^2\) Adjusted standard deviation
\(A_l\) Surface area of the LCZ (m\(^2\))
\(A_{sL}\) The surface area of the LCZ (m\(^2\))
\(A_u\) Surface area of the UCZ (m\(^2\))
\(a\) Constant (0.36, Equation 2.3)
\(a\) The percentage of the thickness of the LCZ to the total thickness of the LCZ and
the gel layer \(a = \text{LCZ}/((\text{LCZ} + \text{gel}))\)
\(a_1\) Constant (Equation 6.22)
\(a_2\) Constant (Equation 6.23)
\(b\) Constant (0.08, Equation 2.3)
\(b^\prime\) The percentage of the gel layer’s thicknesses to the total thickness of the LCZ and
the gel layer \(b^\prime = \text{gel}/((\text{LCZ} + \text{gel}))\) (Equation 4.13)
\(b^\prime\)'' The concentration of the gel solution (Equation 4.13)
\(C_1\) The excavation charge/m\(^3\)
\(C_2\) The water charge/m\(^3\)
\(C_3\) The salt cost/tonne
\(C_4\) The liner cost/m\(^2\)
\(C_5\) The clay cost/tonne
\(C_6\) The cost of bricks/1000 bricks
\(C_7\) The cost of cement/bag
\(C_8\) The cost of sand/m\(^3\)
\(C_9\) The cost of the brick lining/m\(^3\)
\(C_{10}\) The cost of the wave suppressor/m\(^2\)
\(C_3\) The cost of the salt in the gel pond/tonne
\(C_3\) The cost of the gel materials/ tonne
\(C_s\) Humid heat capacity of (kJ/kg K)
\(c_{pl}\) Heat capacity of water in the LCZ (J/kg K)
\(C_p\) The capital cost
\(c_{pu}\) Heat capacity of water in the UCZ (J/kg K)
The concentrations of the LCZ (kg/m³)

$C_{LCZ}$

The concentrations of the UCZ (kg/m³)

$C_{UCZ}$

c₁ Constant (Equation 6.22)

c₂ Constant (Equation 6.23)

$D$ The salt diffusivity (m²/s)

$D_g$ Distance between the bottom insulation and the water table (m).

$D_i$ Thickness of the bottom insulation (m)

d The pond’s depth (m)

$E$ Pond’s efficiency

$EP$ The evaporation pond

$Ev$ Evaporation rate (l/m² day)

$F$ Constant ($F = \frac{1}{\rho u c p u h_{UCZ}}$) (Equation 6.59)

$F_r$ Transmission parameter

$F_R$ Froude number

$G$ Constant ($G = \frac{86400U_g}{\rho c p t A h_{LCZ}}$) (Equation 6.61)

$g$ The acceleration due to gravity (m/s²)

$H$ The incident solar radiation on the pond’s surface (W/m²)

$h$ Represents any chosen height along the depth of the pond (m)

$h_c$ Convective heat transfer coefficient from pond’s surface to the air (W/m² K)

$H_x$ Fraction of solar radiation that reaches a depth $x$ (W/m²)

$h_o$ Heat transfer coefficient from outside wall surface to the atmosphere (W/m² K)

$h_1$ Heat transfer coefficient between the NCZ and the UCZ (W/m² K)

$h_2$ Heat transfer coefficient between the LCZ and the NCZ (W/m² K)

$h_3$ Heat transfer coefficient between the LCZ with surface at the bottom of the pond (W/m² K)

$h_4$ Heat transfer coefficient at the surface of the ground water sink (W/m² K)

$h_{LCZ}$ Thickness of the LCZ (m)

$h_{UCZ}$ Thickness of the UCZ (m).

$j$ The index of refraction (Equation 2.2)

$K$ Constant ($K = \frac{h_{LCZ}x_{NCZ}}{D}$) (Equation 6.10)

$K_1$ Constant ($K_1 = (\frac{W_t L + W_b}{2})h_{LCZ} \frac{x_{NCZ}}{D W_t L}$) (Equation 6.32)
\( K_2 \) Constant \( (K_2 = \frac{86400U_t}{\rho_u c_w h_{UCZ}}) \) (Equation 6.59)

\( k \) Number of variables

\( k_g \) Thermal conductivity of the soil under the pond (W/m K)

\( k_i \) Thermal conductivity of the insulation in Wang and Akbarzadeh (1983)’s model (W/mK)

\( k_w \) Thermal conductivity of water (W/m K)

\( k_1 \) Thermal conductivity of the first layer of insulation (W/m K)

\( k_2 \) Thermal conductivity of polystyrene (W/m K)

\( k_3 \) Thermal conductivity of wood (W/m K)

\( L \) Laplace transform

\( L_d \) The length at a specific depth \( h \) (m)

\( L^{-1} \) Inverse Laplace transform

\( l_1 \) Thickness of the first layer of insulation (m)

\( l_2 \) Thickness of polystyrene layer (m)

\( l_3 \) Thickness of third layer of insulation (m)

\( L_t \) The length of the pond (m)

\( M \) Constant \( (M = \frac{1}{\rho_l c_p A_l h_{LCZ}}) \) (Equation 6.61)

\( M_l \) Mass of the LCZ (kg)

\( M_u \) Mass of the UCZ (kg)

\( m \) Empirical parameter \ (Equation 3.37)

\( N \) Constant \( (N = \frac{86400h_c}{\rho_u c_w h_{UCZ}}) \) (Equation 6.59)

\( N' \) The number of the day in the year

\( n \) Number of observations

\( p \) Pond perimeter (m)

\( p_a \) The partial pressure of water vapour in the ambient temperature (mmHg)

\( p_{atm} \) Atmospheric pressure (mmHg)

\( p_u \) Water vapour pressure at the upper layer temperature (mmHg)

\( Q_{ground} \) Heat loss to the ground (W/m²)

\( Q_{load} \) Heat extracted from the LCZ (W/m²)

\( Q_{loses} \) Overall heat loss from the surface of the pond (W/m²)

\( Q_R \) Heat absorbed in any layer of the NCZ from the solar radiation (W/ m²)
Solar radiation entering the UCZ (W/m$^2$)

Solar radiation exiting the UCZ (W/m$^2$)

The solar radiation comes out the UCZ in the gel pond (W/m$^2$)

The solar radiation enters and absorbs in the LCZ in the gel pond (W/m$^2$)

The solar radiation which enters and is stored in the LCZ (W/m$^2$)

Solar radiation that is absorbed in the NCZ (W/m$^2$)

Heat transfer by conduction to the UCZ (W/m$^2$).

Convective heat loss from the surface of the pond (W/m$^2$)

Evaporative heat loss from the surface of the pond (W/m$^2$)

Radiation heat loss from the surface of the pond (W/m$^2$)

Heat loss through walls of the pond (W/m$^2$).

Heat stores in the LCZ (W/m$^2$)

Standard deviation

Constant ($R = \frac{h_{UCZ}X_{NCZ}}{D}$) (Equation 6.32)

Constant ($R_1 = (\frac{W_{bu}+W_{l}}{2})h_{UCZ}\frac{x_{NCZ}}{D}W_{bu}$) (Equation 6.33)

Constant ($R_2 = \frac{86400U_t}{\rho c p h_{LCZ}}$) (Equation 6.11)

The average of the ambient temperature (°C)

The temperature of water table under the pond (°C)

Sky temperature (°C)

Temperature of the LCZ (°C)

Temperature of the UCZ (°C)

Time (s)

Over all heat transfer coefficient to the ground (W/m$^2$ K)

Overall heat transfer coefficient (W/m$^2$ K)

Monthly average wind speed in the region of study (m/s)

Volume of the LCZ in the gel pond (m$^3$)

Volume of the UCZ in the gel pond (m$^3$)

Volume of the LCZ in the SGSP (m$^3$)

Volume of the UCZ in the SGSP (m$^3$)

The width at the bottom surface of the pond (m)

The width of the pond at the bottom surface of the UCZ (m)
\\[ W_d \quad \text{The width at a specific depth} \, h \, (\text{m}) \]
\\[ W_t \quad \text{The width at the top surface of the pond} \, (\text{m}) \]
\\[ W_{tL} \quad \text{The width of the pond at the top surface of the LCZ} \, (\text{m}) \]
\\[ X_{NCZ} \quad \text{The thickness of the NCZ} \, (\text{m}) \]
\\[ x_g \quad \text{Distance of water table from the pond’s bottom} \, (\text{m}) \]
\\[ x \quad \text{The depth of the water layer} \, (\text{m}) \]
\\[ y_0 \quad \text{Constant in Wang and Akbarzadeh (1983)’s model} \quad \text{(Equation 3.4)} \]

**Greek letters**

\\[ \beta \quad \text{The gap width of the diffuser in meters} \quad \text{(Equation 2.1)} \]
\\[ \lambda \quad \text{The latent heat of vaporisation} \, (\text{kJ/kg}) \]
\\[ \gamma_h \quad \text{Relative humidity} \]
\\[ \sigma \quad \text{Stefen –Boltzmann’s constant} \, (5.673 \times 10^{-8} \, \text{W/m}^2 \text{K}^4) \]
\\[ \epsilon \quad \text{Emissivity of water} \]
\\[ \rho \quad \text{Density of the surrounding saline water} \, (\text{kg/m}^3) \quad \text{(Equation 2.1)} \]
\\[ \rho_t \quad \text{Density of the LCZ} \, (\text{kg/m}^3) \]
\\[ \rho_u \quad \text{Density of the UCZ} \, (\text{kg/m}^3) \]
\\[ \delta \quad \text{The thickness of the UCZ in meters in Wang and Akbarzadeh (1983)’s model} \]
\\[ \Delta \quad \text{The angle of declination} \]
\\[ \Delta T \quad \text{The temperature difference} \, (\text{°C}) \]
\\[ \Delta \rho \quad \text{The density difference between the injected and surrounding fluids} \, (\text{kg/m}^3) \]
\\[ \Delta C_{LCZ}(t) \quad \text{The change in the concentration of the LCZ at any time} \]
\\[ \Delta C_{UCZ}(t) \quad \text{The change in the concentration of the UCZ at any time} \]
\\[ \eta_j \quad \text{The fraction of solar radiation having absorption coefficient} \, \mu_j \]
\\[ \mu_j \quad \text{The absorption coefficient} \]
\\[ \theta_r \quad \text{The refractive angle} \]
\\[ \theta_i \quad \text{The angle of the incident solar insolation on a horizontal body} \]
\\[ \phi \quad \text{The latitude of the location} \]
\\[ \omega \quad \text{The solar hour angle in degrees} \]
\\[ \nu \quad \text{The injection velocity} \, (\text{m/s}) \quad \text{(Equation 2.1)} \]
\\[ \tau \quad \text{The coefficient of transmission} \quad \text{(Equation 2.2)} \]
Abbreviations

CCSGSP  Closed cycle salinity gradient solar pond
GDDC  Gujarat Dairy Development Corporation Ltd
GEDA  Gujarat Energy Development Agency
GHG  The greenhouse gases
G-SGSP  Geothermal salinity gradient solar pond
IEA  International Energy Agency
IPCC  Intergovernmental Panel on Climate Change
LCZ  Lower convective zone
MATLAB  Matrix laboratory
MED  Multi-effect distillation
M.V.S.P.  Membrane viscosity solar pond
MSF  Multi-stage flash distillation
NASA  National Aeronautics and Space Administration
NCZ  Non-convective zone
PVC  Polyvinyl chloride
RMIT  Royal Melbourne Institute of Technology
SGSP  Salt gradient solar pond
TERI  Tata Energy Research Institute
UCZ  Upper convective zone
Abstract

Solar energy is likely to be the energy of the future; solar ponds, especially salinity gradient solar ponds (SGSPs), facilitate simple and cost-effective thermal energy storage. Research on maximising their potential is of particular relevance to developing countries, which often have an abundance of solar energy and a critical need for increased power supplies. For this research, a theoretical model for heat transfer in a SGSP was developed to study the energy balance in the three separate zones: the upper convective zone (UCZ), lower convective zone or storage zone (LCZ) and non-convective zone (NCZ). The model showed that the LCZ temperature could reach more than 90 °C in summer and more than 50 °C in winter, in a pond in the Middle East. It was also concluded that surface heat loss occurred mainly by evaporation.

The new model was also used to examine the feasibility of a second type of solar pond, the gel pond; this offers solutions to some of the SGSP’s challenges, but presents other difficulties relating to cost and labour.

To verify the theoretical results of the SGSP, a small experimental pond was constructed and operated for 71 days in Nasiriyah, Iraq. It was observed that adding a thin surface layer (0.5 cm) of paraffin eliminated the significant evaporation seen in the uncovered pond. Further analysis of the evaporation rate showed a significant correlation with temperature, solar radiation and humidity. Crucially, it was also noted that while the salinity gradient in the NCZ remained substantially intact, the temperature profile became approximately uniform throughout the pond after about 50 days.

Analytical formulae to describe the concentrations and temperatures of the UCZ and LCZ were derived. The results achieved and comparisons with the experimental data showed that these equations can be used to compute both concentrations and temperatures.
Chapter 1

Introduction
1.1 General introduction

Energy is a key factor in the economic growth and quality of life of all countries and communities. The availability of energy services is essential for most human activities, and has clear links with poverty, health issues and many other critical areas of society. More than two billion people have no access to affordable energy services, and without this, their opportunities for better living standards and a comfortable and decent life are restricted (Goldemberg and Johansson, 2005).

Demand for energy and related services to meet human needs and improve health services is noticeably increasing as humanity develops. Generally, all societies require energy services to meet basic human requirements (e.g. lighting, cooking, heating and communication) and business and industrial needs. However, with the serious challenge of climate change facing the world, it is essential to exploit renewable energies, helping reduce the impact of climate change by cutting emissions of greenhouse gases (GHG). Increasing investment in this energy sector worldwide might change the future of the next generations by enhancing the environment. Keles and Bilgen (2012) claimed that renewables offer the best opportunity to reduce greenhouse gases and introduce sustainable and desirable solutions to the increasing demand for energy. It should also be noted that while the consumption of fossil fuels is highest in the developed world, the impact of climate change will be felt disproportionately in developing and least developed countries.

Human health and prosperity are threatened by the high levels of pollution resulting from the use of conventional fossil fuels (coal, oil and oil derivatives) for energy generation; limiting the utilisation of these energy sources is therefore an important aim. Economic development has been positively correlated with increases in both energy use and GHG emissions. Renewable energy can undoubtedly change that correlation, since renewables are sustainable with low or no GHG emissions (IPCC report, 2012). Continuation of international dialogue, cooperation and coordination between nations (developed, and developing), along with new policies on energy for sustainable development, can substantially improve the usage of renewables.

The use of renewable energies for power generation has increased significantly in recent years. Their contribution to global energy supply is shown in Figure 1.1.
It is evident from Figure 1.1 that renewable energy sources supplied 12.9% of total global energy in 2008, and more than 10% of this global energy was produced by exploiting biomass. In spite of financial difficulties, renewable energy growth has continued significantly, including wind power, hydropower, geothermal power, solar energy and other types of renewables (Keles and Bilgen, 2012). Figure 1.1 also illustrates that in 2008 more than 60% of global energy was generated from oil and coal combustion. It is broadly accepted that the continuous use of these resources will profoundly affect the environment; the recent global consensus is to reduce such usage by exploiting renewables and extending green areas around the world.

1.2 Solar energy
In the last decade the use of solar energy for power generation has progressed tremendously, particularly in developed nations. Its development from 2004-2012 is shown in Figure 1.2.
Figure 1.2 shows a continuous increase in solar power generation from 2004-2012, reflecting the increasing interest in this technology. Most of this energy was generated in developed countries, as shown in Figure 1.3.

It is evident from Figure 1.3 that solar power generation achieved a significant increase over 10 years in the leading supplier countries, rising from around 2 terawatt-hours (TWh) in
2003 to more than 90 TWh in 2012. The figure shows Germany as the leader in this field, followed by Spain and Italy, with most of the energy being generated in Europe and the USA, and with Japan and China as the leading contributors in Asia and the Pacific.

The benefits of any energy source must be assessed not only in terms of economics but also in terms of its short- and long-term impacts on ecology and human life. Solar power-based technologies could be the most natural form of energy harvesting, offering unlimited power generation as long as the sun shines on the surface of our planet. They could be the only technologies capable of providing unlimited energy production, regardless of human population growth, as long as the production tools are available (Gevorkian, 2012; Gevorkian, 2016; Napoleon and Akbarzadeh, 2014). Most technologies linked to power generation, including electrical power generated from conventional fuels, atomic energy or biofuel, require a constant supply of feedstock. On the other hand, solar energy uses natural resources to generate electricity, with no need for fuel or feedstock. The technologies convert the abundant energy of the sun into useful power. Solar energy is clean and sustainable, and is appropriate for many developing countries because they have suitable weather (most developing countries are in Africa and the Middle East, with some countries in Asia and Southern America). However, a lack of advanced technologies and funding, along with the presence of conflicts in some of these countries, is delaying the full utilisation of this energy.

1.3 Types of solar energy application

Solar energy applications can be divided into two categories according to their use:

1. Water and space heating applications
2. Electricity generation applications

The different types of solar energy applications are illustrated in Figure 1.4.

Figure 1.4: Types of solar applications according to their utilisation
1.3.1 Water and space heating applications

1.3.1.1 Flat plate solar collectors

A flat plate solar collector is essentially a flat box comprised of four main parts:

(i) a transparent cover plate to allow sunlight to enter and be absorbed in the water body;
(ii) tubes which carry the fluid to transfer the thermal heat between the solar collector and
   the storage tank or any end use, usually made of copper or material with high thermal
   conductivity;
(iii) an absorber plate to absorb the incoming solar radiation;
(iv) a thermal insulation layer to minimize heat loss from the unit and increase collection
   efficiency (Gevorkian, 2016; Norton, 2013).

Figure 1.5 shows photos and a cross-section of a flat plate collector.

![Figure 1.5: Images of flat plate solar collectors showing (a) photo of installation on rooftop; (b) photo of external appearance; (c) cross-section of components](https://www.google.co.uk/search?q=solar+collectors+images&tbm=isch&imgil)

1.3.1.2 Evacuated tube solar collectors

Evacuated-tube collectors are made up of either concentric glass tubes or a metal tube, sealed at one end, within a glass tube. A surrounding evacuated annular space and a selective absorber surface ensure that there is little overall heat loss. The evacuated space between the glazing and absorber reduces convective loss. Evacuated tube solar collectors are much lighter and
Chapter 1: Introduction

more efficient than flat plate solar collectors for high-temperature operation, and they heat up more rapidly than the flat plate collectors (Norton, 2013; Budihardjo et al., 2007). Photos of the evacuated tube unit and a cross-section of the vacuum tube are illustrated in Figure 1.6.

![Figure 1.6: Images of evacuated tube solar collectors showing (a) and (b) photos of tubes connected to a tank or pipe to exchange heat with cold water; (c) cross-section of tube; (d) photo of collectors installed on roofs (www.siliconsolar.com; interestingenergyfacts.blogspot.co.uk; www.sunmaxxsolar.com)](image)

Figure 1.6 (c) illustrates that the principle behind solar vacuum tubes is not complicated; the absorbed solar radiation transfers to the heat transfer fluid (a small amount of water or non-toxic liquid) in the tube located in the middle of the enclosed tube. The liquid heats up quickly, converting to vapour, and rises to the top. The hot vapour then exchanges heat with water and moves down again. This process continues for as long as sunlight is available.

1.3.1.3 Solar ponds
A solar pond is a body of water which can collect and store solar energy. Further explanation of solar ponds, and in particular SGSPs, will be included later in this chapter and in Chapter 2.

1.3.2 Electricity generating applications
1.3.2.1 Photovoltaic panels
Photovoltaic (PV) cells are electronic devices that convert solar energy directly into electrical power. Unlike many power generation technologies, PV cells have the ability to convert
abundant and free solar energy into electricity. This conversion occurs without producing the damaging pollution usually associated with conventional methods of generating electricity such as fossil fuels, nuclear power stations or other non-renewable methods. The solar cells convert energy for as long as there is sunlight. The energy generation decreases during cloudy conditions and stops entirely at dusk. Solar panels have no ability to store electricity, and consequently batteries are required to store the generated power. These panels can be installed on roofs or as a field of panels covering a large area. PV technology has recently become a competitor to other methods of power generation, such as fossil fuels and nuclear energy (Gevorkian, 2012; Kaltschmitt et al., 2007). Solar photovoltaic panels are illustrated in Figure 1.7.

Figure 1.7: Images of solar panels showing (a) photo of solar panels on a roof; (b) photo of a field of solar panels; (c) schematic of power generation and electrical current flow through the load (www.solarenergyxpert.com; www.scienceabc.com)

Solar panels absorb photons of the incident solar radiation, and these photons energise electrons in the semiconductor material of the panel to create a flow of electrical current. The current is transferred via conductors (wires, usually made of copper, aluminium or a particular alloy) to the end use or storage batteries. PV cells have many advantages: they can turn free solar radiation into useful electrical power; their annual degradation is very small, with some companies offering a guarantee of 25 years; they require minimal maintenance; and production and construction costs continue to decrease (Gevorkian, 2016; Anderson, 1977). However, the
efficiency of the solar panel decreases as temperatures increase, and above 45 °C the efficiency reduces by about 10%; this means a reduction in electricity generation in hot areas even in sunny conditions.

1.3.2.2 Concentrating solar power

In this technology, plain or curved mirrors or lenses are used to reflect and concentrate a large area of sunlight onto a small absorbing area, thus increasing the energy received per unit of surface area in this absorbing small zone. The concentrated energy from sunlight is used to create steam, which drives turbines in power stations to generate electrical power.

Concentrating solar power technology has three main types: the parabolic trough, parabolic dish and solar tower. This solar energy technology has several advantages including:

(i) it reduces the absorber surface area and consequently costs, as the absorber is made of expensive material, while much cheaper materials are used to reflect the light onto it;
(ii) it enables much higher temperatures (more than 500 °C) to be reached, which are significant in the process of power generation (Chauliaguet et al., 1979; Kaltschmitt et al., 2007; and Napoleon and Akbarzadeh, 2014).

Figure 1.8 illustrates concentrating solar power technologies.

Figure 1.8: Photos of concentrating solar power technologies showing (a) field of parabolic troughs; (b) field of solar dishes; (c) solar tower in Seville, Spain
1.4 Iraqi challenges

The energy sector is the cornerstone of any country’s economy; for Iraq, it is the most important factor which will enable the country to recover from decades of war, conflict and economic sanctions. The conflicts and sanctions have profoundly affected the country’s infrastructure and have caused a significant fall in living standards (IEA, 2012).

Damage to the environment can be observed clearly in Iraq: deforestation, poor agriculture and water resources management, dust and sand storms, and erosion have all negatively influenced the environment. Moreover, energy generation stations have added millions of tonnes of CO₂ gas and other pollutants (gases and suspended particles), due to the burning of massive quantities of crude oil and some petroleum products. This situation pointedly invites the authorities and others to take action, and accordingly, serious practical steps have to be taken in two directions. Firstly, increase efforts to reduce the dependency of power generation on traditional fuels (crude oil and petroleum products), and compensating for this reduction by expanding investment in renewable energy. Secondly, moves to create a new public attitude towards the environment by applying new policies and obligations.

A report by the International Energy Agency (IEA) in 2012 pointed out that 60% of Iraq’s water resources came from Turkey and Syria, i.e beyond its national borders, via the Tigris and Euphrates rivers, and noted that it was therefore impractical for Iraq to depend only on these rivers for its water supply. The report also indicated that the lack of electricity was an obstacle to the development of Iraq’s industries and the rebuilding of its infrastructure. Until now, about 80% of the electrical power in Iraq has been generated by burning traditional fuels; this percentage is very high compared with less than 50% in other Middle East countries. The present electricity supply does not meet demand, and there are ongoing programmed power cuts in most parts of the country. These power cuts, a daily occurrence usually involving three hours of supply followed by a three-hour cut, have prompted many people to use private diesel generators, creating another source of pollution and noise.

1.4.1 Renewable energy in Iraq

The role of renewable energy sources in Iraq is small but significant. There is a clear case for supporting and enhancing electricity production from renewables, in order to diminish the country’s reliance on conventional fuels, decrease pollution and develop the country’s economy. Hydropower is the major kind of renewable currently being exploited for power generation in Iraq. There is considerable government interest in extending it, particularly in Kurdistan in the north of the country (IEA, 2012). However, with water availability clearly the
main factor required for this technology to function, water shortages will affect its potential for further exploitation. Other renewables also face particular challenges in Iraq: for example, the use of wind power would be impractical given the relatively low wind speeds in the country; while biomass energy is quite a new technology in the country, and has no solid base. Solar energy therefore emerges as the best renewable energy resource for exploitation. It offers considerable untapped potential and fulfils all the central goals of reducing reliance on conventional fuels, reducing pollution and helping the economy develop.

### 1.4.1.1 Solar energy for Iraq

Solar thermal technology can be used for collecting and storing solar energy in the form of thermal heat and in a range of 100–500 °C. Non-concentrating collectors such as solar ponds, evacuated tube and flat plate solar collectors can be used to supply low-grade heat for domestic hot water supplies, space heating for residential premises and for some industrial processes which require only low temperatures. The solar pond, and particularly the salinity gradient solar pond (SGSP), is a type of collector which can supply large amounts of low-temperature heat inexpensively. The SGSP can also store heat from the sun for a long period (Yaakob, 2013; Swift et al., 1987).

Iraq has abundant solar resources, suitable weather and land availability for establishing projects to exploit solar energy for power generation and other thermal applications. In 2012, the IEA reported that Iraq has the best solar irradiance in the Middle East, with levels similar to those in North Africa.

The role of renewables in Iraq is still in its early stages, but it is already clear that solar energy can make a tremendous contribution towards solving the country’s energy and water shortages, as well as reducing GHG emissions. The use of photovoltaics presents difficulties including the high cost compared with fossil fuels, and the dusty conditions which are common in Iraq and might decrease efficiency over time as dust accumulates on the surface of the panels. Moreover, as already noted the efficiency of solar panels declines as temperatures increase and Iraq experiences very hot summers.

The solar pond can be considered as a suitable source of thermal power for many applications requiring low-grade temperature, for the following reasons:

1. **It provides clean, sustainable energy with reasonable construction costs and its thermal capacity is massive compared with other solar thermal collectors; this capacity can be improved by increasing the depth of the LCZ:**
(ii) It can store thermal heat for an extended period; heat can be collected in the hot summer and extracted in the colder winter;

(iii) It can supply heat even in cloudy weather and overnight.

(iv) It can be coupled with other solar energy applications such as the solar still and solar panels (El-Sebaii et al., 2008; Appadurai and Velmurugan, 2015; and Bozkurt and Karakilcik, 2012).

It is possible to generate electrical power using the SGSP, but the relatively low efficiency of this process renders it uncompetitive. However, coupling the SGSP with other solar energy applications and with other technologies increases its potential and can be expected to result in greater interest in it. Using SGSPs to run applications such as water desalination, greenhouse heating, biogas production, crop drying, and aquaculture for farming warm water fish and shrimps, will enable other electricity supplies to be used for other purposes.

For the purposes of this study, in order to generate data from a SGSP sited in Iraq, it was decided to construct an experimental pond in Nasiriyah in the south of the country, enabling the potential of the SGSP to be fully explored and to study the parameters affecting its performance.

1.5 Salinity gradient solar ponds

A SGSP is a large pool of salt water which collects and stores solar thermal energy. The pond comprises three layers: the upper convective zone (UCZ), lower convective zone (LCZ) and non-convective zone (NCZ). The UCZ normally contains fresh or low salinity water which floats on top of the NCZ. The NCZ has layers of salt solutions that increase in concentration (and therefore density) with depth. There is no convection in this layer: the stratification in the concentration restrains the convection phenomenon. The NCZ floats on the third layer, the LCZ or storage zone, which has the highest salt concentration (near saturation), and in this layer, solar energy is trapped and stored. A schematic of the SGSP is illustrated in Figure 1.9.
Figure 1.9: Zones of the SGSP - the UCZ, which loses heat from the surface by convection, evaporation and radiation; the NCZ, with concentration and temperature gradients, and no convection currents; and the LCZ, the hottest layer with the highest salt concentration.

Figure 1.9 shows that when the solar radiation falls on the surface of the pond, some of this radiation will be reflected, and some will penetrate inside the pond. When fresh water is heated, it becomes less dense than the cooler water above it, and convection begins. The NCZ in the SGSP prevents the convection from continuing through the whole pond, and therefore convection occurs separately in the UCZ and the LCZ. In the NCZ, natural convection will be suppressed by the salinity gradient in this zone. The salinity of the NCZ increases from the top to the bottom of the zone. When a specific layer is heated, its density will decrease slightly. However, it will remain heavier than the layer above. This action will prevent convection which would be common in fresh water. In this case, the NCZ acts as a slab.

The NCZ significantly reduces heat loss from the LCZ, and heat moves upward only by conduction. This results in the temperature of the LCZ increasing to 100 °C or even more, while maintaining the UCZ at a lower temperature close to the ambient level. The heat stored in the LCZ can then be extracted for use in many different applications.

Evaporation suppression is an enormous task in areas of little rainfall and low runoff, and makes an important contribution to saving water. George et al. (1960) revealed that many factors affect evaporation: the surface area of the body of water, ambient temperature, wind
speed and relative humidity. Evaporation results in the loss of both heat and mass, and its elimination is therefore significant and will enhance the performance of the solar pond.

The variation in thickness of the SGSP’s layers has a substantial effect on the temperatures of all three layers. The thickness of the UCZ has to be kept as small as possible while the optimum thickness of the NCZ is 1-2 m (Jaefarzadeh, 2005; Kanan et al., 2014). The optimal thickness of the LCZ varies according to the pond’s purpose and operating temperature (Jaefarzadeh, 2005; Wang and Akbarzadeh, 1983).

The SGSP presents a number of challenges, such as the instability of the NCZ and high levels of surface evaporation. This study has explored these challenges, including successfully experimenting with the addition of a thin layer of paraffin on the surface of the pond to reduce evaporation. As solar gel ponds have been suggested as a means of overcoming these challenges, their viability has been studied and compared with SGSPs as part of this research.

1.6 Aims and objectives of the study

This study has two main aims:

(i) To study parameters affecting the performance (in terms of the temperature of the LCZ) of solar ponds, and in particular the SGSP, both theoretically and experimentally. The temperature of the LCZ is taken as an indicator of the performance because in the SGSP, temperatures are relatively low (under 100 °C) and therefore the quantity of heat stored is a function of the brine temperature in the LCZ; the useful heat is extracted from the LCZ. For a liquid system, the thermodynamic properties are only a strong function of temperature and so temperature and energy are entirely analogous. When the pond was covered, the UCZ became as an additional storage, and it is considered in the performance calculations achieved in Chapter 6; and

(ii) To investigate the viability of constructing SGSPs and gel solar ponds in southern Iraq.

To achieve these aims, the following objectives have been fulfilled:

1. The development of a model to describe the theoretical behaviour of temperatures within the SGSP. The model has also been utilised to study the gel solar pond.

2. The measurement of evaporation levels in the area of the study, to investigate their impact on the performance of the SGSP.
3. The investigation of the influence of meteorological factors on the evaporation from the surface of the solar pond.

4. The construction of a small experimental unit in Nasiriyah in southern Iraq to collect experimental measurements; these measurements have been compared with the theoretical data to verify the model that has been developed.

5. The studying of the SGSP’s behaviour when covered with a thin layer of paraffin to eliminate evaporation, to evaluate the benefits of covering the pond.

6. The derivation of analytical equations to compute the concentrations of the UCZ and LCZ, in addition to obtaining two analytical formulae to calculate temperatures in the same two layers. These concentrations and temperatures are compared with the experimental measurements and with some existing data from established ponds.

1.7 Structure of the thesis

This thesis consists of seven chapters including this introductory chapter. A brief description of the remaining chapters follows.

Chapter 2 presents a review of the existing literature on solar ponds in general and the SGSP in particular. For the SGSP, it draws together the most important theoretical and experimental studies. Salt type, water body construction, heat extraction from the pond and some applications are also discussed.

Chapter 3 presents the model developed for this study, in which heat conservation equations are applied to the SGSP’s zones and solved by a MATLAB code using the ode45 MATLAB function. The temperatures of the SGSP zones are calculated with and without heat extraction from the LCZ; the results are plotted against time and presented in the chapter. The validation of the model is also presented, and an acceptable agreement is observed. The model is used to study the impact of the thickness of the pond’s zones (UCZ, NCZ and LCZ) on the temperature of the LCZ and the UCZ.

Chapter 4 studies the gel pond. The temperature profiles of its layers are investigated using the model developed for the study. The chapter also presents a comparison between the SGSP and the gel pond, and estimates costs for both ponds.

Chapter 5 describes the small experimental unit in Iraq, including a full explanation of the tools, devices and procedures used. The pond’s make-up is discussed in detail, including the insulators and the filling of its zones.

Chapter 6 has been divided into two parts. In Part 6.1, the experimental results are illustrated and discussed. The temperature profiles in the SGSP zones are plotted against time
before and after the pond was covered with a thin layer of paraffin, and a significant divergence is observed. The influence of meteorological parameters on surface evaporation, and consequently on performance, is investigated and presented. Evaporation levels were found to be particularly high in summer, and prevention therefore needs to be considered. Salt diffusion (NaCl) from the LCZ upwards, as well as among the other layers of the pond is measured, and the results are presented and discussed. A comparison between the experimental results and the theoretical results given by the model is also presented in Part 6.1.

Part 6.2 presents derivations of analytical formulae to describe the changes in the concentrations and temperatures of the LCZ and UCZ over time. Several assumptions were adopted for this purpose. The results computed using the derived equations were compared to the experimental results of the current study and with some existing data. A good agreement is observed.

Finally, Chapter 7 presents the conclusions of this study regarding the temperatures and concentrations in the experimental unit. Findings concerning the evaporation levels are also presented, along with the theoretical results and recommendations for future research.

1.8 Publications Arising from this Work
Some of the materials presented in this thesis are published previously and the publishing materials are listed below.


Chapter 2

Literature review
2.1 Introduction

Scientists are worried about the high levels of pollutants, and they are therefore seeking alternative sources of energy. The best alternatives to the traditional sources of energy are renewable energies; they are clean and have sustainable resources. Solar energy is one of the important types of renewable, and solar ponds are a form of this energy.

2.2 Applications of solar ponds

Solar ponds and particularly SGSPs have been used in many applications which require temperatures less than 100 °C. Solar ponds are used to provide warm air for commercial salt production, crops drying, space heating, desalination, power production and hot water for the dairy industry. For this last application as an example, a 6000 m² SGSP was constructed at Bhuj in India to supply hot water to a dairy plant. The design capacity of the pond was to provide 80 m³ of hot water per day at 70 °C. Solar ponds could also utilise to provide thermal heat to any industrial process in a rural environment requiring low-grade thermal heat (up to 80 °C). This form of heating is significant in reducing fossil fuel consumption and consequently decreasing the emissions of GHG (Akbarzadeh et al., 2008; Kumar and Kishore, 1999; Lu et al., 2001; Velmurugan and Srithar, 2008; Valderrama et al., 2015). Power generation and desalination could be considered the most important applications among others and they are discussed in turn below.

2.2.1 Power production

Electrical power was generated from a SGSP by Tabor in 1963. The procedure was difficult and costly because the temperature in the pond was low (Nielsen, 1975). With solar ponds, electricity can be generated by using a turbine exploiting a low boiling point working fluid in a Rankine Cycle, but with low efficiency (El-Sebaii et al., 2011). When the thermal efficiency is defined as the percentage of the amount of heat removed from the solar pond to the amount of the incident solar radiation on the surface of the pond during a particular period, it will be higher. For this definition to be meaningful, the considered period should be long enough. It was found that the solar pond could supply heat with an efficiency of 15% and 20% for temperatures of 87 and 65 °C respectively (Wang and Akbarzadeh, 1983). The cost of an Organic Rankine Cycle (ORC), which is used with solar ponds, is high when compared with conventional fuels. However, electricity from solar ponds can be competitive when the pond is large and when environmental pollution treatment costs related to traditional fuels are taken into account (Leblanc et al., 2011). On the other hand, Alrowaished et al. (2013)
implied that the solar pond could be very promising for power generation for regions with suitable solar insolation and land to construct large solar ponds. Developing new types of organic fluids for the Rankine Cycle can decrease prices and increase the efficiency of solar ponds for power generation. Figure 2.1 shows the Alice Spring salinity gradient solar pond in southern Australia and the ORC engine installed on the pond.

![Alice Spring SGSP](http://members.optusnet.com.au) 

The pond had a 0.5 hectare surface area, and was designed to produce 15 kW of electricity; the research project continued for five years.

### 2.2.2 Desalination

Simply, desalination means removing salt from water to make it potable. The definition of desalination can include treatment of all impurities in water such as salts, biological organisms, chemicals and other contaminants in order to be drinkable. These impurities cannot be removed by conventional methods of water treatment such as coagulation, sedimentation and other processes (Younos and Tulou, 2005).

Coupling desalination with solar ponds could be a very beneficial process, and there are many industrial units and studies dealing with this technology. The conventional process is coupling a desalination unit with a SGSP. Several technologies have been used for coupling desalination with solar ponds; thermal desalination is one of them. It involves multi-stage flash distillation (MSF) and multi-effect distillation (MED). Thermal desalination consumes enormous quantities of energy, and that will increase the cost of water production. Coupling of a thermal desalination unit with a SGSP will decrease the cost of water production substantially.
and also the pollution problems (Lu et al., 2004, Walton and Swift, 2001; Al-Hawag and Darwish, 1994)

Caruso and Naviglio (1999) designed a desalination unit which was connected to a solar pond. The proposed desalinator was made entirely from titanium - in spite of the high cost of titanium, there are several properties which make it valuable for using in this system. First of all, it has a high resistivity to salty water and chemicals. Consequently, the unit will have a long life and the cost of maintenance will diminish. The unit was connected to the salt gradient solar pond in the University of Ancona in Italy. After one year of experimental research, it was concluded that a titanium unit is suitable for desalination when coupled with a SGSP.

Many other studies have investigated utilizing a salinity gradient solar pond for desalination (e.g. Lu et al., 2001; Liu et al., 2013; Glueckstern, 1995; Agha, 2009; Leblanc et al., 2010; Velmurugan et al., 2009; Velmurugan and Srithar, 2007; Antipova et al., 2013; Gude et al., 2012; and Gude, 2015).

2.3 Classification of solar ponds

There are several types of solar ponds; they can be classified into two categories: convective and non-convective solar ponds (Alrowaished et al., 2013). A simple diagram (Figure 2.2) can be drawn to illustrate types of the solar ponds.

![Diagram showing the different types of solar ponds.](image)

**2.3.1 Convective solar ponds**

By definition, convection commonly occurs in this type of pond, and they are typically shallow as well. A shallow solar pond is a saltless pond. Jayadev and Edesess (1980) claimed that the main advantage of shallow ponds is that they can be located rooftops- if the structure
of the building is strong enough. Anderson (1980) considered the shallow pond as a batch process, with a warming operation during the day followed by a storage process in the night. Abdelsalam (1985) described a shallow pond comprising a plastic bag made from PVC which is transparent at the top with a thickness of 0.3 mm. The PVC which covers the bottom of the pond is black to absorb radiation and 0.5 mm thick.

In these ponds there is no insulating zone or non-convective zone (NCZ) to prevent heat transfer by convection throughout the water body, the pond is operated under normal atmospheric conditions (Anderson, 1980). The pond is covered by plastic or any other non-opaque material lid. Figure 2.3 shows schematics of two approaches of the shallow solar pond.

Figure 2.3: Two schematic diagrams of the Shallow pond, (a) a simple shallow pond (batch process), (b) a shallow pond has a heat exchanger to circulate water for the heat extraction (closed process)

Figure 2.3 shows that the make-up of a shallow pond is not complicated, and the essential parameter it needs to function is the sunlight. Figure 2.3(a) illustrates that solar energy is absorbed and converted to thermal energy by heating the water in the pond during the daytime. Hot water is transferred to an insulated storage tank; this can be in the night time or when the collection efficiency approaches zero. Figure 2.3(b) demonstrates that thermal heat is transferred via utilization of a coil heat exchanger.

Kishore et al. (1987) considered the shallow solar pond as a cheap source of energy. They used PVC glazing, and they suggested that a PVC cover can be utilized for approximately one year because the resistance of PVC to the sun heat might decrease after this period. The pond is by definition not deep, and its maximum depth is 15 cm (Garg, 1987). Prasad (2001) implied that
the typical depth of a shallow pond is only a few centimeters. El-Sebaii et al. (2011) claim that the efficiency of heat collection (in the shallow pond) from the sun is directly proportional to the water depth, whereas the water temperature is inversely proportional to the depth of water in the pond.

Three modes have been used for the heat extraction from the shallow pond: (i) batch process, (ii) closed process (iii) and open continuous cycle. The batch mode is shown in Figure 2.3(a); in this mode, the pond is filled with water in the morning, and the warm water is withdrawn from the pond when the temperature reaches the maximum. In the closed process which is shown in Figure 2.3(b), an appropriate heat exchanger is used; the working fluid (water) is continuously circulated at a constant rate to transfer thermal heat between the shallow pond and the storage tank. In the open continuous cycle mode; the cold water at initial temperature is followed continuously at a constant flow rate throughout the pond and taken either to storage tank or to some end use for domestics or other purposes (Aboul-Enein et al., 2004; El-Sebaii et al., 2006; El-Sebaii et al., 2011).

