Salinity Gradient Solar Ponds: Theoretical Modelling and Integration with Desalination

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Acknowledgements

‘To the soul of my mother and to the soul of my father; the words cannot describe how much I wish that you are here to share with you this happy occasion. This thesis is dedicated to my parents’ memory’

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Abstract

Solar thermal energy generated by a salinity gradient solar pond (SGSP) is one of the most promising techniques for providing heat for desalination and other applications. A solar pond is a unique, free-energy-source system for collecting, converting and storing solar energy. Saudi Arabia is one of the most solar-radiation abundant countries on the planet, but the region also has limited water resources. Studying the thermal behaviour of a SGSP under Saudi Arabian conditions for heat generation for a thermal desalination application is the aim of this study.

An empirical equation is developed and a Matlab script is programmed to calculate hourly-averaged daily solar radiation (from sunrise to sunset). The results are validated through NASA’s 22-year-average data for solar radiation. Mathematical models are developed to describe and simulate the thermal behaviour of a SGSP. The results are compared with a SGSP in Kuwait; the results of the steady state model are sufficiently close to the measurements. The efficiency of a solar pond depends on the salt gradient stability in the middle non-convecting zone, and the diffusion and erosion of these salt layers are considered in this study.

The proposed SGSP in Riyadh, Saudi Arabia, has an area of 100 x 100m², and the predicted temperature of the storage zone is about 100°C. Higher temperatures can be reached through improved insulation and covering the surface. Additionally, an SGSP in a cold climate is suggested to compare with and test our model. The University of Surrey SGSP exceeded 80°C.

This renewable and sustainable heat source can be employed in desalination; the energy cost of desalinated water constitutes over 50% of operating costs. The heat removal process from the solar pond is investigated, and coupling the proposed solar pond with a Multi-Effect Evaporator (MEE) is described; the effects of various factors on the SGSP-MEE coupling are studied.
Aim and Objective:

The aim of this study is to predict the performance of a salinity gradient solar pond in terms of its ability to provide heat energy to a Multi-Effect Evaporator for desalination in water stressed areas and sunny climates (such as Saudi Arabia). In order to satisfy this aim, a number of objectives are addressed:

- Existing solar pond technology has been reviewed, and the various aspects of solar radiation that are relevant to this technology have been explained.
- The concept of solar pond thermal performance is explained, and the various equations necessary for assessing the performance are described.
- Matlab software has been utilized to calculate the aforementioned equations in order to describe with rigour the performance of a solar pond throughout the year.
- For comparative purposes, three ponds are described; one in a hot climate, one in a cold one, and one proposed pond (in Saudi Arabia, for desalination purposes).
- A one-dimensional steady state model has been used to predict the temperature variations with the proposed Saudi Arabian pond.
- In order to ensure that the proposed solar pond is stable against the salt mass transfer and temperature variation, the stability of the solar pond is assessed.
- In order to utilize this solar pond heat for desalination purposes, the different thermal desalination techniques are reviewed; the Multi-Effect Evaporator method is selected accordingly. The required operational temperature and heat transfer area for various numbers of effects have also been studied.
Chapter 1

Introduction to Solar Ponds
1. Introduction

Lack of drinking water is a major challenge facing the world. The most sustainable source of water is the sea but it is too salty; the process of removing salt from seawater and producing fresh potable water is desalination. Among the various desalination technologies is thermal desalination, which is the leading desalination technique, employed in the Gulf countries due the availability of cheap energy; it is also one of the earliest techniques to become established. Examples of thermal desalination include Multi-Effect Distillation (MED) and the commonly used Multi-Stage Flash desalination (MSF). In 1996, these processes represented about 70% of seawater desalination capacity worldwide [1]. MSF thermal desalination consumes about 1.3kWh (3%) electrical and about 48.5kWh (97%) heat energy for each cubic metre of water produced [2], as compared with about only 5kWh/m³ of electrical consumption in the case of the membrane-based desalination process Reverse Osmosis (RO).