2.3.2 Non-convective solar ponds

The interest in solar ponds, particularly the salinity gradient form has increased substantially as a consequence of greenhouse gas emissions that result from the combustion of fossil fuels in power generation processes. There are several types of non-convective solar ponds (Figure 2.2), and in these ponds heat transfer due to convection in the water body is suppressed by the middle layer of the water body. These are discussed in turn below.

2.3.2.1 Salinity gradient solar ponds (SGSP)

Historical Background

Salinity gradient solar ponds were discovered as a natural phenomenon in Transylvania by Kalecsinsky when he presented measurements on Lake Medve (Yaakob, 2013). The temperature in summer was approximately 60 °C at a depth of 1.3 m; the sodium chloride concentration at the bottom was found to be near saturation. Interestingly, there was fresh water in the surface layer. Kalecsinsky concluded that artificial solar ponds might be useful for heat collection and storage. The salinity gradient solar pond was suggested as a source of energy by collecting and storing solar energy from the sun, by Bloch (1948) in Israel. Significant research efforts began in the 1960s, mostly concerned with generating electricity using the heat from the ponds. Studies continued until 1967 in the same country (Israel) (Nielsen, 1975). The aim was the production of electrical power from solar energy captured by the salinity gradient solar
pond. In 1977, a 1500 m$^2$ pond was constructed in Israel to generate 6 kW of electricity by a turbine operating a Rankine cycle. A pond of area 6250 m$^2$ in Ein Boqeq was built in the same year to produce 150 kW of electricity (Weinberg and Doron, 2010). In 1983, the El Paso solar pond was established, and it has been in operation since 1985 (Alenezi, 2012). In 1986 electrical power was produced from this pond, and it was the first pond in the USA which generated electricity. The maximum temperature in the storage zone (El Paso pond) reached 69-90 °C (Leblanc et al., 2011). Photos of El-Paso solar pond are shown in Figure 2.4.

![Figure 2.4: Photos of the El-Paso solar pond; (a) the pond and the facilities; (b) the top surface of the pond; it shows tubes use for the heat extraction (Leblanc et al., 2011).](image)

**Description of the SGSP**

Salinity gradient solar ponds are the most important solar ponds which are globally constructed and implemented for many different purposes. They can supply thermal energy to a wide range of applications that need only low-grade heat to run (Ruskowitz et al., 2014; Hull
et al., 1988; Alrowaished et al., 2013; Caruso and Naviglio, 1999; Dehghan et al., 2013; Kurt et al., 2000; Sakhrieh and Al-Salaymeh, 2013; and Abbassi Monjezi, and Campbell, 2016). A salinity gradient solar pond is a body of water with a depth of 2-5 m and a gradient of salt concentration. It consists of three distinct zones: the surface layer or the upper convective zone (UCZ), the middle layer or the non-convective zone (NCZ) and the lower convective zone (LCZ) (Jaefarzadeh, 2004). The UCZ is approximately homogenous, and it is a relatively cold layer made from freshwater or low salinity brine. The NCZ has a salinity gradient i.e. the salinity increases from the top to the bottom of the layer. When a particular layer in the NCZ is heated, its density will decrease but will remain higher than the layer above due to the salinity gradient. Consequently, upward movement due to buoyancy will cease, and heat can only move by conduction, from the lower layer to the top, through the NCZ.

Nielsen (1975) considered the SGSP a simple means of collecting and storing solar energy. Solar radiation, which enters the lower layer of the pond, is stored by suppression of convection currents (Hull et al., 1984). To prevent convection, salty solution (water) is used in the solar ponds. Therefore, scientists named them salt gradient solar ponds or salinity gradient solar pond (SGSP) (Velmurugan and Srithar, 2008; Tundee et al., 2010; Weinberg and Doron, 2010). A schematic of the SGSP is illustrated in Figure 2.5(a).

Figure 2.5: (a) A schematic diagram of a salinity gradient solar pond (SGSP). The pond surrounded by an insulator to minimize the heat loss, particularly from the bottom, the pond zones are the UCZ, the NCZ and the bottom layer (LCZ), convection currents only in the top and bottom layers, (b) The change in the density of sodium chloride brine with the salinity and temperature (Perry, 1999). 

Figure 2.5(a) illustrates that 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, and its existence is the key to the operation of a SGSP (Lu et al., 2004; Karakilcik et al., 2006; Karakilcik et al., 2013; and Valderrama et al., 2011). Jaefarzadeh (2004) pointed out that the thermal capacity, maintenance and construction costs of the salinity gradient solar pond determine its viability. Figure 2.5(b) shows that the brine density increases as its salinity rises. The figure clarifies (Figure 2.5(b)) that the brine density with a salinity of 2 wt% is around 1 gm/cm$^3$ while it is more than 1.2 gm/cm$^3$ for the brine of 26 wt%. Moreover, Figure 2.5(b) illustrates that the impact of the temperature on the brine density is insignificant in the range of 0-100 °C.

Thermal storage capacity can be changed with the thickness variation of the storage zone (LCZ). Many theoretical and experimental studies have aimed to investigate ways to enhance the performance of the SGSPs (e.g. Bezir et al., 2008; Suarez et al., 2014; Jaefarzadeh, 2006; and Andrews and Akbarzadeh, 2005). The thickness of the different zones of the SGSP has a substantial effect on its performance. This issue has been discussed by many researchers in the past (e.g. Jaefarzadeh, 2005; Wang and Akbarzadeh, 1983; and Kanan et al., 2014). Further investigation regarding the influence of the pond’s zone thickness on the temperatures of the LCZ and its relationship with heat extraction is required.

**Geometrical shape**

Solar ponds can take any geometrical shape. There are square, rectangular or circular cross section ponds, and the walls can also be vertical or sloping. However, a trapezoidal shape is often preferred and it is shown in Figure 2.6.

![Figure 2.6: The most common shape of solar pond (trapezoidal) (Leblanc et al., 2011).](image)

Slopping walls (Figure 2.6) have several advantages. Firstly, their construction is simple and cheap. Secondly, the quantity of the salt required for water body construction is less than...
a pond with vertical walls and that means decreasing the cost of construction and a reduced threat of environmental pollution by the salt contamination. Thirdly, the temperature of the LCZ will increase faster since the area which receives solar radiation is much higher the storing area. Additionally, people accidentally falling in the pond can easily climb to the top of the pond without assistance if the slope is suitable (Unsworth et al., 1985). The effect of inclination of the pond’s walls on the salinity gradient was investigated theoretically by Akbarzadeh (1984). The results showed that sloping walls would increase the concentration gradient at the bottom of the LCZ, and that will enhance the stability of the layer. On the other hand, it will decrease the gradient at the top of the LCZ. It was also found that the effect of sloping walls is small in the case of large ponds.

Salinity gradient solar pond world wide

USA

Nielsen commenced the research on the SGSPs as long term heat storage devices in 1974. The research was at the Ohio State University, a prototype of a SGSP with 200 m² surface area was built in the University, and it started work in summer 1975 (Nielsen, 1975). The pond achieved a maximum temperature of 69 °C in August 1977. Another SGSP was constructed by the University of New Mexico in 1975; the geometrical shape was circular with a horizontal cross section, and the maximum temperature reached 93 °C in August 1977. The aim of the construction was to support the heating of a single house. The Hydrodynamics of the pond were studied by Zangrando (1991) to obtain a useful guidance on SGSP operation (Yaakob, 2013; Alenezi, 2012).

In 1983, the El Paso Solar Pond was established by the University of Texas. The pond was built for research and development purposes, and it was the first pond to provide energy to the industrial factory when it delivered thermal heat to a food canning factory, where 350×10⁶ kJ of thermal heat has been supplied to the adjacent canning factory. The surface area of this pond is 3000 m², and the depths of its layers are 0.7, 1.2 and 1.35 m for the UCZ, NCZ, and the LCZ respectively. An aqueous solution of sodium chloride (NaCl) was used in this pond to form the three layers of the water body (Lu et al., 2001).

Israel

Many salinity gradient solar ponds were constructed in Israel because of the suitability of the weather in this area for utilizing this type of thermal collection and storage. A pond with a
surface area of 6250 m$^2$ and a depth of 2.6 m was built in Ein Boqeq in 1978 on the shore of the Dead Sea (Yaakob, 2013).

Ormat Company constructed two SGSPs in Bet Ha-Arava in 1982 with a total surface area of 250,000 m$^2$ on the north shore of the Dead Sea. The aim was to generate 5 MW of electrical power. This pond was decommissioned in 1990 for several reasons; some of these reasons were geopolitical. In addition, some technical difficulties appeared such as the efficiency of the whole system being at a low 1%. This efficiency was calculated as the overall efficiency of conversion from incident sunlight to electricity produced by the ORC turbine. Interestingly, the actual annual pond efficiency was 16% which was the heat absorbed to the incident solar radiation on the pond’s surface. Moreover, design problems with some units in the project were apparent, such as in the heat exchanger and cooling facilities (Date and Akbarzadeh, 2013; Hull et al., 1988).

**Australia**

A salinity gradient solar pond was constructed at Pyramid Salt’s facility in northern Victoria in Australia. It was a collaborative project between two Australian companies (Geo-Eng Australia Pty Ltd. and Pyramid Salt Ltd.) and RMIT University (Leblanc et al., 2011). The surface area of the pond was 3000 m$^2$ with a total depth of 2.3 m with layer thicknesses of 0.3, 1.2 and 0.8 for the UCZ, NCZ, and the LCZ respectively. The construction commenced in February 2000, and pond began supplying heat in June 2001 (Yacoob, 2013). The heat was used in industry for high-grade salt production at the Pyramid salt factory and later also used for aquaculture.

A small and experimental SGSP was constructed in 1998 in the school of Aerospace, RMIT University, Melbourne, Australia; the geometrical shape was circular with a surface area of 53 m$^2$ and a total depth of 2.05 m. The pond was utilised for the experiments (Leblanc et al., 2011).

**Other countries**

There are many salinity gradient solar ponds which have built in many different parts around the world. In India, research on solar ponds and particularly on the SGSP commenced in 1970. Many experimental salinity gradient solar ponds were built: in Bhavnagar, Gujarat in 1970, in Pondicherry in 1980, Bangalore and other places. These experimental ponds were not connected to any application (Kishore and Kumar, 1996).

The first salinity gradient solar pond which was linked to an industrial process was the pond at Bhuj, India in the state of Gujarat in western India; it was cooperation between Gujarat
Energy Development Agency (GEDA), Tata Energy Research Institute (TERI) and Gujarat Dairy Development Corporation Ltd (GDDC). The surface area of the pond was 6000 m² with a total depth of 3.5 m; there is no precise information about the individual thickness of the layers of the pond. The construction was started at 1987 and the temperature in the lower zone reached about 99 °C in May 1991. However, heat extraction from the pond was launched at 1993. To decrease the construction cost, an indigenous lining was developed by using some local materials (Kumar and Kishore 1999). There are many salinity gradient solar ponds in other countries, for example, one is located at Apulia region of southern Italy with a surface area of 25000 m² and has been connected with a desalination unit. In China, a SGSP with a surface area of 2500 m² and a depth of 3 m and it is been used to produce lithium carbonate (Li₂CO₃) (Yacoob, 2013; Date and Akbarzadeh, 2013). A small experimental SGSP 8 m² with dimensions of 2×4×0.9 m was constructed in Kuwait City, and it was utilised to study the annual behaviour of the SGSP (Ali, 1986). Abdullah et al. (2016) built a SGSP with a surface area of 113 m² at Umm Al-Qura University in Saudi Arabia. The purpose of the pond construction was to investigate a new scheme for the measurements of temperature throughout the pond. Their pond (Abdullah et al., 2016) had a circular shape with horizontal cross section and a diameter of 12 m. The pond had a layer’s thickness of 1.35, 1.5, and 0.25 m for the LCZ, NCZ, and the UCZ respectively. Some artificial salinity gradient solar ponds are listed in Table 2.1.
Table 2.1: Some artificial salinity gradient solar pond around the world

<table>
<thead>
<tr>
<th>Location</th>
<th>Name</th>
<th>Year</th>
<th>area (m²)</th>
<th>Depth (m)</th>
<th>Salt</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Israel</td>
<td>Ein Boqeq</td>
<td>1978</td>
<td>6250</td>
<td>2.6</td>
<td>Dead Sea brine</td>
<td>Yaakob (2013)</td>
</tr>
<tr>
<td>Israel</td>
<td>Bet Ha Arava SGSP</td>
<td>1982</td>
<td>40,000</td>
<td>4.5</td>
<td>Dead Sea brine</td>
<td>Hull et al. (1988)</td>
</tr>
<tr>
<td>Israel</td>
<td>Bet Ha Arava SGSP</td>
<td>1983</td>
<td>210,000</td>
<td>4.5</td>
<td>Dead Sea brine</td>
<td>Hull et al. (1988)</td>
</tr>
<tr>
<td>USA</td>
<td>El-Paso SGSP</td>
<td>1983</td>
<td>3000</td>
<td>3.25</td>
<td>NaCl</td>
<td>Huanmin et al. (2001)</td>
</tr>
<tr>
<td>USA</td>
<td>Nevada power Co., Moapa</td>
<td>1988</td>
<td>160,000</td>
<td>3</td>
<td>Na₂SO₄</td>
<td>Hull et al. (1988)</td>
</tr>
<tr>
<td>Argentina</td>
<td>University of Salta</td>
<td>1982</td>
<td>400</td>
<td>2.4</td>
<td>Na₂SO₄/NaCl</td>
<td>Lesino et al. 1982</td>
</tr>
<tr>
<td>India</td>
<td>Bhuj SGSP</td>
<td>1987</td>
<td>6000</td>
<td>3.5</td>
<td>NaCl</td>
<td>Kumar and Kishore (1999)</td>
</tr>
<tr>
<td>Italy</td>
<td>University of Ancona</td>
<td>1987</td>
<td>625</td>
<td>3.5</td>
<td>NaCl</td>
<td>Caruso and Naviglio (1999)</td>
</tr>
<tr>
<td>Australia</td>
<td>RMIT University</td>
<td>1998</td>
<td>53</td>
<td>2.05</td>
<td>NaCl</td>
<td>Leblanc et al. (2011)</td>
</tr>
<tr>
<td>Australia</td>
<td>Pyramid Hill SGSP</td>
<td>2000</td>
<td>3000</td>
<td>2.3</td>
<td>NaCl</td>
<td>Date and Akbarzadeh (2013)</td>
</tr>
<tr>
<td>Spain</td>
<td>Solvay- Catalonia</td>
<td>2009</td>
<td>50</td>
<td>2.8</td>
<td>NaCl</td>
<td>Valderrama et al. (2011)</td>
</tr>
<tr>
<td>China</td>
<td>Tibet plateau</td>
<td>2002</td>
<td>2500</td>
<td>3</td>
<td>NaCl brine</td>
<td>Nie et al. (2011)</td>
</tr>
<tr>
<td>Saudi</td>
<td>Umm Al-Qura</td>
<td>2016</td>
<td>113</td>
<td>3.1</td>
<td>NaCl</td>
<td>Abdullah et al. (2016)</td>
</tr>
<tr>
<td>Arabia</td>
<td>University’s Pond</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Salt selection

Salt type has a vital role in the construction of a SGSP. A suitable salt should be safely handled and its solution should have a positive absorptivity to the incident solar radiation. The change of the solubility with the temperature for sodium chloride (NaCl) and some other salts are illustrated in Figure 2.7.
It is shown in Figure 2.7 that the solubility of NaCl varies very slightly with temperature between 0-100 °C. It changes approximately between 35 and 40 g/100 g of water in the range of 0-100 °C. Sodium chloride (NaCl) is the most common salt that used in the construction of the SGSP because it is cheaper, safer, most available and more chemically stable than other salts. Most other salts solubility changes substantially with temperature (Figure 2.7), and this behaviour is not desirable in the SGSP and to elucidate further, the solubility of some other salts and sodium chloride (NaCl) in water is shown in Figure 2.8.
The solubility of the salt in water is of fundamental significance because it determines the range of salt concentration (salinity), and consequently, the salinity gradient (Hull et al., 1988). Figures 2.7 and 2.8 show that the solubility of the NaCl is nearly constant with the temperature increase and that means there are no difficulties expected with the saturation when the pond is warming up, or when heat is extracted from the pond (no salt precipitation). On the other hand, the solubility varies with the temperature change for other salts, and that will affect the salinity gradient, and consequently the stability of the pond and salt precipitation is anticipated when the temperature of the LCZ decreases due to the heat extraction. This explains why NaCl is desirable in the construction of the SGSP.

**Construction of the salinity gradient**

The site selection before start the construction of the pond is significant; the selected site should have plentiful of flat land to decrease the cost of the excavation. Moreover, it is preferable if the ground water table is deep to minimise the heat loss to the ground and the cost of the base insulation of the pond. In addition, the site must have a suitable level of incident solar radiation and weather most days of the year. The construction of a solar pond in general and a SGSP, in particular, can be divided into two main parts. The first is the civil engineering work which includes excavation, walls building and lining. The lining is a significant process, and the liner should be efficient to prevent water and salt leakage to the ground. The liner material should have a long lifetime and be capable of resisting the high temperature (around 100 °C) and the salty environment (Lu et al. 2004; Andrews and Akbarzadeh, 2005; Yacoob, 2013). Figure 2.9 shows the installation of lining system at El Paso solar pond.
The second part of the construction of the SGSP is the establishment of the water body including the salinity gradient throughout the NCZ. Establishing the water body of the pond and the salinity gradient, in particular, is the key to the work of the SGSP. The conventional method to create the salinity gradient is water injection through a suitable diffuser. Hull et al. (1988) pointed out that, based on laboratory tests by Zanardo and Johnstone (1988) and observations at the El Paso salinity gradient solar pond by Liao et al. (1988), the fluid mixing in the pond at the diffuser level is a strong function of the Froude number, which is defined as:

\[ F_R = \left( \frac{\rho v^2}{g \Delta \rho} \right)^{1/2} \]  

(2.1)

where, \( \rho \) is the density of the surrounding saline water in kg/m\(^3\), \( v \) is the injection velocity in m/s, \( g \) is the acceleration due to gravity in m/s\(^2\), \( \Delta \rho \) is the density difference between the injected and surrounding fluids in kg/m\(^3\) and \( \beta \) is the gap width of the diffuser in m. Figure 2.10 shows a picture of the diffuser utilized in the construction of the water body of the SGSP.

![Figure 2.10: Picture and scheme of the diffuser used in the formation of the salinity gradient of the 50 m\(^2\) experimental solar pond at Solvay-Martorell facilities, Catalonia (Spain) (Valderrama et al., 2011)](image)

Equation 2.1 demonstrates that Froude number is a dimensionless number. It represents the ratio between the kinetic energy and the gravitational energy of the injected fluid. It was concluded that to achieve perfect mixing at the injection diffuser level, it is required to maintain the Froude number approximately constant at 18 (Leblanc et al., 2011) and this can be performed by controlling the parameters that appeared in Equation 2.1. When a particular flow rate is chosen, and the radius of the diffuser is determined, the gap of the injection diffuser can be adjusted frequently to any level in the pond to have a Froude number around 18.
To construct the layers of the water body, the pond is partially filled with the concentrated brine for a depth higher than the depth of the LCZ, and after that fresh or low salinity water is injected gently (Hull et al., 1988). Date and Akbarzadeh (2013) explained the same previous method, but with a slight difference. Firstly, the pond is filled with fresh water up to a certain depth from the bottom. Secondly, the salt (commonly sodium chloride NaCl) is added and allowed to dissolve for the LCZ layer creation. The concentration is approximately 25% wt. Thirdly, to create the NCZ layer, a suitable diffuser is used which can inject fresh or low salinity water. The first location for the diffuser can be fixed according to the required thicknesses of layers above the bottom, and it is gradually moved upward. This method was used to construct the layers of a pond of 53 m² in RMIT University in 1998 and refilled in 2007 and many other large ponds around the world. It might be that this method is suitable for the large ponds. Photos of RMIT pond are shown in Figure 2.11.

![RMIT pond photos](image)

Figure 2.11: Photos of the RMIT experimental salinity gradient solar pond, (a) the external appearance of the pond showing it full of water and built on the ground, (b) the salt charger, and showing also the floating rings to reduce the impact of wind, (c) the diffuser used to setup the salinity gradient (Leblanc et al., 2011)

Aizaz and Yousaf (2013) constructed the salt layers by using different procedures. The pond had a volume of 2.4 m³. The area of the base was 1 m² and depth of the pond was 1.28 m with
inclined walls of 12° angle. The solution with high density for the LCZ was prepared in a separate mixing tank, and it was transferred to the pond to form the storage layer (LCZ). To create the NCZ, many solutions with different concentrations were prepared (less than the concentration of the LCZ), and they transferred to the pond consecutively to form layers of the NCZ. Figure 2.12 shows a schematic of the unit which was used by the researchers (Aizaz and Yousaf, 2013).

![Figure 2.12: A schematic of a solar pond and the units used for the water body formation](image)

Similar procedures were used by Suarez et al. (2014) to build up an experimental solar pond. Their pond had a 2 m² surface area and a depth of 1 m. It may be that this method is more convenient to construct the water body of small ponds.

Construction of other types of solar ponds is more complicated than the construction of the SGSP because, with these types of solar ponds, chemicals and membranes will be used. This work requires additional technologies and experience with chemical substances, such as polymers and chemical solvents.

**Parameters affecting the performance of the SGSP**

Several parameters can influence the performance of the SGSP such as evaporation from the surface, heat loss to the ground and layer thicknesses of the pond.
Evaporation

Solar ponds, in general, are an open water body, and consequently, evaporation from the surface of the pond is expected to occur particularly in hot weather. Many meteorological parameters can influence the evaporation from the surface of the pond such as ambient temperature, wind speed, humidity and solar radiation.

Evaporation is the process by which a liquid becomes a vapour. It can occur at any temperature, even below the boiling point. Finch and Hall (2001) implied that the evaporation rate from an open body of water depends on the energy of the surface and the ability of vapour to mix with the atmosphere. More than one technique can be used to prevent or reduce evaporation from open water. Opaque plastic spheres have been used to reduce evaporation from water reservoirs (Manges and Craow, 1966).

Ali (1989) theoretically studied the covering of the surface of the SGSP with a polystyrene sheet from the beginning of autumn. It was concluded that adding insulation does not provide a substantial enhancement in the pond behaviour. However, polystyrene is an opaque material, and it will prohibit solar radiation penetrating through to the LCZ when the pond is covered. In a case such as that considered by Ali (1989), the cover, therefore, acts simply as an additional insulator, which reduces heat losses. This is offset by the reduced heat absorbed due to the attenuation of the incoming radiation.

Assouline et al., (2010) used non-transparent polypropylene sheets as an evaporation suppressor. It was concluded that the water loss in the case of many small openings among sheets was higher than the case of a single wide space. The main aim of Assouline et al.’s (2010) work was to suppress evaporative losses without taking into consideration the increase in the heat trapped in the pond. Consequently, any opaque floating material can be used to reduce or eliminate evaporative losses. However, for solar ponds, the use of opaque materials is not appropriate because the solar radiation penetrating the water will be significantly attenuated and therefore the performance of the pond will decrease.

Ruskowitz et al. (2014) considered evaporation as a significant barrier to the success of salinity gradient solar ponds. They investigated the suppression of evaporative losses from a SGSP in the laboratory. Three methods to diminish evaporation from the surface of the SGSP were tested. In the first method, a transparent continuous plastic cover was used. In the second and third tests, two floating element designs (discs and hemispheres) were used. The materials used were transparent. Configurations used by Ruskowitz et al. (2014) are shown in Figure 2.13.
In their experiment, firstly, the solar pond was fully covered with a continuous transparent cover as illustrated in Figure 2.13(a). Temperature evolution of the covered solar pond was monitored, and the evaporation rate was measured. Next, equal-sized openings (squares) were cut into the cover as shown in Figure 2.13(b) to incrementally decrease solar pond percent coverage from 100% coverage to 60%. To attain lower solar pond coverages, the size of each square was increased progressively to reach the lowest coverage (60%). At each coverage percentage, the temperature increase and the evaporation rate were measured.

Secondly, and for the floating discs experiment, 96 floating discs were used and placed on the surface of the solar pond (Figure 2.13(c)), and with the 96 discs, about 88% of the surface area of the pond was covered. Then, as achieved with the continuous cover, the covered area of the pond was reduced from 88% to 10% by successively removing a calculated number of floating discs from the surface, and the same procedures were repeated to monitor evaporation level and temperature.
Thirdly, after completion of the floating discs experiments, floating hemispheres were used to cover the surface of the pond. With this configuration, the percent coverage was incrementally increased from about 10% to 97% by consecutively adding hemispheres to the solar pond surface. In their research (Ruskowitz et al., 2014), in the case of hemispheres (Figure 2.13(d)), the maximum area of coverage was computed by multiplying the number of hemispheres used to cover the surface of the pond by the individual floating hemispheres surface area. The computed area was divided by the measured surface area of their experimental pond. However, it was claimed that an overlap occurred along the edges of hemispheres due to these hemispheres rocking and changing their tilt on the water surface. This overlap was not quantified and ignored from the surface area calculations, this, of course, will add some uncertainties to their results regarding the covered surface area in this case. Results of Ruskowitz et al. (2014) regarding temperatures and evaporation rates for all used configurations are shown in Figure 2.14.

Figure 2.14: Results of Ruskowitz et al. (2014) regarding evaporation rates and temperatures. (a) Evaporation rate from the solar pond surface as a function of percent coverage for the continuous cover, floating discs, and floating hemispheres during daylight operation. (b) Highest recorded LCZ temperatures for maximum percent coverage of the continuous cover, floating discs, and floating hemispheres and the average temperature of the LCZ in the uncovered pond.
As shown in Figure 2.14, it was found that the most efficient of the three methods was the use of the floating discs, which covered 88% of the surface. With floating discs covering the surface, evaporation decreased by 47%, and there was an increase in the temperature of the LCZ by 26%. It might be unusual that covering 88% of the pond’s surface is more efficient than the continuous cover. However, Ruskowitz et al. considered both the evaporation suppression and the temperature of the LCZ in their assessment of the examined configurations; Figure 2.14(b) shows that in the case of the continuous cover, there was a little increase in the temperature of the LCZ compared with the case of 88% floating discs. On the other hand, an entire covering of a solar pond might be operationally challenging when large ponds are considered. Of course, Ruskowitz et al.’s, (2014) study was accomplished in the lab, and an artificial light source was used. This means that the effects of natural climatic factors (incident solar radiation, relative humidity, ambient temperature and wind speed) on the pond were excluded.

Evaporation has also been positively utilised to re-concentrate and re-use salt from the overflow water which comes out from the UCZ. In this application, evaporation ponds are coupled with solar ponds. Alagao (1996) studied the closed-cycle salt gradient solar pond (CCSGSP) by suggesting an evaporation pond construction beside the SGSP. It was concluded that area of the evaporation pond in the CCSGSP depends on the rate of salt transport through the SGSP. Date and Akbarzadeh (2013) stated that for an efficient and complete salt recovering and reusing, it is required to construct an evaporation pond with a surface area twice or at least equal to the surface area of the utilised SGSP.

Layer thickness

The depth of the SGSP and the thickness of its layers have been discussed in many studies. The thermal capacity of the pond will naturally increase with a further increase of its surface area, but the zones’ depths also have a significant effect on the capacity of the solar pond.

Al-Jamal and Khashan (1998) claimed that the best thickness for the NCZ is 1 m while the thickness of the LCZ depends on the purpose of the construction of a SGSP. Their results showed that the temperature of the LCZ decreases with a further increase in its depth. In contrast, with small LCZ depth, the temperature will be higher.

Jaefarzadeh (2005) used a finite difference model to study the thermal behaviour of a large solar pond in the city of Mashhad in Iran. Temperatures in the zones of the pond were calculated, and the optimal layer thickness to the zones of the pond was also investigated. It
was concluded that the best thickness of the NCZ might be 1-2 m. Heat loss to the ground was also studied. It was found (Jaefarzadeh, 2005) that a well-insulated base of the pond is necessary and will improve the temperature in the LCZ.

According to German and Muntasser (2008), the optimum thickness of the layers of the SGSP which is practical for MED desalination, (requires 60 °C) are 0.3, 1.1 and 4 m for the UCZ, NCZ, and the LCZ respectively. Four meters depth for LCZ will give the pond a lower surface area (temperature in the LCZ around 60 °C). The minimum depth of the UCZ should not be less than 0.3 m to protect the pond from the weather conditions and to ensure that a high quantity of solar radiation will pass (Garman and Muntasser, 2008). They concluded that below 1.1 m for the thickness of the NCZ, the temperature of 60 °C cannot be achieved.

Jayatissa et al. (2012) concluded that the thickness of the NCZ is the largest and depth of the UCZ is the smallest. On the other hand, when the wind speed is high, the depth of the UCZ should be about 50 cm to prevent pond’s layers mixing. About 45% of the incident solar radiation absorbs in the UCZ and it loses again to the environment and around 25% is absorbed and stored in the LCZ as a thermal heat. Approximately 5% of the stored solar radiation in the LCZ (thermal heat) is lost to the ground (Date and Akbarzadeh, 2013). Further investigation regarding the influence of zone thicknesses of the pond on the temperatures of the LCZ and its relationship with heat extraction is required.

Studies on the salinity gradient solar pond

Theoretical studies

There is a large number of theoretical studies concerned the SGSPs. Different issues have been investigated and discussed, such as heat loss from the pond, salt diffusion, and stability of the pond, temperature distributions in the layers of the pond, maintenance and efficiency of the pond as a thermal storage (e.g. Kurt et al., 2000; Husain et al., 2003; Angeli and Leonardi, 2004; Bezir et al. (2008); Busquets et al., 2012; Dah et al., 2010; Husain et al., 2012; Andrews and Akbarzadeh, 2005; and Monjezi and Campbell, 2016).

Akbarzadeh and Ahmadi (1979) studied the influence of the heat loss to the soil under the pond on the temperature of the salinity gradient solar pond. It was concluded that it is preferable not to insulate the bottom of the SGSP, claiming that heat flows from the bottom of the pond to the ground during the hot season while it moves in the opposite direction during the cold season. However, their conclusions might be appropriate when the LCZ of the pond reaches
low temperatures. When the aim of the pond construction is to achieve high temperatures (≈ 100 °C), the bottom of the pond must be efficiently insulated.

Rabl and Nielsen (1975) claimed that the absorption of the radiation passing through the water body cannot be described by a simple exponential, and this because different wavelengths vary in their absorption coefficient. They considered water is practically opaque, and they have divided the wavelength spectrum between 0.2-1.2 μm into four bands. They created a formula to calculate the solar radiation in a body of water as follows:

\[ H_x = \tau H \sum_{j=1}^{4} \eta_j e^{-\mu_j x} \]  

(2.2)

where \( \tau \) is the coefficient of transmission (\( \tau = 1 \) - reflective losses), \( \mu_j \) is the absorption coefficient, \( \eta_j \) is the fraction of solar radiation having absorption coefficient \( \mu_j \) and \( j \) is the index of refraction.

The absorption coefficients and fractions of solar radiation for each band were determined. The following data (Table 2.2) was created by the researchers.

<table>
<thead>
<tr>
<th>( j )</th>
<th>( \eta )</th>
<th>( \mu ) (m(^{-1}))</th>
<th>Wavelengths (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.237</td>
<td>0.032</td>
<td>0.2-0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.193</td>
<td>0.45</td>
<td>0.6-0.75</td>
</tr>
<tr>
<td>3</td>
<td>0.167</td>
<td>3</td>
<td>0.75-0.9</td>
</tr>
<tr>
<td>4</td>
<td>0.179</td>
<td>35</td>
<td>0.9-1.2</td>
</tr>
</tbody>
</table>

Bryant and Colbeck (1977) suggested a simpler formula to calculate the solar radiation in a body of water and it is as follows:

\[ H_x = \tau H (a - blnx) \]  

(2.3)

Here \( a \) and \( b \) are constants and their values are 0.36 and 0.08 respectively, \( x \) is the depth of the water body in meters. This relationship is valid from 0.01 to 10 m water depth. They also investigated (Bryant and Colbeck, 1977) the suitability of constructing a SGSP in the city of London. It was concluded (Bryant and Colbeck, 1977) that when the indoor and the outdoor temperatures are considered to be 18.3 and 11.6 °C respectively, a house in London with a floor space of 186 m\(^2\) would require 184 m\(^2\) of a SGSP for heating with a rate of 20 W/m\(^2\) of heat extraction. Moreover, for a house near London, the required SGSP for the same purpose has a surface area equal to the house floor’s surface area.
However, in their calculation (Bryant and Colbeck, 1977), it was considered that the thermal conductivity of the soil beneath the SGSP is 0.96 W/m K and this value is relatively small, and consequently, heat loss to the ground will be low, and the temperature in the LCZ remains relatively high. Most soils have a thermal conductivity more than 1 W/m K, and with the wet soils, the thermal conductivity becomes higher. The weather in the United Kingdom, including London, is cloudy and rainy most days of the year and this will keep the soil beneath the SGSP wet, and therefore its thermal conductivity will be relatively high.

Theoretical studies of the effect of many parameters on the performance of the SGSP were done by Kooi (1979) and Wang and Akbarzadeh (1983). With Kooi’s, (1979) model, heat loss to the ground was ignored while it was considered with Wang and Akbarzadeh’s (1983) model. These two models are discussed with more details in Chapter 3 when the model of the present study is explained.

Bansal and Kaushik (1981) presented a theoretical analysis of a SGSP as a steady state flat plate solar energy collector; individual heat conservation for every layer was done on the three zones of the pond. They stated that a superposition of five exponentials introduces a better approximation of the solar radiation in a body of water and therefore the equation of Rabl and Nielsen (1975) (Equation 2.2) was re-written as:

\[ H_x = \tau H \sum_{j=1}^{5} \eta_j e^{-\mu_j x} \]  
\( (2.4) \)

Where \( \eta_1-\eta_4 \) and \( \mu_1-\mu_4 \) have the same values which were given by Rabl and Nielsen (1975) (Table 2.2) and the new values for the \( \eta_5 \) and \( \mu_5 \) and are given by Bansal and Kaushik (1981) as 0.224 and 255 m\(^{-1}\) for wavelength \( > 1.2 \) \( \mu m \). It was concluded (Bansal and Kaushik, 1981) that the efficiency of the SGSP can be enhanced to achieve the maximum by adjusting the thickness of the NCZ.

The efficiency of the salinity gradient solar pond based on similar methods to obtain the efficiency of the flat plate solar collector was studied by Hongfei et al. (2002). A mathematical model was suggested to calculate the performance. In the model (Hongfei et al., 2002), it was assumed that the pond consists of three zones, the UCZ, NCZ and the LCZ and the solar radiation that reaches the LCZ is stored there. It was obtained that thickness of the NCZ is very significant and its optimum thickness depends on the operating temperature, solar radiation, and thickness of the UCZ.
Experimental studies
A small experimental salinity gradient solar pond was built in Kuwait city by Ali (1986) and it had dimensions of $2 \times 4$ m ($8 \text{ m}^2$ surface area), and a water depth of 0.9 m. Sodium chloride was used in the pond, and the depth of layers of the pond were 0.2, 0.4 and 0.3 for the UCZ, NCZ, and the LCZ respectively. The study was conducted over one year from January-December. It was observed from the temperature measurements that there was a clear temperature gradient in the NCZ and the highest temperature were always in the LCZ throughout the study. The maximum temperature achieved in the LCZ ($\approx 78 \degree C$) and it was in July.

It can be concluded from the study of Ali (1986) that the SGSP can supply heat for many applications because with small depths of the whole pond (0.9 m) and the LCZ (0.3 m), the temperature in the storage zone reached 78 \degree C. With larger areas and depths, thermal capacity and temperatures could be higher.

The evolution of the temperature and salinity profiles in a SGSP was studied in the lab by Dah et al. (2005). A small experimental pond was utilised to achieve this purpose. The pond was a cylindrical plastic tank with a black base and the experiment was done during a period of 29 days. The solar radiation incident on the small pond was simulated by using a 2000 W light projector. It was observed that the salinity profile remained strong and stable during the study. Moreover, the temperature profile was established after 5 days and temperature in the LCZ reached its maximum of 45 \degree C after 20 days.

In spite of the fact that this study was a worthy trial to understand the development of the profiles of the salinity and temperature in the SGSP, the climatic conditions which have a significant influence on both profiles were excluded since the experiment was performed in the laboratory. These climatic conditions such as humidity, ambient temperature, and wind speed have to be considered for a better understanding to the behaviour of the SGSP.

Valderrama et al. (2011) studied the annual temperature distribution experimentally in a salinity gradient solar pond. A SGSP was constructed in Solvay-Martorell, facilities, Catalonia in Spain. The body of the pond was a cylindrical reinforced concrete tank and had 3 m height, 8 m diameter and a total surface area of about $50 \text{ m}^2$. The depth of the water body in the pond was fixed at 2.8 m. To maintain the stability of the pond, a salty solution of NaCl was delivered to the bottom of the pond through a cylindrical salt charger. Simultaneously, freshwater was continuously dispersed to the surface layer to keep its salinity at a low level and to substitute losses due to evaporation. The average consumption of freshwater was 3000 l/month in winter and almost twice during the summer season; this means that the water loss due to evaporation.
was 60 l/month m² in winter and about 120 l/month m² in the summer months. In Valderrama et al. (2016)’s study, the amount of fresh water to compensate the losses of water in the UCZ caused by evaporation is relatively high. This amount of water could be much greater in areas have arid and dry weather. Photo and schematic view of Valderrama et al.’s pond are shown in Figure 2.15.

![Figure 2.15: A schematic and photo of the pond in Solvay-Martorell, facilities, Catalonia in Spain (a) Schematic view of the pond showing the distribution of the three zones, and (b) photo of the 50 m² experimental salinity gradient solar pond.](image)

The maximum temperature was achieved in summer, August (54 °C), and it was observed in the NCZ and the temperature in the LCZ was slightly lower than 54 °C. It was claimed (Valderrama et al., 2011) that this behaviour was due to a lack of suitable insulation of the bottom surface of the pond which compromises the thermal storage in the LCZ. Consequently, heat loss from the LCZ was high and affected the temperature in the zone, causing it to fall slightly lower than the temperature in the NCZ. Abbassi Monjezi and Campbell (2016) observed that the LCZ does not immediately become the hottest zone within the pond. Their
model illustrated that as the pond starts to get warmer; the hottest zone gradually moves from the NCZ towards the LCZ and settles there. They claimed that this phenomenon defies the conventional model which assumes that the LCZ becomes the hottest zone in the SGSP directly after the beginning of the thermal heat collection operation.

The results of Valderrama et al. (2011) indicated that the bottom of the pond has to be well insulated to enhance the performance of the pond by decreasing heat loss to the ground. This point needs to be considered carefully in the design of the pond and precise information about the type of the soil beneath the pond, and its thermal conductivity is significant.

Nie et al. (2011) investigated the utilisation of the SGSP for the production of lithium carbonate from salt lake to decrease the cost of energy required for the precipitation process. The lithium concentration in the natural lake is small, and it is increased by the extended exposure to the sunlight. When the brine from the lake is heated, lithium carbonate precipitates. A chemical reaction will occur as follows:

$$2\text{Li}^+1 + \text{CO}_3^{2-} \rightarrow \text{Li}_2\text{CO}_3$$

A considerable amount of energy is needed during the process of the precipitation of lithium carbonate in the plant using this method, and a long time is also required. The ideal crystallisation of lithium carbonate is at 45 °C (Yu et al., 2015). Using the SGSP could decrease the period of the exposure and the cost of the extraction. For their purpose (Nie et al., 2011), an experimental SGSP with a surface area of 2500 m$^2$ and a depth of 1.9 m was constructed in the natural brine of Zabuye salt lake in the Tibet Plateau. The natural brine of the lake was used to form layers of the pond. It was run for 105 days, and the LCZ reach the maximum of 40 °C. In spite of the period of the study was short, it is claimed that the study showed that solar ponds have the potential to be exploited for the lithium carbonate production. Photos of Nie et al.’s experimental pond are illustrated in Figure 2.16.
Yu et al. (2015) pointed out that in the case of utilizing the SGSP in the production of lithium carbonate which was studied by Nie et al. (2011); it is true that exploiting the SGSP in the extraction operation has decreased the time of the production. However, the technology significantly depends on the environment and the weather conditions. Moreover, the temperature increase in the LCZ of the pond would take an extended period. This will, therefore, prolong the production period and consequently reduce the annual output, and they suggested the utilisation of the G-SGSP to improve the process. The G-SGSP is a kind of enhanced special solar pond; it comprises a conventional SGSP and a heat exchanger fixed in the LCZ. Its function is to increase the rate of heat transfer to the LCZ of the pond as well as to raise the LCZ temperature above that achievable by solar energy by utilizing the geothermal energy. A small experimental G-SGSP was built beside the Salt Lake which is located in Tibet Plateau in China. Photos and a schematic diagram of the Yu et al.’s G-SGSP are shown in Figure 2.17 a and b.