Thus, desalination is an energy-intensive process, requiring an average of about 150 kilojoules of primary energy per kilogram (i.e. 41.67kWh/m³) of desalted water [3]. Current desalination costs are estimated to be between US$ 1.0-2.0 per cubic metre of produced fresh water for large-scale applications, although actual costs are higher for older plants and fuel-powered plants. For RO, which is currently the most widely-used and cost-effective desalination process, the breakdown of these costs reveals that energy accounts for more than 40% of total production costs. It is estimated that the energy requirements for desalination are 70-90kJ/kg (i.e. 19.5-25kWh/m³) for fresh water from RO processes, and 400-500kJ/kg (i.e. 111 - 139kWh/m³) for distilled water from thermal MSF methods [3]. This roughly corresponds to an average oil consumption of 3.5-10 litres for every cubic metre of fresh water produced, depending on the desalination method used and the plant size. It has been estimated that the production of 22 million m³/day requires about 203 million tons of oil per year [4]. Therefore, reducing the use of fossil fuels for desalination is highly desirable both for financial and environmental considerations. Based on today’s oil prices (of about US$ 60 per barrel), this is roughly equivalent to between $ 1.3-3.7 per cubic metre, in terms of energy costs alone, i.e., about 40% of the total desalination costs. This
means that actual desalination costs would range from $3.0-8.0 per cubic metre; with increasing oil prices, the cost is likely to rise accordingly.

Alternatively, the sun is the largest and most stable source of energy, and this energy is abundantly available all over the earth. Solar thermal energy could provide the most sustainable source of energy to power thermal desalination techniques.

There is a general coexistence correlation between areas of fresh water shortage (and hence desalination requirement) and abundant of solar irradiation. This should make the use of solar-powered desalination technologies an attractive option in arid and semi-arid regions such as the Middle East and North of Africa. During the last thirty years, extensive research has been done on solar desalination, from which the solar pond seems to be one of the most promising techniques [13].

1.1 Historical Background

Kalecsinsky observed Medve Lake in Transylvania, Hungary (42°44’ N, 28°45’ E) in 1902 [5,6] and wrote the first report on a natural solar lake. This lake had a temperature of 70°C at a depth of 1.32m at the end of the summer; even in the early spring, the minimum temperature recorded was about 26°C.

Although this report was followed by a number of studies on the same natural lake, there were no attempts to construct solar ponds for the collection and utilization of solar energy until the middle of the twentieth century [5]. More recently, a hot lake created after some mining works in Washington USA was described by Anderson; he recorded more than 50°C in the summer [32]. In 1948, Bloch suggested the salinity gradient solar pond (SGSP) as a solar collector and as a heat storage device. Ten years later, solar pond research was started in Israel [7] (it carried on until 1967, and this research, in which the main goal was to produce electrical power, provided important data that are still relevant today). Tabor [7], Weinberger [93], and Tabor and Matz [8] reported a series of theoretical and experimental studies of these salt gradient ponds [3]. These studies and reports are the ones that introduced salinity gradient solar pond technology to the world.
Solar ponds were generally designed for electricity production but they were not cost-competitive vis-à-vis other conventional technologies [8], and so they were largely abandoned in 1975 [5]. However, in 1974, research on solar ponds as long-term heat storage devices began in the USA at Ohio University [9]. Initially, theoretical studies were conducted on space heating [9] and soon after, some experiments were successfully completed [10]. Another solar pond was established in the USA at the University of New Mexico in 1975 [11].

During the past three decades, there has been increased interest in solar ponds, and they have been studied in many countries such as Chile, the former USSR and India. Solar ponds have now been established all over the world, and one of the most famous is El Paso Solar Pond, which was initiated in 1983 in Texas, USA as a research development and demonstration project operated by the University of Texas. This pond has been operational since 1985, and in that year, it was considered as the first solar pond designed for electrical power generation the USA. In 1987, it served as the first pond for desalination purposes in the USA (solar pond technology is a relatively new method for thermal desalination). The measurements taken at El Paso Solar Pond recorded temperatures reaching about 90°C but soon after that, the gradient layers were destroyed as a result of heat rising to the saline water boiling temperature. The pond gradient was rebuilt and the system was improved to avoid such problems in the future. Recently, El Paso research has focused on coupling solar ponds with thermal desalination techniques [13]. In the Gulf, a small pond with an area of 8m² was constructed in Kuwait during the mid-1980s, and temperatures of more than 80°C were reported in summer [23].

1.2 Types of Solar Ponds

Solar ponds represent one of the simplest methods for directly collecting solar irradiation and converting it to thermal energy. Moreover, it is a solar power collector and a thermal storage unit at the same time. All natural ponds and lakes convert solar radiation into heat although most of that energy is lost to the atmosphere mainly as a result of convection and evaporation. The principle of the salinity gradient solar
pond, on the other hand, is to prevent vertical convection and/or evaporation (according to the type of solar pond) [14].

Based on the convection behaviour of the saline solution in solar ponds, they may be classified into two main categories: non-convecting and convecting solar ponds.

### 1.2.1 Non-convecting Solar Ponds

This type of pond suppresses heat loss by preventing convection currents from developing within the liquid body. They usually consist of three saline water layers, where the salt concentration is highest in the bottom layer and lowest in the shallow surface layer.

The concept of this technique is based on collecting and storing the solar radiation as heat in a relatively small pond in order to raise the water temperature. In nature, when the sun’s rays fall on surface of a lake or pond, the water molecules absorb the heat and the temperature then rises accordingly. Therefore, the water in the bottom becomes warmer then it rises to the surface and loses its heat to the atmosphere, this phenomenon is called convection. However, the solar pond technology inhibits this phenomenon by dissolving salt into the bottom layer of the pond, making the molecules too heavy to rise to the surface, even when hot. Thus the temperature gain in the bottom layer is cumulative, and this can increase the temperature there to more than 100°C. Once a high temperature is obtained, the bottom layer can be used as a heat source to provide continuous heat through an internal or external heat exchanger at any time of the year, regardless of season.

Non-convective solar ponds can be sub-divided into two main types: salinity gradient and membrane ponds.

#### 1.2.1.1 Salinity Gradient Solar Pond (SGSP)

Non-convective solar ponds are simple in design and can be constructed at reasonable cost; they can provide heat for domestic, agricultural, industrial and desalination purposes and they can also generate power. A typical salinity-gradient solar pond consists of three main zones (as shown in Figure 1.1):

a- The Upper Convecting Zone (UCZ); this part is sometimes called the surface layer. This involves the least cost, has the lowest level of salinity, and its temperature is close to ambient temperature. The thickness of this zone is typically 0.3m and it
should be kept as shallow as possible. The cost of constructing the UCZ is usually neglected, as it can be constructed and operationally maintained through the use of any low-salinity water such as fresh, brackish water or seawater. This layer is essential for preventing the lower layers from being exposed to evaporation, wind effects and falling impurities.

b- The Non-Convecting Zone (NCZ); this region can be also called the gradient zone or the middle layer. It is located between the upper and the lower zones of the pond. As the temperature and salinity increase with depth, this layer is not homogeneous. If the salinity gradient is large enough, the NCZ exhibits a convection phenomenon.

c- The Lower Convecting or Storage Zone (LCZ); this is a homogenous layer and has considerably high salinity and high temperature. Heat is stored in this zone and it can be exchanged in or out of the pond. As the LCZ’s depth increases, the heat storage unit increases and the temperature variation decreases.

**Figure 1.1:** Salinity and temperature profiles through the salinity gradient solar pond zones.

The gradient layer consists of multi sup-layers in which each sup-layer is heavier and hotter than the ones above it. This stratification can make the saline molecules heavy enough to not obey to the convection phenomenon. In other words, the whole gradient zone can be established to prevent the convection from taking place inside
the pond's body and, as a result, the heat loss from the lower zone to the upper zone may occur by conduction but not convection. By this manner, the middle acts as insulator layer to reduce the lower zone upward heat loss significantly.