Figure 2.16: Photos of Nie et al.’s pond, (a) The experimental SGSP in operation, (b) The pond after operation.

Figure 2.17 (a): The construction of Yu et al.’s G-SGSP and the constructed pond
Figure 2.17 (b): Schematic diagram of lithium extraction by G-SGSP and a picture showing the heat exchanger submerged in the LCZ of the experimental pond and connected with the geothermal water simulation system to form a semi-enclosed hot-water circulation system (Yu et al., 2015).

Figure 2.17 illustrates that the constructed pond had a rectangular shape with horizontal cross section with a bottom length of 2 m and a width of 1 m. The vertical walls of the ponds had a depth of 0.5 m, and the depths of the layers of the G-SGSP were 30, 10 and 5 cm for the LCZ, NCZ and the UCZ. It was concluded that elevation of the heat exchanger illustrated in Figure 2.17(b) in the LCZ has a significant impact on the temperature of this layer. The heat exchanger being closer to the bottom of the pond can cause a higher temperature of the LCZ and vice versa.

**Theoretical and experimental studies**

Jayaprakash and Perumal (1998) investigated experimentally and theoretically behaviour of the SGSP. It was concluded that deeper LCZ would give the pond more stability; this because the amount of salt diffusion decreases for the large depth and it is also beneficial for increasing the thermal capacity of the LCZ. Additionally, it was suggested that continuous surface washing of the UCZ of the pond and brine injection into the LCZ are significant to maintain layers of the pond.

Karakilcik et al. (2006) studied experimentally and theoretically the behaviour of a SGSP for three separate months (January, May and August). The experimental pond was built at Cukurova University in Adana City, Turkey. The pond was made from iron steel of 5 mm thickness surrounded by a 5 cm glass wool insulator, and the whole pond was mounted on a steel base which was 0.5 m above the ground. The experimental pond was insulated from the
steel base by 2 cm thick wooden slats positioned on the base. It was concluded that temperature of each layer of the pond depends on the incident solar radiation, layer thickness and shading area.

A theoretical and experimental study of a SGSP with an insulated and reflective cover was carried out by Bezir et al. (2009). In this study, the aim was to investigate the suitability of the pond to supply hot water to a leather workshop. This workshop was located in the campus area of Vocational College, Suleyman Demirel University, Isparta, Turkey. The results obtained illustrated that the SGSP can be exploited as a source of warm water needed for the leather workshop and consequently it is potentially suitable for domestic requirements.

Sakhrieh and Al-Salaymeh (2013) have investigated the behaviour of a SGSP under Jordanian climate conditions during April. A MATLAB code was implemented to predict the temperature distributions through the layers of the pond. The results illustrated that a salinity gradient solar pond could be implemented in Jordan for some applications requiring low temperatures, such as domestic heating and for some applications in agriculture. However, the study was done for a short period (1 month). There is not enough information about the model used in the study to have full confidence in it. There was no information provided as to how the temperatures of the pond’s layers were calculated. In addition, there was no indication of any assumptions that may have been adopted in the model. Details of ponds above are listed in Table 2.3.

Table 2.3: Detail of ponds of Jayaprakash and Perumal (1998), Karakilcik et al. (2006), Bezir et al. (2009), and Sakhrieh and Al-Salaymeh (2013)

<table>
<thead>
<tr>
<th>Name</th>
<th>Surface area m²</th>
<th>UCZ (m)</th>
<th>NCZ (m)</th>
<th>LCZ (m)</th>
<th>Total depth (m)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jayaprakash and Perumal (1998)</td>
<td>5.712</td>
<td>0.12</td>
<td>0.60</td>
<td>0.155</td>
<td>0.875</td>
<td>India</td>
</tr>
<tr>
<td>Karakilcik et al. (2006)</td>
<td>4</td>
<td>0.1</td>
<td>0.6</td>
<td>0.8</td>
<td>1.5</td>
<td>Cukurova University in Adana City, Turkey</td>
</tr>
<tr>
<td>Bezir et al. (2009)</td>
<td>3.5</td>
<td>0.1</td>
<td>1.4</td>
<td>0.5</td>
<td>2</td>
<td>Suleyman Demirel University, Isparta, Turkey</td>
</tr>
<tr>
<td>Sakhrieh and Al-Salaymeh (2013)</td>
<td>3.57</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>Jordan</td>
</tr>
</tbody>
</table>
2.3.2.2 The Gel pond

The gel pond was developed by Wilkins et al. (1981). The salinity gradient zone was replaced with a viscous and transparent gel layer (Wilkins and Lee 1987). Disadvantages have been implied about the SGSPs by Shaffer and Dorothy (1979). They claimed that salt diffusion through the pond’s layers negatively affects the pond stability. Moreover, evaporation from the surface of the pond, particularly in arid climates, will continuously reduce the quantity of water in the UCZ. Therefore, fresh water must regularly be supplied to the UCZ, and salty water has to be injected into the storage zone (LCZ) to maintain the volume of the pond and the concentration gradient. Additionally, the quantity of salt required for the construction of a SGSP is enormous, and it will potentially be a source of pollution because salts can be spread to the areas around the pond. Furthermore, heat extraction from the SGSP might disturb the interface between layers of the pond and consequently cause oscillation and hence convection. In contrast, convection currents can be inhibited by using a viscous cover instead of the salinity gradient zone (NCZ). To avoid the disadvantages associated with a SGSP, thick materials have been used. These materials must have some essential specifications, e.g.: little or no alteration to the light transmission, transparent and have low molecular weight. Water is the preferred liquid for the storage layer because it has a high heat capacity and suitable transparency. To overcome or decrease the concentration gradient influences and convection a polyacrylamide polymer has been suggested instead of the NCZ (Shaffer and Dorothy, 1979).

The first gel pond was constructed at New Mexico University with an area of 18 m². The gel layer floats on the storage zone (LCZ) and works as an insulator, much like the non-convecting zone (NCZ). The salt concentration in the LCZ beneath the gel can be 2-7 % or more (Wilkins, 1991). A thin water layer (UCZ) about (5cm) was used to catch dust and dirt (its function is only to protect the gel layer located beneath it), and it is obvious that the upper water layer is small when compared with the 25-50 cm (UCZ) freshwater layer in the SGSP (Wilkins and Lee, 1987). The thermal conductivity of some polymers which can be used in the gel pond construction is lower than the conductivity of water by about 18 %. Therefore, the heat loss to the surface will be less than in the case of the SGSP.

Yogev and Mahlab (1984) illustrated that the used gel in the gel pond must be stable at high temperatures, even at 100 °C or greater. They pointed out that for a large gel pond, such as a 10,000 m² pond, the gel solution required to build 50 cm thick layer is approximately 5,000 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. Figure 2.18 demonstrates the pond which was suggested by Yogev and Mahlab (1984).
It is clear from Figure 2.18 that a layer of gel (polymer) was used to substitute the salt gradient zone, and the polymer is covered by a layer of water. The water layer acts both as a protector to the gel layer from the climatic conditions and as a cooler to condense vapour coming from the turbine.

According to Wilkins and Michael (1985) non-ionic polyacrylamide polymer, a relatively small molecular weight and it can be utilized to construct the gel layer. Table 2.4 shows some properties of this polymer.

Table 2.4: Some physical properties of polyacrylamide (Wilkins and Michael, 1985)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>White powder</td>
</tr>
<tr>
<td>Viscosity 0.1% solution</td>
<td>1.8-2.2 cps</td>
</tr>
<tr>
<td>Volatiles % by weight</td>
<td>14 maximum</td>
</tr>
<tr>
<td>PH 1% solution</td>
<td>6-6.5</td>
</tr>
</tbody>
</table>

The prepared polymer floated on the salty water surface and insulated the storage layer (LCZ). The polymer solution could be added to the salty water with stirring because there is no gradient zone to be disturbed when mixing occurs. In the storage zone (LCZ), any suitable fluid can be used e.g. water, organic chemicals, glycerol or clear oil. However, the cheapest and safest substance is water.
Matsumoto et al. (1998) 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 polyacrylamide polymer (SPR-402 polymer) was tested using a range of thicknesses 1-15 cm and concentrations (0.1-0.5 wt. %). It was claimed that the ionized polyacrylamide polymer is the suitable polymer to be an insulator that covers the lower convective zone (LCZ). However, there was no clear comparison with a SGSP at the same conditions, for example comparing the temperature of the LCZ for a particular depth of the NCZ in a SGSP, with the temperature in the case of a gel layer which has the same depth. This comparison can be helpful to evaluate both the positive and negative factors for the gel pond relative to the SGSP.

Sozhan et al. (2013) considered a gel pond to be an inventive method to eliminate the problems of the conventional gradient solar pond with low maintenance requirements. A polymer gel (Carbowax) was used to construct the insulating layer (gel layer) as it has some positive properties. It was claimed that Carbowax (polyethylene glycol polymer with molecular weight 3600-4000) 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. Its stability should be high physically and chemically, and non-opaque with high solar insolation absorptivity. A glass pool with dimensions $0.5 \times 0.5 \times 0.5$ m was used as the small experimental gel solar pond in the study. 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 experimental prototype model is illustrated in Figure 2.19. The transmissivity of 1 cm of the polymer was measured as 97.43 %.
It was suggested that Carbowax polymer was promising because there was no reaction with the salty solution of sodium chloride (NaCl). The average temperature difference between storage and gel zone was 10 °C. The thickness of the gel layer was small -1 cm -, and consequently, heat transfer by conduction could be high.

The gel solar pond introduces suitable technical solutions for the difficulties of the NCZ in the salinity gradient solar pond. Stability problems can be solved. Moreover, corrosion will be diminished because the solutions in the storage zone can be dilute or oily solutions. However, difficulties relating to cost and labour decrease their potential exploitation. Energy suppliers need to introduce a distinct balance between the gel and the salinity gradient solar ponds to decide which pond is economically and environmentally efficient. Cost, pond maintenance, materials availability, efficiency and pond age might be taken into consideration to make the decision.

2.3.2.3 Membrane solar pond

To reduce the negative impacts of a salinity gradient in the SGSP, transparent membranes could be used in the insulating area above the water surface or the storage region (LCZ).
Anderson (1980) implied that the distance between any two membranes in the membrane solar pond must be small for complete convection suppression. Figure 2.20 shows a cross section of a membrane solar pond.

![Figure 2.20: A cross section of a membrane solar pond (Anderson, 1980).](image)

Figure 2.20 illustrates that the upper layer has divided into many sub-layers, which are occupied by suitable fluid and they are separated by the chosen membrane. Anderson (1980) explained that if water is used in the insulating layer, Teflon is a suitable material for the membrane because the refractive index of Teflon and water are nearly equal, and also Teflon is reliably available. Ethanol can be used instead of water in the insulating layer since it has low thermal conductivity and high transparency.

Hull (1980) discussed several methods to reduce convective heat transfer from solar ponds. Several advantages for the membrane solar ponds were revealed by the researcher. There is no need for continuous maintenance as is the case for the SGSP (the SGSP requires continuous salty water injection to the LCZ to substitute the decrease in its salinity, and fresh water addition to the UCZ to compensate the water lack due to evaporation), and different liquids could be used instead of water. A new method was invented to develop the solar ponds and to suppress convection. Three alternative configurations were suggested.
In the first configuration, the insulating layer is divided into many layers by using a suitable membrane. Consequently, direct connection between layers will be avoided. The region below the lowest membrane is the convective layer and the layers above represent the insulating layer (divided into many layers). For low temperatures, it was proposed that at least three membranes are required and five membranes with a viscous pond when the target is to achieve a temperature of 80-100 °C. In the second configuration, a clear plastic material with a refractive index 1.45-1.5 was used as a membrane. In addition, sugar solution can be used to form the insulating layer. High sugar concentration (viscous solution) will decrease convection between layers and thereby, heat transfer upwardly will decrease. The third method is dividing the membrane solar pond into two layers: the storage layer or the lower layer (LCZ) and the upper or insulating layer by using one membrane. The liquid in the bottom layer can be water or any other liquid.

The alternative configurations which were introduced by Hull (1980) may give appropriate solutions to the salt gradient stability problems. Dividing the pond into two regions seems to be the best amongst the three alternatives because it is practically more flexible than the others since it requires only one membrane to separate the convective layer from the insulating layer. However, there are some disadvantages to the membrane solar pond e.g. significant quantities of membranes are required in case of the large pond, and that means high cost. In addition, the chemicals used between the membranes, such as sugar or organic materials, could thermally decompose and generate gases or other materials. New studies can focus on tackling these issues to make this type of solar pond economical.

Taga et al. (1990) investigated the advantages of partitioning the insulating layer in the membrane solar pond by a transparent film. Several experiments were performed. Firstly, only a layer of polymer was used as an insulating layer; the preferred polymer was a polyacrylamide (SPR-402). The experiment was repeated with the use of many transparent membranes to divide the insulating layer into many partitions. They discovered that this process would decrease the required insulating layer. Consequently, the light transmittance to the lower layer of the pond would be high. The pond is called the membrane viscosity solar pond (M.V.S.P.). The concentrations of the polymer used were varied between 0.1-0.8 wt%; the recommended concentration was 0.3 wt%. To inhibit colour change, anti-oxidizing and anti-algae agents were added. Furthermore, the polymer layer was covered by an ultraviolet absorbing layer.

Some positive and negative points for the different types of solar ponds are summarized in Table 2.5.
Table 2.5: Advantages and disadvantages of the convective (Shallow pond) and non-convective solar ponds (SGSP, gel, and membrane ponds)

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow pond</td>
<td>Cheap, environmentally friendly</td>
<td>Low efficiency (Anderson, 1980)</td>
<td>It is used in many different parts of the world to supply energy for many purposes varied from a small to large projects. It is the most common type of solar pond. Recently, intensive studies focus on salinity gradient solar ponds and more studies are required, and they can cooperate to improve the efficiency and storing capability.</td>
</tr>
<tr>
<td>Salinity gradient solar pond (SGSP)</td>
<td>Low cost of operation, simple construction, and high thermal storage (Alrowaished et al., 2013). Suitable for a wide range of applications require low-grade heat. Capacity is high, and it can supply energy continuously with low rates of heat extraction. The used salt can be recycled and returned to the pond and that will decrease the cost.</td>
<td>It could be a source of soil contamination if the lining process is inefficient, the wind can disturb the surface layers of the pond and evaporation from the surface layer is high particularly in dry and arid areas (Shaffer and Dorothy, 1979). However, the wind influence can be diminished by using plastic rings floating on the surface (Date and Akbarzadeh, 2013)</td>
<td></td>
</tr>
<tr>
<td>Gel pond</td>
<td>Mixing at the surface is diminished, stable, low maintenance cost and environmentally friendly (Wilkins and Lee, 1987). Low salt concentrations can be used in the LCZ.</td>
<td>The cost of chemicals is high (Alrowaished et al., 2013). Labourers with good skills to deal with chemicals are also required. When the polymer’s lifetime finishes, it is complicated to re-use the polymer in the pond, and a new polymer has to be utilised.</td>
<td>Its usage has been confined to small pilot plants or experimental works. It is observed that during the last two decades, the interest in this type of solar pond is much lower than the interest in SGSPs.</td>
</tr>
<tr>
<td>Membrane pond</td>
<td>Convection is inhibited efficiently by the membranes (Anderson, 1980). Low salt concentrations can be implemented in the LCZ.</td>
<td>High cost and might be inapplicable for industrial purposes. It is not suitable for a pond with a large area. The used membrane cannot be re-used in the pond after expiring, and new membranes are required. This will increase the cost and decrease its usage</td>
<td>There are no industrial applications or even pilot plants and there has been no significant interest in this type of solar pond during the last two decades since it is apparently difficult to implement.</td>
</tr>
</tbody>
</table>
2.4 Heat extraction

After establishing a solar pond, the most vital question is how to extract heat from the pond to be exploited in different applications. Heat extraction is similar for all types of solar ponds previously described. More than one system has been used for this purpose, but there are two conventional methods for heat removal from the LCZ of the pond, and they were explained by Leblanc et al. (2011). The first method uses an in-pond heat exchanger, and the process is shown schematically in Figure 2.21.

![Diagram of a conventional in-pond closed heat extraction system](image)

**Figure 2.21:** Conventional in-pond closed heat extraction system (Leblanc et al., 2011).

Figure 2.21 shows that the heat transfer fluid (commonly water) is circulated through a closed cycle which consists of internal and external heat exchangers. It was used in the 3000 m² Pyramid Hill pond, Australia. The internal heat exchanger is located in the LCZ, and the external heat exchanger was 200 m away. Polyethylene pipes were used in the construction of the internal heat exchanger to reduce corrosion challenges. Leblanc et al. (2011) pointed out that the disadvantage of the in-pond heat exchanger is the inability to clean the surface of the pipes of the precipitated salt and that will affect the heat exchange considerably. The in-pond heat exchanger used in Pyramid Hill pond is illustrated in Figure 2.22.
In the second method, the heat extraction can be accomplished by pumping the hot brine from the top of the LCZ to an external heat exchanger and returning it back to the bottom of the layer. The process is shown in Figure 2.23.

Figure 2.23: Second conventional method of heat extraction (Leblanc et al., 2011)

Figure 2.23 shows that the brine enters the lower part of the LCZ at a reduced temperature after exchanging its heat with the cold fluid. This method of heat extraction is used in the El-Paso SGSP in the USA. The pipes were made from steel, and consequently, heat transfer through...
the walls of the pipes is high, simultaneously, corrosion problems were encountered. Withdrawing brine from the LCZ and then returning it might result in pond disturbance and the destruction of its layers. To avoid layer destruction, the velocity of the pumped brine has to be carefully controlled. With pipes made from polymer, corrosion could be eliminated, but the heat transfer efficiency might be decreased. A distinct balance is vital to compare the efficiency reduction with the pipes’ cost. Srinivasan (1993) claims that both the internal and external heat exchangers could be utilised, and he believes that for a pond with an area of 1000 m² or less an in-pond heat exchanger is suitable, and its pipes should be manufactured from copper or plastic to improve corrosion resistance. In a pond with a surface area of more than 1000 m², the external heat exchanger is more convenient with stainless steel or titanium pipes. Hull et al. (1985) pointed out that a polypropylene heat exchanger is suitable for solar ponds in spite of its efficiency being lower than a metal heat exchanger.

Jaefarzadeh (2006) studied heat extraction from the LCZ of a small scale SGSP by using an in pond heat exchanger. A salinity gradient solar pond with a surface area of 4 m² and a depth of 1.1 m was implemented; experiments were performed in winter and summer seasons. Figure 2.24 demonstrates the heat extraction system which was used in these experiments.

![Figure 2.24: Heat extraction system which was used by Jaefarzadeh (2006).](image)

The internal heat exchanger was made from polyethylene pipes, and fresh water was circulated in a closed loop. The air chamber shown in Figure 2.24 was utilised to regulate the
volume of the circulated water, and fine bubbles of air can be released in this chamber for the achievement of this purpose. It is concluded that changing the ambient temperature has an insignificant impact on the temperature of the LCZ during a month. Removing energy from the LCZ substantially reduced its temperature; meanwhile, it had little effect on the temperature of the UCZ.

Tundee et al. (2010) used a heat pipe heat exchanger for the heat extraction from the LCZ of a salinity gradient solar pond. Experimental results were collected from a small SGSP with a surface area of 7 m$^2$ and a depth of 1.5 m, and it was built at Rajamangala University in the north east of Thailand. A one-dimensional mathematical model was developed, and it was based on the energy conservation for the zones of the SGSP (UCZ, NCZ, and LCZ). It was supposed that the upper and the lower convective zones are fully mixed, and consequently, their temperatures are uniform. Moreover, it was considered that temperature discrepancies inside the pond depend on the intensity of the incident solar radiation, climatic conditions of the area of the site and rate of the heat removal. A good agreement between the experimental and theoretical results was obtained, and it was found that the heat extraction rate has a significant effect on the temperature of the LCZ.

Andrews and Akbarzadeh (2005) investigated theoretically an alternative method (unconventional) for the heat extraction from a SGSP to enhance the thermal efficiency of the pond by extracting heat from the NCZ instead of the LCZ; a schematic to their heat extraction system is shown in Figure 2.25.

Figure 2.25: A schematic of the heat extraction approach suggested by Andrews and Akbarzadeh, 2005, showing that the heat exchanger is installed in the NCZ
It was assumed that an in-pond heat exchanger is fixed in the NCZ as shown in Figure 2.25. Heat loss from the bottom and walls of the pond was ignored, and it was concluded that heat extraction from the NCZ has the potential to increase the efficiency of the salinity gradient solar pond by up to 50% compared with the heat extraction only from the LCZ. In their analysis, they assumed water as the working fluid.

Heat extraction from both the NCZ and the LCZ and the LCZ alone was studied theoretically by Date et al. (2013) using an in-pond heat exchanger; a schematic of their system is illustrated in Figure 2.26.

The impact of mass flow rate through the heat exchanger was examined. A comparison between the performance of the pond when the heat removal is only from the LCZ, and when heat is extracted from the both layers (LCZ and NCZ) was performed. In studying the heat extraction from the NCZ and LCZ, two scenarios were considered. In the first scenario, a constant flow rate of the heat transfer fluid through the heat exchangers in the two layers (NCZ and LCZ) was considered. In the second scenario, different mass flow rates for the heat transfer fluid were used. A substantial increase in efficiency was observed when the heat is removed from the two layers (LCZ and NCZ). It was also concluded that the annual salinity gradient solar pond efficiency and the temperature of the LCZ are highly influenced by the mass flux of the heat transfer fluid that flows through the heat exchanger.
2.5 Summary

Solar ponds are a simple, low-priced and efficient way to collect and store incident solar radiation; they have enormous capacity and tremendous unrealised potential. Many parameters affecting the construction and performance of solar ponds have been investigated. However, further studies are required to address many other issues. These include further research on the relationship between zone thickness variation and heat extraction to understand the influence of zone thickness on temperatures of the LCZ and to estimate the cost of the pond when it is deeper with less surface area. In spite of technology of solar energy, and in particular, solar ponds being suitable for countries located in the Middle East, there is an apparent lack of studies in general and experimental measurements in particular in this region. Moreover, the scientific literature lacks analytical studies on the concentration and temperature, and more research in this area is required. For these reasons, it is decided to carry out the present study to address the gap in this field of knowledge.
Chapter 3
Theoretical modelling of heat transfer
3.1 Introduction

This chapter presents a theoretical analysis of temperatures in the UCZ, NCZ and the LCZ with and without heat extraction. The model is verified by comparing the theoretical results with some available previous experimental results. The monthly average temperature of layers of the salinity gradient solar pond was calculated through one year. Temperatures of the storage zone (LCZ) with variable rates of heat extraction are also predicted. In addition, the optimal thickness of layers of the pond basis on the temperature of the LCZ is assessed.

3.2 Previous theoretical models

Kooi (1979) developed a model to describe the SGSP. Figure 3.1 shows the pond which was suggested in the model.

The steady state heat conduction equation was used to calculate the vertical temperature distribution $T_x$:

$$k_w \frac{d^2 T_x}{dx^2} = H \frac{dH_x}{dx}$$

(3.1)

where $k_w$ is the thermal conductivity of water in W/m K, $H$ is the solar insolation in W/m$^2$, $H_x$ is the fraction of $H$ that reaches a depth $x$ and $T$ is the temperature in K. The following set conditions were applied:

$0 \leq x \leq x_1 \, ,\, T_x = T_{x1}$

$x_3 \geq x \geq x_2 \, ,\, T_x = T_{x2}$ where $x_1$, $x_2$ and $x_3$ are positions on the pond’s depth as shown in Figure 3.1. The final equation for the heat collection in the pond (in the LCZ) from the solar incident solar radiation was given as:

$$q = \left[ \frac{\int_{x_1}^{x_2} H_x dx}{x_2-x_1} \right] H - \frac{k_w}{x_2-x_1} [T_{x_2} - T_{x_1}]$$

(3.2)
Many assumptions were adopted in the model. Firstly, it was considered that the pond’s walls are vertical and well insulated. Secondly, the UCZ and LCZ were considered uniform with constant temperature and $k_w$ were held constant (0.64 W/m K). Thirdly, the temperature of the UCZ zone was assumed to be close to the ambient temperature. Finally, the temperature was assumed to change only in the vertical direction. Kooi (1979) claimed that light is highly absorbed in the UCZ and approximately half of the solar insolation is trapped there. It was concluded that if the NCZ is thin, the heat loss will be significant and that will affect the efficiency of the pond. On the other hand, if it is very thick, that will decrease the amount of insolation that reaches the LCZ substantially.

Wang and Akbarzadeh (1983) used the same steady state heat conduction equation with a slight modification. It was assumed that the pond also consists of three zones as proposed in Kooi’s model. Moreover, the top and bottom were well mixed. Furthermore, the temperature of the UCZ is considered equal to the ambient temperature. They allowed the ground temperature below the bottom of the pond at a depth of $(D_i + D_g)$ to be equal to the average ambient temperature $(T_a)$. Here $D_i$ represents the thickness of the bottom insulation, and $D_g$ is the soil layer thickness between the bottom insulation of the pond and the underground water level. The heat loss to the ground was therefore taken into account in this model with two different types of soil below the pond. The first one was a clay soil with a thermal conductivity of 1.28 W/m K and the second one was a wet soil with a thermal conductivity of 2.5 W/m K.

Wang and Akbarzadeh’s model started with the following equation:

$$\frac{d}{dx} \left( -k_w \frac{dT}{dx} \right) + \frac{dH_x}{dx} = 0$$ (3.3)

Here $x$ is positive in the downward direction, $H_x$ was calculated by using the formula of Bryant and Colbeck (1977), with a slight modification:

$$H_x = F_r H_b \ln \left[ \frac{y_0}{(x+\delta)\cos \theta_r} \right]$$ (3.4)

where $b$ is a constant which is given in Bryant and Colbeck’s formula (1977), $y_0$ is a constant of value of 90 m, $\delta$ is the thickness of the UCZ in meters and $\theta_r$ is the refractive angle. The final parameter in the formula is the transmittance parameter, $F_r$. The pond’s surface is considered to be smooth, and for a smooth water surface, $F_r$ is given by Fresnel’s equation as:

$$F_r = \frac{1}{2} \left[ \frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)} + \frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)} \right]$$ (3.5)

In Equation (3.5), $\theta_i$ is the angle of the incidence solar insolation on the horizontal body. For water,

$$\frac{\sin \theta_i}{\sin \theta_r} = 1.33$$ (3.6)
To calculate $\theta_i$ the following equation was used.

$$\cos \theta_i = \cos \theta \cos \Delta \cos \omega + \sin \Delta \sin \theta$$

(3.7)

where $\theta$ represents the latitude of the location and $\omega$ is the solar hour angle in degrees. This is an expression of the time measured from solar noon. At solar noon $\omega = 0$. Before solar noon $\omega < 0$ and after solar noon $\omega > 0$. Finally, $\Delta$ is the angle of declination, given as:

$$\Delta = 23.45 \sin(2\pi \frac{284+N'}{365})$$

(3.8)

where $N$ is number of the day in the year.

The value of $F_r$ was considered to be constant (0.85) by Wang and Akbarzadeh (1983) in their model. The following two boundary conditions were used.

When $0 \leq x \leq x_1$ then $T = T_2$.

The second boundary condition is when $x_2 \geq x$, $T = T_{x_2}$

The final equation for heat stored in the LCZ was given as:

$$q = F_r bH + \frac{F_r b}{(x_2-x_1)} \ln \left[ x_1^{x_1} \left( \frac{y_0 \cos \theta \cos \Delta}{x_2} \right)^{x_1} \right] H - (U_{\text{ground}} + \frac{1}{(x_2-x_1)})(T_{x_2} - T_a)$$

(3.9)

In Wang and Akbarzadeh’s model (1983) the heat transfer coefficient to the ground $U_{\text{ground}}$ was given as:

$$U_{\text{ground}} = \frac{1}{\frac{D_i}{k_i} + \frac{D_g}{k_g}}$$

(3.10)

The thermal conductivity of the insulation is represented by $k_i$, and $k_g$ represents the thermal conductivity of the soil beneath the pond. Values of all parameters are given in Wang and Akbarzadeh (1983).

It was concluded that the ground heat loss has a significant effect on the performance of the solar pond, particularly, with wet soil and if the level of the underground water table is high. Wang and Akbarzadeh (1983) defined the efficiency of the pond as:

$$E = \frac{q}{H}$$

(3.11)

It was observed that, if the thickness of the UCZ is decreased from 0.2 to 0.1 m, the efficiency will increase from 18.5% to 19.7 %. On the other hand, if it reaches 0.5 m, the efficiency will drop to 15.5 %. It was also noticed that the efficiency increases with the increase of depth of the LCZ until a maximum value is reached. Thus, a further increase will lead to the efficiency declining. Consequently, it was recommended (Wang and Akbarzadeh, 1983) that the UCZ should be kept as thin as possible and the LCZ depth should be varied depending on the desired operating temperature, to achieve the maximum efficiency.
Bansal and Kaushik (1981) developed a model which was substantially different from the two previous models because each zone in the pond was analysed separately. An individual heat transfer coefficient between each zone was used in this model.

Alagao et al. (1994) discussed a closed cycle salt gradient solar pond (CCSGSP). The surface water was flushed to an evaporation pond (EP); in this pond, the solution was concentrated and re-injected at the bottom of the solar pond. It was concluded that construction a CCSGSP depends on the net rate of evaporation and the cost of salt and land.

Alagao (1996) described the transient behaviour of a solar pond with a complete salt recycling system. The results showed that the area of the evaporation pond in a CCSGSP operation was affected by the rate of salt transport throughout the solar pond. In recent years, other models have been developed; most of them were solved numerically, and this is discussed in Chapter 2.

3.3 Proposed model

In the present study, a model for a SGSP has been developed to solve the non-linear first order differential equations for conservation of energy. It depends on the ode45 MATLAB function which uses a modified 4th order Runge-Kutta numerical method with variable time stepping in the solution. Several assumptions have been adopted. Firstly, the pond consists of three zones; (i) the upper convective zone which contains approximately fresh water, (ii) the non-convective zone which has a gradual variation in salt concentration from top to bottom, and finally, (iii) the lower convective zone, where the concentration of salt is very high (0.25 kg/l). Secondly, both the UCZ and LCZ are considered well mixed. Thirdly, the solar radiation which reaches the LCZ is totally absorbed in this layer and heat accumulation in the NCZ has been neglected in the calculation of temperatures in the LCZ and UCZ. Finally, the solar insolation data from NASA has been considered and the value of transmission index $F_r = 0.85$ as was taken by Wang and Akbarzadeh (1983).

3.3.1 Upper convective zone (UCZ)

The upper convective zone of the pond is represented schematically in Figure 3.2.
Theoretical modelling of heat transfer

Figure 3.2: Schematic diagram showing heat flows through the upper convective zone

The heat conservation equation is given as:

$$\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = Q_{ru} + Q_{ub} - Q_{uc} - Q_{ur} - Q_{ue} - Q_w$$  \hspace{1cm} (3.12)

The left hand side of Equation (3.12) represents the useful heat accumulated in the upper convective zone, $\rho_u$ is water density, $c_{pu}$ water heat capacity for the UCZ, $A_u$ surface area of the UCZ and $h_{UCZ}$ is the thickness of the UCZ. For the right hand side of the equation, $Q_w$ is the heat loss through walls of the pond. In this work $Q_w = 0$ (i.e. it is supposed that walls are well insulated), $Q_{ru}$ is the solar radiation that is absorbed in the upper layer. It can be calculated as:

$$Q_{ru} = Q_{rin} - Q_{rout}$$  \hspace{1cm} (3.13)

where $Q_{rin}$ is the solar radiation enters the UCZ and $Q_{rout}$ out represents the solar radiation which exits the UCZ. The value of $Q_{ru}$ changes with time and varies with the pond location. The incident radiation can be directly recorded from climatological data for any place, and it also can be calculated. In the present study data from NASA has been considered (NASA, 2014). Some of the incident sunlight ($H$) reflects back to the sky, and the rest of the solar radiation is absorbed by the water body. Rabl and Nielsen (1975) claim that the absorption of solar radiation through a body of water cannot be described by a simple exponential. Their opinion is based on the fact that light has different wavelengths with wide variation in their absorption coefficients. They divided the wavelength spectrum between 0.2-1.2 $\mu$m into four bands. After that, they determined the absorption coefficients and fractions of solar radiation for each band. Their suggested formula was previously mentioned in Chapter 2 (Equation (2.2)), and it is as follows:
\[ H_x = \tau H \sum_{n=1}^{4} \eta_n e^{-\mu_n x} \]  
(3.14)

where \( \tau \) is the coefficient of transmission = refractive losses.

Bryant and Colbeck (1977) suggested an alternative formula to compute the solar radiation in a body of water as:

\[ H_x = \tau H (a - b \ln x) \]  
(3.15)

That means:

\[ H_x = \tau H (0.36 - 0.08 \ln x) \]  
(3.16)

Equation (3.16) has been used to compute the absorbed solar radiation in the water body in the present study, thus

\[ Q_{ru} = \tau H (1 - 0.36 + 0.08 \ln h_{UCZ}) \]  
(3.17)

Wang and Akbarzadeh (1983) implied that both formulas of Rabl and Nielsen (1975) and Bryant and Colbeck (1977) are approximations to the results which were obtained by Schmidt (1908) and those results are reported by Defant (1961).

The heat transfer to the UCZ by conduction from the LCZ is calculated by using the following equation:

\[ Q_{ub} = U_t A_u [T_L - T_u] \]  
(3.18)

Here, \( T_u \) and \( T_L \) are temperatures of the UCZ and the LCZ respectively, and \( U_t \) is the overall heat transfer coefficient which can be computed as:

\[ U_t = \frac{1}{r_{total}} = \frac{1}{\frac{1}{h_1} + \frac{X_{NCZ}}{k_w} + \frac{1}{h_2}} \]  
(3.19)

In Equation (3.19), \( h_1 \) and \( h_2 \) are the convective heat transfer coefficient between the NCZ and the UCZ, and between the LCZ and the NCZ. Their values are 56.58 and 48.279 W/m\(^2\) K respectively. The thermal conductivity of water (\( k_w \)) is 0.596 W/m K (Bansal and Kaushik, 1981). The values of heat transfer coefficients were calculated theoretically by Bansal and Kaushik (1981). Finally, \( X_{NCZ} \) represents the thickness of the NCZ in meters.

Equation (3.18) can therefore be written as:

\[ Q_{ub} = \frac{A_u [T_L - T_u]}{\frac{1}{h_1} + \frac{X_{NCZ}}{k_w} + \frac{1}{h_2}} \]  
(3.20)

The symbols \( Q_{uc}, Q_{ur} \) and \( Q_{ue} \) represent heat which is lost from the surface which can be written as.

\[ Q_{losses} = Q_{uc} + Q_{ur} + Q_{ue} \]  
(3.21)

Heat loss by convection \( Q_{uc} \) is given as:

\[ Q_{uc} = h_e A_u [T_{u} - T_{\alpha}] \]  
(3.22)
Here, \( h_c \) is the convective heat transfer coefficient from the water surface to the air in W/m\(^2\) K and it is calculated by using a formula which was introduced by McAdams (1954) as:
\[
h_c = 5.7 + 3.8 \, v
\]  
(3.23)
where \( v \) is the monthly average wind speed in m/s.

Radiation heat loss can be calculated as:
\[
Q_{ur} = \sigma \varepsilon A_u (T_u^4 - T_k^4)
\]  
(3.24)
where \( \sigma \) is the Stefan–Boltzmann’s constant = 5.673x10\(^{-8}\) W/m\(^2\) K\(^4\), \( \varepsilon \) is the emissivity of water = 0.83 (Kanan et al., 2014), and \( T_k \) is the sky temperature. It is calculated as:
\[
T_k = 0.0552 T_a^{1.5}
\]  
(3.25)

Finally, the heat loss from the surface by evaporation (\( Q_{ue} \)) is given by Kishore and Joshi (1984) as:
\[
Q_{ue} = \left[ \frac{\lambda h_c (p_u - p_a)}{(1.6 C_s p_{atm})} \right] A_u
\]  
(3.26)
where \( C_s \) is the humid heat capacity of air in kJ/kg. K, given by:
\[
C_s = 1.005 + 1.82 \gamma_h
\]  
(3.27)
The symbol \( \lambda \) represents the latent heat of vaporisation in kJ/kg, \( p_u \) is the water vapour pressure at the upper layer temperature in mmHg and it is calculated as:
\[
p_u = \exp[18.403 - 3885/(T_u + 230)]
\]  
(3.28)
The partial pressure of water vapour in the ambient temperature in mmHg is represented by \( p_a \) and it is calculated as:
\[
p_a = \gamma_h \exp[18.403 - 3885/(T_a + 230)]
\]  
(3.29)
where \( p_{atm} \) is the atmospheric pressure in mmHg, \( \gamma_h \) is the relative humidity. Equation (3.12) which represents energy conservation in the UCZ can therefore be rewritten as:
\[
\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = A_u [Q_{ru} + \frac{T_L - T_u}{K_1} + \frac{T_{NCZ} - T_u}{K_2} - \{(5.7 + 3.8 v)[T_u - T_a]\} - 4.708 \times 10^{-8} T_u^4 - 0.0552 T_a^{1.5} - \{\lambda h_c (p_u - p_a)\}/[(1.6 C_s p_{atm})]].
\]  
(3.30)

There are two variables in Equation (3.30), i.e. \( T_u \) and \( T_k \). Another equation with the same variables is required to find values of the unknowns. A conservation equation for energy in the storage or lower convective zone (LCZ) must also be defined.

### 3.3.2 Lower convective zone (LCZ)

A schematic of heat flows throughout the LCZ is illustrated in Figure 3.3, and the heat balance on the layer is given in Equation (3.31).
Chapter 3: Theoretical modelling of heat transfer

Figure 3.3: Schematic diagram showing heat flows through the lower convective zone (storage zone).

\[ \rho_l c_{pl} A_t h_{LCZ} \frac{dT}{dt} = Q_{rs} - Q_{ub} - Q_{ground} - Q_{load} - Q_w \]  \hspace{1cm} (3.31)

Here, \( \rho_l \) is the density of the LCZ, \( c_{pl} \) represents the heat capacity of water for the LCZ, \( h_{LCZ} \) is the thickness of the LCZ, \( A_t \) is the surface area of the LCZ, \( Q_{ground} \) is the heat loss to the ground and \( Q_{load} \) is the heat that is extracted from the LCZ. It is assumed to begin with that there is no load i.e. \( Q_{load} = 0 \). This corresponds to the initial warming period of the pond. In addition, it is assumed that \( Q_w = 0 \) i.e. it is supposed that walls are well insulated. Equation (3.31) can be rewritten as:

\[ \rho_l c_{pl} A_t h_{LCZ} \frac{dT}{dt} = Q_{rs} - Q_{ub} - Q_{ground} \]  \hspace{1cm} (3.32)

The solar radiation which enters and is stored in the LCZ (\( Q_{rs} \)) can be computed by using Equation (3.16) and in this case:

\[ Q_{rs} = \tau H (0.36 - 0.08 \ln(h_{UCZ} + X_{NCZ})) \]  \hspace{1cm} (3.33)

Heat which moves upward from the LCZ (\( Q_{ub} \)) can be calculated from Equation (3.20). This is considered to be the same as the heat that moves to the UCZ.

To calculate \( Q_{ground} \), the equation is:

\[ Q_{ground} = U_{ground} A_b (T_L - T_G) \]  \hspace{1cm} (3.34)

where \( T_G \) is the temperature of water table under the pond and \( A_b \) represents area of the bottom surface of the pond. The overall heat transfer coefficient to the ground, \( U_{ground} \), is given as:

\[ U_{ground} = \frac{1}{R_3 + R_g + R_4} \]  \hspace{1cm} (3.35)

The symbols \( R_3 \), \( R_g \) and \( R_4 \) represent the resistances to heat transfer to the ground.

\[ R_3 = \frac{1}{h_3}, \quad R_g = \frac{x_g}{k_g}, \quad R_4 = \frac{1}{h_4} \]
Here $h_3$ is the convective heat transfer coefficient at the boundary between the storage zone and the surface at the bottom of the pond in W/m$^2$ K, $h_4$ is the convective heat transfer coefficient at the surface of the ground water sink. Their values are 78.12 and 185.8 in W/m$^2$ K respectively (Sodha et al., 1980). They were calculated theoretically by the researchers from the standard expressions of McAdams (1954). The distance of the water table from the bottom of the pond in meters is given by $x_g$. It depends on the pond’s site. Finally, $k_g$ is the thermal conductivity of the soil under the pond in W/m K.