1.2.1.2 Membrane Ponds
Membrane ponds utilize the same concept as solar gradient solar ponds, except for the fact that a thin transparent membrane is fixed to separate each zone of the pond. Heat can be exchanged from the pond using the same procedure as in a SGSP. Not much information on their construction or application is available on this type.

1.2.2 Convecting Solar Ponds
A convecting solar pond is usually a horizontal solar collector that normally consists of one homogenous liquid layer with a transparent cover on the pond’s surface. This transparent cover reduces heat loss by impeding evaporation and convection/conduction. The cover can also prevent external effects such as wind shear, dust, falling impurities, etc.
Convecting solar ponds have classified in varying ways, for example, Kreider and Kreith categorized these ponds according to depth, differentiating between shallow and deep saltless solar ponds [14]. Other researchers consider all convecting solar ponds to be shallow solar ponds and, therefore, have classified these ponds on the basis of operational modes, relating to batch and continuous shallow pond systems [5].

1.2.2.1 Shallow Solar Pond (SSP)
The shallow solar pond is a large solar energy collector that consists of a plastic envelope containing water [3]. As the name of convective shallow pond suggests, the depth of water is relatively small, usually between 4 and 15cm [90], and the layer is homogeneous.

The concept underpinning the SSP has been known since the beginning of the twentieth century, when Willisie and Boyle [15] used the idea to produce shaft power. They tried various designs of solar pond and one of these was composed of a wooden
tank lined with tar paper and covered with a double glass window, while each side and bottom were insulated with hay. The water level in the tank was 7.5cm. Other designs included asphalt and sand for insulation, however, the latter could not be kept dry, so the heat loss from the base was high. In 1906 and 1908, Willsie and Boyle succeeded in raising the temperature from 38 to 80°C by using dual stages, and single and double glass covers (of 110m²); 11kW of peak power was obtained. Also in the beginning of the twentieth century, Shuman [16] ran a steam engine on the same system used by Willsie and Boyle. Furthermore, shallow ponds were used in Japan for domestic purposes in the 1930s [22].

After about half a century, the shallow pond technique was suggested to produce power by D’Amelio [17], and research to develop SSPs was adopted by The Office of Saline Water, US Department of Interior [18].

More recently, a research team at the University of Arizona developed an SSP to be combined with a multiple-effect solar still for the purpose of desalination. This system produced 19m³/day of distilled water using 5 ponds (each about 90m x 2m) [19].

A group of researchers at Texas A&M University [20] tried to improve the SSP by using a completely black butyl rubber bag. However, the result was exactly the opposite of what they had tried to achieve: the temperature of the top surface of the bag was 30°C hotter than the water directly underneath. So, the conclusion confirmed that the upper cover should be a transparent film.

Around 1975, the Lawrence Livermore Laboratory in California, USA [5] and the Solar Energy Laboratory at the Institute for Desert Research in Israel [21] were established and teams were formed for solar energy research. The former research centre constructed several large-scale SSP projects in different designs [14] and soon after, many significant results were obtained and published by W. Dickinson and other researchers [5]. In the latter centre, the SSP was involved in a large-scale project of solar energy and good experiment results were delivered. After that, Kudish and Wolf [29] designed a portable shallow pond for camping and military use. During the past 30 years, SSPs have been used in many countries, such as Iran [23] and Egypt [24].
A typical SSP consists of a low-depth volume of water enclosed in 60m x 3.5m (approximately) plastic bag, with a blackened bottom and colourless top film. This bag is insulated below with foam insulation and on the top with single or double glazed panel, as shown in Figure 1.2 [14]. The shallow solar pond can be operated in batch or continuous modes. In batch operation, the water is insulated during daytime. Before nightfall, it is pumped into a large insulated tank for night storage and then pumped back into the bag after sunrise every day. If the water flows continuously through the water bag, this operational method is then called the flow-through mode, which is also named by some researchers [14] as deep saltless solar pond [26].

![Figure 1.2: A typical shallow solar pond [25].](image)

### 1.3 Salinity Gradient Solar Ponds

The salinity gradient solar pond (SGSP) is the one to be considered in this study, as its constructional cost is reasonable, and it represents a clean and free source of energy. In addition, the solar pond is a unique system for collecting, converting and storing the solar energy. Certain factors affecting the SGSP performance will be investigated.