Equation (3.34) will be:

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

Hull et al. (1984) claim that heat loss from any pond to the ground is a function of both perimeter and area of the pond. It also depends on the conductivity of the soil and distance to the water table beneath the pond. Their conclusion was based on many experiments and numerical simulations. Hull et al. (1988) assumed that the temperature of the water table under the pond is constant and proposed a new equation to model this transfer.

$$U_{ground} = \frac{k_g}{x_g} + m k_g \frac{p}{A_u}$$

The value of empirical parameter $(m)$ varies depending on whether the walls of the pond are vertical or inclined. Moreover, $p$ represents the pond perimeter in meters and $A_u$ is the surface area of the pond in m$^2$. Equation (3.34) can be re-written including this formulation as:

$$Q_{ground} = \left\{ \left( \frac{k_g}{x_g} + m k_g \frac{p}{A_u} \right) A_b (T_L - T_g) \right\}$$

In the present study another case for the pond has been considered. It is supposed that the pond is unburied; i.e. it is above ground with a space between it and the ground. It is suggested that bottom of the pond consists of three layers, two layers of wood and a layer of polystyrene between. In this situation $U_{ground}$ can be given as.

$$U_{ground} = 1/\left[ \left( \frac{1}{h_3} \right) + \left( \frac{l_1}{k_1} \right) + \left( \frac{l_2}{k_2} \right) + \left( \frac{l_3}{k_3} \right) + \left( \frac{1}{h_o} \right) \right]$$

In Equation (3.39), $l_1$, $k_1$ are the thickness and thermal conductivity of the first layer of insulation (wood). Their values are 0.01m and 0.13 W/m K respectively. Similarly, $l_2$, $k_2$ are the thickness and thermal conductivity for the second layer of insulation (polystyrene). Their values are 0.06 m and 0.03 W/m K respectively. Finally, $l_3$, $k_3$ are the thickness and thermal conductivity for the third layer of insulation. Their values are similar to $l_1$ and $k_1$. The heat transfer coefficient from the outside surface to the atmosphere ($h_o$) is taken as 5.43 W/m$^2$ K.

Equation (3.34) will be.
Chapter 3: Theoretical modelling of heat transfer

\[ Q_{\text{ground}} = \left[ \frac{1}{\left( \frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_3} + \frac{1}{h_4} \right)} \right] A_b (T_L - T_a) \]  \hspace{1cm} (3.40)

Equation (3.31) can be rewritten as.

\[ \rho_l c_pl A_l h_{LCZ} \frac{dT_L}{dt} = A_l [Q_{rs} - \frac{[T_L - T_u]}{h_1} - \frac{x_{NCZ}}{k_w} - \frac{Q_{load}}{h_2} - \frac{A_b (T_L - T_g)}{h_3} + \frac{1}{h_4}] \]  \hspace{1cm} (3.41)

Three different expressions have been used in Equation (3.41) to represent \( Q_{\text{ground}} \). For three or four months \( Q_{\text{load}} \) can be neglected to give the pond time to warm up.

3.4 Results and discussion

Equations (3.30) and (3.41) have been solved by using MATLAB. Three different formulae for \( Q_{\text{ground}} \) were used and different results have been observed. By this method, Equations (3.30) and (3.41) can be solved depending on the initial values of the unknown parameters \( T_u \) and \( T_L \). These initial values vary with the location of the pond and the time of year when the pond starts working. The values of the constants which are used in the model are as follows, \( \rho_u = 1000 \text{ kg/m}^3 \), \( \rho_l = 1200 \text{ kg/m}^3 \), \( c_{pu} = 4180 \text{ J/kg K} \), \( c_{pl} = 3300 \text{ J/kg K} \), \( A_u = A_l = A_b = 1\text{ m}^2 \), \( h_1 = 56.58 \), \( h_2 = 48.279 \), \( h_3 = 78.12 \), \( h_4 = 185.8 \) (all values in W/m\(^2\) K as mentioned before) and \( k_w = 0.596 \text{ W/m K} \), \( T_g = 23 \degree \text{ C} \). The value of \( x_g \) and \( k_g \) depend on the soil properties under the pond. For example their values in the El Paso pond in the USA are different from values for Ein Boqeq pond in Israel. The effect of evaporation, radiation and convection on the pond has been investigated. The values of solar radiation can change according to the location. The pond is first considered to be in Kuwait to compare with available experimental data for this city. The climatic conditions for Kuwait City are listed in Table 3.1.
It is beneficial to plot the profile of the incident solar radiation at the location of the pond to observe its behaviour during the year. The radiation profile can help to observe easily the changes in the radiation throughout the year and to identify when it is high or low. The profile appears in Figure 3.4 for Kuwait City.

![Figure 3.4: The profile of solar radiation of Kuwait City during one year](image)

It is clear from Figure 3.4 that the incident solar radiation on this city increases gradually from the winter (it is 345.6 MJ/m$^2$.month in January) to the summer season and it reaches the maximum value in June (852.12 MJ/m$^2$.month) and then decreases. There is clearly a very large seasonal range in the insolation, which will significantly affect the behaviour of the pond.
3.4.1 Validation of the model

3.4.1.1 Kuwait City

To test the model, the calculated temperature of the LCZ is compared with the experimental data of Ali (1986) for a pond in Kuwait City (there was no heat extraction from the pond). The pond had dimensions of $4 \times 2 \times 0.9$ m and the depth of layers was 0.2, 0.4 and 0.3 m for the UCZ, NCZ, and LCZ respectively. The comparison is shown in Figure 3.5.

![Figure 3.5: Validation of temperature distribution of the LCZ of the present model with experimental data for Kuwait City (initial temperatures are 14 and 23 °C for UCZ and LCZ respectively).](image)

Figure 3.5 illustrates that there is an acceptable agreement between the model and experimental data for the temperature in the storage zone (LCZ) with an average relative error of 9%. A slight difference in the temperatures of the LCZ is apparent. The difference in the experimental and proposed temperatures might occur due to the difference between the real and assumed values of the heat transfer coefficients.

The efficiency of the pond in Kuwait is calculated utilizing Equation (3.11), and the term $q$ in this equation is computed as $q = \rho_l c_{pl} A_l h_{LCZ} \Delta T$. Values of the incident solar radiation on the pond were taken from Table 3.1, the efficiency of the Kuwaiti’s pond was found to be 1.6%. In the calculation of the efficiency, only the LCZ is considered, details of the calculation are listed in Appendix B.

3.4.1.2 El Paso

The present model is also compared with experimental data from the El Paso solar pond. The surface area of this pond is 3000 m$^2$ and the depths of layers are 0.7, 1.2 and 1.35 m for
the UCZ, NCZ and the LCZ respectively (Lu et al., 2001). The depth is large compared with
the Kuwait solar pond. The climatic conditions of El Paso are shown in Table 3.2 and the
comparison is shown in Figure 3.6.

Table 3.2: Climatic conditions of El Paso, Texas (1999), (Lu et al., 2001)

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar radiation MJ/m².month</th>
<th>Ambient temperature °C</th>
<th>Relative humidity %</th>
<th>Wind speed m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>378</td>
<td>6</td>
<td>51</td>
<td>3.2</td>
</tr>
<tr>
<td>February</td>
<td>486</td>
<td>8.9</td>
<td>42</td>
<td>3.5</td>
</tr>
<tr>
<td>March</td>
<td>637</td>
<td>12.8</td>
<td>32</td>
<td>4.4</td>
</tr>
<tr>
<td>April</td>
<td>766</td>
<td>17.4</td>
<td>27</td>
<td>4.4</td>
</tr>
<tr>
<td>May</td>
<td>842.4</td>
<td>22.1</td>
<td>27</td>
<td>4.1</td>
</tr>
<tr>
<td>June</td>
<td>864</td>
<td>26.9</td>
<td>30</td>
<td>3.5</td>
</tr>
<tr>
<td>July</td>
<td>799</td>
<td>27.9</td>
<td>44</td>
<td>3.2</td>
</tr>
<tr>
<td>August</td>
<td>734</td>
<td>26.7</td>
<td>48</td>
<td>3</td>
</tr>
<tr>
<td>September</td>
<td>637</td>
<td>23.6</td>
<td>51</td>
<td>2.9</td>
</tr>
<tr>
<td>October</td>
<td>529</td>
<td>17.8</td>
<td>47</td>
<td>2.8</td>
</tr>
<tr>
<td>November</td>
<td>410</td>
<td>11.3</td>
<td>47</td>
<td>3.1</td>
</tr>
<tr>
<td>December</td>
<td>345</td>
<td>6.7</td>
<td>52</td>
<td>3</td>
</tr>
<tr>
<td>Average</td>
<td>618</td>
<td>17.3</td>
<td>41.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Figure 3.6: Comparison profiles of the LCZ temperature of the present model with the El Paso pond experimental data (1999) (initial temperatures are 6 and 70 °C for the UCZ and the LCZ respectively).

The profile of the experimental measurement in the LCZ tends to show little variation in
the temperature. This slight variation might be due to the high initial temperature because it
has an effect on the behaviour of temperature in the LCZ. This effect has been discussed by
many researchers e.g. Jaefarzadeh (2004, 2005) and Madani (2014). It was concluded that the initial temperature has only a slight effect on the LCZ temperature and after few months the difference in maximum temperature among cases with different initial temperatures becomes low. In other words, if two ponds start with two different temperatures for the LCZ with one of them being low and the other one high, then the temperature in the LCZ in the first one will increase while in the second one temperature will decrease slightly. Subsequently, it will increase slowly as the radiation intensity increases. However, after few months the gap between the two temperatures will be small. As demonstrated in Figure 3.6, for the model, the behaviour is approximately similar to the described behaviour because before May, the temperature decreases, after that it increases gradually. It reaches maximum value in August. A gradual decrease in temperature is seen after August to be close to the experimental results. The difference between the two values of temperatures becomes small from September. The difference between the experimental data of the El Paso pond and theoretical values according to the present study may be because of the difference between theoretical and experimental heat transfer coefficient, but also the clarity of the pond because it was working for a long time prior to the measurements in 1999.

The efficiency of the El-Paso pond is also calculated using Equation (3.11), and similarly to the calculation of the Kuwait’s pond. It was found that the efficiency of the pond is 2.7% (details are listed in Appendix B).

It can be observed from values of the efficiency of the two previous ponds, and from Figures 3.5 and 3.6 that the efficiency of the both two ponds is low; there is a small thermal gain. It will be when the temperature of the pond is high a balance between heat gain and heat loss will occur. The pond receives heat from the incident solar radiation, and the rate of increase in temperature is relatively small, and at the same time, there is a continuous heat loss to the surface and the ground. Date et al. (2013) implied that solar pond efficiency would have meaning when heat extraction from the pond is performed. When heat removal is begun, the temperature of the pond will decrease and consequently water will absorb solar radiation to increase its temperature and in this case the efficiency of the pond will be sensible.

### 3.4.2 Effect of ground heat loss

The experimental data for the LCZ of Ali’s (1986) pond in Kuwait is also compared with the present model, but by using Equations (3.38) and (3.40) to represent heat loss to the ground, the comparison is illustrated in Figure 3.7.
Chapter 3: Theoretical modelling of heat transfer

Figure 3.7: Comparison of the experimental temperature distribution of the lower layer LCZ of the Kuwait pond with unburied and Hull et al. (1988) formulae for heat loss to the ground.

It is evident from Figure 3.7, that in the case of an unburied pond (Equation (3.40) has been used for $Q_{\text{ground}}$), the temperatures are higher than the experimental values for most of the year. This difference could be explained by two facts. Firstly, the buried pond in the present model loses heat to the ground because the shallow layers of soil have high thermal conductivity. Consequently, heat loss to the soil from the bottom of the pond (no heat loss from walls, as they are considered well insulated) is higher than in the unburied case and has an impact on the pond, causing a decrease in temperature. Secondly, the temperature of the air reaches more than 37 °C in some areas, particularly in arid and desert places including Kuwait (Table 3.1). In this situation heat loss to the atmosphere in the proposed unburied pond will be small as compared with the buried pond with continuous heat loss to the soil. The profile of the LCZ in the case of unburied pond gives an indication that this pond can reach a temperature higher than a buried pond during the year, particularly, in hot areas. However, new parameters will appear in this case and need to be tackled. An economic balance will be very helpful to evaluate the positive and negative factors.

When heat loss to the ground is calculated by utilizing the formula which is suggested by Hull et al. (1988), (Equation (3.38)), it is apparent from Figure 3.7 that the increase in temperature is slower than the experimental changes. The reason for this behaviour could be the effect of perimeter because Hull et al. (1988) considered it has a significant impact on the temperature of the pond. That impact can be observed from the formula of Hull et al. (1988) in Equation (3.37) for $U_{\text{ground}}$. 

77
\[ U_{ground} = \frac{k_g}{x_g} + m k_g \frac{p}{A_u} \]

The suggested formula shows mathematically that the second term has a significant influence on the value of \( U_{ground} \) for small ponds because the contribution of \( \frac{p}{A_u} \) is important. In large ponds the influence of \( \frac{p}{A_u} \) will decrease considerably. To investigate this situation, a pond of the same depth as the Kuwait pond \( 2 \times 4 \times 0.9 \) m, but with different dimensions \( 30 \times 100 \times 0.9 \) m was modelled and compared with the small pond. The specifications of the two ponds are shown in Table 3.3.

<table>
<thead>
<tr>
<th>Location, Layer depth (m)</th>
<th>UCZ, NCZ, LCZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small pond</td>
<td>Kuwait</td>
</tr>
<tr>
<td>Dimensions (m)</td>
<td>4 × 2 × 0.9</td>
</tr>
<tr>
<td>Large pond</td>
<td>Kuwait</td>
</tr>
<tr>
<td></td>
<td>30 × 100 × 0.9</td>
</tr>
</tbody>
</table>

It is clear from Table 3.3 that the difference between ponds is only in surface area and perimeter. The profiles of temperature for both ponds are shown in Figure 3.8.

Figure 3.8: Comparison of the temperature distribution of the LCZ between small and large pond when formula of Hull et al. (1988) is used.

Figure 3.8 illustrates that the temperature of the suggested large pond with 3000 m\(^2\) of surface area and 260 m perimeter is much higher than the temperature of the small pond 8 m\(^2\) and 12 m perimeter throughout the year. The shape of the pond can be significant because perimeter changes with the geometrical shape. The temperature can also increase by increasing.
the depth of the pond because the selected layer’s depth is small (0.2, 0.4, 0.3) m for the UCZ, NCZ and the LCZ respectively.

3.4.3 Temperature distributions in suggested model pond
3.4.3.1 Temperature profiles in the UCZ and LCZ

The profiles of temperature for both upper and lower layers have been plotted for a pond with dimensions of $1 \times 1 \times 1.5$ m and thicknesses of 0.2, 0.8 and 0.5 m for the UCZ, NCZ and the LCZ respectively. Once again the pond is assumed to be in Kuwait City. The profiles are shown in Figure 3.9.

![Figure 3.9: The profile of temperature in LCZ and UCZ during one year (initial temperatures are 12.6 °C for both layers and month 1 is January).](image)

It is obvious from Figure 3.9 that the temperature of the lower layer LCZ increases substantially with time to reach maximum values of around 90 °C during July. After that the temperature decreases slightly with time to remain between 50 and 60 °C in December. The reason for this behaviour is that solar radiation incident on the pond also increases steadily in the first part of the year and it reaches the highest value in June. In the latter half of the year the radiation decreases. This behaviour can be seen apparently in Figure 3.4. It is clear from Figure 3.9 that the temperature of the LCZ is around 50-60 °C at the end of the year even with cold weather in winter. This is due to the accumulation of heat. Moreover, heat loss from the walls is neglected and that means the pond might remain warm for a long time. The variation of upper layer temperature is small. This is as a consequence of heat exchange between water surface and the surrounding air and that leads to the temperature of the UCZ tending to the air...
temperature. Similar behaviour has been observed by many researchers, e.g. Srinivasan (1993), Al-Jamal and Khashan (1998), Date et al. (2013), Karakilcik et al. (2006), German and Muntasser (2008) and Jaefarzadeh (2005).

### 3.4.3.2 Non-convective zone

The temperatures of NCZ have also been calculated for every month by dividing the layer into many layers. The thickness of every layer is chosen as 0.1 m. Figure 3.10 shows the NCZ layers.

![Figure 3.10: The NCZ section of the pond which shows the suggested partitions.](image)

An energy balance on every layer in the NCZ layer can be written as:

\[
Q_{ub} = k_w A_u \frac{\delta T}{\delta x} + Q_R A_u
\]  

(3.42)

where \( k_w \) represents the thermal conductivity of water solution in W/m K, \( \delta T \) is the temperature difference between centres of two layers, \( \delta x \) is a layer thickness and \( Q_R \) is the heat accumulated in the layer by solar radiation.
The energy transferred through the NCZ by conduction is computed by:

\[ Q_{ub} = U_t A_u \Delta T \quad (3.43) \]

The overall heat transfer coefficient \( U_t \) is calculated by applying Equation (3.19). The distribution of temperature through the NCZ can be calculated for any month during the year and it can be started from the upper or lower layer. The profile of temperature for the whole pond can be drawn through any month of the year. It is illustrated in Figure 3.11 for four months.

As shown from Figure 3.11, temperature is constant in both upper and lower layer because the two layers are considered to be well mixed in the model. The temperature of the middle layer (NCZ) decreases gradually from the bottom to the top of the pond. The same behaviour is observed in both experimental and theoretical studies on the salt gradient solar pond. The highest difference between temperature in the LCZ and UCZ is in July (more than 60 °C) whereas the lowest is in February (less than 30 °C).

3.5 Surface heat loss

The rate at which heat is lost from the surface of the pond obviously plays a significant role in determining its performance. Three heat loss mechanisms operate in parallel, namely radiation, convection and evaporation. To assess the relative importance of each of these mechanisms, each was considered to occur in isolation. The effect of this mechanism for heat loss on the performance of the pond could then be ascertained by inspection of temperatures reached in the pond. Firstly, evaporation and convection have been neglected to observe the
The effect of radiation only. The same process is repeated for evaporation and convection. It is apparent that evaporation has the highest influence on both LCZ and UCZ temperatures. In contrast, radiation has the lowest effect on both temperatures. Convection has also a substantial effect on both temperatures. Data is plotted and shown in Figures 3.12 and 3.13 for the LCZ and UCZ respectively.

![Figure 3.12](image1.png)

**Figure 3.12:** The temperature of the LCZ with different cases of heat loss from the surface.

![Figure 3.13](image2.png)

**Figure 3.13:** The temperature of the UCZ with different cases of heat loss from the surface.

It is apparent from the two figures that when only radiation is considered, the temperatures of both the storage layer and upper layer reach high (and obviously unphysical) values and that means it has a small effect on the temperature of the UCZ and the LCZ. With evaporation temperatures in the UCZ and the LCZ become low; the lowest values for both layers (UCZ and LCZ) are observed in the only evaporation case. For the UCZ, the temperature in case of
evaporation only is lower than the temperature when the three types of heat loss are considered. To explain this behaviour it is helpful to plot the ambient temperature in area of the pond (Kuwait) with the temperature of the UCZ. The profiles of both temperatures are illustrated in Figure 3.14.

![Figure 3.14: Profiles of both the ambient and the calculated temperatures of UCZ.](image)

It can be seen that the ambient temperature is higher than the temperature of the UCZ for most months during the year. That means heat would be transferred from the atmosphere to the pond according to the Equation (3.22). In the El Paso pond it is observed that ambient temperature is higher than upper layer temperature of the pond for most months through one year (Lu et al., 2001). The data which published by the researchers is plotted in Figure 3.15.

![Figure 3.15: Profiles of both measured ambient and UCZ temperatures for El-Paso pond (1999), extracted from (Lu et al., 2001).](image)
It is clear from Figure 3.15 that ambient temperature is higher than temperature of upper layer. The difference continues from the first month to October when it becomes very small.

### 3.6 Effect of layer thicknesses

The impact of changing the thicknesses of different layers of the pond on its performance is investigated in this section. The SGSP this time is considered to be in Nasiriyah City in the South of Iraq (Latitude: 31.05799, Longitude: 46.25726) with 1 m² surface area. The model has been employed to determine the temperatures in the UCZ and the LCZ for different cases. The meteorological data for Nasiriyah City is given in Table 3.4.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar radiation MJ/m².month</th>
<th>Ambient temperature °C</th>
<th>Relative humidity %</th>
<th>Wind speed m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>349.92</td>
<td>11.7</td>
<td>57.3</td>
<td>3.77</td>
</tr>
<tr>
<td>February</td>
<td>451.44</td>
<td>13.6</td>
<td>46.4</td>
<td>4.08</td>
</tr>
<tr>
<td>March</td>
<td>527.04</td>
<td>18.3</td>
<td>38.5</td>
<td>4.42</td>
</tr>
<tr>
<td>April</td>
<td>608.04</td>
<td>25.1</td>
<td>29.9</td>
<td>4.57</td>
</tr>
<tr>
<td>May</td>
<td>717.12</td>
<td>31.3</td>
<td>20.7</td>
<td>4.87</td>
</tr>
<tr>
<td>June</td>
<td>825.12</td>
<td>35.3</td>
<td>15.5</td>
<td>5.16</td>
</tr>
<tr>
<td>July</td>
<td>784.08</td>
<td>37.4</td>
<td>15.5</td>
<td>4.83</td>
</tr>
<tr>
<td>August</td>
<td>741.96</td>
<td>37.1</td>
<td>16.5</td>
<td>4.7</td>
</tr>
<tr>
<td>September</td>
<td>624.24</td>
<td>33.3</td>
<td>19.4</td>
<td>4.38</td>
</tr>
<tr>
<td>October</td>
<td>448.2</td>
<td>27.6</td>
<td>28.6</td>
<td>4.16</td>
</tr>
<tr>
<td>November</td>
<td>334.8</td>
<td>19.6</td>
<td>43.4</td>
<td>3.85</td>
</tr>
<tr>
<td>December</td>
<td>304.56</td>
<td>13.6</td>
<td>53.7</td>
<td>3.82</td>
</tr>
<tr>
<td>Average</td>
<td>559.44</td>
<td>25.4</td>
<td>32.1</td>
<td>4.38</td>
</tr>
</tbody>
</table>

Table 3.4 illustrates that for this city the solar radiation increases gradually from winter to summer to reach the maximum in June and then the decrease continues to reach the minimum in December.

#### 3.6.1 Effect the thickness of the UCZ

The 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 0.1-0.5 m with an interval of 0.1 m. The temperatures of the LCZ are plotted with time throughout a year for these proposed thicknesses in Figure 3.16.
Figure 3.16 shows that the 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 in 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 needs to be replaced on a regular basis. On the other hand, the thickness can be increased in arid and windy areas to avoid layer disturbance which might diminish the efficiency of the pond. When the thickness of the UCZ becomes lower than 0.2 m, the temperature of the LCZ can be slightly higher (Figure 3.16). However, the effect of wind may disturb the stability of the SGSP because the protective layer (UCZ) becomes too thin. Jaeferzadeh (2005) emphasised that the thickness of the UCZ should be kept as thin as possible. He recommended a thickness of 0.2 m. 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 the temperatures of this zone. Temperatures of the UCZ during a year for different thicknesses of the UCZ (0.1, 0.2, 0.3, 0.4 and 0.5) and the ambient temperatures are listed in Table 3.5.
Table 3.5: The temperatures of the UCZ and ambient temperatures in °C during a year with various thicknesses of the UCZ (month 1 is January)

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
<td>16.26</td>
<td>20.7</td>
<td>25.74</td>
<td>32.96</td>
<td>36.5</td>
<td>38.6</td>
<td>39.9</td>
<td>36.3</td>
<td>27.6</td>
<td>19.6</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>15.15</td>
<td>16.94</td>
<td>20.42</td>
<td>22.99</td>
<td>24.31</td>
<td>24.72</td>
<td>24.61</td>
<td>23.70</td>
<td>21.22</td>
<td>17.01</td>
<td>12.01</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>15.09</td>
<td>17.17</td>
<td>20.65</td>
<td>23.21</td>
<td>24.54</td>
<td>24.94</td>
<td>24.81</td>
<td>23.84</td>
<td>21.36</td>
<td>17.08</td>
<td>12.03</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>15.12</td>
<td>17.27</td>
<td>20.77</td>
<td>23.35</td>
<td>24.67</td>
<td>25.07</td>
<td>24.94</td>
<td>23.98</td>
<td>21.49</td>
<td>17.23</td>
<td>12.24</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>15.28</td>
<td>17.35</td>
<td>20.86</td>
<td>23.50</td>
<td>24.84</td>
<td>25.25</td>
<td>25.08</td>
<td>24.12</td>
<td>21.63</td>
<td>17.40</td>
<td>12.47</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>15.34</td>
<td>17.41</td>
<td>20.91</td>
<td>23.50</td>
<td>24.84</td>
<td>25.25</td>
<td>25.08</td>
<td>24.12</td>
<td>21.63</td>
<td>17.40</td>
<td>12.47</td>
</tr>
</tbody>
</table>

It is evident from Table 3.5 that there is no significant change in the temperature of the UCZ with variation of its thickness throughout the year. It is also obvious 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.

3.6.2 Effect the thickness of the NCZ

The effect of varying the thickness of the NCZ on the temperature of the LCZ and the UCZ is presented in this section. The thickness of the NCZ was changed from 0.5-2.5 m with an interval of 0.5 m and simultaneously, the thicknesses of the UCZ and LCZ were considered to be 0.2 (as previously selected to be the optimum) and 1.5 m respectively. Temperature profiles of the LCZ are plotted against time (month) and are shown in Figure 3.17.

Figure 3.17: The temperature profiles of the LCZ for various thicknesses of the NCZ, (UCZ = 0.2 m and LCZ = 1.5 m, month 1 is January, the initial temperatures of the UCZ and the LCZ are 15 and 17 °C respectively)
From Figure 3.17, it can be seen that with a small thickness of the NCZ (0.5 m), the temperature of the LCZ is the lowest. The 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. The 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 (Figure 3.17). 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. When the thickness is considered to be 2.5 m, it can be observed that there is a drop in the temperatures of the LCZ during most months of the year (dashed line). It is evident (Figure 3.17) that any increase in the thickness of the NCZ past 2 m will not be beneficial, and it will reduce the efficiency of the pond. It can therefore be concluded that the optimum thickness of the NCZ is between 1.5-2 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.

To elucidate the behaviour of the SGSP with the change of thickness of the NCZ, this zone can be considered as a thermal insulator for the storage zone (LCZ). 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 will influence the quantity of solar radiation that reaches the LCZ and will lead to a decrease in the temperature of this zone. German and Muntasser (2008) studied a SGSP connected to a multi effect desalination (MED) unit. A model has been suggested by this study and it concludes that the suitable depth of the NCZ is 1.1 m. However, the study focused on the suitability of a solar pond coupled to desalination and therefore this depth is optimal for that particular application as it requires the brine temperature of the LCZ to be around 60 °C. Al-Jamal and Khashan (1995) suggested a mathematical model to include many parameters affecting the performance of the SGSP. It is suggested that the optimal depth of the NCZ is 1 m. Jaefarzadeh (2005) explains that the increase in the thickness of the NCZ can enhance the pond’s performance (LCZ temperature) significantly. He concluded that raising thickness of the NCZ from 0.5-1 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 increased the maximum temperature 15 °C and only 6.5 °C respectively. Additionally, it was observed that
varying the thickness of the NCZ will result in no significant impact on the temperature of the UCZ.

### 3.6.3 Effect the thickness of the LCZ

In this part of investigation, the influence of varying the thickness of the LCZ on its temperature and the UCZ temperature is studied. The thickness of this layer (LCZ) is changed from 0.5-4 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 (both are selected as the optimum as previously discussed) respectively. The results are illustrated in Figure 3.18.

![Figure 3.18: The temperature profiles of the LCZ for various thicknesses of the LCZ, (UCZ = 0.2 m and NCZ = 2 m, month 1 is January, the initial temperatures of the UCZ and the LCZ are 15 and 17 °C respectively)](image)

It is clearly illustrated in Figure 3.18 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 (unphysical, 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, it is shown (Figure 3.18) that 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. 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 °C. Such applications will, therefore, benefit from increasing the depth of the LCZ rather than the surface area of the pond. Table 3.6 corresponds to the results shown in Figure 3.18. It provides a better understanding of the impact of the LCZ thickness variation on the temperatures obtained in this zone.

Table 3.6: Minimum and maximum temperatures in the LCZ for various thicknesses of this zone (UCZ = 0.2 m, NCZ = 2 m).

<table>
<thead>
<tr>
<th>Depth (meter)</th>
<th>Maximum Temperature °C (November)</th>
<th>Minimum Temperature °C (December)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>115 (July)</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ increases quickly, it reaches 69 °C in March and 83 °C in April, and heat extraction can commence early.</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>109 (August)</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ reaches 70 °C in April.</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>102 (September)</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ reaches 73 °C in May.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>96 (September)</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ reaches 64 °C in May and 76 °C in June.</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>89 (September)</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ reaches 70 °C in June</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>84 (October)</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ reaches 63 °C in June and 72 °C in July.</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>80 (October)</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ reaches 67 °C in July.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>75 (October)</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Temperature of the LCZ reaches 62 °C in July and 70 °C in August.</td>
<td></td>
</tr>
</tbody>
</table>

Generally speaking, each industrial application coupled to a solar pond requires heat at its own specific 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 3.6, if the pond is implemented for power generation purposes, the depth of the LCZ cannot be greater 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 these cases, depths 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 chapter 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 3.6 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.

Another observation that can be made from Table 3.6 is that the warm 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 3.6).

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 to. However, it can be said that the thickness of 1-2 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 96-109 °C and the minimum temperatures are 75-82 °C. Further increase in depth does not enhance the minimum temperature and causes a decrease in the maximum temperature (Table 3.6). On the other hand, a higher depth means increasing the heat capacity of the pond, but that requires a considerable addition to the capital cost of the SGSP. Jaefarzadeh (2005) claims that the appropriate thickness depends on the design conditions and the required operating temperatures. German and Muntasser (2008) pointed out that the thickness of the LCZ can be 4 m. 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 (1983) concluded that depth of the LCZ should vary depending on the desired operating temperature, to accomplish the maximum efficiency. Varying the thickness of the LCZ has no considerable impact on the temperatures of the UCZ.

Finally, it can be said that based on the results of this investigation, the optimum thicknesses of the UCZ and the NCZ in SGSPs are 0.2 and 2 m respectively. The thickness of the LCZ should be determined with respect to the type of application.

3.7 Loading

3.7.1 Loading with constant LCZ thickness

The behaviour of the SGSP is examined with heat extractions of 10, 20, 25, 30 and 40 W/m² load and these values are compared with the case of no load. Once again, the pond is considered to be in Nasiriyah City with a 1 m² surface area and with layer thicknesses of 0.2, 2 and 1.5 m for the UCZ, NCZ and LCZ respectively. The obtained results are shown in Figure 3.19.
Figure 3.19: 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, the initial temperatures of the UCZ and LCZ are 15 and 17 °C respectively).

As indicated in Figure 3.19, 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/m² load, the temperature of the LCZ continuously rises to reach the maximum of 93 °C (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/m² but with lower values of maximum and minimum temperatures. With loads of 30 and 40 W/m², it is shown that there is a sudden decrease in temperatures during June. However, the temperature rises again for two months and then starts declining. For the 30 W/m² case, it reaches around 47 °C and for 40 W/m² it is around 35 °C. The reason for this decrease 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 Figure 3.20.
As mentioned previously for the heat extraction over one year, the heat extraction can be started 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 Figure 3.20 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 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 layer thicknesses of 0.2, 2 and 1.5 m for the UCZ, NCZ and the LCZ respectively.

Similar behaviour to Figure 3.20 was observed by Date et al. (2013) when they investigated the behaviour of the SGSP with different rates of heat extraction from the LCZ. In their theoretical study, pond was left for two months for warming up, and with this period temperature in the LCZ reached about 45 °C.

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.
3.7.2 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 is investigated. The results are demonstrated in Figure 3.21.

![Figure 3.21: The temperature of the LCZ with various thicknesses and 30 W/m$^2$ load for one year (month 1 is January and initial temperatures of the UCZ and LCZ are 15 °C and 17 °C respectively, thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively).](image)

Figure 3.21 illustrates that with a 1 m thickness, heat extraction (30 W/m$^2$) can start from March when the temperature in the LCZ is 69 °C. It is also indicated that due to the low 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/m$^2$) starts in April with the similar temperature of the LCZ at 69 °C and temperature in December reaches 46 °C. With a 2 m thickness, heat extraction (30 W/m$^2$) 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/m$^2$) 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 Figure 3.22.
Figure 3.22: The temperature of the LCZ with various thicknesses and 30 W/m² load over two years (month 1 is January and initial temperatures of the UCZ and LCZ are 15 °C and 17 °C respectively, thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively).

Figure 3.22 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 necessary to stop heat extraction in October to February. It is shown in Figures 3.21 and 3.22 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 Tables 3.7 and 3.8 are provided.
Table 3.7: Variation of the LCZ thickness and the load throughout one year (NCZ = 1.5 m); in this table it is considered that depths of the UCZ and NCZ are 0.2 and 1.5 m respectively, and depth of the LCZ is changed from 0.5-4 m.

<table>
<thead>
<tr>
<th>Total Depth (m)</th>
<th>LCZ (m)</th>
<th>Maximum temperature of the LCZ °C (no load)</th>
<th>Load W/m²</th>
<th>Maximum temperature after heat extraction</th>
<th>$T_{LCZ}$ in December (after heat extraction)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>0.5</td>
<td>112(July)</td>
<td>10</td>
<td>101</td>
<td>47</td>
<td>Heat extraction can be started from March, in April the temperature in the LCZ is 82 °C which can be used for power generation with low rates of load 10-20 W/m² to keep the temperature in the LCZ high. Time for warming up has to be considered.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>90</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>80</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>69</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td>59</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>1</td>
<td>107(Aug)</td>
<td>10</td>
<td>97</td>
<td>57</td>
<td>The temperature of the LCZ in April is 69 °C. It can be used for power generation and other application that require low temperatures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>87</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>78</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>68</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td>58</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>1.5</td>
<td>100(Aug)</td>
<td>10</td>
<td>93</td>
<td>64</td>
<td>In May, the temperature of the LCZ reaches 73 °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 a load of 30 W/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>85</td>
<td>53</td>
<td></td>
</tr>
</tbody>
</table>
The temperature of the LCZ reaches around 77 °C in June and it can be used for different applications with all loads. With a load of 50, warming up period is required.

Similar to the LCZ depth of 2 m. The temperature in June reaches around 70 °C. It cannot be used for power generation.

The temperature in July reaches around 73 °C, it is suitable for desalination or domestic heating because it can provide heat for an extended period and a short period for warming up is needed. It cannot be used for applications that require temperatures higher than 70 °C. It can supply energy continuously for domestic heating with a heat extraction rate of 50 W/m².
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Temperature (°C)</th>
<th>Period</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>3.5</td>
<td>80(Sep)</td>
<td>67</td>
<td>61</td>
<td>55</td>
<td>48</td>
<td>42</td>
</tr>
<tr>
<td>5.7</td>
<td>4</td>
<td>76(Oct)</td>
<td>66</td>
<td>60</td>
<td>54</td>
<td>48</td>
<td>43</td>
</tr>
</tbody>
</table>

Similar to the LCZ depth of 3 m. In July the temperature of the LCZ is 68 °C which can be implemented for applications with low temperatures between 40-60 °C and it can supply heat continuously for all loads with a short period for warming up in case of 40 and 50 w/m².

The temperature in July reaches 64 °C. This depth is suitable for applications requiring low temperatures from 40-60 °C with continuous and low rate of heat extractions (10-30 W/m²) and with short period to warm up for 40-50 W/m² loads.
Table 3.8: Variation of the LCZ thickness and the load throughout one year (NCZ = 2 m); in this table it is considered that depths of the UCZ and NCZ are 0.2 and 2 m respectively, and depth of the LCZ is changed from 0.5-4 m.

<table>
<thead>
<tr>
<th>Total Depth (m)</th>
<th>LCZ (m)</th>
<th>Maximum temperature of the LCZ °C (no load)</th>
<th>Load W/m$^2$</th>
<th>Maximum temperature after heat extraction</th>
<th>$T_{LCZ}$ in December (after heat extraction)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>0.5</td>
<td>115 (July)</td>
<td>10</td>
<td>103</td>
<td>53</td>
<td>Heat extraction can be started from March. In April the temperature in the LCZ is 84 °C and in March 89 °C.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>91</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>80</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>69</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td>57</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>1</td>
<td>109 (August)</td>
<td>10</td>
<td>100</td>
<td>63</td>
<td>The temperature of the LCZ in April is 70 °C. It can be used for power generation and other applications that require low temperatures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>90</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>80</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>71</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td>61</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>1.5</td>
<td>102 (September)</td>
<td>10</td>
<td>93</td>
<td>69</td>
<td>In May, the temperature of the LCZ reaches 71 °C (2 degrees below the case of NCZ = 1.5 m) 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$^2$.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>84</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>74</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>65</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3: Theoretical modelling of heat transfer

<table>
<thead>
<tr>
<th>Depth</th>
<th>Temperature in June</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m</td>
<td>~76 °C</td>
<td>Suitable for different applications with all loads.</td>
</tr>
<tr>
<td>3 m</td>
<td>~69 °C</td>
<td>Suitable for desalination or domestic heating because it can provide heat for an extended period and a short period for warming up is needed. It cannot be used for applications that require temperatures higher than 70 °C (similar to the pond with NCZ = 1.5 m, Table 3).</td>
</tr>
<tr>
<td>3 m</td>
<td>~67 °C</td>
<td>Similar to the LCZ depth of 3 m, in July the temperature of the LCZ is 67 °C (1 degree below the case of NCZ=1.5 m). Pond can be implemented for applications with low temperatures between 40-60 °C and it can supply heat continuously for all loads with a short period for warming up in case of 40 and 50 w/m² (similar to the case of NCZ = 1.5).</td>
</tr>
</tbody>
</table>
The temperature in July reaches 62 °C (2 degrees below the case of NCZ = 1.5), this depth is suitable for applications requiring low temperatures from 40-60 °C with 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.
Chapter 3: Theoretical modelling of heat transfer

Tables 3.7 and 3.8 have extracted from 16 tables, to avoid prolongation these tables are listed in Appendix A.

3.8 Summary

A model to calculate temperature in the three zones of a SGSP is suggested. The results were validated by comparison with experimental data and a good agreement has been obtained. The solar pond can supply heat temporarily during the year, even in the winter season with cloudy and cold weather, but it needs time to warm up. The model was used in the calculations of temperatures in the UCZ and the LCZ. The results showed that the optimum thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively. It is also observed that thickness of the LCZ depends mainly on the type of the application coupled with the SGSP. When heat extractions from the pond are 10-20 W/m², the pond (UCZ = 0.2, NCZ = 2 and LCZ = 1.5 m) can supply thermal heat continuously regardless the season. The minimum temperatures of the LCZ of the pond were between 50-60 °C for those loads (10-20 W/m²). Interestingly, increasing the depth of the LCZ could increase the heat capacity, and this will decrease the temperature of the layer (LCZ). However, increasing the depth of the LCZ could be beneficial to decrease the surface area of the pond, and it remains suitable for applications require low temperatures (40-60 °C).
Chapter 4
The Gel pond
4.1 Introduction

The evaporation from the surface of the SGSP, the attenuation of the solar radiation in the UCZ when it becomes deeper and the stability of the NCZ are disadvantages relating to the use of the SGSP. The effect of evaporation is discussed theoretically in Chapter 3, and the experimental results will be considered and presented in Chapter 6. The gel pond was suggested as an alternative to the SGSP. In the gel pond, the UCZ can be very thin, and its function is only to protect the gel layer, and there is no salt diffusion to this layer. Moreover, the NCZ will be replaced by a gel layer. In this chapter, the feasibility of the construction of a gel pond will be investigated, and a comparison with the SGSP will also be considered. Moreover, the temperature evolution in the UCZ and LCZ will be studied.

4.2 Previous theoretical models

Wilkins et al. (1981) suggested a one dimensional model to predict the performance of a gel pond. In this model many assumptions were adopted (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.

Wilkins et al. (1982) 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 temperatures in the gel pond. Heat loss from the surface of both the gel pond and the SGSP was also calculated. It was concluded (Wilkins et al., 1982) that heat loss from the surface of the SGSP is higher than that from the gel pond. Wilkins et al. (1985) 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 (1979), Wang and Akbarzadeh’s model (1983) and Bansal and Kaushik’s model (1981). 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.

4.3 Proposed model

To calculate temperatures in the UCZ, and LCZ in the gel pond, the model described in Chapter 3 is used. It is proposed that the pond consists of three layers, (i) the storage layer which is covered by (ii) a gel layer and finally (iii) a water layer to protect the gel layer from the environment. A cross-section of the proposed gel pond is illustrated in Figure 4.1.
The analysis began with establishing a heat balance on the upper water layer (UCZ); heat flows through the UCZ is illustrated in Figure 4.2.

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

\[ M_u C_{pu} \frac{dT_u}{dt} = Q_{rin} + Q_{ub} - Q_{o1} - Q_{uc} - Q_{wr} - Q_{ue} - Q_w \]  \hspace{1cm} (4.1)

\[ M_u = \rho_u v_u \] \hspace{1cm} (4.2)

\[ M_u = \rho_u h_{UCZ} A_u \] \hspace{1cm} (4.3)
\[
\frac{dt_u}{dt} = \frac{1}{M_u c_{pu}}[Q_{rin} + Q_{ub} - Q_{o1} - Q_{uc} - Q_{ur} - Q_{ue}] - \frac{1}{M_u c_{pu}}[Q_w]
\] (4.4)

where \(Q_{rin}\) represents the solar radiation entering the UCZ of the pond, and the data from NASA is considered to calculate this term. The solar radiation comes out of the UCZ is \(Q_{o1}\), and it is calculated using Brayant and Colbeck’s (1977) formula as shown.

\[
Q_{o1} = \tau H [0.36 - 0.08 \ln h_{UCZ}]
\] (4.5)

where, \(H\) is the solar insolation fallen on the surface of the pond in W/m\(^2\), and \(h_{UCZ}\) is the depth of the UCZ in meters. The terms of the Equation (4.4), \((Q_{ub}, Q_{uc}, Q_{ur}, Q_{ue})\) are calculated similarly to terms of the Equation (3.12) with the exception of changing the thermal conductivity of the water solution of the NCZ to the thermal conductivity of the gel layer. Moreover, the thickness of the gel layer is used instead of the thickness of the NCZ. The walls of the gel pond are considered well insulated, and therefore heat loss from them \((Q_w)\) is neglected.

The heat flows through of the storage zone (LCZ) is shown in Figure 4.3.

![Figure 4.3: A schematic of heat flows through the LCZ of the gel pond](image)

The energy conservation equation for the LCZ can be written as:

\[
M_l c_{pl} \frac{dT_L}{dt} = Q_{o2} - Q_{ub} - Q_{ground} - Q_{load} - Q_w
\] (4.6)

\[
M_l = \rho_l v_l
\] (4.7)

\[
\frac{dT_L}{dt} = \frac{1}{M_l c_{pl}}[Q_{o2} - Q_{ub} - Q_{ground} - Q_{load}] - \frac{1}{M_l c_{pl}}[Q_w]
\] (4.8)

The parameter \(Q_{o2}\) represents the solar radiation entering and absorbed in the LCZ. Wilkins et al. (1985) claimed that the transmissivity of a 15-40 cm thickness of gel is very close to the transmissivity of 10-60 cm fresh and 16% salt water. Accordingly, \(Q_{o2}\) can be calculated by using Equation (4.5) as below:

\[
Q_{o2} = \tau H [0.36 - 0.08 \ln (h_{UCZ} + x_{ge})]
\] (4.9)

where \(x_{ge}\) is the thickness of the gel layer in meters.
\( Q_w = 0 \) \hspace{1cm} \text{(walls are well insulated)}

Equation (4.8) can be rewritten as:

\[
\frac{dT_k}{dt} = \frac{1}{M \cdot c_p} \left[ Q_{o2} - Q_{ub} - Q_{ground} - Q_{load} \right] \quad (4.10)
\]

Once again, the terms of the Equation (4.10), \( Q_{ub} \) and \( Q_{ground} \), have been calculated similarly to the terms of the Equation (3.31).

The case of no load is considered, so the term \( Q_{load} \) in Equation 4.10 is neglected.

4.4 Results and discussions

Equations (4.4) and (4.10) have been solved using the model described in Chapter 3 which used the ode45 MATLAB function to solve the first order ordinary differential equations.

4.4.1 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 the New Mexico University in 1981. The pond had a diameter of 4.8 m and a depth of 1.22 m (Wilkins et al., 1981). The physical properties of the gel used are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Specific heat ( \text{kJ/kg K} )</th>
<th>Density ( \text{Kg/m}^3 )</th>
<th>Thermal conductivity ( \text{W/m K} )</th>
<th>Viscosity at 25 °C ( \text{(cp)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.284</td>
<td>1166</td>
<td>0.556</td>
<td>3 \times 10^4</td>
</tr>
</tbody>
</table>

The thermal conductivity of the ground 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 (14.1 °C) (Wilkins et al., 1986). The climatic conditions of Albuquerque City are given in Table 4.2.
Table 4.2: The climatic conditions of the Albuquerque City

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar radiation measured MJ/m².month (Wilkins, Lee and Chakraborti, 1986)</th>
<th>Ambient temperature measured °C (Wilkins, Lee and Chakraborti, 1986)</th>
<th>Relative humidity % (NASA)</th>
<th>Wind speed m/s (NASA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>347.3</td>
<td>2</td>
<td>70</td>
<td>3.9</td>
</tr>
<tr>
<td>February</td>
<td>456.19</td>
<td>4.8</td>
<td>66.8</td>
<td>4.1</td>
</tr>
<tr>
<td>March</td>
<td>601.3</td>
<td>8</td>
<td>64.3</td>
<td>4.4</td>
</tr>
<tr>
<td>April</td>
<td>759.4</td>
<td>13.6</td>
<td>55.8</td>
<td>4.4</td>
</tr>
<tr>
<td>May</td>
<td>865.7</td>
<td>18.8</td>
<td>53</td>
<td>4.1</td>
</tr>
<tr>
<td>June</td>
<td>912.3</td>
<td>24</td>
<td>55.2</td>
<td>4</td>
</tr>
<tr>
<td>July</td>
<td>847.5</td>
<td>26.5</td>
<td>62.7</td>
<td>3.7</td>
</tr>
<tr>
<td>August</td>
<td>780.1</td>
<td>25</td>
<td>69.7</td>
<td>3.7</td>
</tr>
<tr>
<td>September</td>
<td>671.3</td>
<td>21.5</td>
<td>73.8</td>
<td>3.8</td>
</tr>
<tr>
<td>October</td>
<td>526.1</td>
<td>15</td>
<td>76.2</td>
<td>3.8</td>
</tr>
<tr>
<td>November</td>
<td>386.2</td>
<td>7.3</td>
<td>72.8</td>
<td>4</td>
</tr>
<tr>
<td>December</td>
<td>316.2</td>
<td>2.7</td>
<td>69.5</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>622.4</td>
<td>14.1</td>
<td>65.8</td>
<td>4</td>
</tr>
</tbody>
</table>

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 4.1 (Wilkins et al., 1981). The comparison is illustrated in Figure 4.4, and the relative errors of the theoretical results from the experimental data are illustrated in Table 4.3.

![Figure 4.4](image-url)

**Figure 4.4:** A comparison between the present calculation and the experimental data of Wilkins et al. (1981) (from 15 of March to 6 of April 1981)
Table 4.3: Relative errors of the theoretical results from the previous experimental results of Wilkins et al. (1981)

<table>
<thead>
<tr>
<th>Date</th>
<th>20 March</th>
<th>25 March</th>
<th>30 March</th>
<th>2 April</th>
<th>3 April</th>
<th>6 April</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative error %</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4.3 shows that the average of the disparity between the experimental results and the results of the present model is 6 % and it is reasonable. Wilkins and Lee (1987) 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 4.4.

Table 4.4: The change in the temperature of the Albuquerque gel pond with time (Wilkins and Lee, 1987)

<table>
<thead>
<tr>
<th>Date</th>
<th>7/5/1981</th>
<th>31/5/1981</th>
<th>14/6/1981</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature °C</td>
<td>55.25</td>
<td>56.31</td>
<td>57 (maximum)</td>
</tr>
</tbody>
</table>

The Temperatures in Table 4.4 are also compared with the theoretical temperatures of the LCZ which were calculated by the 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 shown in Figure 4.5.

![Figure 4.5: The comparison of the 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).](image)
It is evident from Figures 4.4 and 4.5 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 developed in Chapter 3 can be used to describe the temperature behaviours of the UCZ and the LCZ in the gel pond.

4.4.2 Temperature distributions in the suggested model gel pond

The temperatures of both the UCZ and the LCZ are calculated and plotted against time. The results are shown in Figure 4.6 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\textsubscript{ge}) is taken as 0.556 W/m K (Wilkins et al., 1981), thermal conductivity of the ground (k\textsubscript{g}) as 2.15 W/m K and temperature of the ground (T\textsubscript{g}) is 23°C (Kanan et al., 2014).

Figure 4.6: 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).

Figure 4.6 shows that the temperature of the LCZ increases steadily 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 Figure 4.6 that the gel pond 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 chapter.
4.4.3 Effect of the layer thicknesses of the gel pond

4.4.3.1 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 Figure 4.7.

![Temperature evolution of the LCZ with different depths of the UCZ and constant depths of the gel and the LCZ at 0.6 and 1.25 m respectively (the initial temperature of the UCZ and the LCZ are 15 and 17 °C respectively).](image)

It is evident from Figure 4.7 that there is a smooth 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 (Figure 4.7). Increasing the thickness of the UCZ to 0.2 m reduces the temperature of the LCZ by 2 °C. It can be observed from Figure 4.7 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. (1986) suggest 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. Clearly, however, changing the thickness of the UCZ does not have a substantial influence on its temperature.

### 4.4.3.2 Effect of the thickness 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 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 Figure 4.8.

![Figure 4.8: 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 (the initial temperature of the UCZ and the LCZ are 15 and 17 °C respectively).](image)

Figure 4.8 shows 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 small thickness 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 be 1 m, there is a decrease in the temperature of the LCZ for 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 Figure 4.8. Firstly, when the thickness of the gel layer is increased from 0.2 m to 0.3 m, there is a significant increase in temperatures of the LCZ 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. 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 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.

### 4.4.3.3 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, while the thickness of the LCZ changes between 0.5-6 m at intervals of 0.5 m. The temperature profiles of the LCZ are illustrated in Figure 4.9.

![Figure 4.9: 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 (the initial temperature of the UCZ and the LCZ are 15 and 17 °C respectively).](image)

Figure 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. It is unphysical because the boiling point of the saturated NaCl solution is 108 °C. 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 (Figure 4.9) that the
gaps among 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 has less obvious curvature.

The previous discussion shows that the gel pond behaves approximately similarly to the
SGSP. The optimal thicknesses of the gel pond’s layers are 0.05, 0.9 m for the UCZ and the
gel layer respectively while the thickness of the LCZ depends on the type of the application
coupled with the gel pond. For example, the MED desalination requires a specific temperature
(≈ 60 °C). That means a particular depth to the LCZ is required which is different from that is
needed for the domestic heating (≈ 40 °C is required) and for the power generation (≈ 80 °C),
it is also a different thickness to the LCZ is required. Wilkins and Lee (1987) claimed that for
the domestic requirements with constant temperature 40 °C and 107 W/m² load, the suitable
depths are 0.6 m and 4 m for the gel and the LCZ respectively. Moreover, for the electricity
generation, but with constant temperature 80 °C and 32 W/m² they implied that those same
thicknesses are appropriate. In the current study, it can be observed from Figure 4.9 that when
the thicknesses of the gel pond’s layers are 0.05, 0.9 and 4 m for the UCZ, gel layer, and the
LCZ respectively, the maximum temperature (October) is around 80 °C and 78 °C in
December. Moreover, it reaches more than 60 °C in July. Consequently, the pond with these
thicknesses can be used comfortably for the domestic purposes or applications require low
temperatures and it is difficult to be used for the power generation and for this purpose a LCZ
with a smaller thickness (2 m) might be suitable as shown in Figure 4.9. 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.

4.5 Comparison with the SGSP

A theoretical comparison between 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
Chapter 4: The gel pond

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 LCZ respectively. For this gel pond, the maximum temperature is 90 °C in October, and it is about 82 °C in December, it reaches more than 70 °C in July, at which point heat extraction can be commenced (Figure 4.9). For the SGSP, the thicknesses are considered to be 0.2, 2 and 2.5 m for the UCZ, NCZ and the LCZ respectively, which were previously concluded in Chapter 3 (Figure 3.18). The SGSP with these thicknesses can supply sufficient heat for the MED desalination. The maximum temperature in this SGSP is 90 °C in September, and it is about 80 °C in December, it reaches around 70 °C in June which heat extraction can be started efficiently. Both ponds with these thicknesses are suitable for the 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 illustrated in the Figure 4.10.

Figure 4.10: Temperature profiles of the LCZ in the gel pond and the SGSP, the two pond have a surface area of 1m², 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.

Figure 4.10 shows that for the whole year, the difference between temperatures of 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 of the LCZ is smaller in the case of the SGSP and might be the temperature
increases faster. After September, the temperature in the SGSP becomes a bit lower than in the gel pond for the rest period 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.

\[ q = mc_{pl}\Delta T \]  

(4.11)

where \( q \) is the heat stored in the LCZ. The results are illustrated in Figure 4.11.

![Figure 4.11: Heat capacities of the LCZ of the SGSP and gel pond](image)

Figure 4.11 shows that the thermal mass of the LCZ in the gel pond is mostly higher than that of the LCZ in the SGSP for the selected thicknesses; and the trend in Figure 4.11 is similar to the temperature trend seen in Figure 4.10. 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 of the LCZ between the two ponds. Interestingly, the heat capacity of the gel pond might vary with the change of the concentration of the LCZ, for the results in Figure 4.11, it is considered that the concentration of the salty water of the LCZ is 0.25 kg/l for both ponds. The influence 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 have an effect on the temperature and the heat capacity of water in the LCZ. Their variations with different salt concentration are shown in Figures 4.12 and 4.13.
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. (1986), 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 heat capacities of the LCZ in the gel pond with these concentrations have been calculated by using Equation (4.11) and the results are illustrated in Figure 4.14.

Figure 4.14: Change of the heat capacity of the gel pond throughout one year and a comparison with the SGSP

Figure 4.14 shows that the concentration of the salty water in the LCZ has a small effect on its heat capacity in the gel pond. The highest capacity is with the lowest concentration (10%).
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. Figures 4.12 and 4.13 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 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 (Figure 4.14). It is evident from Figure 4.14 that the heat capacity of the SGSP is lower than the heat capacities of the gel pond, except for the first two months.

4.6 Cost calculations

4.6.1 The cost of the SGSP

The essential parameter in any industrial application is the cost. Srinivasan (1993) claimed that the cost of a salt gradient solar pond is much less than the cost of a flat plate collector. He also implied that the initial cost of the SGSP is high and it strongly depends on the site of the pond. Site factors such as the local cost of excavation and the 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 thermal conductivity of the ground, 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 conditions. Rao and Kishore (1989) have proposed the following equation to calculate the capital cost of the SGSP per square meter.

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

(4.12)

where \( C_1 \) is the excavation charge/m\(^3\), \( C_2 \) is the water charge/m\(^3\), \( C_3 \) is the salt cost/tonne, \( C_4 \) the liner cost/m\(^2\), \( C_5 \) 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/m\(^3\), \( C_9 \) the cost of the brick lining/m\(^3\) and \( C_{10} \) is the cost of the wave suppressor/m\(^2\). Hull et al. (1988) published some of these costs based on experimental data which was collected from ponds constructed in Israel and the USA. These costs are as follows: the cost of excavation is $5/m\(^3\) for small ponds, decreasing to $1/m\(^3\) for large ponds. The cost of the lining is typically $10-15/m\(^2\), even for small ponds. The Cost of salt depends on the site: for example, Hull et al. (1988) put it at $0.04/kg, while the price recently reached
around $0.4/kg. The cost of the wave suppressor is $1/m^2, decreasing to $0.35/m^2 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 Equation (4.12) can be set out as follows: the cost of excavation is $17.5/m^3 (wisconsinlpr.com, 2016). The cost of cement in Iraq is around $100/tonne, or $5 per 50kg bag for the salt-resistant type (southren-cement.com, 2016). Sand is not expensive, costing around $20/m^3; while the cost of bricks has recently been put at around $90 per 1,000 bricks (cosit.gov.iq, 2016). To calculate the cost of 1 m^3 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/m^3. The cost of water is around $4/m^3, and the cost of the NaCl salt in Iraq is around $0.25/kg or even less. Considering these costs and applying Equation (4.12), the cost of a SGSP with a 1 m^2 surface area in Iraq will be approximately $304.

The real cost of a proposed SGSP for many depths has been calculated per 1 m^2, and has been compared with the cost which has been computed by using the Rao and Kishore’s equation (1989) (Equation 4.12). 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 4.5.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>4.5</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>proposed cost ($)</td>
<td>191</td>
<td>246</td>
<td>300</td>
<td>353</td>
<td>407</td>
<td>461</td>
<td>514</td>
<td>568</td>
</tr>
<tr>
<td>Cost by the Rao and Kishore’s equation ($)</td>
<td>304</td>
<td>304</td>
<td>304</td>
<td>304</td>
<td>304</td>
<td>304</td>
<td>304</td>
<td>304</td>
</tr>
<tr>
<td>Relative error %</td>
<td>59</td>
<td>23</td>
<td>1</td>
<td>13</td>
<td>25</td>
<td>34</td>
<td>40</td>
<td>46</td>
</tr>
</tbody>
</table>

Table 4.5: The calculated real costs of the proposed SGSP and the comparison with the cost computed using Rao and Kishore’s equation (1989)

Table 4.5 illustrates that the Rao and Kishore equation (1989) can give 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 range. For example, the El Paso solar pond at Texas in the USA is a 3000 m^2 pond with a depth of 3.25 m; the Pyramid Hill solar pond in Australia is a 3000 m^2 pond with a 2.3 m depth (Leblanc et al., 2013); a 6000 m^2 SGSP at Bhuj in India with a 3.5 m depth (Kumar and Kishore, 1999); Bet Ha-Arava 4000 m^2 in Israel, which has a 2.5 m depth; and Ein Boqeq, also in Israel, a 7500 m^2 pond with a depth of 2.6 m (Hull et al., 1988).
According to William and Tolbert (1981) and Hull et al. (1988), 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 34-42% of the total cost. It increases with the pond’s depth, confirming the findings of previous studies. The results are shown in Table 4.6.

Table 4.6: Change of the salt’s cost with the depth of the pond and its percentage to the total cost

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>4.5</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pond’s cost $</td>
<td>191</td>
<td>246</td>
<td>300</td>
<td>353</td>
<td>407</td>
<td>461</td>
<td>514</td>
<td>568</td>
</tr>
<tr>
<td>Salt’s cost $</td>
<td>66</td>
<td>91</td>
<td>116</td>
<td>140</td>
<td>165</td>
<td>191</td>
<td>215</td>
<td>240</td>
</tr>
<tr>
<td>Percentage of the salt cost %</td>
<td>34</td>
<td>36</td>
<td>38</td>
<td>39</td>
<td>40</td>
<td>41</td>
<td>42</td>
<td>42</td>
</tr>
</tbody>
</table>

4.6.2 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 a proposed gel pond for many gel thicknesses has been investigated, a specific depth to the pond is taken (2.5 m) with a thickness of 0.05 m to the UCZ and concentration of the storage zone is considered to be 0.25 kg/l. The polymer used to construct the gel layer is considered to be polyacrylamide; the results are shown in Figure 4.15. Once again the proposed gel pond is considered to be in the Iraqi city of Nasiriyah.
It is evident from Figure 4.15 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 thickness and the concentration of the gel are fixed at 0.2 m and 30% respectively. The results are demonstrated in Figure 4.16 for different depths of the gel pond.

It can be observed from Figure 4.16 that the cost of the gel pond increases with higher salt concentrations in the LCZ, for all depths. Moreover, the figure illustrates clearly that the depth of the LCZ in the gel pond has a significant influence on its cost; the cost with a LCZ with a 4.75 m depth is approximately double the cost where the depth is 1.25 m.

A slight modification to Equation (4.12) 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 costs of the salt and the gel materials respectively. Once again, polyacrylamide is considered as the gel of the gel pond, and its cost is taken from alibaba.com. For the gel pond, most construction 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 estimation to the capital cost of the gel pond, Equation (4.12) can be rewritten as:
\[ C_p = 2.546(C_1 + C_2) + 0.675(a \ast C_3 + (b \ast b \ast C_3)) + 1.3C_4 + 0.456C_5 + 0.0415C_6 + 0.124C_7 + 0.021C_8 + 0.085C_9 + C_{10} \]  \hspace{1cm} (4.13)

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 for the used 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. Equation (4.13) illustrates that the capital cost of the gel pond depends on four factors: the salt concentration of the LCZ and its thickness percentage (represented by \( a = \frac{LCZ}{LCZ + gel} \)), the percentage of the gel thickness (represented by \( b = \frac{gel}{LCZ + gel} \)) and the gel concentration. For example, if the gel pond of Wilkins and Lee (1987) 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 Figure 4.17.

Figure 4.17: The proposed costs of the gel pond and the costs calculated by the modified Rao and Kishore’s equation.

Figure 4.17 shows that Equation (4.13) gives a reasonable approximation for the cost of the gel pond with an average error of 20\%; that means if a gel pond is proposed with a particular depth, gel thickness and gel concentration, Equation (4.13) 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 in section 4.4 have been calculated. The thickness of the SGSP’s layers for MED in section 4.4 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. (Table 3.6, total depth, 4.2, UCZ = 0.2 NCZ = 1.5, LCZ = 2.5). 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), and it is still suitable for the MED process, but with lower capacity. Some of these choices are given in Table 4.7

<table>
<thead>
<tr>
<th>Pond type</th>
<th>Layer’s thickness (m)</th>
<th>Cost ($)</th>
<th>Optimal thicknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGSP</td>
<td>UCZ = 0.2, NCZ = 2, LCZ = 2.5 (concentration of LCZ = 0.25 kg/l)</td>
<td>493</td>
<td></td>
</tr>
<tr>
<td>SGSP</td>
<td>UCZ = 0.2, NCZ = 1.5, LCZ = 2.5 (concentration of LCZ = 0.25 kg/l)</td>
<td>476</td>
<td>Thickness of the NCZ is decreased (1.5 m)</td>
</tr>
<tr>
<td>SGSP</td>
<td>UCZ = 0.2, NCZ = 2.5, LCZ = 2.0 (concentration of LCZ = 0.25 kg/l)</td>
<td>444</td>
<td>Thickness of the LCZ is decreased (2 m)</td>
</tr>
<tr>
<td>Gel pond</td>
<td>UCZ = 0.05, gel = 0.9, LCZ = 3 (concentration of LCZ = 0.25 kg/l)</td>
<td>600</td>
<td>Optimal thicknesses</td>
</tr>
<tr>
<td>Gel pond</td>
<td>UCZ = 0.05, gel = 0.9, LCZ = 3 (concentration of LCZ = 0.2 kg/l)</td>
<td>584</td>
<td>Concentration of the LCZ is decreased (0.2 kg/l)</td>
</tr>
<tr>
<td>Gel pond</td>
<td>UCZ = 0.05, gel = 0.9, LCZ = 3 (concentration of LCZ = 0.15 kg/l)</td>
<td>568</td>
<td>Concentration of the LCZ is decreased (0.15 kg/l)</td>
</tr>
<tr>
<td>Gel pond</td>
<td>UCZ = 0.05, gel = 0.7, LCZ = 3 (concentration of LCZ = 0.15 kg/l)</td>
<td>505</td>
<td>Gel thickness is decreased (0.7 m)</td>
</tr>
<tr>
<td>Gel pond</td>
<td>UCZ = 0.05, gel = 0.6, LCZ = 3 (concentration of LCZ = 0.25 kg/l)</td>
<td>469</td>
<td>Gel thickness is decreased (0.6 m)</td>
</tr>
</tbody>
</table>

Table 4.7 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.
Based on the previous discussions, several essential factors have to be fundamentally considered in order to construct and design a solar pond, and in particular, a SGSP. Firstly, the site selection is highly significant and has a vital role in minimising the construction cost. A suitable site should have plentiful of irradiance (the key to the solar pond to function) and flat land to minimise the excavation cost. Moreover, for the SGSP, it is essential for the site to be close or with easy access to the salt and water resources. These two resources are critical to the formation and sustainability of the water body of the SGSP. Properties of soil and distance from the water table beneath the pond are also significant to determine the insulation to minimise the heat loss to the ground. The knowledge of evaporation levels and meteorological conditions (wind speed, ambient temperature, relative humidity and solar radiation) of the site are extremely beneficial to decide if the pond would be economically viable. Evaporation is heat and mass loss and will directly affect the performance of the pond, and therefore its cost has to be considered, or it has to be suppressed.

Secondly, after the site selection, it is very significant to identify the purpose of the solar pond construction because the type of application coupled with the solar pond can determine its depth and surface area. For example, if the objective of the construction is to use the solar pond or in particular the SGSP for the space and water heating (require a temperature of ≈ 40-50 °C); this pond can be deeper with less surface area. As previously concluded in Chapters 3 and 4, the depth of the LCZ of the pond can be 3-4 m, and it can achieve temperatures more than 60 °C. The cost of maintenance of a small pond is lower than that of the large one. For power generation, the solar pond is coupled with an Organic Rankine Cycle engine. In this case, the required temperature is 80-90 °C, and with these temperatures, the depth of the LCZ cannot be more than 2 m. To supply large quantity of thermal energy, a pond with large surface area is required, and consequently, for the power generation, the solar pond would be shallower with large surface area.

Finally, for the SGSP, any salt which has adequate solubility in water, suitable transparency, with no adverse impact on the environment can be used for the water body and salinity gradient construction. However, as shown in Chapter 2, sodium chloride salt is commonly used for the formation of the water body of a SGSP, it is cheap, safe, and widely available.
4.7 Summary

This chapter has 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 challenges encountered with the SGSP; however, difficulties 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. Many points have to be taken into account to make a decision between the gel pond and the SGSP. Those points relate to the lifetime, impact on the environment and costs.
Chapter 5
Experimental design and method
5.1 Experimental unit, general description

The experimental study was carried out from 29/7-7/10/2015 (71 days). A small SGSP with a surface area of 1 m$^2$, and a depth of 1 m (1m$^3$ volume) was constructed in Nasiriyah in southern Iraq, which is located in the south of Iraq (Latitude: 31.05799°, Longitude: 46.25726°). The temperature in the pond was monitored both during the day and night time. Moreover, the concentration variation with time was measured to observe the diffusion of salt (NaCl) throughout the pond during the study. Concentration measurements were performed ex-situ by taking samples from the LCZ, NCZ, and the UCZ after 6, 12, 30 and 50 days of operation. The salt concentration in these samples was measured using a calibrated HANNA HI2300 conductivity meter, which can measure a range of concentrations from 0-400 g/l NaCl (accuracy ±1%). The experimental unit was a tank made of galvanized steel sheets of 1 mm thickness. The side walls and base of the tank were surrounded by a wooden frame of thickness 2 cm. In between these layers was a 6 cm layer of polystyrene which acted as an insulator, to reduce heat loss from the walls. The small pond was mounted on a closed wooden box of height 10 cm. Thus, the entirety of the pond was above ground. The wooden box’s walls were 2 cm thick. Between these walls, a layer of 6 cm thick polystyrene was inserted to minimize heat loss to the ground, and this layer is in addition to that between the wood and steel (Figure 5.2). The inner sides of the pond were painted black, providing an anti-corrosion barrier and increasing the solar radiation absorptivity. Figure 5.1 (a and b) shows pictures to the experimental SGSP, and Figure 5.2 illustrates a schematic of the experimental unit.
Chapter 5: Experimental design and method

Figure 5.1: Pictures of the experimental SGSP, (a) the external appearance of the pond, (b) the water body of the pond.

127
Figure 5.2: Schematic diagram showing the cross section through the experimental salinity gradient solar pond. The distribution of the thermocouples which monitor the spatio-temporal evolution of the temperature field within the pond is also shown. The dashed horizontal lines in the NCZ show the layers that were used to construct the salinity gradient.
5.2 Water body construction

The three layers of the SGSP – the UCZ, NCZ and LCZ - must be constructed carefully to ensure the correct salinity gradient is established. The methods used were similar to those used by Suarez et al. (2014) and Aizaz and Yousaf (2013). The procedure started with the filling of the LCZ. A solution with high salt (NaCl) concentration (0.25 kg/l) was prepared in a mixing tank and transferred to the experimental pond by using a small pump; this forms the storage zone of the pond. The layer had a depth of 0.4 m.

The second layer to be added, the NCZ, is considered critical to the operation of a SGSP (see e.g. Karakilcik et al., 2006, Karakilcik et al., 2013, Velmurugan and Srithar, 2008). The layer is transparent, allowing the incident solar radiation to penetrate to the LCZ. Simultaneously, it prevents the trapped heat in the LCZ moving upward by convection as the thermal gradient that would drive such a flow is opposed by the density gradient that arises due to the salinity gradient. Heat transfer will therefore only occur by conduction through the NCZ. It was constructed by adding many layers of salty water whose salt concentration (and hence density) decreased from the top of the LCZ toward the UCZ. For the construction of the NCZ, five 10 cm layers of varying salt concentration (0.2, 0.15, 0.1, 0.05 and 0.025 kg/l) were added sequentially to the top of the LCZ. This formed the NCZ with a total depth of 0.5 m. The solution for each layer was prepared separately in the mixing tank, and the pre-mixed solution was pumped gently on the surface of the previous layer. At the end of the pipe which carried the salty water from the mixing tank to the experimental pond, a small network of pipes with many small holes (of 0.5 mm diameter) was used to add the water to the pond with minimal momentum, to minimise mixing between layers. To further reduce the momentum of the exiting water, the small network of pipes was wrapped by a piece of perforated cloth. This distribution, combined with the low flow rate (0.25 l / min) minimised any disturbance of the layers.

The final layer, the UCZ had a thickness of 0.1 m and was created with fresh water. This layer needs continuous observation as it is open to the atmosphere. The water level and transparency of the layer can be affected by many parameters, such as wind speed, rainfall, and dust impurities. After construction, the pond was exposed to the natural solar radiation and other climatic factors. Figure 5.3 shows schematically the system which was used in the water body formation.
After 12 days of heat collection, a paraffin layer with a thickness of 0.5 cm was added above the UCZ. This period (12 days) was chosen to ensure that the salinity and temperature gradients became established before the paraffin was added. It was observed that paraffin layer floated effortlessly on the fresh water since the variance in the densities of the two layers was relatively high. The physical properties of the paraffin used in the experiment are illustrated in Table 5.1, and Figure 5.4 shows how the paraffin floats on the water surface.

Table 5.1: Some physical properties of paraffin used in the experimental pond

<table>
<thead>
<tr>
<th>Appearance</th>
<th>Density kg/m$^3$</th>
<th>Boiling point °C</th>
<th>Melting point °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>transparent</td>
<td>0.9</td>
<td>158</td>
<td>-21</td>
</tr>
</tbody>
</table>
5.3 Temperature measurements

The experimental temperature distributions were measured using 16 calibrated K type thermocouples. The uncertainty of the thermocouples in the experimental unit was tested by calibration against boiling (100 °C) and melting (0 °C) water. The thermocouples used in the experimental unit were used to measure temperatures of boiled (100 °C) and ice (0 °C) water. The reading of any thermocouple was compared with the reading of a thermometer which was used to measure the same boiling and freezing temperature of water. The difference between the two measurements of any thermocouple is a reasonable estimate of the error. The uncertainty was estimated to be ±3 °C. As shown in Figure 2, the thermocouples were fixed along the vertical centreline of the inner zones of the pond, to measure the temperature profiles of the pond’s zones (UCZ, NCZ, LCZ and the paraffin layer). Thermocouples were located, measuring from the bottom of the pond to the edge of the LCZ, at heights of 0, 0.05, 0.15, 0.25 and 0.35 m. Two further thermocouples were placed in the LCZ to monitor temperature change in the horizontal direction (Figure 5.2). Seven sensors were placed in the NCZ, at intervals of 10 cm. As with the LCZ, two additional thermocouples were placed at the bottom of the NCZ (Figure 5.2) to measure horizontal temperature distribution.

For the UCZ a single thermocouple was fixed in the centre of the layer to measure the temperature there. The last sensor was used to measure temperature in the paraffin layer.

All thermocouples were connected to a control board with a multichannel digital reader by 2 m extension wires. Figure 5.5 shows the control board and the digital reader. As shown in
Figure 5.5, by pressing a particular button, reading of a particular thermocouple which is connected to this button will appear on the screen of the digital reader. The temperatures in all zones of the pond were measured two times a day (2 p.m., and 2 a.m.).

![Figure 5.5: The control board, showing the buttons and the digital reader.](image)

The relative humidity, ambient temperature and wind speed above the water surface of the pond were measured using a device made by Gray Wolf Company (model IQ-610 to measure relative humidity and ambient temperature and model AS-201 to measure wind speed). This device is shown in Figure 5.6.

![Figure 5.6: Gray Wolf devices which were used to measure the relative humidity, ambient temperature and wind speed.](image)
5.4 Concentration

The Concentration of the layers of the pond was measured using a calibrated conductivity meter type HANNA (HI2300) with a range of concentrations 0-400 g/l NaCl (accuracy ±1%) and it is shown in Figure 5.7.

![HANNA (HI2300) device](image)

Figure 5.7: HANNA (HI2300) device which was used for concentration measurements.

Samples were taken from the three layers of the experimental pond in days 6, 12, 30 and 50. The concentrations of these samples were measured directly after they were taken from the pond. For the NCZ, a sample from every layer of the zone has been taken, and for the LCZ, samples were taken from many depths of the zone.

5.5 Algae growth

During the study, it was noticed that there was no growth of any algae. There was no change in the colour of the water body of the pond. No chemicals were added to the experimental pond to prevent the algae growth.
Chapter 6

Experimental Results and Discussions
6. Introduction

Experimental work is important to understand the behaviour of the SGSP. The results calculated using the model developed in Chapter 3 showed that the salinity gradient solar pond could reach a maximum temperature in the LCZ of 90 °C or even more. Moreover, the results presented in Chapter 3 illustrated that evaporation from the surface of the SGSP is a significant parameter affecting the efficiency of the pond because it is heat and mass loss from the pond.

In the first part of this chapter, the viability of constructing a SGSP in the area of the study (the city of Nasiriyah, Southern Iraq) was investigated, and parameters affecting evaporation from the pond and covering its surface have also been studied. The aim was to use the experimental unit for one year’s study to observe the development of temperatures of the pond’s zones through four seasons and to compare the results with the theoretical results. However, demolition of the site of the experimental unit ceased the experiment after 71 days. It was impossible to move or transfer the pond because this will mix its layers and consequently destroy the whole unit. Annual study for both uncovered and covered ponds could be considered for the future work.

In the second part of this chapter, analytical formulae to describe the change in the concentrations and temperatures of the LCZ and UCZ over time were derived. Many assumptions were considered to perform the derivation, and the results were found to be reasonable.

6.1 Experimental results

6.1.1 Evaporation

Evaporation levels were measured daily for the 12 days before the pond was covered by reading the water level in the UCZ before and after fresh water was injected into this layer to maintain the depth of the pond. It was observed that evaporation levels were high, reaching 21 l/m² day, which represents 2.1% of the total water of the pond (1000 litres). The weather on these days was windy, hot and dry. The major factors which can influence evaporation significantly are humidity, ambient temperature, wind speed, and incident solar radiation. The incident solar insolation was not measured due to unavailability of a pyranometer.

Figure 6.1 shows the measurements of the evaporation rate, relative humidity and ambient temperature for the 12 days before the paraffin addition, when the surface of the UCZ was exposed to the atmosphere.
Figure 6.1: (a) Daily average measurements of evaporation rate, relative humidity and the ambient temperature for the experimental pond for 12 days from 29/7-9/8/2015. (b) Scatter plot of daily evaporation rate versus average temperature. (c) Scatter plot of the evaporation rate versus average relative humidity.

Figure 6.1(a) illustrates that the ambient temperature has only a small impact on the evaporation over the 12 days considered. The average temperature was relatively high and consistent at around 39-41 °C, whereas the evaporation rate shows significant scatter. However, it is evident from Figure 6.1(b) that for this 12-day period, there is a weak negative correlation between ambient temperature and evaporation rate. The correlation coefficient of the ambient temperature with the evaporation is -0.59 which indicates only a relatively moderate negative correlation.
From Figure 6.1(a), it appears that relative humidity has a significant effect on the evaporation rate. The results show that relative humidity and evaporation rate are negatively correlated. For example, on Day 3 there was a noticeable increase in relative humidity and an apparent decrease in evaporation level. Similarly, on Days 5 and 8 when relative humidity decreased (Day 5), evaporation increased significantly; when it increased (Day 8), there was a substantial reduction in evaporation level. Similar behaviour can be observed on other days. This makes intuitive sense as the higher the humidity, the lower the driving force for mass transfer from the water to the air, and vice versa. Figure 6.1(c) also shows that there is a much stronger correlation between evaporation rate and relative humidity with correlation coefficient of -0.85.

The effect of the wind speed on the evaporation levels is shown in Figure 6.2.

![Figure 6.2: (a) Daily average measurements of evaporation rate and wind speed above the pond for 12 days from 29/7-9/8/2015, (b) Scatter plot of evaporation rate against wind speed](image)

Figure 6.2(a) shows that during the 12 days, wind speed has influenced evaporation: evaporation increased in line with increasing wind speed, and fluctuated similarly. On the other hand, Figure 6.2(b) illustrates that during the 12 days considered; the impact of the wind speed on the evaporation is low comparing with the impact of the relative humidity (0.85) and approximately similar to the effect of the ambient temperature (-0.59). The correlation coefficient of the wind speed with the evaporation is 0.6. This value is moderate and it indicates that the linear relationship between the two parameters is relatively low.

These results are for a short-term study (12 days) which is clearly insufficient to establish a clear understanding of the effects of the various climatic factors on evaporation. Therefore, the meteorological measurements from Nasiriya City’s metrological station were considered for a
long-term study (nine months, January to the end of September, 2015) to build up a clearer picture.

Firstly, results from the 12 days before the paraffin addition were compared with the measurements of the Nasiriyah meteorological station. Comparisons including the ambient temperature, relative humidity and the evaporation levels are illustrated in Figures 6.3-6.5.

![Ambient temperature comparison](image1.png)

Figure 6.3: Comparison between the daily average ambient temperature of the present study and the measurements of the meteorological station for 12 days (29/7-9/8/2015)

![Relative humidity comparison](image2.png)

Figure 6.4: Comparison between the daily average relative humidity of the present study and the measurements of the meteorological station for 12 days (29/7-9/8/2015)
Figure 6.5: Comparison between the daily average evaporation levels of the present study and the measurements of the meteorological station for 12 days (29/7-9/8/2015).

Figures 6.3 and 6.4 illustrate that the discrepancies between the ambient temperature and the relative humidity of the present study and recorded at the meteorological station are not significant. Differences in the measured temperatures (about 1.5 °C) might be because the experimental SGSP site was about 5 km from the meteorological station. A similar explanation could account for the difference in the relative humidity (Figure 6.4, variation around 1% in relative humidity). Nevertheless, the agreement is acceptable.

Interestingly, Figure 6.5 shows that evaporation rates in the present study were predominantly lower than the meteorological measurements. This discrepancy could result from the variation in salinity of the two sources used for measurement: the meteorological measurements used fresh water, while in the study; the water which evaporated from the pond surface of the experimental pond (UCZ) and this layer had a non-zero salt concentration due to the upward diffusion of the salt from the bottom of the pond. This concentration changed daily as a result of the continuous diffusion. Finch and Hall (2001) claimed that the evaporation rate decreases by approximately 1% for each 1% increase in the salt concentration. This is because the vapour pressure of the saline water will decrease.

According to the meteorological measurements, the rate of water losses increased from March (≈5.35 l/m² day) and reached its highest value in June (≈ 17.68 l/m² day). After June, there was a small decrease to reach ≈ 11.78 l/m² day in September. These levels are significant: for example, if a pond has a surface area of 1000 m², 5350 litres of freshwater would be needed each day in March to replenish the UCZ; and in June, July and August, around 17000 l/ day would be required. These amounts might decrease by 10-15% because of the effect of salinity of the UCZ. However, the amount of freshwater required to maintain the inventory of the SGSP
remains large. Ruskowitz et al. (2014) implied that when a solar pond is used for freshwater production in locations with a shortage of freshwater or clean water, suppressing surface evaporation is entirely worthy. They based their conclusions on the fact that in some previous studies (e. g. Walton et al. 2004, and Solis, 1999), where the aim was study the freshwater production from a membrane distillation system coupled with a SGSP, it was observed that the volume of water produced by the process was less than the volume that evaporated from the surface of the SGSP. Therefore, to replenish the UCZ, freshwater or available clean local water is required in large quantities. The monthly average relative humidity, the ambient temperature and evaporation levels at Nasiriyah weather station for 9 months are plotted against time in Figure 6.6.

Figure 6.6: (a) Monthly average relative humidity, ambient temperature and evaporation levels plotted against time, where month 1 is January, (b) Daily measurements of evaporation rate plotted against ambient temperature, (c) Daily evaporation rate plotted against relative humidity
Figure 6.6(a) shows that there was an increase in the evaporation rate as the ambient temperature increased for the first five months, from January to May. From May to August the increase in the ambient temperature was small (≈5 °C). However, the increase in the evaporation levels continued, with a maximum being reached in June. While the ambient temperature increased from May to reach a maximum in August, there was a gentle decrease in the evaporation rate from June to August. That behaviour clarifies that the other factors (humidity, solar radiation and wind speed) might also affect the evaporation. It is notable from the long-term measurements (Figure 6.6(a)) that the effect of the ambient temperature (in Nasiriayah City) is significant during the cold and moderate weather from January to May (winter and spring seasons). Moreover, Figure 6.6(b) (daily measurements) demonstrates that the temperature in the long term investigation (9 months) has a substantial effect on the evaporation. The correlation coefficient of the measurements of Figure 6.6(b) is 0.88 and it is higher than that for the short term data (~ 0.59). This high value (0.88) illustrates that there is a very strong uphill linear relationship and that means the temperature has a considerable effect on the evaporation in the area of the study. Nevertheless, the effect was small in the summer season. Again, the long term data appears to show a similar behaviour to the short period investigation (Figure 6.1(a)) since in both cases the temperature has a little influence on the evaporation levels in the case of hot weather.