#### 1.3.1 Effect of Layer Depth

The depth variation of the layers in a solar gradient pond leads to considerably different performances, and therefore it is important to optimize the depth of each layer of the pond in order to obtain the best possible results. In some cases, it is also
possible and useful to design a pond with varying from the optimum depths; this may be advised when the insulation is the issue of most concern or when the collected heat and energy extraction is completely controlled.

The upper convective layer should be kept thin; the optimal thickness may be 30cm of fresh water [30]. This layer needs to be continuously supplemented by fresh water to maintain the required depth, which shrinks due to evaporation. Adding fresh water to this layer is also essential for maintaining the gradient profile, which may affect the solar pond’s performance and stability.

The non-convecting or gradient layer may vary in depth, depending upon the heat storage requirements, as its thickness plays a significant role in terms of insulation. Shah and his group [27] studied the effects of different thicknesses (2.5, 2, 1.5 and 1.0m) of the NCZ on the storage zone insolation. The total depth of the solar pond is 3m. The study shows that although the temperature in the storage zone increases with increased thickness of the NCZ, the maximum stored energy actually decreases, as shown in Table 1.1. It was found that there was 61% increase in the maximum energy stored by decreasing the depth of the gradient layer from 2.5 to 2m, and 40% and 97% additional increases as a result of reducing the depth to 1.5 and 1m, respectively. Thus, the suggested optimal thickness for the NCZ is 1m [27].

Table 1.1: The effect of gradient zone depth on storage zone thermal performance of a solar pond with 3m total depth[27].

<table>
<thead>
<tr>
<th>Depth of NCZ (m)</th>
<th>Total radiation (GJ)</th>
<th>Peak temp. (°C)</th>
<th>Max. stored energy (GJ)</th>
<th>Surface heat loss (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>135</td>
<td>53</td>
<td>65.5</td>
<td>90.9</td>
</tr>
<tr>
<td>1.5</td>
<td>115.3</td>
<td>61</td>
<td>51</td>
<td>70.9</td>
</tr>
<tr>
<td>2</td>
<td>100.3</td>
<td>67</td>
<td>40.8</td>
<td>61.8</td>
</tr>
<tr>
<td>2.5</td>
<td>89.1</td>
<td>82</td>
<td>25.4</td>
<td>58.6</td>
</tr>
</tbody>
</table>

GJ = Giga Joules

Any increase in the thickness of the lower convective zone in a salinity gradient solar pond decreases both the maximum obtained temperature and the heat loss from this zone, and it increases the maximum storage heat in the lower zone. Although most research has reported that the optimal thickness for the LCZ is about 1m, it was
concluded by German and Muntasser [28] that the optimal thickness of the storage zone is 4m. The depth of this zone depends on the purpose of the pond and on the method of heat extraction from this layer. For example, it should be kept as shallow as 0.5m or even less when high temperatures are required and the withdrawal of heat is in operation; this is to control the steep temperature fluctuation that typifies an LCZ with a very shallow depth. For this reason, Hall et al. [33] stated that the depth of this layer should not be less than 0.5m [33] if the pond is not in operational mode in order to avoid the effects of this rapid temperature variation on the salinity gradient solar pond’s stability.

1.3.2 Effect of Top Insulation
The majority of solar ponds are designed with uncovered surface, however 50-60% of heat lost is exchanged with the air via the surface during autumn and winter (if there is no mechanical heat extraction) [27].

The effect of having a surface cover was studied by Shah et al. [27]; they used varying thicknesses of polystyrene insulation, from 0 - 40cm. It was estimated that the heat losses were reduced by 55% and that the stored heat was increased by 80% when the cover’s thickness was increased from 0 to 10cm at the peak temperature on 10th September. When the thickness was increased from 10 to 20cm, heat loss was further reduced by 6%, while the stored energy was raised by another 15%. There was no further significant change in heat loss or storage by increasing the thickness up to 40cm. The surface insulation had no considerable effect if there was heat extraction, or during the summer and spring seasons, as shown in Figure 1.3.
Figure 1.3: Effect of increasing the thickness of polystyrene insulator on the surface of the solar pond [27].