The measured relative humidity shows that the highest value was in January (around 54 %), and after that it decreased to reach the lowest value in August (about 17.5 %) (Figure 6.6(a)). After August the relative humidity increased again. The evaporation rate appeared to vary inversely with the relative humidity: while the relative humidity of the air over the water surface decreased from January, evaporation increased and reached its maximum in June (Figure 6.6(a)). Interestingly, when the fluctuation in the relative humidity was small during June, July and August, there was little variation in the evaporation levels throughout these months. Figure 6.6(a) illustrates clearly that evaporation reduced significantly with the high relative humidity. As previously mentioned in Chapter 3 that Kishore and Joshi (1984) calculated evaporation heat loss by using the equation (Equation 3.26) below:

\[
Q_{ue} = \frac{\{(\lambda h_c(p_u - p_a)\} / (1.6 C_s p_{atm})\}}{A_u}
\]

where \(C_s = 1.005 + 1.82\gamma_h\) is the humid heat capacity of air in kJ/kg K, \(\lambda\) is the latent heat of vaporization of water in kJ/kg and \(\gamma_h\) is the relative humidity, \(p_u\) and \(p_a\) are the water vapour
pressure at the UCZ, and the partial pressure of water vapour in the ambient temperature respectively (Equations 3.28 and 3.29 in Chapter 3). From the equation above, it can be concluded that $Q_{ue} \propto \frac{1}{f(C_s)}$, but $Q_{ue} = \dot{m}_v \lambda$, where $\dot{m}_v$ is the quantity of the evaporative water losses. Evaporation is large in warm and dry atmospheric conditions and small in cold and humid conditions. In warm conditions ($p_a - p_a$) will be large and consequently evaporation will be high. On the other hand ($p_a - p_a$) is small in cold and humid conditions and therefore evaporation will be small. That means $\dot{m}_v = \frac{Q_{ue}}{\lambda}$ and finally, it can be said that $\dot{m}_v \propto \frac{1}{f(C_s)}$. From the above relationships, it can be seen that there is an inverse relationship between $Q_{ue}$ and the relative humidity ($\gamma_h$). This implies that the relative humidity has a vital role on the rate of the evaporation in different weather conditions (all seasons). The daily measurements (Figure 6.6(c)) show that there is a considerable impact to the relative humidity on the evaporation with a correlation coefficient of -0.83 and this indicates of a strong negative linear relationship. The long-term data clearly supports the conclusions of the short term investigation (Figure 6.1). Similar behaviours can clearly be observed in Figures 6.1(a) and 6.6(a).

The effect of wind speed was also studied throughout the 9 months. The dependence of the evaporation rate on the wind speed is shown in Figure 6.7.
During the 9 months considered, the average monthly wind speed varied between \( \approx 3.7 \) to \( \approx 5.1 \) m/s, and the maximum speed was in June. The wind speed throughout the period increased slightly from winter toward summer. Interestingly, with the relatively small increase in the wind speed over time, there was a considerable increase in the evaporation rate. From April to June, in spite of the average wind speed increasing only a little (from 4.5 to 5.1 m/s), there was a considerable increase in the evaporation rate, which reaches its maximum level in June (from 8.56 to 17.68 l/m\(^2\) day). From June to September, it is apparent from Figure 6.7(a) that the evaporation rate decreases, as does the average wind speed. Figure 6.7(b) (all daily measurements of evaporation plotted against wind speed) shows a clear trend of increasing evaporation with increasing wind speed. The data in Figure 6.7(c) and (d) further illustrate this relationship, with the daily measurements for January to May and June to September, respectively, demonstrating the increase in evaporation with wind speed.
measurements) shows that for the whole period (9 months), there is a little correlation between the wind speed and the evaporation. The points are somewhat scattered in a wide band and the correlation coefficient is 0.26. Results in Figure 6.7(b) contradict the results of the short term study (Figure 6.2(b)), where the correlation coefficient is 0.6) since short term results showed a moderate linear pattern to the wind speed with the evaporation level. Figure 6.7(b) can be divided into two parts. The first where there is a weaker correlation between wind speed and evaporation (from January until end of May); this period is illustrated in Figure 6.7(c). The second part, where there is a slightly stronger correlation, runs from June to the end of September and is shown in Figure 6.7(d). Apparently, wind speed has a lesser influence on the evaporation from the surface in the colder weather. However, its impact is more significant in the warm and hot weather (from May to September in Figure 6.7(a)).

The final climatic factor, which can affect the evaporative losses from the pond is the incident solar radiation. This was not measured in the short-term study. For the long-term study, the measurements of radiation from NASA (2014) have been considered to study the effect of this factor on the evaporation from the surface of the pond. Results are shown in Figure 6.8.

![Figure 6.8](image)

Figure 6.8: Measurements of monthly average evaporation levels and incident solar radiation against time, (b) Evaporation rate plotted against solar radiation for each day of the nine months

Figure 6.8 shows that as radiation increases almost linearly from January to June, there is also an increase in the evaporation rate. The increase slow down from January to April and it is faster from April. Noticeably, the incident solar radiation and evaporation attained their maximum in June. From June, both evaporation and radiation reduced, reaching their lowest magnitudes in September. It is apparent from Figure 6.8(a) that radiation might be the most
important climatic factor affects the evaporation from the pond surface. Therefore, this factor which ultimately drives the pond does not come without an associated cost in the form of increased losses. Figure 6.8(a) shows the impact of the solar radiation on the evaporation is significant, while Figure 6.8(b) showing daily measurements decreases this importance. It can be seen (Figure 6.8(b)) that the dependence of daily evaporation on solar radiation might be lower than the reliance on temperature and relative humidity. The correlation coefficient is 0.80: it shows a strong positive linear relationship, but not one as strong as the other climatic factors (ambient temperature 0.88 and relative humidity -0.83). Simultaneously, it is much higher than the correlation coefficient of the wind speed with evaporation (0.26). Table 6.1 summarises the correlation coefficients of different climatic factors with the evaporation from the surface of a SGSP.

Table 6.1: The correlation coefficients of the different parameters affecting the evaporation from a solar pond

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
<td>0.88</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>-0.83</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>0.8</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 6.1 illustrates that the ambient temperature has the highest correlation coefficient throughout the 9 months of the long-term study meanwhile the wind speed has the lowest. In Figures 6.6(a), 6.7(a) and 6.8(a) the evaporation levels are relatively low in the cold season (winter) and they increase toward the hot season (summer) in the area of the study.

6.1.1.1 Regression analysis

In order to find a relationship which can gather all climatic factors together with the evaporation, a statistical analysis was performed on the long period measurements to predict this relationship. Table 6.2 gives some statistical data which were generated using a multiple regression analysis (in the present investigation, only the linear term is considered, and interaction effects were neglected except the interaction between temperature and the relative humidity).
Table 6.2: Statistical data of multiple regression analysis

\[ R^2 = 0.81156, \ AdjR^2 = 0.80838 \]

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-1.2234</td>
<td>-0.64992</td>
<td>0.516375</td>
</tr>
<tr>
<td>Solar radiation (H)</td>
<td>0.106939</td>
<td>0.059791</td>
<td>1.788545</td>
</tr>
<tr>
<td>Ambient temperature ( (T_a) )</td>
<td>0.380862</td>
<td>0.045975</td>
<td>8.284036</td>
</tr>
<tr>
<td>Relative humidity ( (\gamma_h) )</td>
<td>-9.31657</td>
<td>2.287592</td>
<td>-4.07265</td>
</tr>
<tr>
<td>Wind Speed ( (v) )</td>
<td>0.412576</td>
<td>0.123479</td>
<td>3.341269</td>
</tr>
</tbody>
</table>

Table 6.2 shows that evaporation can be predicted by the following equation:

\[
Ev = -1.2234 + 0.106939H + 0.380862T_a - 9.31657\gamma_h + 0.412576v \tag{6.1}
\]

The evaporation calculated by Equation 6.1 is plotted against the measured evaporation, and the results are illustrated in Figure 6.9(a). For more investigation to the suitability of the model, the predicted evaporation by the model is plotted against the residuals, the results are shown in Figure 6.9(b).

![Figure 6.9(a)](image1)

![Figure 6.9(b)](image2)

Figure 6.9: The results when all parameters affecting evaporation are considered, (a) the predicted results against the measured values, (b) the predicted evaporation against the residuals.

Figure 6.9(a) illustrates that the model gives an acceptable estimation to the evaporation, points scatter in approximately narrow area around the fitted line. Figure 6.9(b) also shows that points dispersed randomly around the zero horizontal line of the residuals, and the variation is between -6 and 6.
It is also beneficial to plot separately the independent variables with the residuals to observe the distribution of points around the zero line. Consequently, the four parameters are plotted with the residuals and the results are illustrated in Figure 6.10.

![Figure 6.10](image)

Figure 6.10: The residuals against the four meteorological parameters, (a) the solar radiation with the residuals, (b) the ambient temperature with the residuals, (c) the relative humidity against the residuals, and (d) the wind speed against the residuals.

It is known in statistics that when points are randomly dispersed around the horizontal axis, a linear regression model is appropriate, otherwise the model is unacceptable (Petruccelli et al., 1999, Freedman et al., 1998). Figure 6.10 shows that the points’ distribution around zero horizontal line is reasonable except the case with the solar radiation (Figure 6.10(a)). In the case of the solar radiation, the scattering is not uniform around the zero line. For example, from 7 -13 mJ/m² day (on the horizontal axis), it can be seen that points concentrated above the
horizontal line and the area below the line is empty. Moreover, from 19-23 mJ/m\(^2\) day on the same axis, points condensed below the line, and there are no points above the line (Figure 6.10(a)). Additionally, Table 6.2 shows that all of the climatic factors have a statistically significant impact on the model \((p < 0.001)\) except for the solar radiation, which is not significant even at \(p < 0.05\).

As usual, \(R^2\) represents the deviation of measured data from the fitted or predicted model or equation. It is expected that the value of \(R^2\) increases when a new variable is added to the analysis. However, this increase in \(R^2\) does not mean that the accuracy increases. The adjusted \(R^2\) \((Adj R^2)\) is more accurate than \(R^2\) because it considers values of \(R^2\) and the number of variables in addition to the number of the observations. It is represented as:

\[
Adj R^2 = 1 - (1 - R^2)\frac{n-1}{n-k-1}
\]  

(6.2)

where \(n\) is the number of observations, and \(k\) is the number of variables. If a useful variable is added to the statistical analysis, the \(Adj R^2\) will increase. However, if the added variable is insignificant, there will be no improvement in the \(Adj R^2\). When this occurs the variable can be excluded from the suggested model or equation. The model generated by the regression analysis, including all four variables, has \(R^2 = 0.81156\) and \(Adj R^2 = 0.80838\) (Table 6.2).

If the solar radiation is excluded and the regression analysis performed again, then the results shown in Table 6.3 are achieved.

Table 6.3: Statistical data of multiple regression analysis (incident solar radiation is excluded)

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.146</td>
<td>1.791627</td>
<td>-0.08149</td>
</tr>
<tr>
<td>Ambient temperature ((T_a))</td>
<td>0.42634</td>
<td>0.03848</td>
<td>11.07939</td>
</tr>
<tr>
<td>Relative humidity ((\gamma_h))</td>
<td>-10.0035</td>
<td>2.265518</td>
<td>-4.41553</td>
</tr>
<tr>
<td>Wind Speed ((v))</td>
<td>0.45441</td>
<td>0.121802</td>
<td>3.730722</td>
</tr>
</tbody>
</table>

A new model can be written depending on the results of Table 6.3, and it is as follows:

\[
Ev = -0.146 + 0.42634T_a - 10.0035\gamma_h + 0.454416v
\]  

(6.3)

The predicted evaporation by Equation 6.3 is plotted against the measured evaporation; the results are illustrated in Figure 6.11(a). Similar to the previous model (when all parameters are
considered), the results gathered using the model (Equation 6.3) are plotted against the residuals and shown in Figure 6.11(b).

Figure 6.11: The results when the solar radiation is excluded, (a) the predicted results against the measured values, (b) the predicted evaporation against the residuals.

Figure 6.11((a) and (b)) shows that this model could introduce satisfactory results even with the exclusion of the solar radiation. Figure 6.11(b) also shows that points distributed randomly up and down the zero horizontal line, and the variation is mostly between -5 and 5.

Similar to the case when the four parameters were considered, the three measured parameters are plotted against the residuals. The results are illustrated in Figure 6.12 (a), (b), and (c).
Figure 6.12: Points distribution of the three meteorological parameters (the solar radiation is excluded) around the horizontal line, (a) the solar radiation with the residuals, (b) the ambient temperature with the residuals, (c) the relative humidity against the residuals, and (d) the wind speed against the residuals.

It is evident from Figure 6.12(a), (b), and (c) that for the three considered parameters points are scattered on both sides of the zero horizontal line. This means that the model can be used to predict the evaporation in the area of the study at any time. Interestingly, Table 6.3 shows that there is a slight reduction in the value of both $R^2$ and $AdjR^2$. This means that solar radiation can be excluded from the fitted model.

The interaction between the ambient temperature and the relative humidity has been investigated. The regression analysis performed again, and the results are shown in Table 6.4 are achieved (solar radiation is excluded).
Table 6.4: Statistical data of multiple regression analysis (interaction between the ambient temperature and the relative humidity is taken into account)

<table>
<thead>
<tr>
<th></th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-5.39656</td>
<td>2.15419</td>
<td>-2.50514</td>
<td>0.012912</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>0.475285</td>
<td>0.118037</td>
<td>4.026586</td>
<td>7.62E-05</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>0.625366</td>
<td>0.061093</td>
<td>10.2362</td>
<td>1.33E-20</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>5.868927</td>
<td>4.440881</td>
<td>1.321568</td>
<td>0.187586</td>
</tr>
<tr>
<td>Ambient temperature*Relative humidity</td>
<td>-0.7239</td>
<td>0.176108</td>
<td>-4.11055</td>
<td>5.44E-05</td>
</tr>
</tbody>
</table>

Equation 6.4 can be extracted from Table 6.4 to represent the model which considers the interaction between the ambient temperature and the relative humidity, the model as follows:

\[ Ev = -5.39656 + 0.475285T_a + 0.625366γ_h + 5.868927v - 0.7239T_aγ_h \quad (6.4) \]

Table 6.4 shows that there is an improvement in both the \( R^2 \) and the adjusted \( AdjR^2 \), and as previously mentioned that the increase in the value of the \( AdjR^2 \) indicates that the model is enhanced. On the other hand, the table illustrates that the significance of the wind speed decreases. For more clarification, the calculated values of the evaporation are plotted against the measured evaporation and the residuals, and illustrated in Figure 6.13. The residuals are also plotted with the independent variables and the results are shown in Figure 6.14.

Figure 6.13: The results when the solar radiation is excluded and the interaction between the ambient temperature and the relative humidity is considered, (a) the predicted results against the measured values, (b) the predicted evaporation against the residuals.
Figure 6.14: The residuals against with the independent variables, (a) the residuals against the ambient temperature, (b) the residuals against the wind speed, (c) the residuals against the relative humidity, (d) the residuals against the ambient temperatures * the relative humidity.

Figures 6.13 and 6.14 illustrate that the interaction between the ambient temperature and the relative humidity is significant. However, Table 6.4 shows that the $P$-value of wind speed is 0.187586 and this decreases its significance in the statistical analysis. That means, further analysis is required to thoroughly investigate the interaction between factors affecting evaporation from the surface of the solar ponds. Therefore Equation 6.4 will be excluded in the calculation of evaporation in section 6.1.5. Further statistical analysis could be carried out in the future.

Apparently, evaporation leads to heat loss and water loss from the surface of the solar pond to the atmosphere, which influences performance of the pond and increases the cost of maintenance. It was concluded in Chapter 3 that heat loss from the surface of the SGSP by
evaporation has the largest impact on temperatures of the LCZ and UCZ whereas radiation heat loss has the smallest effect. As a consequence of the high levels of evaporation at the site of the experimental pond, it is suggested to cover the pond with a transparent floating liquid to suppress the evaporation from the pond surface. Liquid paraffin oil (some physical properties were given in Table 5.1 in Chapter 5) was used to form a thin layer on top of the UCZ.

6.1.2 Temperature distributions

6.1.2.1 Temperature distribution before the pond coverage

After construction, the pond was ready to collect and store solar insolation. For the first 12 days, it was left uncovered. The temporal temperature development in the UCZ and LCZ, as well as the ambient temperature are shown in Figure 6.15(a) and (b) at 2 pm and 2 am local time respectively.

![Figure 6.15: (a) Evolution of the daytime temperature (2 p.m.) in the UCZ, LCZ and ambient over the first 12 days of operation (29/7-9/8/2015), (b) evolution of the night-time temperature (2 a.m.) in the UCZ, LCZ and ambient over the first 12 days of operation (29/7-9/8/2015).](image)

The results show that the temperature in the LCZ increased from ≈ 27 °C on the first day to around 54 °C on Day 12 with an average rate of increase about 2.25 °C/day, as shown in Figure 6.15(a). On Day 12 the difference between temperatures in the LCZ and UCZ was around 23 °C during the day-time and 25 °C at night. Figures 6.15(a) and (b) illustrate that the gap between the ambient temperature and UCZ temperatures is large in the day, but smaller at night. This behaviour could be a result of two things. Firstly, in the daytime, ambient temperatures throughout the 12 days were high (around 47 °C), falling at night to around 30
°C. Secondly, the evaporation rate is high in the day due to the presence of the solar radiation, low relative humidity, high temperatures and hot wind. Evaporating water will remove the latent heat from the water in the UCZ, and that will result in a decrease in its temperature. The temperature variation at different depths in the daytime is illustrated in Figure 6.16 for Days 2, 6, 11 and 12, i.e. before it was covered.

Figure 6.16: Temperature variation with depth for Days 2, 6, 11 and 12, measured at 2 p.m.

It is clear from Figure 6.16 that the temperature gradient in the NCZ increased and there was also an increase in the difference between the temperatures of the LCZ and UCZ. This difference was about 3 °C on the second day, rising to ≈ 19 °C on Day 6 and ≈ 23 °C on Day 12. It is evident that after 12 days, the three zones in the pond have become established, with an approximately uniform temperature in the LCZ, the 40 cm layer at the bottom of the pond. There is also an almost linear variation in temperature over the next 50 cm of depth corresponding to the NCZ and then a uniform temperature in the top 10 cm where the UCZ is again well-mixed.

6.1.2.2 Covering the SGSP

As a consequence of the high levels of evaporation at the site of the experimental pond, it was suggested to cover the pond with a transparent floating liquid to suppress the evaporation from the surface of the pond. After 12 days, and once it was clear that the three layers of the pond had become established, the pond was covered by the thin paraffin layer to eliminate the effect of evaporation. The behaviour of each zone is considered, and the temperature profiles both during the day and at night are considered. For completeness, and to aid understanding, the temperature profiles before coverage have also been included.
Behaviour of the UCZ

The profiles of the UCZ and ambient temperature are shown in Figures 6.17(a) and (b) for the daytime (2 p.m.) and night time (2 a.m.) through the study.

![Figure 6.17: (a) Measurements of the UCZ, and ambient temperature from 29/7-7/10/2015 (daytime 2 p.m.), (b) Measurements of the UCZ and ambient temperature from 29/7-7/10/2015 (night-time 2 a.m)]

Figures 6.17(a) and 6.15(a) (for the uncovered pond) show that in the first 12 days, when the pond was uncovered, the temperature of the UCZ was lower than the ambient temperature and its variation was similar to that of the ambient temperature. This behaviour is because the UCZ receives heat from the LCZ by conduction and some of the incident solar radiation accumulates in this layer. However, the layer also loses heat to the atmosphere by radiation, convection, and evaporation. Moreover, it also loses heat through the walls, although this heat loss is very small and can be neglected when the walls are well insulated. Due to heat loss, the temperature in the UCZ tended to be lower than the ambient air in the daytime during the current study, and the gap between the two temperatures was relatively large (before pond coverage). This behaviour has also been observed by many other researchers e.g. Garman and Muntasser (2008); Al-Jamal and Khashan (1996); and Jaefarzadeh and Akbarzadeh (2002).

After the addition of the paraffin layer, the evaporation process was stopped or considerably reduced. There was no further drop in the water level of the pond, so no additional water was required for the remainder of the study to maintain the pond inventory. This is obviously a significant operational improvement. Figure 6.17(a) illustrates that the daytime temperature of the UCZ increased significantly to reach a maximum of 51 °C after about a month. Then there
was a small decrease in the UCZ temperature to \( \approx 47 \, ^\circ\text{C} \) from the middle of September 2015 to the end of the study. As evaporation has been shown to be the dominant mode of heat loss, then most of the heat entering will now be trapped by the paraffin layer, so heat will accumulate, and the temperature will increase. In other words, suppressing evaporation from the surface of the UCZ increases its temperature significantly. Figure 6.17(a) shows that the evolution of the UCZ temperature is different from the ambient temperature’s behavior. While there was a daily fluctuation in the ambient temperature, only a very slight variation can be observed in the profile of the UCZ. Moreover, the gap between the two temperatures in the daytime is relatively small.

From Figures 6.17(b) and 6.15(b) (for the uncovered pond), it can be noticed the night-time UCZ temperature was lower than the ambient temperature; it behaved similarly to the ambient temperature in the first 12 days when the pond was uncovered. Its variation was similar to the ambient temperature’s variation. On the other hand, the gap between the two temperatures was much smaller than in the day-time. After the pond coverage (i.e. when there is no evaporation), the temperature of the UCZ increased above the ambient temperature as seen in Figure 6.17(b), and the gap between the two temperatures was bigger than in the daytime. While the ambient temperature decreased noticeably in the night, the reduction in the UCZ temperature remained insignificant due to heat accumulation from the LCZ. The night-time UCZ temperature reached a maximum value around 44 \( ^\circ\text{C} \), and then decreased to be \( \approx 37 - 39 \, ^\circ\text{C} \) until the end of the study.

Apparently, the UCZ became in effect a new storage zone in which heat accumulated to a much greater degree than in the uncovered pond. This is clearly demonstrated by the fact that its temperature reached 51 \( ^\circ\text{C} \) and remained approximately constant with only a very gentle decline to \( \approx 47 \, ^\circ\text{C} \) (daytime) over a period about 20 days. Date and Akbarzadeh (2013) claimed that around 45% of the incident solar radiation is absorbed in the UCZ of a conventional SGSP, but it lost again to the atmosphere. It was concluded in Chapter 3 that heat loss from the pond’s surface is mainly due to evaporation. With the new approach (covered pond), most of the heat which is absorbed or transferred from the LCZ throughout the NCZ and accumulated in the UCZ can be exploited, since heat loss to the atmosphere becomes relatively small with the evaporation suppression.
Behaviour of the LCZ

The case when the pond was uncovered is taken into account for a clearer explanation, as it was explained in the description of the UCZ. The profiles of the LCZ, UCZ and the ambient temperature are illustrated in Figure 6.18.

![Temperature vs Time Graph](image)

Figure 6.18: Change in LCZ, UCZ and ambient temperature in daytime (2 p.m) from 29/7-7/10/2015

In the first 12 days before adding the cover, the rate of the increase in the temperature of the LCZ was relatively fast, at approximately 2.25 °C/day. However, when the pond was covered, the rate of the increase became slightly lower as shown in Figure 6.18. It was observed that dust accumulated on the surface of the paraffin layer, thereby attenuating the incoming radiation. After the pond was covered, the rate of the temperature increase reduced to 1.25 °C/day, for the period from Day 12 to Day 30. The LCZ temperature reached its maximum on 26/8/2015 (Day 30). The reduction in the temperature growth might result not only from adding the cover, but that the intensity of the incident solar radiation in the area of the study decreases. As shown in Figure 6.8, the incident solar radiation reaches the maximum in June and then decreases gradually toward winter. In addition, and as already mentioned that dust accumulated on the surface decreased the solar radiation penetrating to the LCZ. Figure 6.18 shows that the temperature in the LCZ attains the maximum near the end of August (69 °C) and then there is a gradual decrease to be ≈ 50 °C at the end of the study. Figure 6.18 also illustrates that when the pond was open to the atmosphere, the gap between temperatures of the LCZ and the UCZ was relatively large. This gap becomes smaller and smaller from the beginning of September to the end of the study. In the final few days of the current study, the difference between the two temperatures was small. Figure 6.18 shows that before the pond was covered, the LCZ
temperature fluctuated slightly in an identical way to the ambient temperature. After coverage, the LCZ fluctuation was significantly different from the ambient temperature variation.

**Temperature distribution with depth**

The change in temperature profile within the pond, before and after the pond was covered is shown in Figure 6.19.

![Temperature distribution in the experimental pond on different days before and after coverage](image)

Many interesting features can be identified in Figure 6.19. Firstly, after the pond was covered, the LCZ temperature continued to increase, reaching its maximum of 69 °C on Day 30, after which it decreased. Interestingly, there was also a growth in the UCZ temperature and the difference between the two temperatures on Day 30 was 21 °C. This is a new behaviour; normally, when the LCZ reaches the maximum temperature, the temperatures of the UCZ also reaches the maximum, and they both behave similarly to the ambient temperature (Torkmahalleh et al., 2017; Jaefarzadeh and Akbarzadeh, 2002). In a pond where evaporation is suppressed, the behavior is significantly different. As previously discussed, it might be that the dust accumulated on the surface of the pond decreased the quantity of the solar radiation that reaches the LCZ and consequently decreased its temperature.

Secondly, it is also interesting to note that on Day 30, there was a clear and uniform temperature gradient through the NCZ. As time progressed, however, this gradient diminished substantially. This might be due to the accumulation of heat in the UCZ, which will thus raise its temperature. The disruption of the temperature gradients in the pond could be thought to be
indicative of the destruction of the salinity gradient, and hence the pond becoming well-mixed. However, the measurements of the salinity indicated that there were salinity gradients in the NCZ (Figure 6.21) and that in spite of these salinity gradients, there was a significant decrease in the temperature gradients. This would support the hypothesis that it is not convective heat transfer that has made the temperature profile uniform; rather it is a conductive effect. Figure 6.21 shows that there are clear salinity gradients for the chosen days. For example, at Day 50, there is a salinity gradient, but the temperature gradient at that day is small as shown in Figure 6.19.

Thirdly, it is usual in the conventional SGSP that temperature of the UCZ is lower than or equal to the temperature of the top of the NCZ. In the new configuration (covered pond with a thin paraffin layer), Figure 6.19 shows that UCZ temperature increases progressively to be higher than the NCZ below it. That is apparent on Day 70, where the temperature at the top of the NCZ is \( \approx 40 \, ^\circ\text{C} \) while the temperature of the UCZ is \( \approx 43 \, ^\circ\text{C} \). This is, in fact, hotter than the bulk of the NCZ. The accumulated heat in the UCZ can be extracted regularly from the layer, and this heat can be employed for the pre-heating process, and this can make solar ponds more practical and flexible for applications with low-grade heat. Assarri et al. (2015) observed that in the covered pond with glazing plastic, the temperature of the UCZ increased and it became significantly different from the ambient temperature. This was attributed to the prevention of evaporation.

Finally, it is important to note that in the conventional SGSP UCZ temperature changes from high to low magnitude when moving from summer to winter and vice versa. In this pond, there was an increase towards winter to reach the maximum and then a small decrease was observed.

6.1.2.3 Temperature variation between day and night

Measurements of the temperature of the LCZ and UCZ during day and night for 16 days before and after the pond coverage are shown in Figure 6.20. These 16 days were chosen because after that the difference in temperatures of the two layers between the two times remained approximately constant during the study.
Figure 6.20: Measurements of day and night temperatures of the LCZ and UCZ

Figure 6.20 shows that for the first six days, there was a small variation in the temperature of the LCZ between day and night (3 °C) while variation was slight for the temperature in the UCZ. After six days, the figure illustrates that for the UCZ, there is a variation in temperatures between day and night of about 2 °C. After the pond was covered, the difference between day and night becomes bigger than the days before the coverage for both layers. The difference is approximately around 5-6 °C for the LCZ and around 4 °C for the UCZ.

Temperature measurements of the present study illustrated that the horizontal change in temperatures of the LCZ and the second layer of the NCZ is 1-2 °C. Therefore, it can be concluded that the horizontal change in temperatures of the SGSP’s layers is insignificant.

6.1.2.4 The efficiency of the experimental pond

The efficiency of the pond is calculated utilizing Equation 3.11, and for the present study, the equation can be written as:

\[ E = \frac{q_1 + q_2}{H} \]  

(6.5)

where \( q_1 \) and \( q_2 \) are the heat accumulated in the UCZ and the LCZ respectively. The UCZ is considered because it also captured heat from the incident solar radiation. The computed efficiency for the pond is 5.8%, with the UCZ adding 0.8% to the efficiency. Meanwhile, the efficiency of the LCZ is 5%. Comparing the efficiency of the present study with the efficiency of the Kuwait’s City (its efficiency is 1.6% as calculated in Chapter 3, and its layer depths are 0.2, 0.4, and 0.3 for the UCZ, NCZ, and the LCZ, respectively) indicates that upon coverage the efficiency becomes about 4 times the efficiency of the uncovered pond. The results provide
a motivation for more investigation in this field of salinity gradient solar ponds. Two reasons could account for the increase in the efficiency of the pond. The first is the evaporation suppression from the UCZ which increased temperatures in both the UCZ and the LCZ and consequently increased the efficiency. The second is that the present experimental pond was carried out in August and September and it reached the maximum faster than the Kuwaiti’s pond. The experiment on the pond in Kuwait commenced from January, and it took 6 months to reach the maximum. It might be the comparison has to be between two ponds operated exactly under the same conditions. However, the previous comparison gave a clear indication that covering the SGSP with a liquid cover is beneficial. The Kuwaiti’s pond was selected for the comparison because this country has approximately similar solar radiation and climatic conditions with the area of the present experimental pond.

6.1.3 Concentration measurements

As previously mentioned in Chapter 5, concentrations of the pond’s layers were measured using a calibrated conductivity meter type HANNA (HI 2300). Concentration measurements are illustrated in the Figure 6.21 for four different days.

![Figure 6.21: Salinity gradient of the experimental SGSP for four different days.](image)

Figure 6.21 shows that after 6 days there was a clear salinity gradient. The salinity was high in the LCZ and then there is a concentration gradient along the NCZ and at the top of the pond a little salinity in the UCZ was apparent. After about 12 days, a slight decrease in the concentration of the LCZ has occurred. Moreover, on Day 30, the figure shows that there was decrease and increase in the salinity of the LCZ and UCZ respectively. After Day 30, 8 litres
of concentrated NaCl solution (0.25 kg/l) were injected to the deepest zone of the LCZ of the experimental pond to address the shortage of the salt concentration. The rate of injection was 1 l/day, and with this injection 2 kg of salt was added to the pond. Injection has been achieved using a technique which was suggested by Date and Akbarzadeh (2013); a schematic of this technique is shown in Figure 6.22.

Figure 6.22: Schematic of the injection system (Date and Akbarzadeh, 2013)

Figure 6.22 demonstrates that the brine solution or salt crystals can be injected gently through the tube in which is situated in the centreline of the pond. After the injection, the salt solution diffuses into the LCZ to substitute the reduction in the salinity due to the diffusion to the upper layers. The final salinity measurements were taken after 50 days, on 16th of September, and they indicated that there was a further reduction in the salinity of the LCZ with a noticeable increase in the salinity of the UCZ. Measurements have also indicated (Figure 6.21) that although 8 litres of brine solution were injected to the LCZ, but there was a decrease in its concentration. It can be observed from Figure 6.21 that erosion occurred in the top of the NCZ of the pond, and there is an increase in the thickness of the UCZ.

Measurements show that during 50 days there was a reduction in the salinity of the LCZ in general, and also there was a slight variation in the concentration of the LCZ with its depth. The change in concentration of the LCZ with its depth is illustrated in Figure 6.23.
Figure 6.23: Change in concentrations of the LCZ with its depth during 50 days. The depths considered are, 0.05, 0.15, and 0.35 m; 8 litres of brine was injected to the bottom of the LCZ through 8 days (from Day 31-Day 39 with an injection rate of 1l/day)

It is evident from Figure 6.23 that the change in the concentration of the LCZ decreases with its depth. The Depth of the LCZ in the experimental pond was 0.4 m and even this depth is relatively small, Figure 6.23 shows that the change in the concentration of the LCZ decreases when it becomes deeper. In other words, the erosion in the LCZ occurred in its concentration, and the erosion becomes smaller when the pond is deeper; it can be said also that the LCZ with the time progress could be deeper, but with less concentration than the initial state, and this can also be seen in Figure 6.21 Day 50. This also means that the NCZ has been eroded and its thickness diminished over time. Further depth of the LCZ means further heat capacity for the pond and further stability to the zone and the whole pond. In spite of increasing the depth of the LCZ might decrease its temperature, but some applications which could be coupled with the SGSP require relatively low temperature (40-60 °C). This means that for some applications need low-grade thermal heat, the depth of the pond can be increased instead of increasing the surface area and that will improve the stability of the pond and decrease the erosion in the LCZ concentration. However, the erosion in the bottom of the NCZ will remain; this erosion could be diminished by continuous heat extraction from the LCZ to keep the temperature difference small as possible. Li et al. (2001) claimed that erosion in the bottom of NCZ could be decreased by making the temperature difference in the LCZ small, and this could be achieved by controlling the operating conditions of the SGSP.
6.1.3.1 Concentration of the UCZ

Concentration measurements of the UCZ and the top point of the NCZ which is located directly beneath the UCZ are shown in Figure 6.24.

Figure 6.24: Concentrations of the UCZ and the top measured point of the NCZ; pond dimensions of the experimental pond were 1\times 1\times 1 \text{ m} and had depths of 0.1, 0.5 and 0.4 \text{ m} for the UCZ, NCZ and the LCZ respectively.

Figure 6.24 illustrates that there is approximately a consistent increase in the concentrations of the UCZ and the top point of the NCZ. The figure shows that the gap in concentration between the two zones declines progressively to be narrow in Day 50. This behaviour demonstrates that after about 50-60 days, the thickness of the UCZ will extend to be \approx 20 \text{ cm}; this includes the previous UCZ (10 cm) and the top 10 cm beneath the UCZ (this with no surface wash of the UCZ). In other words, after about 50-60 days, erosion occurred in the top of the NCZ. To avoid any layers destruction, renovating the UCZ and injecting the same amount of the removed salt into the LCZ before 50-60 days maximum are essential. Alternatively, regular surface washing to the UCZ to replenish the water lack due to evaporation and continuous replenishment to the LCZ are necessary in the case of the uncovered pond.

During approximately 50 days around 4.1 kg/m\^{2} of salt accumulated in the UCZ. This quantity of salt moved from the lower layers to the UCZ due to the diffusion. Alagao et al. (1994) found that 3.875 kg/m\^{2} diffused to the UCZ over 75 days and they concluded that this value is equivalent to 19 kg/m\^{2} per year. Based on Alagao’s et al.’s findings, 29 kg/m\^{2} per year could diffuse to the UCZ according to the measurements of the current study. Date and
Akbarzadeh (2013) indicated that the rate of diffusion in a sodium chloride SGSP could be up to 20 kg/m$^2$ year. Seemingly, the salt diffusion to the UCZ in the present study is relatively high in this covered pond. Li et al. (2001) assumed that convection in the UCZ caused mainly by the wind and in the LCZ by the temperature difference throughout the zone; in the covered pond, it was observed that the temperature of the UCZ increased significantly. This means that in the new approach (covered pond with a thin liquid layer), the two mechanisms of convection might work simultaneously and consequently accelerate erosion of the top of the NCZ and increase the depth of the UCZ. The current study has been achieved in August and September; August is one of the windiest and hottest months in the area of the study as shown in Table 3.4. The rate of salt diffusion could decrease in the quiet and cold days of the year, and consequently, a drop in the annual rate of the salt diffused to the UCZ is anticipated. However, the results show that in the covered pond, the NCZ of the pond could be eroded faster than the open pond, and a continuous monitoring to the pond is significant. It might be thermal heat could be extracted from the UCZ to decrease its temperature and therefore decrease the convection, and consequently decrease the erosion in the top of the NCZ. Hull et al. (1988) reported that depending on the experiences collected from some SGSPs (El-Paso pond, SGSPs in Australia and SGSPs in Israel), it was estimated that the upward salt diffusion can be about 40 kg/m$^2$ year in the hot and sunny climate.

6.1.4 Comparison between experimental and theoretical temperatures of the LCZ and the UCZ

Figures 6.25 and 6.26 show the comparisons between the experimental results and the calculated temperatures by the model which presented in Chapter 3.
Figure 6.25: Comparisons between theoretical and experimental results before the pond covering. The pond had dimensions of $1 \times 1 \times 1$ m and a layer thickness of 0.1, 0.5 and 0.4 m respectively for the UCZ, NCZ, and the LCZ. Figure 6.25 illustrates that a reasonable agreements have been achieved for temperatures of both the LCZ and the UCZ when the pond was uncovered; the relative errors are respectively 3% and 10% for the LCZ and the UCZ. The results shown in Figure 6.25 introduce further evidence to verify the validity of the model developed in Chapter 3 for the uncovered SGSP.

Figure 6.26: Comparison between theoretical and experimental results after the pond covering. The pond had dimensions of $1 \times 1 \times 1$ m and a layer thickness of 0.1, 0.5 and 0.4 m respectively for the UCZ, NCZ, and the LCZ. Figure 6.26 illustrates that the temperature of the UCZ increases noticeably after the pond was covered (after Day 12) to reach the maximum ($51 ^\circ C$), and then it slightly decreases to remain around $40 ^\circ C$ for the remained period of the study. The figure also shows that the
calculated temperature behaves similarly to the experimental temperature, and an acceptable agreement between theoretical and experimental results is obtained.

For the temperature of the LCZ, Figure 6.26 shows that a noticeable disagreement is obtained after the pond was covered (after Day 12) between the experimental and the calculated temperature of the layer. The figure shows that for Days 12-30, the agreement is acceptable between the two temperatures, the experimental temperature reached the maximum (69°C) on Day 30 and remained around this degree for about 10 days, and then decreased significantly.

On the other hand, the increase in the calculated temperature continued to reach the maximum (80°C) but on Day 40, and remained around this degree for approximately 15 days and then decreases slightly. The significant and slight decrease in the measured and calculated temperatures respectively made the gap between the two profiles wider. Nevertheless, both experimental and theoretical trends are similar. The average reduction in the experimental temperature from the theoretical temperature of the LCZ is 16.8%. This reduction could be due to the dust accumulated on the surface of the paraffin layer. The dust and other float contaminants might be attenuated the solar radiation penetrating to the LCZ. Moreover, the effect of the refractive index (R.I) of paraffin has been excluded throughout the calculation. The difference between the R.I of paraffin and the R.I of water is about 0.07.

The model developed in Chapter 3 is used to test the behaviours of covered and uncovered ponds throughout one year and the results are illustrated in Figure 6.27.

Figure 6.27: Theoretical temperature distributions of the LCZ and UCZ of the covered and uncovered ponds. The pond had dimensions of 1x1x1 m and a layer thickness of 0.1, 0.5 and 0.4 m respectively for the UCZ, NCZ, and the LCZ.
Experimental measurements (Figure 6.26) showed that 16.8% an average reduction in the temperature of the LCZ occurred with the covered pond. In other words, although there is a temperature reduction in the LCZ, but it will remain higher that the temperature of the uncovered pond since the average of the enhancement is 19.6% (Figure 6.27). In the covered pond, evaporation from the surface is eliminated, so it is not required to the daily replenishment of the UCZ and therefore, cost of the maintenance will reduce considerably (it is required only to change water of the UCZ from time to time to protect the stability of the pond). To maintain the UCZ of the SGSP, fresh water must be added to the layer gently and continuously. The amount of water required to replenish the UCZ is two to three times of the yearly rate of evaporation (Date and Akbarzadeh (2013)). Akbarzadeh et al. (2005) implied that the rate of addition of water to the UCZ must exceed the average of water removal from the pond surface through the overflow by the rate of evaporation. The conclusions of Date and Akbarzadeh (2013) and Akbarzadeh et al. (2005) give an indication that preventing the evaporation from the surface of the pond will substantially decrease the total cost of the pond. Figure 6.26 shows that temperature of the UCZ increases to reach the maximum (≈ 49 °C) in July and it remains above 40 °C from May to the end of September (≈ 5 months). This is relatively a high temperature for a long period and it can be exploited for pre-heating before the working fluid is pumped through the heat exchanger to the LCZ. These results are for a pond with dimensions of 1 × 1 × 1 m with layer depths of 0.4, 0.5, 0.1 and 0.005 m for the LCZ, the NCZ, the UCZ and the paraffin layer respectively. This pond is supposed to be in Nasiriyah City, south of Iraq. Temperature of the LCZ can be higher when the depth of the pond’s layers is changed.

The temperature of the NCZ of the experimental pond has been calculated using the model of the present study for two specific days (Days 30 and 50). The theoretical results are compared with the experimental results for the same days (Figure 6.19) and the comparison is illustrated in the Figure 6.28. The figure shows also the comparison between the experimental and the calculated temperature at Day 12 before the pond coverage.
Figure 6.28: The comparison between the experimental and calculated temperatures in the NCZ for the experimental pond, (a) the comparison for days 30 and 50 (UCZ = 0.1 m, NCZ = 0.5 m and LCZ = 0.4 m), (b) the comparison for day 12 before the pond coverage.

Figure 6.28 that for the NCZ, the temperature decreases from the bottom of the zone (from the LCZ) to the top (to the UCZ). The pond reached the maximum temperature in the LCZ in both theoretical and experimental profiles in Day 30 (Figure 6.28(a)); it was 81 °C for the theoretical temperature (Figure 6.28) and 69 °C for the experimental temperature as previously discussed (Figures 6.18 and 6.19). The variance in the maximum temperature resulted from the effect of the dust accumulated on the surface which decreased the solar radiation penetrating to the LCZ, and also the solar radiation decrease toward winter. The difference between the two maximum temperatures is 12 °C, and it is not large. In day 50, Figure 6.26(a) clarifies that the variance between experimental and theoretical temperatures of the LCZ and consequently the NCZ becomes bigger, and the maximum temperature drops for both to be 79 and 54 °C for the calculated and the measured temperatures respectively, and these variance and reduction might be came from two facts; firstly, the accumulated dust increased over time (20 days) and this affected the penetration of the solar radiation to the LCZ. Secondly, the incident solar radiation decreased moving from Day 30 to Day 50. Figure 6.28(b) shows that the trends of both the experimental and calculated temperature are similar.

In general, the decrease in the temperature of the LCZ and the increase in the temperature of the UCZ affected the temperature gradient in the NCZ and that is apparent on Day 50 of the experimental measurements. Figure 6.26 shows also that in Day 50, the temperature of the UCZ (44 °C) became higher than the temperature of the layer of the NCZ below it (41 °C) and this agrees with the experimental measurements. These measurements show that the
temperature of the UCZ in Day 30 was 48 °C and for the point of the NCZ below it is 47 °C (Figure 6.19).

It is significant to mention here that in the current study; there was no surface washing to the UCZ or any evacuation to the layer during the experimental work and when this process is achieved, the temperature of the UCZ will decrease due to the addition of fresh water with lower temperature. Consequently the temperature gradient through the NCZ will be bigger and the gradient being uniform. In spite of there was a decrease in the experimental temperature gradient of the NCZ for day 50, and that is illustrated in Figures 6.28 and 6.19; Figure 6.21 shows that there was a clear salinity gradient in this day and for Day 70.

6.1.5 Experimental and theoretical evaporation levels

The evaporation levels for 9 months were calculated using Kishore and Joshi’s equation (1984), and the results are compared with the available evaporation measurements of Nasiriyah meteorological station, evaporation was also calculated using Equations 6.1 and 6.3, and compared with the measurements (Equation 6.4 is excluded). The comparisons are illustrated in Figure 6.29.

![Figure 6.29: The comparison between the experimental measurements and the theoretical evaporation (calculated by the Kishore and Joshi’s equation, Equation 6.1, and Equation 6.3) levels (month 1 is January).](image)

It is apparent from Figure 6.29 that the theoretical trend is approximately similar to the experimental trend for the considered nine months. The relative errors between the measured and the calculated results, which are represented in Figure 6.29, are given in Table 6.5.
Table 6.5: The relative errors between the theoretical calculations and the experimental measurements of the evaporation for 9 months (January-September); the theoretical values were calculated using Kishore and Joshi’s equation, Equation 6.1, and Equation 6.3.

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>Average</th>
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<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kishore and Joshi’s equation</td>
<td>0.20</td>
<td>0.14</td>
<td>0.13</td>
<td>0.01</td>
<td>0.10</td>
<td>0.11</td>
<td>0.11</td>
<td>0.16</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>Statistical equation (Equation 6.1)</td>
<td>0.7</td>
<td>0.18</td>
<td>0.06</td>
<td>0.1</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>0.05</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Statistical equation (Equation 6.3)</td>
<td>0.7</td>
<td>0.2</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.1</td>
<td>0.04</td>
<td>0.01</td>
<td>0.12</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 6.5 shows that the average relative errors are 0.1, 0.15, and 0.13 for Kishore and Joshi’s equation, Equation 6.1, and Equation 6.3 respectively. These values are reasonable. Figure 6.29 and Table 6.5 also show that Equations 6.1 and 6.2 could be used to calculate evaporation from the surface of the pond. Equation 6.3 requires only knowledge of the ambient temperature, relative humidity and wind speed. The daily rate of evaporation per month for the whole year in the area of the study is calculated using the three equations. The results are shown in Figure 6.30.

Figure 6.30: The theoretical evaporation rates during one year calculated by Kishore and Joshi’s equation (1984), Equation 6.1, and equation 6.3 in the site of the experiment (Nasiriyah City) (month 1 is January)

Figure 6.30 shows that in the area of the study, the evaporation level is relatively low during months January, February, March, November, and December. Evaporation levels throughout these months are below 6 kg/m² day. For the rest months of the year (7 months), it is apparent that evaporation levels are high. It can be concluding that depending on the previous discussion that the evaporation from the surface of a solar pond in the area of the study has to be seriously
considered. This consideration is essential to achieve both a significant decrease to the cost of maintenance and a valuable enhancement to the performance of the pond by preventing or reducing evaporation levels.

6.2 The Derivation of the analytical equations

6.2.1 Diffusion
6.2.1.1 A pond with vertical walls

In this part of Chapter 6, analytical formulae to describe the change in the concentrations of the LCZ and the UCZ over time were derived. Several assumptions were adopted to derive these analytical formulae. They are:

(i) The pond consists of three zones, the UCZ, NCZ and LCZ, and there is no salt accumulation in the NCZ;
(ii) The concentration profile of the NCZ is linear;
(iii) There is no salt injection to the LCZ;
(iv) The salt diffusivity is constant (and does not change with temperature);
(v) The addition of water to the UCZ is only to substitute water loss due to evaporation without overflow;
(vi) The pond has vertical walls, and the wind effect is neglected.

The following equations represent respectively the mass balance of salt of the LCZ and the UCZ.

\[ \frac{d}{dt} (h_{LCZ}A_l C_{LCZ}(t)) = -\left[\frac{D}{X_{NCZ}} A_l (C_{LCZ}(t) - C_{UCZ}(t)) \right] \]  \hspace{1cm} (6.6)

\[ \frac{d}{dt} (h_{UCZ}A_u C_{UCZ}(t)) = \frac{D}{X_{NCZ}} [A_u (C_{LCZ}(t) - C_{UCZ}(t))] \]  \hspace{1cm} (6.7)

where \( h_{LCZ} \) is the depth of the LCZ, \( A_l \) is the surface area of the LCZ, \( C_{LCZ} \), \( C_{UCZ} \) are the concentrations of the LCZ and the UCZ respectively, \( h_{UCZ} \) and \( A_u \) are the UCZ depth and surface area respectively. Finally, the symbols \( D \) and \( X_{NCZ} \) are the salt diffusivity and depth of the NCZ respectively. Time is taken in days and consequently the diffusivity is shown as \( \text{m}^2/\text{d} \) and concentration as \( \text{kg}/\text{m}^3 \).

Equations 6.6 and 6.7 are rearranged as below:

\[ \frac{h_{LCZ}X_{NCZ}}{D} \frac{dC_{LCZ}(t)}{dt} = -[C_{LCZ}(t) - C_{UCZ}(t)] \]  \hspace{1cm} (6.8)

\[ \frac{h_{UCZ}X_{NCZ}}{D} \frac{dC_{UCZ}(t)}{dt} = C_{LCZ}(t) - C_{UCZ}(t) \]  \hspace{1cm} (6.9)
For simplification, it can be considered that $K = \frac{h_{LCZ}X_{NCZ}}{d}$ and $R = \frac{h_{UCZ}X_{NCZ}}{d}$, so Equations 6.8 and 6.9 are rewritten as:

$$K \frac{dC_{LCZ}(t)}{dt} = -[C_{LCZ}(t) - C_{UCZ}(t)]$$

(6.10)

$$K \frac{dC_{LCZ}(t)}{dt} = C_{UCZ}(t) - C_{LCZ}(t)$$

(6.11)

Taking Laplace transform to Equations (6.10) and (6.11) gives (details of the derivation are given in Appendix B):

$$C_{LCZ}(t) = \frac{h_{LCZ}C_{LCZ}(t=0)+h_{UCZ}C_{UCZ}(t=0)}{h_{LCZ}+h_{UCZ}} + \frac{h_{UCZ}(C_{LCZ}(t=0)-C_{UCZ}(t=0))}{h_{LCZ}+h_{UCZ}} e^{-\frac{D}{X_{NCZ}}(\frac{h_{LCZ}+h_{UCZ}}{d})}$$

(6.12)

Equation (6.12) can be used to calculate the salt concentration of the LCZ at any time after setting up the pond. It requires knowledge of the initial concentrations of the LCZ and UCZ, the salt diffusivity, and the thickness of all three zones (UCZ, NCZ and LCZ). The change in concentration of the LCZ at any time ($\Delta C_{LCZ}(t)$) can be computed from the following equation:

$$\Delta C_{LCZ}(t) = C_{LCZ}(t = 0) - C_{LCZ}(t)$$

(6.13)

It is supposed that there is no salt accumulation in the NCZ, and consequently:

$$\Delta C_{LCZ}(t)A_{LCZ} = \Delta C_{UCZ}(t)A_{UCZ}$$

(6.14)

For a pond with vertical walls; $A_{LCZ} = A_{UCZ}$ Equation (6.14) gives:

$$\Delta C_{UCZ}(t) = \Delta C_{LCZ}(t)\left(\frac{h_{LCZ}}{h_{UCZ}}\right)$$

Consequently, the concentration of the UCZ can be as follow:

$$C_{UCZ}(t) = C_{UCZ}(t = 0) + \Delta C_{LCZ}(t)\left(\frac{h_{LCZ}}{h_{UCZ}}\right)$$

(6.15)

Equation (6.15) can be used to compute the changing concentration of the UCZ over time. To avoid prolongation, the full steps of the derivation given in Appendix B.

To verify the derived analytical equations, concentration profiles were calculated using Equations (6.12) and (6.15), and the results were compared with measurements from the experimental pond and data from previously established ponds. The experimental pond had a surface area of 1 m$^2$ and layer depths of 0.1, 0.5, and 0.4 m for the UCZ, NCZ, and the LCZ, respectively. The initial concentrations of the UCZ and LCZ of the experimental pond were 5 and 250 kg/m$^3$ respectively. The diffusivity of sodium chloride in water is taken as $1.35 \times 10^{-9}$ m$^2$/s (0.00011 m$^2$/day) (Coulson and Richardson, 1996).
Comparison with experimental measurements

Applying the dimensions and concentrations of the experimental pond, Equations (6.12) and (6.15) become:

\[ C_{\text{LCZ}}(t) = 201 + 49e^{-0.0027t} \]  \hspace{1cm} (6.16)

\[ C_{\text{UCZ}}(t) = C_{\text{UCZ}}(t = 0) + 4\Delta C_{\text{LCZ}}(t) \]  \hspace{1cm} (6.17)

The concentrations of the upper and lower convective zones \((C_{\text{LCZ}}(t), C_{\text{UCZ}}(t))\) were calculated and compared with the experimental pond measurements; the comparisons are shown in Figure 6.31.

Figure 6.31: Comparison of the experimental pond concentration profiles with profiles computed using the analytical equations for three different days, the pond had a surface area 1 m\(^2\), depth 1 m, and zone depths of 0.1, 0.5 and 0.4 for the UCZ, NCZ and LCZ respectively.

Figure 6.31 shows that a good agreement is achieved between the experimental and calculated concentrations on the days used for comparison. The relative errors are 0.17, 0.14 and 0.11 for days 6, 30 and 50 respectively. The difference between the experimental and theoretical results might be because the effect of wind was neglected in the analytical assumptions, and this can increase the salt concentration of the UCZ by mixing the water with the saltier layer beneath it. August is a windy month in the area of the experimental pond, resulting in the UCZ receiving an extra amount of salt from the NCZ, and possibly explaining why the experimental concentrations of the UCZ are slightly higher than the theoretical concentrations. The variance between measured and calculated concentrations of the LCZ might be as a consequence of the temperature impact which was ignored in the derivation of analytical formulae. It is significant to noting that 2 kg were injected to the LCZ of the
experimental unit and this also might increase the difference between the theoretical and experimental results.

Equations (6.16) and (6.17) were used to estimate the concentration profiles of the pond for many other days and the results are shown in Figure 6.32.

Figure 6.32: Theoretical concentration profiles of the pond over time, estimated using Equations (6.16) and (6.17) in a pond with surface area of 1 m², depth of 1 m, and zone depths of 0.1, 0.5 and 0.4 for the UCZ, NCZ and LCZ respectively

Figure 6.32 illustrates that there are continuous decreases and increases in the concentrations of the LCZ and the UCZ respectively. It suggests that after 1,700 days (4.7 years), the concentration profile will be uniform and the concentration gradient throughout the NCZ will disappear, based on the assumptions adopted in the analytical derivation. Figure 6.2.2 also shows that the reduction and growth in the concentrations of the LCZ and UCZ after day 600 become smaller over time. This occurs because the driving force \((C_{LCZ} - C_{UCZ})\) becomes weaker as time progresses. The change in the concentrations of the LCZ and UCZ have been plotted against time, as illustrated in Figure 6.33.
Figure 6.33 shows that the rate of increase in the concentration of the UCZ is slightly faster than the rate of reduction in the salinity of the LCZ; this might be due to the difference in their volumes (the volume of the LCZ is four times that of the UCZ).

**Comparison with established and modelled ponds**

Equations (6.12) and (6.15) were also utilized to estimate the concentration profiles of the pond used by Karakilcik et al. (2006); the results are compared with their experimental measurements. In the 2006 study, temperature distributions were investigated experimentally and theoretically in an insulated SGSP. The experimental salinity profiles in January, May and August were also plotted against the pond’s depth. The concentrations extracted from the researchers’ salinity chart were compared with the computed concentrations using the derived equations. The pond used for the 2006 study had a depth of 1.5 m, with zone thicknesses of 0.10 m, 0.6 m and 0.8 m for the UCZ, NCZ and LCZ respectively. Using the dimensions of the pond in the Karakilcik et al. 2006’s study, and the same initial concentrations (LCZ = 202 and UCZ = 15 kg/m$^3$), Equations (6.12) and (6.15) will be expressed as:

$$C_{LCZ}(t) = 181.22 + 29.53e^{-0.0021t} \quad (6.18)$$

$$C_{UCZ}(t) = C_{UCZ}(t = 0) + 8\Delta C_{LCZ}(t) \quad (6.19)$$

Comparisons for May and August (period four months and seven months are considered from January to May and August respectively) are shown in Figure 6.34(a). Also, the change in the concentrations of both the UCZ and the LCZ with time is illustrated in Figure 6.34(b).
Figure 6.34: Experimental and computed concentrations of Karakilcik et al. 2006’s pond, with zone depths of 0.10, 0.6 and 0.8 m for the UCZ, NCZ and LCZ respectively, where (a) shows comparisons between experimental results and calculated concentrations for May and August and (b) shows the UCZ and LCZ profiles over time.

Figure 6.34(a) illustrates that the agreement between the experimental and theoretical results is acceptable with relative errors of 0.18 and 0.3 for May and August respectively. It might be that the surface washing of the UCZ of the experimental pond contributed to make the difference between the experimental and theoretical results bigger. Moreover, Figure 6.34(b) shows that the concentration gradient becomes uniform throughout the pond after about 2,500 days. The difference in the concentration of the LCZ is relatively small, changing from 202 to 180 kg/m$^3$ after 2,500 days. Meanwhile, the concentration of the UCZ changed from 15 to 180 kg/m$^3$, when the gradient became uniform throughout the whole pond. This variation in behaviour between the two zones (UCZ and LCZ) occurred because the volume of the LCZ is eight times larger than the volume of the UCZ. Figure 6.34 (a) also illustrates that in the experimental study, erosion occurs at the top of the LCZ and the erosion decreases towards the bottom of the zone; this might indicate that a pond with a deep LCZ could be more stable than a pond with a shallow LCZ.

To expand further, the Equations (6.12) and (6.15) are used to compute the concentrations of a pond modelled by Kanan et al. (2014), and the results compared with their theoretical results. The results of Kanan et al. were found by solving equations of mass transfer of the salt numerically. The theoretical pond suggested by Kanan et al. had zone thicknesses of 0.3 m, 1 m and 0.7 m in the UCZ, NCZ and LCZ respectively. The initial concentrations of the LCZ and the UCZ were considered (Kanan et al., 2014) as:
\(C_{LCZ}(t = 0) = 178 \text{ kg/m}^3, \ C_{UCZ}(t = 0) = 10 \text{ kg/m}^3\), with diffusivity \(D = 3 \times 10^{-9} \text{ m}^2/\text{s}\). Using the dimensions of the pond and these initial concentrations, Equations 6.12 and 6.15 will be:

\[
C_{LCZ}(t) = 127.6 + 50.4e^{-0.0012t} \\
C_{UCZ}(t) = C_{UCZ}(t = 0) + 2.33\Delta C_{LCZ}(t)
\]  

(6.20)  

(6.21)

The comparison with the suggested theoretical pond and the change in concentrations of the UCZ and the LCZ are shown in Figure 6.35(a) and (b) respectively.

![Figure 6.35: Theoretical and computed concentrations of Kanan et al. (2014), for a pond with zone depths of 0.3, 1 and 0.7 m for the UCZ, NCZ and LCZ respectively, where (a) shows current computed concentrations compared with the theoretical results of Kanan et al. and (b) shows the UCZ and LCZ profiles over time](image)

Figure 6.35(a) shows that there is a good agreement between the results of the present study and the theoretical results of Kanan et al. (2014) with relative errors of 3%, 12%, and 5% for Day 30, Day 360, and Day 720 respectively. Moreover, the results illustrate that this pond will take about 3500 days (9.7 years) for the concentration gradient to be uniform, under the assumptions of the present study. Figure 6.35(b) illustrates that the rate of increase in the concentration of the UCZ over time is slower than in the case of the pond used by Karakilcik et al. in 2006. This behaviour might be because the UCZ in the theoretical pond studied by Kanan et al. has a large volume (UCZ depth = 0.3 m); its volume is approximately half the volume of the LCZ (LCZ depth = 0.7 m). Meanwhile, it can be observed in Figure 6.35(b) that the decline in the LCZ salinity is relatively fast compared with the 2006 pond of Karakilcik et
al. This means that percentage between volumes (depths) of the UCZ and the LCZ might have an impact on the change in their concentrations over time.

6.2.1.2 A pond with a trapezoidal shape

A slight modification to Equations 6.6 and 6.7 is considered in order to include a pond with a trapezoidal shape, which is common in SGSPs. As illustrated in Figure 6.36, the width narrows as the pond deepens, due to the inclination of the walls.

As Figure 6.36 clearly shows, the top surface area of the pond is larger than the bottom surface area, because the inclination of the walls. Figure 6.36 also illustrates that the top surface area of the LCZ (where diffusion starts) is smaller than the bottom surface area of the UCZ (where salt molecules enter the UCZ). This variation in areas results from the continuous change in the width of the pond with its depth. In order to find the required widths (length is assumed constant) and consequently the required surface areas (top surface area of the LCZ and the bottom surface area of the UCZ), the width at the top of the LCZ ($W_{UL}$) and the bottom of the UCZ ($W_{bu}$) have to be found. Figure 6.36 clarifies that:

\[
W_d = f(h)
\]

Or \( L_d = f(h) \) (if width is constant)
where $W_d$, $L_d$ and $h$ are the width and the length at a specific depth $h$, and $h$ represents any chosen height along the depth of the pond and $d$ is the pond’s depth, change in width will be considered.

It can be considered from Figure 6.36 that width of the pond varies linearly with the depth and thus:

$$W_d = a_1 h + c_1$$  \hspace{1cm} (6.22)

In similar way if length is changed so:

$$L_d = a_2 h + c_2$$  \hspace{1cm} (6.23)

where $a_1$, $c_1$, $a_2$ and $c_2$ are constants. To find these constants, conditions at the top and the bottom of the pond are used; by applying these conditions, the width of the pond can be found at any point of its depth. The conditions are applied on Equation 6.22 as follows:

Conditions at the top surface of the pond:

$h = 0$, $W_d = W_t$, thus $c_1 = W_t$

Conditions at the bottom surface of the pond:

$h = d$, $W_d = W_b$ thus $W_b = a_1 d + c_1$, $W_b = a_1 d + W_t$, $a_1 = \frac{W_b - W_t}{d}$, so Equation 6.22 will be:

$$W_d = (\frac{W_b - W_t}{d}) h + W_t$$  \hspace{1cm} (6.24)

$W_t$, and $W_b$ are the widths at the top and bottom surfaces of the pond respectively.

Equations 6.6 and 6.7 are rewritten to fit the trapezoidal shape as follows (once again, it is assumed that the concentration profile of the NCZ is linear):

For the LCZ (Equation 6.6) becomes

$$\frac{d}{dt} \left( V_{LCZ} C_{LCZ}(t) \right) = -\left[ \frac{D_{NCZ}}{x_{NCZ}} A_{cL} (C_{LCZ}(t) - C_{UCZ}(t)) \right]$$  \hspace{1cm} (6.25)

$$\frac{d}{dt} \left( V_{LCZ} C_{LCZ}(t) \right) = \frac{D_{NCZ}}{x_{NCZ}} A_{sL} (C_{UCZ}(t) - C_{LCZ}(t))$$  \hspace{1cm} (6.26)

$$V_{LCZ} = A_{cL} L_t$$  \hspace{1cm} (6.27)

As shown in Figure 6.36, $A_{cL}$ can be calculated as (trapezoidal shape):

$$A_{cL} = \left( \frac{W_{tL} + W_b}{2} \right) h_{LCZ}$$  \hspace{1cm} (6.28)

While $A_{sL}$ can be computed as:

$$A_{sL} = W_{tL} L_t$$  \hspace{1cm} (6.29)

where $V_{LCZ}$ is the volume of the LCZ; $A_{cL}$ is the cross-sectional area of the LCZ; $A_{sL}$ is the surface area of the LCZ; $L_t$ is the length of the pond; and $W_{tL}$ is the width of the pond at the top surface of the LCZ.
\[ W_{tl} = \left(\frac{W_b - W_t}{d}\right)(d - h_{LCZ}) + W_t \]  

(6.30)

The reason why \((d - h_{LCZ})\) is used in Equation 6.24 instead of \(h_{LCZ}\) is because in the derivation of Equation 6.24, it is considered that at the top \(h = 0\) and at the bottom it is considered the bottom \(h = d\). Consequently \(d - h_{LCZ}\) will represent the point at the top of the LCZ.

Substituting \(V_{LCZ}\) and \(A_{sl}\) in equation 6.26 gives:

\[
\frac{d}{dt}\left(\frac{W_{tl} + W_b}{2}h_{LCZ}L_tC_{LCZ}(t)\right) = \frac{D}{x_{NCZ}}W_{tl}L_t\left(UCZ(t) - C_{LCZ}(t)\right)
\]

The equation above gives:

\[
\left(\frac{W_{tl} + W_b}{2}\right)h_{LCZ} \frac{x_{NCZ}}{dW_{tl}} \frac{dC_{LCZ}(t)}{dt} = \left(C_{UCZ}(t) - C_{LCZ}(t)\right)
\]

(6.31)

Equation 6.31 can be re-written as:

\[
K_1 \frac{dC_{LCZ}(t)}{dt} = C_{UCZ}(t) - C_{LCZ}(t)
\]

(6.32)

Where \(K_1 = \left(\frac{W_{tl} + W_b}{2}\right)h_{LCZ} \frac{x_{NCZ}}{dW_{tl}}\)

Similarly, using Equation 6.7 for the UCZ, it gives:

\[
R_1 \frac{dC_{UCZ}(t)}{dt} = C_{LCZ}(t) - C_{UCZ}(t)
\]

(6.33)

Where \(R_1 = \left(\frac{W_{bu} + W_t}{2}\right)h_{UCZ} \frac{x_{NCZ}}{dW_{bu}}\)

For the UCZ, and to find \(W_{bu}\) which represents the width of the pond at the bottom surface of the UCZ, Equation 6.24 becomes:

\[
W_{bu} = \left(\frac{W_b - W_t}{d}\right)(h_{LCZ}) + W_t
\]

(6.34)

Similarly to Equations 6.10 and 6.11, Equations 6.32 and 6.33 have been solved using the Laplace transform, giving:

\[
C_{LCZ}(t) = \frac{K_1 C_{LCZ}(t=0) + R_1 C_{UCZ}(t=0)}{(K_1 + R_1)} + \frac{R_1 (C_{LCZ}(t=0) - C_{UCZ}(t=0))}{(K_1 + R_1)} e^{-\frac{(K_1 + R_1)t}{K_1 R_1}}
\]

(6.35)

Equation 6.35 can be used to calculate the concentration of the LCZ in a pond with a trapezoidal shape. The terms \(K_1\) and \(R_1\) in Equation 6.35 can be replaced by their formulae, and this has been done to find the expression in the case of the pond with vertical walls (Equation 6.12).
However, in the case of the trapezoidal pond, it is preferable to find the values of \( K_1 \) and \( R_1 \) and then substitute them in Equation 6.35, because substituting them in Equation 6.35 will make it longer and more complicated.

Since there are differences in the surface area and volume of diffusion, Equation 6.15 will be expressed as:

\[
C_{UCZ}(t) = C_{UCZ}(t = 0) + \Delta C_{LCZ}(t)(\frac{V_{LCZ}}{V_{UCZ}})
\]  
(6.36)

When the term \( \frac{V_{LCZ}}{V_{UCZ}} = \frac{A_{CLt}}{A_{CuL}} \) and this means that:

\[
\frac{V_{LCZ}}{V_{UCZ}} = \frac{A_{CL}}{A_{Cu}} = \frac{(\frac{W_{TL}+W_b}{2})h_{LCZ}}{(W_{bu}+W_d)h_{UCZ}}
\]  
(6.37)

If the formula of Equation 6.37 is substituted in Equation 6.36, it gives:

\[
C_{UCZ}(t) = C_{UCZ}(t = 0) + \Delta C_{LCZ}(t)(\frac{W_{TL}+W_b}{2}h_{LCZ})
\]  
(6.38)

The formulae of \( W_{TL} \) and \( W_{bu} \) are substituted in Equation 6.38:

\[
C_{UCZ}(t) = C_{UCZ}(t = 0) + \Delta C_{LCZ}(t)(\frac{W_b-W_t}{2}(d-h_{LCZ})+W_t+W_b)h_{LCZ}
\]  
(6.39)

The term \( \frac{W_b-W_t}{2}(d-h_{LCZ})+W_t+W_b \) is simplified as follows:

\[
\frac{W_b-W_t}{2}(d-h_{LCZ})+W_t+W_b = \frac{W_b-W_t}{2}(h_{UCZ})+W_t+W_b = \frac{dW_b-W_t}{2}(h_{LCZ})+W_t+W_b = \frac{W_b(h_{LCZ})+W_t}{2}(h_{LCZ})+W_t+W_b
\]

Equation 6.39 will be as follows:

\[
C_{UCZ}(t) = C_{UCZ}(t = 0) + \Delta C_{LCZ}(t)(\frac{(W_b-h_{LCZ})+W_t}{2}h_{LCZ})
\]  
(6.40)

When Equation 6.40 for the trapezoidal shape is compared with Equation 6.15 for the pond with vertical walls, it can be concluded that the difference is that the term of \( \frac{h_{LCZ}}{h_{UCZ}} \) is multiplied by the term of \( \frac{(W_b-h_{LCZ})+W_t}{W_t(h_{LCZ})+W_b} \).

Equation 6.40 can be used to calculate the UCZ concentration in the trapezoidal pond at any time after the pond’s exploitation. Equations 6.36, 6.37 and 6.40 give an indication that inclination has an impact on the concentration of the UCZ because the sloping walls decrease the volume and the surface area of the LCZ and consequently the concentration of the UCZ.
Validation equations of the trapezoidal shape

To validate Equations 6.35 and 6.40, the pond used by Karim et al. in their 2010 research is considered. Their study investigated the stability of two SGSPs with and without porous materials at the bottom of the LCZ. Experimental concentration gradients of the pond without porous materials were considered. The pond had a trapezoidal shape with a surface area of 3.6 m² and zone depths of 0.15, 0.5 and 0.35 m for the UCZ, NCZ and LCZ respectively. The initial concentrations were approximately 260 and 33 kg/m³ for the LCZ and UCZ respectively. The pond is shown in Figure 6.37.

\[ C_{LCZ}(t) = 184.5 + 75.5e^{-0.0021t} \] (6.41)

\[ C_{UCZ}(t) = C_{UCZ}(t = 0) + 1.424\Delta C_{LCZ}(t) \] (6.42)

Equations 6.41 and 6.42 are used to compute the concentrations in the LCZ and UCZ respectively. The results are compared with the original experimental data of Karim et al. Comparisons for days 10 and 20 are shown in Figure 6.38(a) and (b).
Chapter 6: Experimental results and discussions

Figure 6.38: Comparison of computed results with the experimental results of Karim et al. (2010) on (a) Day 10 and (b) Day 20, for a pond with surface area of 3.6 m² and layer depths of 0.15, 0.5 and 0.35 for the UCZ, NCZ and LCZ respectively.

The comparisons in Figure 6.38 are separated into two subfigures (a and b) for clarity, because the experimental results for the two days are very close; this also occurs with the theoretical results computed by Equations 6.41 and 6.42. Figure 6.38 illustrates that even with the trapezoidal pond’s shape, the analytical equations can give a satisfactory results and might therefore be helpful for making such calculations.

To elucidate the effect of the inclination of the walls, it is considered that pond of Karim et al. (2012) has vertical walls, and in this case equations 6.12 and 6.15 can be applied, and they will give:

\[
C_{LCZ}(t) = 193.1 + 66.9e^{-0.0021t}
\]  
(6.43)

\[
C_{UCZ}(t) = C_{UCZ}(t = 0) + 2.33\Delta C_{LCZ}(t)
\]  
(6.44)

Two interesting features can be noted here:

Firstly, if the two equations of the LCZ concentration (for inclined and vertical walls) are compared (Equations 6.41 and 6.43):

\[
C_{LCZ}(t) = 184.5 + 75.5e^{-0.0021t}
\]  
(6.41)

\[
C_{LCZ}(t) = 193.1 + 66.9e^{-0.0021t}
\]  
(6.43)

Equations 6.41 and 6.43 show only a slight difference between the cases of the inclined walls (Equation 6.41) and vertical walls (Equation 6.43); this indicates that the inclination in this pond has a small effect on the concentration of the LCZ. This might be due to the small
difference in the depths of the two layers (0.15 for the UCZ and 0.35 for the LCZ), and this also means that the difference between their volumes is small.

Secondly, if the two equations for concentration (for inclined and vertical walls) of the UCZ (Equation 6.42 and 6.44) are compared:

\[ C_{UCZ}(t) = C_{UCZ}(t = 0) + 1.424\Delta C_{LCZ}(t) \] (6.42)

\[ C_{UCZ}(t) = C_{UCZ}(t = 0) + 2.33\Delta C_{LCZ}(t) \] (6.44)

The two equations show that in the case of the vertical walls (Equation 6.44), \( \Delta C_{LCZ} \) is multiplied by 2.33, approximately double the rate seen in the case of the inclined walls (Equation 6.42). This behaviour means that inclination has a significant influence on the concentration of the UCZ.

For further exploration of the effects of inclination, the width of the bottom base of the pond (\( W_b \)) is changed many times, thereby varying the inclination. This allows examination of the effect of the inclination on the concentration of the UCZ and LCZ layers. Their depths remain constant at 0.15 and 0.35 m respectively. The concentrations of the LCZ and UCZ are computed and plotted against time, including for a pond with vertical walls. The results are shown in Figure 6.39.

![Figure 6.39: Calculated concentration profiles of the UCZ and LCZ for the pond used by Karim et al. (2010) for vertical and many different inclined walls, where zone depths of the pond are 0.15, 0.5, and 0.35 for the UCZ, NCZ and LCZ respectively](image)

Figure 6.39 shows that for all cases (including the vertical walls), the change in the concentration of the LCZ is slight; and for the pond with vertical walls, after about 2000 days, the salinity gradient becomes uniform.

185
The change in the UCZ concentration in ponds with inclined walls is significant; while the increase is relatively quick for a pond with vertical walls, it becomes slower and slower as the inclination decreases (decreasing the inclination decreases the volume and the surface area of the LCZ). It can also be observed from Figure 6.39 that a pond with inclined walls will take longer than a pond with vertical walls for the concentration to be uniform throughout the layers. Figure 6.39 also illustrates that the linearity considered for the concentration profile of the NCZ becomes weaker with the decrease in wall’s inclination of the pond with a trapezoidal shape.

6.2.2 The derivation of the heat transfer equations

In this section of Chapter 6, analytical formulae to describe the change in the temperature of the LCZ and UCZ over time were derived. Several assumptions were adopted to derive these analytical formulae. The two equations of the heat conservation of the UCZ and LCZ are written (there is no evaporation heat loss). They are as follows for the UCZ and LCZ respectively:

\[
\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = Q_{ru} + Q_{ub} - Q_{uc} - Q_{ur} - Q_w
\]

\[
\rho_l c_{pl} A_l h_{LCZ} \frac{dT_L}{dt} = Q_{rs} - Q_{ub} - Q_{ground} - Q_{load} - Q_w
\] (6.45) (6.46)

6.2.2.1 The case with no heat addition or loss (the simple case)

In this pond, it is considered that when the pond reaches its maximum temperature, there will be no heat addition or loss to or from the pond. Heat will transfer only by conduction between the UCZ and LCZ throughout the NCZ (two blocks one is hot and the second is cold with insulation (NCZ) in between). Equations 6.45 and 6.46 will be:

\[
\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = 86400 Q_{ub} \quad (86400 \text{ is a conversion factor to convert to J/day})
\]

\[
\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = 86400 U_t A_u [T_L - T_u]
\]

\[
\rho_l c_{pl} A_l h_{LCZ} \frac{dT_L}{dt} = -86400 U_t A_L [T_L - T_u]
\] (6.47) (6.48)

It is considered that \( K_2 = \frac{86400 U_t}{\rho_u c_{pu} h_{UCZ}} \), \( R_2 = \frac{86400 U_t}{\rho_l c_{pl} h_{LCZ}} \), \( U_t = \frac{1}{R_{total}} = \frac{1}{\frac{1}{h_1} + \frac{X_{NCZ}}{k_w} + \frac{1}{h_2}} \).

where \( h_1 \) and \( h_2 \) are the convective heat transfer coefficients between the NCZ and the UCZ, and between the LCZ and the NCZ respectively. Their values are 56.58 and 48.279 W/m\(^2\) K respectively. The thermal conductivity of water (\( k_w \)) is 0.596 W/m K (Bansal and Kaushik, 1981), and \( X_{NCZ} \) is the thickness of the NCZ.

Equations 6.47 and 6.48 will be:
\[
\frac{dT_u}{dt} = K_2 [T_L - T_u] 	ag{6.49}
\]
\[
\frac{dT_L}{dt} = -R_2 [T_L - T_u] 
\]
\[
\frac{dT_u}{dt} = R_2 [T_u - T_L] 	ag{6.50}
\]

Taking Laplace transform to equations 6.49 and 6.50 gives (the full steps are given in Appendix C):

\[
T_L(t) = \left[ \frac{\rho_l c_p h_{LCZ}}{\rho_l c_p h_{LCZ} + \rho_u c_p h_{UCZ}} \left(T_L(t = 0)\right) + \frac{\rho_u c_p h_{UCZ}}{\rho_l c_p h_{LCZ} + \rho_u c_p h_{UCZ}} \left(T_u(t = 0)\right) \right] + \left[ \frac{\rho_u c_p h_{UCZ}}{\rho_l c_p h_{LCZ} + \rho_u c_p h_{UCZ}} \right] e^{-86400 \frac{\rho_l c_p h_{LCZ}}{\rho_l c_p h_{LCZ} + \rho_u c_p h_{UCZ}} t} (T_L(t = 0) - T_u(t = 0)) \tag{6.51}
\]

Equation 6.51 can be used to calculate the temperature of the LCZ for the period after reaching the maximum temperature. It requires knowledge of the initial temperatures of the UCZ and LCZ, the physical properties of the water of the UCZ and LCZ, and the thicknesses of the three layers of the pond. To find the equation represents the UCZ, and as already suggested that there is no heat accumulation in the NCZ and there is also no heat loss or addition (pond is in a dark place), so the following equations can be written:

\[
(M_l c_p \Delta T)_{LCZ} = (M_u c_p \Delta T)_{UCZ} \tag{6.52}
\]
\[
M_l c_p (T_L(t = 0) - T_L(t)) = M_u c_p (T_u(t) - T_u(t = 0))
\]
\[
T_u(t) = \frac{M_l c_p (T_L(t=0) - T_L(t)) + M_u c_p T_u(t=0)}{M_u c_p} \tag{6.53}
\]
\[
M_l = \rho_l A_l h_{LCZ}
\]
\[
M_u = \rho_u A_u h_{UCZ}
\]

Equation (6.53) can be used to compute the temperature of the UCZ over time. Applying the dimensions and the physical properties of the experimental pond, Equation (6.51) becomes:

\[
T_L(t) = 0.79 \left(T_L(t = 0)\right) + 0.209\left(T_u(t = 0)\right) + 0.209 \left[T_L(t = 0) - T_u(t = 0)\right] e^{-0.209t} \tag{6.54}
\]

The temperatures of the upper and lower convective zones over time \((T_u(t), T_L(t))\) of the experimental pond were calculated using Equations 6.53 and 6.54. The results are shown in Figure 6.40.
Figure 6.40: Change temperatures of the UCZ and the LCZ with time to reach equilibrium when no heat loss or addition is considered after the LCZ reaches the maximum.

Figure 6.40 shows that for the experimental pond (when the pond considered to be in darkness after reaching its maximum), after 16 days both the LCZ and the UCZ reach a temperature of 63 °C.

6.2.2.2 The general case

In this case, it is considered that the solar radiation is absorbed in both the LCZ and UCZ, and there is heat loss from the UCZ to the atmosphere by convection and from the bottom of the pond to the ground. It has to be mentioned that the heat loss by radiation is small, as previously proved in Chapter 3. Thus, the radiation heat loss from the surface is neglected. Additionally, there is no evaporation heat loss, since the pond is considered to be covered with a thin layer of paraffin which entirely eliminated the evaporation from the pond’s surface as seen in the experiment. Heat conservation equations of the UCZ and LCZ can be written as follows:

For the UCZ:

\[ \rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = Q_{ru} + Q_{ub} - Q_{uc} \]  

(6.55)

For the LCZ:

\[ \rho_l c_{pl} A_l h_{LCZ} \frac{dT_L}{dt} = Q_{rs} - Q_{ub} - Q_g \]  

(6.56)

The simplification of Equation 6.55 gives:

\[ \rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = Q_{ru} + 86400 U_t A_u [T_L - T_u] - Q_{uc} \]  

(6.57)

\[ Q_{uc} = h_c (T_u - T_a) \]
\[
\frac{dT_u}{dt} = \frac{Q_{ru}}{\rho_u c_{pu} h_{UCZ}} + \frac{86400 U_t}{\rho_u c_{pu} h_{UCZ}} [T_L - T_u] - \frac{86400 h_c}{\rho_u c_{pu} h_{UCZ}} [T_u - T_a]
\] (6.58)

It is considered that:
\[K_2 = \frac{86400 U_t}{\rho_u c_{pu} h_{UCZ}}, \quad F = \frac{1}{\rho_u c_{pu} h_{UCZ}}, \quad N = \frac{86400 h_c}{\rho_u c_{pu} h_{UCZ}}\]

Equation 6.58 can be written as follows:
\[
\frac{dT_u}{dt} = F Q_{ru} + K_2 [T_L - T_u] - N [T_u - T_a]
\] (6.59)

The simplification of Equation 6.56 gives:
\[
\frac{dT_L}{dt} = \frac{1}{\rho_l c_{pl} A_l h_{LCZ}} Q_{rs} - \frac{86400 U_t}{\rho_l c_{pl} A_l h_{LCZ}} [T_L - T_u] - \frac{86400 U_g}{\rho_l c_{pl} A_l h_{LCZ}} [T_L - T_g]
\] (6.60)

It is also considered that:
\[M = \frac{1}{\rho_l c_{pl} A_l h_{LCZ}}, \quad R_2 = \frac{86400 U_t}{\rho_l c_{pl} A_l h_{LCZ}}, \quad G = \frac{86400 U_g}{\rho_l c_{pl} A_l h_{LCZ}}\]

Equation 6.60 can be re-written as follows:
\[
\frac{dT_L}{dt} = M Q_{rs} - R_2 [T_L - T_u] - G [T_L - T_g]
\] (6.61)

The two differential equations 6.59 and 6.61 have been solved using Mathematica software. Full formulae of the resulted two equations from the solution are given in Appendix C. These two equations are used to calculate temperatures in the LCZ and the UCZ of the experimental pond of the current study; these temperatures are compared with the temperatures calculated by the model and presented in Chapter 3 and also with the experimental measurements. Comparisons are shown in Figures 6.41 and 6.42.

Figure 6.41: Comparisons of the calculated temperature using the analytical equation with the experimental results and temperatures calculated by the model for the LCZ.
Figures 6.41 and 6.42 illustrate that the analytical equations described the UCZ and LCZ give trends similar to the trend given by the. Figure 6.41 shows that the temperature in the LCZ is slightly higher than the temperatures calculated by the model, and both calculated temperatures are greater than the experimental measurements.

For the UCZ, Figure 6.42 illustrates that the experimental measurements of the UCZ temperatures are higher than the temperatures calculated using the model and the analytical equation. Equations 6.59 and 6.61 were used to calculate the temperatures in the UCZ and LCZ. The results are compared with temperatures calculated by the model of the present study, and the comparisons are shown in Figure 6.43.
Chapter 6: Experimental results and discussions

Figure 6.43: The comparisons of the UCZ and LCZ temperatures calculated by the model with the temperatures computed using Equations 6.59 and 6.61.

6.3 Summary

Chapter 6 has been divided into two parts. In part 6.1; the experimental results were presented and discussed. Evaporation from the surface of the SGSP for short and long periods was measured; the results were presented and discussed. The effects of the climatic parameters (solar radiation, the ambient temperature, the relative humidity, and the wind speed) were also investigated. It was concluded that levels of evaporation in the area of the study are high and it has to be considered when a SGSP has to be implemented. Statistical investigation showed that the temperature has a significant impact on the evaporation while the effect of the solar radiation is slight. The experimental results showed that there was a considerable increase in the temperature of the UCZ when the pond was covered.

In part 6.2, the derivation of the analytical equations to directly calculate concentrations of the UCZ and the LCZ over time depending on the layer’s thicknesses and some other physical properties of the water body of the pond were considered. Moreover, two equations have been derived to calculate the temperatures of the UCZ and LCZ over time. It was observed that the derived equations for both the concentrations and the temperatures in the UCZ and LCZ gave the same trends to those observed in the experiment with acceptable agreements.
Chapter 7

Conclusions and recommendations for future work
7.1 Conclusions

The aim of this study was to investigate the behaviour of a SGSP with and without a thin paraffin oil cover to suppress the evaporation from the pond surface. Moreover, to investigate the feasibility of the gel pond as an alternative to the SGSP. Furthermore, the study also aimed to derive new analytical formulae to estimate the concentrations and the temperatures of the UCZ and the LCZ over time. A small SGSP was built in the city of Nasiriyah, Iraq to collect the experimental measurements, and a model was also developed to calculate the temperatures in the solar pond numerically. The key findings extracted from this study are presented below.

7.1.1 Model development and comparisons with previous experimental measurements

A model to calculate the temperature in the three zones of a SGSP is suggested. The results are validated by the comparison with the experimental measurements, and a good agreement has been obtained. It is noticed that the temperature calculated using the model for a pond in Kuwait City reached around 90 °C in July and decreased to around 50 °C at the end of the year. A solar pond can supply heat temporarily during the year, even in winter with the cloudy and cold weather, but it needs time to warm up. In the unburied ponds, the temperature in the LCZ is higher than the temperature of the conventional buried pond. It is concluded that the perimeter has a significant effect on the temperature of the LCZ in small ponds, whereas its effect is unsubstantial in the large ponds. Therefore, the shape of the small pond is significant because of the perimeter changes with the shape. The relative importance of evaporation, convection and radiation heat loss from the surface of the solar pond has been investigated. It is found that heat loss from the surface of the pond by evaporation has the largest effect on the temperature of the LCZ whereas the radiation heat loss has the smallest impact.

The optimum thickness of the three zones present in a SGSP has been studied. The model of the current study was used in the calculations of the temperatures in the UCZ and the LCZ. The results showed that the optimum thicknesses of the UCZ and NCZ are 0.2 and 2 m respectively. It is also observed that the thickness of the LCZ depends mainly on the type of the application coupled with the SGSP. It is also noticed that the thickness variation of the UCZ and NCZ has a major impact on the temperature of the LCZ. Simultaneously, the thickness variation of the NCZ and LCZ on the temperature of the UCZ is minimal. The results illustrated that the temperature of the LCZ varies with the heat extraction rate and the thickness of the LCZ.
Chapter 7: Conclusions and recommendations for future work

7.1.2 Comparisons with the experimental results of the present study
An acceptable agreement has been observed when the pond was uncovered. However, after the pond coverage, a significant disagreement was detected between the experimental and theoretical temperatures of the LCZ. This difference in results could be due to the dust accumulation on the top surface of the paraffin layer. In addition to the influence of the difference in the refractive factors between water and paraffin.

7.1.3 The gel pond
The Gel solar pond has suggested as an alternative to tackle some difficulties encountered with the SGSP. On the other hand, challenges related to the cost and labours would hinder its implementation, and this will limit its applications. Two points can be taken into account in the comparison between the gel pond and the SGSP.

Firstly, it is essential to add salt to the LCZ and water to the UCZ regularly in the SGSP to substitute salt reduction by the upward diffusion from the LCZ and the water decrease by the evaporation from the surface of the pond. This will add cost. However, many chemicals are significant to enhance the gel properties, and this is also a cost. Secondly, the operation cost is mostly similar for both ponds. Nevertheless, with the gel pond, it is significant to employ people who have good experience with chemicals dealing, this will increase the cost of the gel pond.

7.1.4 Conclusions from the experimental work
A small SGSP was built with a 1 m² surface area and a depth of 1 m. It had a layer thickness of 0.1, 0.5 and 0.4 m for the UCZ, NCZ, and the LCZ respectively while the paraffin oil cover had a thickness of 0.5 cm. The effect of the different climatic factors (relative humidity, ambient temperatures wind speed and the solar radiation) on the evaporation from the pond was investigated. It was observed that evaporation was entirely eliminated by the addition of the paraffin layer.

The results do clearly highlight the beneficial aspects of suppressing evaporation on the pond’s performance. If evaporation can be suppressed, it can significantly reduce the cost of water replacement, thus making applications such as desalination more economically viable. This study therefore provides the initial verification that a non-volatile liquid cover can significantly affect and improve the thermal performance of a solar pond. It also highlighted a number of issues that must be addressed going forward. The paraffin layer accumulated dust much more readily than the uncovered pond and this could attenuate the incoming radiation. Furthermore,
Chapter 7: Conclusions and recommendations for future work

the effect of wind (and hence surface waves) and rain on the stability of the surface layer must be investigated further. Finally, this proof-of-concept study used paraffin as the covering fluid as it could be guaranteed to suppress evaporation. It is however not without associated environmental concerns. Given the success in trapping more heat in the pond using the liquid layer, the investigation of other alternative covering fluids must now be considered.

The specific conclusions from the current study may be summarised as:

- The temperature of the storage zone was increased at the rate of 2.25 °C/day before pond was covered. It increased from 27 °C at the beginning to 54 °C.
- The rate of increase in the temperature of the storage zone was about 1.25 °C/day after the pond covering. The temperature increased from 54 °C to 69 °C which was the maximum temperature.
- Temperature has a substantial effect on the evaporation level in the cold and moderate weather, while it has a little influence in the hot climatic conditions.
- In contrast to the temperature, wind impact is significant in the hot weather, but it is small in the cold weather.
- The rate of evaporation in the area of the study is relatively high. It increased from March to be around 5.35 l/m²-day to reach the maximum in June 17.68 l/m²-day. In September it is about 11.78 l/m². Consequently, evaporation has to be considered when a SGSP want to be implemented.

It is beneficial to discuss two points concern the high levels of evaporation. The first one is positive; since the site of the experimental unit has relatively high evaporation levels for more than six months. Consequently, salt recovery from the UCZ may be performed by the natural evaporation, and it might be beneficial to construct an evaporation pond beside the SGSP for the salt recovery. The concentrated brine can be re-injected to the LCZ in the SGSP or it can be sold after purification process. This process might remarkably decrease the cost of the SGSP.

The second point is negative since high quantities of fresh or clean water have to be added to the UCZ to address the water lack due to evaporation. This process could extend for a long period (more than 6 months) to maintain the SGSP structure, and that means the cost of the SGSP would increase. Under meteorological conditions of the area of the study, evaporation is a vital factor which can affect the efficiency of the SGSP. In the area of the study, preventing or diminishing evaporation is increasingly valuable to improve the performance of the SGSP.
The previous positive and negative impacts are operative for the site of the experimental pond of the present study or areas have similar climatic conditions.

7.1.5 Conclusions from the derivation of the analytical equations

Analytical formulae have been derived to compute the concentration of both the UCZ and LCZ over time after setting up the salinity gradient solar pond. These formulae included ponds with vertical walls and also ponds with a trapezoidal shape. The results computed utilizing the analytical equations were compared with the experimental results of the current study and some other previous existing measurements. A reasonable agreement was obtained.

Additionally, analytical equations to calculate the temperatures of the UCZ and LCZ with time were derived. The results were also compared with the experimental measurements, and a good agreement was achieved.

7.2 Future work

Solar ponds are shown to be a suitable resource to the thermal heat for applications need low-grade temperature. However, more experimental and theoretical studies are required for more understanding of the pond’s behaviour when the evaporation is eliminated. Future studies in this field of solar energy are listed below:

7.2.1 Theoretical studies

The work described in the theoretical and analytical parts of this thesis represents the development of a model to investigate the temperature and concentration profiles. Therefore, the model described in Chapter 3 can be developed and refined to examine the change in the temperature of the pond’s zones when the change in the thermal conductivity and density with the temperature increase is considered. Moreover, the effect of the difference between the refractive index of the liquid cover and water underneath can also be included in the model. In terms of the analytical part, new parameters can be considered such as the salt injection to the LCZ of the pond, the effect of wind, and the temperature impact on the salt diffusion, and new equations can be derived to describe the SGSP accurately.

7.2.2 Experimental studies

The work shown in the experimental part of this thesis represents an investigation of the behaviour of a small salinity gradient solar pond before and after coverage with a thin layer of
paraffin liquid. There is, therefore, considerable scope for this work to be extended and many experimental approaches can be examined, and they can be presented as follows:

(i) It would be highly beneficial to study the utility of two similar ponds under the same conditions to give a clearer picture. Conclusions from such study would be more powerful with a side-by-side comparison; (ii) furthermore, it would be interesting to study experimentally the impact of varying the thickness of the liquid cover on the temperatures in all zones of the pond; (iii) in addition, it would be useful to investigate a configuration of a pond which is covered by a layer of air, this layer can be kept inside a case of nylon which floats on the pond’s surface; and (iv) moreover, looking for other alternative liquid materials without associated environmental concerns to cover the pond to stop the evaporation could be valuable for the research in this area and other areas have plentiful of solar radiation.

### 7.2.3 Other future studies

- More studies on evaporation and trying to decrease its impact will be useful, and they might significantly increase the efficiency of the salinity gradient solar pond.
- Investigate the influence of wind speed on the pond performance and the liquid cover distribution in the UCZ.
- Comprehensive financial studies carried out for the particular application of solar ponds are required to further evaluation the optimum thicknesses of the three zones of the pond.
- Investigate the viability of establishing an evaporation pond beside the SGSP theoretically, and experimentally.
- More statistical studies to investigate the interaction between the parameters affecting evaporation from the solar ponds would be beneficial.
References


199


References


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## Appendices

### Appendix A

Tables of the loads, these tables with NCZ=1.5 m and UCZ= 0.2 m, and with NCZ=2 m and UCZ=0.2 m

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Appendix B

Calculation of the efficiency of the Kuwaiti pond, El-Paso pond

\[ E = \frac{q}{H} \]  \hspace{1cm} (B-1)

\[ q = \rho_l c_p l A_l \Delta T \]  \hspace{1cm} (B-2)

The pond in Kuwait City

\[ q = \frac{(1200 \times 3300 \times 1 \times 0.3 \times (76 - 23))}{1000} \text{ (divided by 1000 to convert to kJ)} \]
\[ q = 62964 \text{ kJ/m}^2 \]
\[ H = (345.6 + 456.84 + 545.4 + 630.72 + 757.08 + 852.12 + 825.12)0.85 \times 1000 \text{ (multiply by 1000 to convert to kJ)} \]
\[ H = 3750948 \text{ kJ/m}^2 \]
\[ E = \frac{62964}{3750948} = 1.67\% \]

The El-Paso solar pond.

\[ E = \frac{q}{H} \]
\[ q = \frac{(1200 \times 3300 \times 1 \times 1.35 \times (91 - 70))}{1000} \]
\[ q = 112266 \text{ kJ/m}^2 \]
\[ H = (378 + 486 + 637 + 766 + 842.4 + 864 + 799)0.85 \times 1000 \]
\[ H = 4056540 \text{ kJ/m}^2 \]
\[ E = \frac{112266}{4056540} = 2.76\% \]

Derivation of the analytical equations to calculate time dependent concentrations of the UCZ and the LCZ

The following equations represent the mass balance of the LCZ and the UCZ.

\[ \frac{d}{dt} (h_{LCZ} A_l C_{LCZ}(t)) = -\left[\frac{D}{X_{NCZ}} A_l (C_{LCZ}(t) - C_{UCZ}(t))\right] \]  \hspace{1cm} (B-3)

\[ \frac{d}{dt} (h_{UCZ} A_u C_{UCZ}(t)) = \frac{D}{X_{NCZ}} A_u (C_{LCZ}(t) - C_{UCZ}(t)) \]  \hspace{1cm} (B-4)

where \( h_{LCZ} \) is the depth of the LCZ, \( A_l \) is the surface area of the LCZ, \( C_{LCZ} \) and \( C_{UCZ} \) are the concentrations of the LCZ and the UCZ respectively, \( h_{UCZ} \) and \( A_u \) are the depth and surface area of the UCZ. Finally, symbols \( D \) and \( X_{NCZ} \) are the salt diffusivity and depth of the NCZ.
respectively. Time is taken in days and consequently the diffusivity is taken in \((m^2/d)\),
concentration is in \(kg/m^3\) (it can be \(kg/l\)).

Equation B-3 and B-4 can be as below:

\[
\frac{h_{LCZ}}{D} \frac{dC_{LCZ}(t)}{dt} = -[C_{LCZ}(t) - C_{UCZ}(t)] \tag{B-5}
\]

\[
\frac{h_{UCZ}}{D} \frac{dC_{UCZ}(t)}{dt} = C_{LCZ}(t) - C_{UCZ}(t) \tag{B-6}
\]

For simplification, it is considered that \(K = \frac{h_{LCZ}}{D}\) and \(R = \frac{h_{UCZ}}{D}\), equations B-5 and B-6 will be as follow:

\[
K \frac{dC_{LCZ}(t)}{dt} = -[C_{LCZ}(t) - C_{UCZ}(t)] \tag{B-7}
\]

\[
K \frac{dC_{LCZ}(t)}{dt} = C_{UCZ}(t) - C_{LCZ}(t) \tag{B-8}
\]

Equations B-7 and B-8 will be considered, and it will start with Equation B-7.

Laplace transform of Equation B-7:

\[
LK \frac{dC_{LCZ}(t)}{dt} = L C_{UCZ}(t) - L C_{LCZ}(t) \tag{B-9}
\]

\[
L \frac{dC_{LCZ}(t)}{dt} = s L C_{LCZ}(t) - C_{LCZ}(t = 0) \tag{B-10}
\]

Substituting B-10 in B-9 gives:

\[
K[s L C_{LCZ}(t) - C_{LCZ}(t = 0)] = L C_{UCZ}(t) - L C_{LCZ}(t) \nonumber
\]

\[
Ks L C_{LCZ}(t) - K C_{LCZ}(t = 0) + L C_{LCZ}(t) = L C_{UCZ}(t) \nonumber
\]

\[
L C_{UCZ}(t) = L C_{LCZ}(t)(Ks + 1) - K C_{LCZ}(t = 0) \tag{B-11}
\]

Equation B-11 has two parameters \(C_{UCZ}\) and \(C_{LCZ}\), and now Laplace transform to Equation B-8 will be considered:

\[
LR \frac{dC_{UCZ}(t)}{dt} = L C_{LCZ}(t) - L C_{UCZ}(t) \tag{B-12}
\]

\[
L \frac{dC_{UCZ}(t)}{dt} = s L C_{UCZ}(t) - C_{UCZ}(t = 0) \tag{B-13}
\]

Substituting B-13 in B-12 gives:

\[
R[s L C_{UCZ}(t) - C_{UCZ}(t = 0)] = L C_{LCZ}(t) - L C_{UCZ}(t) \nonumber
\]

\[
R s L C_{UCZ}(t) - R C_{UCZ}(t = 0) = L C_{LCZ}(t) - L C_{UCZ}(t) \nonumber
\]

\[
L C_{UCZ}(t)(R s + 1) = L C_{LCZ}(t) + R C_{UCZ}(t = 0) \nonumber
\]
\[ LC_{UCZ}(t) = \frac{L_{LCZ}(t) + RC_{UCZ}(t=0)}{(Rs+1)} \]  

Substitution of Equation B-14 in B-11 gives:

\[ \frac{L_{LCZ}(t) + RC_{UCZ}(t=0)}{(Rs+1)} = L_{LCZ}(t)(Ks + 1) - KC_{LCZ}(t = 0) \]  

Simplification of Equation B-15 can be as follow:

\[ L_{LCZ}(t) + RC_{UCZ}(t = 0) = [L_{LCZ}(t)(Ks + 1) - KC_{LCZ}(t = 0)](Rs + 1) \]

\[ L_{LCZ}(t) + RC_{UCZ}(t = 0) = L_{LCZ}(t)(Ks + 1)(Rs + 1) - KC_{LCZ}(t = 0)(Rs + 1) \]

\[ L_{LCZ}(t) + RC_{UCZ}(t = 0) = L_{LCZ}(t)[KRs^2 + Ks + Rs + 1] - KC_{LCZ}(t = 0)(Rs + 1) \]

\[ RC_{UCZ}(t = 0) + KC_{LCZ}(t = 0)(Rs + 1) = L_{LCZ}(t)[KRs^2 + Ks + Rs + 1] - L_{LCZ}(t) \]

\[ RC_{UCZ}(t = 0) + KC_{LCZ}(t = 0)(Rs + 1) = L_{LCZ}(t)[KRs^2 + Ks + Rs + 1 - 1] \]

\[ RC_{UCZ}(t = 0) + KC_{LCZ}(t = 0)(Rs + 1) = L_{LCZ}(t)[KRs^2 + Ks + Rs] \]

\[ L_{LCZ}(t) = \frac{RC_{UCZ}(t=0) + KC_{LCZ}(t=0)(Rs+1)}{KRs^2 + Ks + Rs} \]  

More simplification to Equation B-16:

\[ L_{LCZ}(t) = \frac{RC_{UCZ}(t = 0) + KRsC_{UCZ}(t = 0) + KC_{LCZ}(t = 0)}{KRs(s + \frac{1}{R} + \frac{1}{K})} \]

\[ L_{LCZ}(t) = \frac{KR\left[\frac{1}{K}C_{UCZ}(t = 0) + sC_{LCZ}(t = 0) + \frac{1}{R}C_{LCZ}(t = 0)\right]}{KRs(s + \frac{1}{R} + \frac{1}{K})} \]

\[ L_{LCZ}(t) = \frac{sC_{LCZ}(t = 0) + \frac{1}{R}C_{LCZ}(t = 0) + \frac{1}{K}C_{UCZ}(t = 0)}{s(s + \frac{K + R}{KR})} \]

\[ C_{LCZ}(t) = L^{-1} \left[ \frac{sC_{LCZ}(t=0) + \frac{1}{R}C_{LCZ}(t=0) + \frac{i}{K}C_{UCZ}(t=0)}{s(s + \frac{K + R}{KR})} \right] = L^{-1} \left[ \frac{A}{s} + \frac{\frac{B}{s + \frac{K + R}{KR}}}{s + \frac{K + R}{KR}} \right] \]

\[ \frac{A}{s} \left[ s \left( s + \frac{K + R}{KR} \right) \right] + \frac{\frac{B}{s + \frac{K + R}{KR}}}{s + \frac{K + R}{KR}} \left[ s \left( s + \frac{K + R}{KR} \right) \right] = sC_{LCZ}(t = 0) + \frac{1}{R}C_{LCZ}(t = 0) + \frac{1}{K}C_{UCZ}(t = 0) \]

\[ A \left[ s \left( s + \frac{K + R}{KR} \right) \right] + Bs = sC_{LCZ}(t = 0) + \frac{1}{R}C_{LCZ}(t = 0) + \frac{1}{K}C_{UCZ}(t = 0) \]

\[ As + A \left( \frac{K + R}{KR} \right) + Bs = sC_{LCZ}(t = 0) + \frac{1}{R}C_{LCZ}(t = 0) + \frac{1}{K}C_{UCZ}(t = 0) \]
\[(A + B)s + A \left( \frac{K + R}{KR} \right) = sC_{LCZ}(t = 0) + \frac{1}{R} C_{LCZ}(t = 0) + \frac{1}{K} C_{UCZ}(t = 0)\]

To find \(A\):

\[A \left( \frac{K + R}{KR} \right) = \frac{1}{R} C_{LCZ}(t = 0) + \frac{1}{K} C_{UCZ}(t = 0)\]

\[A = \left[ \frac{1}{R} C_{LCZ}(t = 0) + \frac{1}{K} C_{UCZ}(t = 0) \right] \left( \frac{KR}{K + R} \right)\]

\[A = \frac{K}{(K + R)} C_{LCZ}(t = 0) + \frac{R}{(K + R)} C_{UCZ}(t = 0)\]

\[A = \frac{K C_{LCZ}(t = 0) + R C_{UCZ}(t = 0)}{(K + R)}\]

To find \(B\):

\[A + B = C_{LCZ}(t = 0)\]

\[B = C_{LCZ}(t = 0) - A\]

\[B = C_{LCZ}(t = 0) - \left[ \frac{K C_{LCZ}(t = 0) + R C_{UCZ}(t = 0)}{(K + R)} \right]\]

\[B = \frac{(K + R) C_{LCZ}(t = 0) - K C_{LCZ}(t = 0) - R C_{UCZ}(t = 0)}{(K + R)}\]

\[B = \frac{R C_{LCZ}(t = 0) - R C_{UCZ}(t = 0)}{(K + R)}\]

\[B = \frac{R (C_{LCZ}(t = 0) - C_{UCZ}(t = 0))}{(K + R)}\]

Substitution of \(A\) and \(B\) in Equation B-17 gives:

\[C_{LCZ}(t) = L^{-1} \left[ \frac{K C_{LCZ}(t = 0) + R C_{UCZ}(t = 0)}{(K + R)} \right] \frac{1}{s} + L^{-1} \left[ \frac{R (C_{LCZ}(t = 0) - C_{UCZ}(t = 0))}{(K + R)} \right] \frac{1}{s + \frac{K + R}{K R}}\]

\[C_{LCZ}(t) = \frac{K C_{LCZ}(t = 0) + R C_{UCZ}(t = 0)}{(K + R)} + \frac{R (C_{LCZ}(t = 0) - C_{UCZ}(t = 0))}{(K + R)} e^{-\frac{(K + R) t}{K R}}\]  

\[C_{LCZ}(t) = \frac{h_{LCZ} X_{NCZ}}{D} C_{LCZ}(t = 0) + \frac{h_{UCZ} X_{NCZ}}{D} \frac{C_{UCZ}(t = 0)}{D} + \frac{h_{LCZ} X_{NCZ}}{D} \frac{(C_{LCZ}(t = 0) - C_{UCZ}(t = 0))}{D} e^{-\frac{h_{LCZ} h_{UCZ} X_{NCZ}}{D^2} |t|}\]  

219
\[
C_{LCZ}(t) = X_{NCZ}(h_{LCZ}C_{LCZ}(t = 0) + h_{UCZ}C_{UCZ}(t = 0)) \frac{D}{X_{NCZ}(h_{LCZ} + h_{UCZ})} + h_{UCZ}X_{NCZ}(C_{LCZ}(t = 0) - C_{UCZ}(t = 0)) \frac{D}{X_{NCZ}(h_{LCZ} + h_{UCZ})} e^{-\frac{X_{NCZ}(h_{LCZ} + h_{UCZ})}{h_{LCZ} + h_{UCZ}}} \frac{D^2}{X_{NCZ}(h_{LCZ}h_{UCZ})} t
\]

\[
C_{LCZ}(t) = \frac{h_{LCZ}C_{LCZ}(t = 0) + h_{UCZ}C_{UCZ}(t = 0)}{h_{LCZ} + h_{UCZ}} + \frac{h_{UCZ}(C_{LCZ}(t = 0) - C_{UCZ}(t = 0))}{h_{LCZ} + h_{UCZ}} e^{-\frac{D}{X_{NCZ}(h_{LCZ}h_{UCZ})}} \frac{h_{LCZ} + h_{UCZ}}{h_{LCZ}h_{UCZ}} t \quad \text{(B-19)}
\]
Appendix C

The derivation of the analytical equation to calculate the temperatures in the UCZ and LCZ over time (There is no evaporation).

Equation of the heat conservation of the UCZ is as follow:

$$\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = Q_{ru} + Q_{ub} - Q_{uc} - Q_{ur} - Q_w$$

(C-1)

And for the LCZ as:

$$\rho_l c_{pl} A_l h_{LCZ} \frac{dT_L}{dt} = Q_{rs} - Q_{ub} - Q_{ground} - Q_{load} - Q_w$$

(C-2)

The case with no heat addition or loss (the simple case)

The easiest is considered here when the pond reaches the maximum temperature, in this case, it will be considered that there is only heat conduction between the two layers and there is no heat addition (two blocks one is hot and the second is cold with an insulation (NCZ) in between). Consequently, Equations C-1 and C-2 will be as:

$$\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = 86400Q_{ub} \quad (86400 \text{ is a conversion factor to convert to } J/day)$$

$$\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = 86400U_t A_u [T_L - T_u]$$

(C-3)

$$\rho_l c_{pl} A_l h_{LCZ} \frac{dT_L}{dt} = -86400U_t A_L [T_L - T_u]$$

(C-4)

Let consider $K_2 = \frac{86400U_t}{\rho_u c_{pu} h_{UCZ}}$, $R_2 = \frac{86400U_t}{\rho_l c_{pl} h_{LCZ}}$, $U_t = \frac{1}{R_{total}} = \frac{1}{\frac{1}{R_1} + \frac{1}{k_{NCZ}} + \frac{1}{h_2}}$

where $h_1$ and $h_2$ are the convective heat transfer coefficient between the NCZ and the UCZ, and between the LCZ and the NCZ respectively. Their values are 56.58 and 48.279 W/m$^2$ K respectively. The thermal conductivity of water ($k_w$) is 0.596 W/m K (Bansal and Kaushik, 1981), and $X_{NCZ}$ is the thickness of the NCZ.

Equations C-3 and C-4 will be:

$$\frac{dT_u}{dt} = K_2 [T_L - T_u]$$

(C-5)

$$\frac{dT_L}{dt} = -R_2 [T_L - T_u]$$
\[
\frac{dT_L}{dt} = R_2[T_u - T_L] \tag{C-6}
\]

Laplace transform to Equation C-5:

\[
L \frac{dT_u}{dt} = K_2 \left[ LT_L - LT_u \right] \tag{C-7}
\]

\[sLT_u(t) - T_u(t = 0) = K_2 LT_L(t) - K_2 LT_u(t)\]

\[sLT_u(t) + K_2 LT_u(t) = K_2 LT_L(t) + T_u(t = 0)\]

\[LT_u(t)(s + K_2) = K_2 LT_L(t) + T_u(t = 0)\]

\[LT_u(t) = \frac{K_2 LT_L(t) + T_u(t = 0)}{(s + K_2)} \tag{C-8}\]

Laplace transform to Equation C-6 gives:

\[
L \frac{dT_L}{dt} = R_2[LT_u(t) - LT_L(t)]
\]

\[sLT_L(t) - T_L(t = 0) = R_2 LT_u(t) - R_2 LT_L(t)\]

\[sLT_L(t) - T_L(t = 0) + R_2 LT_L(t) = R_2 LT_u(t)\]

\[LT_L(t)(s + R_2) - T_L(t = 0) = R_2 LT_u(t)\]

\[LT_L(t) = \frac{LT_L(t)(s + R_2) - T_L(t = 0)}{R_2} \tag{C-9}\]

Substituting C-9 in C-8 gives:

\[
\frac{LT_L(t)(s + R_2) - T_L(t = 0)}{R_2} = \frac{K_2 LT_L(t) + T_u(t = 0)}{(s + K_2)} \tag{C-10}\]

Equation C-10 is simplified as follow:

\[(s + K_2)[LT_L(t)(s + R_2) - T_L(t = 0)] = R_2[K_2 LT_L(t) + T_u(t = 0)]\]

\[LT_L(t)(s + K_2)(s + R_2) - (s + K_2)T_L(t = 0) = K_2 R_2 LT_L(t) + R_2 T_u(t = 0)\]

\[LT_L(t)(s + K_2)(s + R_2) - K_2 R_2 LT_L(t) = (s + K_2)T_L(t = 0) + R_2 T_u(t = 0)\]

\[LT_L(t)[K_2 R_2 + K_2 s + R_2 s + s^2 - K_2 R_2] = K_2 T_L(t = 0) + sT_L(t = 0) + R_2 T_u(t = 0)\]

\[LT_L(t)[s^2 + K_2 s + R_2 s] = K_2 T_L(t = 0) + sT_L(t = 0) + R_2 T_u(t = 0)\]
\[ LT_L(t) = \frac{sT_L(t=0) + K_2T_L(t=0) + R_2T_u(t=0)}{s^2 + K_2s + R_2s} \]

\[ T_L(t) = L^{-1} \frac{sT_L(t=0) + K_2T_L(t=0) + R_2T_u(t=0)}{s(s + K_2 + R_2)} = L^{-1} \frac{A}{s} + L^{-1} \frac{B}{s + (K_2 + R_2)} \]  \hspace{1cm} (C-11)

A and B are found to be:

\[ \frac{A}{s} [s(s + (K_2 + R_2))] + \frac{B}{s + (K_2 + R_2)} [s(s + (K_2 + R_2))] = sT_L(t = 0) + K_2T_L(t = 0) + R_2T_u(t = 0) \]

\[ A[s + (K_2 + R_2)] + Bs = sT_L(t = 0) + K_2T_L(t = 0) + R_2T_u(t = 0) \]

\[ As + A(K_2 + R_2) + Bs = sT_L(t = 0) + K_2T_L(t = 0) + R_2T_u(t = 0) \]

For A:

\[ A(K_2 + R_2) = K_2T_L(t = 0) + R_2T_u(t = 0) \]

\[ A = \frac{K_2T_L(t=0)+R_2T_u(t=0)}{(K_2+R_2)} \]

To find B:

\[ A + B = T_L(t = 0) \]

\[ B = T_L(t = 0) - \frac{K_2T_L(t=0)+R_2T_u(t=0)}{(K_2+R_2)} \]

\[ B = \frac{T_L(t=0)(K_2+R_2)-K_2T_L(t=0)-R_2T_u(t=0)}{(K_2+R_2)} \]

\[ B = \frac{K_2T_L(t=0)+R_2T_L(t=0)-K_2T_L(t=0)-R_2T_u(t=0)}{(K_2+R_2)} \]

\[ B = \frac{R_2(T_L(t=0)-T_u(t=0))}{(K_2+R_2)} \]

Substituting values of A and B in Equation C-11 gives:

\[ T_L(t) = L^{-1} \frac{K_2T_L(t=0)+R_2T_u(t=0)}{(K_2+R_2)} \frac{1}{s} + L^{-1} \frac{R_2(T_L(t=0)-T_u(t=0))}{(K_2+R_2)} \frac{1}{s + (K_2 + R_2)} \]

\[ T_L(t) = \frac{K_2T_L(t=0)+R_2T_u(t=0)}{(K_2+R_2)} + \frac{R_2(T_L(t=0)-T_u(t=0))}{(K_2+R_2)} e^{-(K_2+R_2)t} \]  \hspace{1cm} (C-12)
Now values of $K_2$ and $R_2$ will be substituted in Equation C-12.

$$K_2 = \frac{86400U_t}{\rho_u c_p h_{UCZ}}, \quad R_2 = \frac{86400U_t}{\rho_{ip} c_{pl} h_{LCZ}}$$

$$K_2 + R_2 = \frac{86400U_t}{\rho_u c_p h_{UCZ}} + \frac{86400U_t}{\rho_{ip} c_{pl} h_{LCZ}}$$

$$K_2 + R_2 = \frac{86400U_t(\rho_{ip} c_{pl} h_{LCZ}) + 86400U_t(\rho_u c_p h_{UCZ})}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}}$$

$$K_2 + R_2 = \frac{86400U_t(\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ})}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}}$$

$$T_L(t) = \frac{86400U_t}{\rho_u c_p h_{UCZ}} T_{L(t=0)} + \frac{86400U_t}{\rho_{ip} c_{pl} h_{LCZ}} T_{U(t=0)} + \frac{86400U_t}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}} (T_u(t=0) - T_u(t=0)) e^{-\frac{86400U_t(\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ})}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}}} t$$

$$T_L(t) = \frac{86400U_t}{\rho_u c_p h_{UCZ}} T_{L(t=0)} + \frac{86400U_t}{\rho_{ip} c_{pl} h_{LCZ}} T_{U(t=0)} + \frac{86400U_t}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}} (T_u(t=0) - T_u(t=0)) e^{-\frac{86400U_t(\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ})}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}}} t$$

$$T_L(t) = \left[ T_{L(t=0)} + \frac{86400U_t}{\rho_{ip} c_{pl} h_{LCZ}} \right] e^{-\frac{86400U_t(\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ})}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}}} t$$

$$T_L(t) = \left[ \frac{\rho_{ip} c_{pl} h_{LCZ}}{\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ}} T_{L(t=0)} + \frac{\rho_u c_p h_{UCZ}}{\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ}} T_{U(t=0)} \right] + \left[ \frac{\rho_u c_p h_{UCZ}}{\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ}} \left( T_L(t = 0) - T_u(t = 0) \right) \right] e^{-\frac{86400U_t(\rho_{ip} c_{pl} h_{LCZ} + \rho_u c_p h_{UCZ})}{\rho_u c_p h_{UCZ}\rho_{ip} c_{pl} h_{LCZ}}} t}$$

(Equation C-13)

Equation C-13 can be used to estimate the temperature of the LCZ for the period after reaching the maximum temperature. Then temperature of the UCZ can be calculated from the following equations:

Since we consider that there is no accumulation in the NCZ and there is no heat loss or addition.
\[(M_1c_{pl}\Delta T)_{LCZ} = (M_u c_{pu}\Delta T)_{UCZ}\]  
\[M_1c_{pl}(T_L(t = 0) - T_L(t)) = M_u c_{pu}(T_u(t) - T_u(t = 0))\]

\[T_u(t) = \frac{M_1c_{pl}(T_L(t=0)-T_L(t)) + M_u c_{pu}T_u(t=0)}{M_u c_{pu}}\]  
\[M_l = \rho_l A_l h_{LCZ}\]
\[M_u = \rho_u A_u h_{UCZ}\]

**The general case:**

In this case, it will be considered that the solar radiation is absorbed in both layers of the pond (LCZ and UCZ), and there is heat loss from the UCZ to the atmosphere by convection and from the LCZ to the ground. It has to be mentioned that the heat loss due to radiation is small, and this was previously proved in Chapter 3. Thus, radiation heat loss from the surface is neglected. Additionally, there is no evaporation since the pond is considered to be covered with a thin layer of paraffin. Consequently, heat conservation equations for the UCZ and the LCZ can be written as:

For the UCZ:

\[\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = Q_{ru} + Q_{ub} - Q_{uc}\]  
\[(C-16)\]

For the LCZ:

\[\rho_l c_{pl} A_l X_l \frac{dT}{dt} = Q_{rs} - Q_{ub} - Q_g\]  
\[(C-17)\]

Working on Equation C-16:

\[\rho_u c_{pu} A_u h_{UCZ} \frac{dT_u}{dt} = Q_{ru} + 86400U_t A_u[T_L - T_u] - Q_{uc}\]  
\[(C-18)\]

\[Q_{uc} = h_c(T_u - T_a)\]

\[\frac{dT_u}{dt} = \frac{Q_{ru}}{\rho_u c_{pu} h_{UCZ}} + \frac{86400U_t}{\rho_u c_{pu} h_{UCZ}} [T_L - T_u] - \frac{86400h_c}{\rho_u c_{pu} h_{UCZ}} [T_u - T_a]\]  
\[(C-19)\]

The number 86400 is used to convert J/s to J/day

\[K_2 = \frac{86400U_t}{\rho_u c_{pu} h_{UCZ}}, \quad F = \frac{1}{\rho_u c_{pu} h_{UCZ}}, \quad N = \frac{86400h_c}{\rho_u c_{pu} h_{UCZ}}\]

Equation C-19 will be:
\[
\frac{dT_u}{dt} = F Q_{ru} + K_2[T_L - T_u] - N[T_u - T_a] \tag{C-20}
\]

Now Equation of the LCZ, Equation C-17

\[
\rho_1 c_p A_1 h_{LCZ} \frac{dT_L}{dt} = Q_{rs} - Q_{ub} - Q_g \tag{C-17}
\]

\[
\frac{dT_L}{dt} = \frac{1}{\rho_1 c_p A_1 h_{LCZ}} Q_{rs} - \frac{86400 U_l}{\rho_1 c_p A_1 h_{LCZ}} [T_L - T_u] - \frac{86400 U_g}{\rho_1 c_p A_1 h_{LCZ}} [T_L - T_g] \tag{C-21}
\]

\[
D = \frac{1}{\rho_1 c_p A_1 h_{LCZ}}, \quad R_2 = \frac{86400 U_l}{\rho_1 c_p A_1 h_{LCZ}}, \quad G = \frac{86400 U_g}{\rho_1 c_p A_1 h_{LCZ}}
\]

Equation C-21 will be:

\[
\frac{dT_L}{dt} = D Q_{rs} - R_2[T_L - T_u] - G[T_L - T_g] \tag{C-22}
\]

The two differential Equations C-20 and C-22 have been solved using Mathematica software.

Full formule of the resulted Equations (C-23 and C-24) from the solution are given as below:

\[
T_L(t) = [e^{2(A_1 + A_2)} \left( (-1 + e^{A_1})(G(K_2 + N) - (K_2 + N)^2 + (-K_2 + N)R_2) - K_2 A_2 - e^{A_1}K_2 A_2 + 2e^{2(A_1 + A_2)}K_2 A_2 - NA_2 -
\right. \]

\[
e^{A_1}N A_2 + 2e^{2(A_1 + A_2)}N A_2 \right) D Q_{rs} + R_2 \left( (-1 + e^{A_1})(G + K_2 + N + R_2) - A_2 - e^{A_1} A_2 + 2e^{2(A_1 + A_2)}A_2 \right) F Q_{rs} + G N R T_a -
\]

\[
e^{A_1}G N R T_a + K_2 R T_a - e^{A_1}K_2 N R T_a + N R T_a - e^{A_1}N R T_a + N R T_a - e^{A_1}N R T_a - R_2 A_2 - e^{A_1}R_2 A_2 +
\]

\[
2e^{A_1 + A_2}R_2 A_2 + G T_a + e^{A_1}G T_a + G R T_a + e^{A_1}G R T_a - e^{A_1}G T_a + G N T_a + e^{A_1}G N T_a - 2G K T_a + e^{A_1}G K T_a + G N T_a -
\]

\[
e^{A_1}G N T_a + K_2 R R T_a + e^{A_1}G N R R T_a - 2G K T_a + e^{A_1}G K T_a + G N R R T_a - e^{A_1}G K T_a + e^{A_1}G N T_a - 2G K T_a - e^{A_1}G K T_a +
\]

\[
e^{A_1}G N R T_a + G N R T_a + N R T_a - e^{A_1}N R T_a + N R T_a - e^{A_1}N R T_a + G K A T_a + e^{A_1}G K A T_a + G N A T_a + e^{A_1}G N A T_a +
\]

\[
e^{A_1}N R A T_a - 2G K R T_a + e^{A_1}G K R T_a - 2G N R T_a + e^{A_1}G K R T_a - 2G N R T_a + e^{A_1}G N R T_a - 2G N R T_a + e^{A_1}G N R T_a
\right) / (2(G(K_2 + N) + N R A_2)) \tag{C-23}
\]
\[
e^{\lambda_2} \left( e^{\frac{\lambda_v}{2} A_2} \right) = \frac{\sqrt{(G + K_2 + N + R_2)^2 - 4(G(K_2 + N) + NR_2)}}{2(G(K_2 + N) + NR_2)}
\]

Where:

\[
A_2 = \sqrt{(G + K_2 + N + R_2)^2 - 4(G(K_2 + N) + NR_2)}
\]

\[
A_1 = G + K_2 + N + R_2
\]