1.3.3 SGSP Cost Estimation Review

There are many factors that can significantly affect the costs associated with solar ponds. These factors include excavation, lining, salt, extraction infrastructure and operation. The effects of these factors could vary from one location to another, for instance, the cost of salt may be negligible if the location is near to salty lakes or a salt mine but it may be very expensive if it is imported or transported great distances.

Salinity gradient solar ponds become more economical when their sizes are approximately 10,000 to 100,000m$^2$ [33]. This is because of the economies of scale associated with construction works such as excavation, salt transport and recycling, insulation works, and operational/labour costs, which decrease proportionately as size increases.

In 1975, four studies took into consideration the costs of four solar ponds, which had different construction purposes, conditions, sizes and locations. The first study, which was in Columbus, Ohio USA where the solar pond was used for winter space heating, demonstrated that it cost US$ 47.50/m$^2$, and in the same city but for preheating water for laundry use, the second study showed that it cost $ 18.33/m^2$. The third study was conducted to determine the cost of solar pond construction for water heating for a resort hotel in Hawaii, and it showed that its cost was $ 12/m^2$. 
The fourth study was on processing heat for a salt works in Texas, and it was reported that the pond cost only $5.30/m². There was additionally a solar pond cost estimation study in Miamisburg, Ohio, which showed that each square metre cost about $31.60 in 1981 [34].

So far, the largest constructed solar pond was in Beit Ha Arava, Israel and its cost was estimated at $10/m² in 1984; it ceased operating in 1988 [35].

Hull et al. [36] in 1986 studied the effect of enlarging the surface areas on reducing the total construction costs; they studied 2,000m², 20,000m² and 200,000m² solar ponds, constructed with evaporation ponds. The study found that the total costs were $84.00/m², $52.50/m² and $42.30/m² respectively, according to the highest salt price in normal conditions, which was in that year $0.04/kg. The same study was carried out for free salt projects, and thus, there was no need for salt recycling or evaporation basins, and the costs were $43.00/m², $17.00/m² and $9.50/m² respectively. Therefore, it is clear that the cost per square metre decreases as the surface area increases.

In India [89], a gradient solar pond was built in 1987 with the intention of supplying heat to a dairy; the cost was about $11.51/m², and the maximum recorded temperature was 99.8°C in May 1991.

In 1991, the cost of the Texas solar pond was approximately $11.30/m²; this price is similar to the $9.50/m² obtained in the aforementioned Columbus, Ohio solar pond in 1986, as the two (at 200,000 m²) are approximately equivalent to the 2007 price of $16/m² (updated prices are presented in Table 2).

In Ancona, Italy, an SGSP was constructed for research purposes; it was coupled to work with thermal desalination units in 1997 [37]. It was reported that each square metre cost about $44.3.

A solar pond heating system was constructed in 2000 at Pyramid Hill in north-central Victoria, Australia to provide heat to be used in high-grade salt production and aquaculture. The 3,000m² solar pond was integrated into a salinity-mitigation scheme and the estimated cost was $21/m² [38].
The above solar pond cost studies are summarized in Table 1.2 but currency values vary from year to year. Therefore, in order to make comparisons between the amounts of money, the costs are updated to the equivalent values for 2007 by using a GDP deflator index.

**Table 1.2:** Examples of solar ponds updated costs

<table>
<thead>
<tr>
<th>Location</th>
<th>Project purposes</th>
<th>Surface area (m$^2$)</th>
<th>Cost ($/m$^2)</th>
<th>Year of cost study</th>
<th>Equiv. cost 2007 ($/m^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Winter space heating</td>
<td>1,963</td>
<td>47.50</td>
<td>1975</td>
<td>149.75</td>
</tr>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Preheating of water for laundry use</td>
<td>7,855</td>
<td>18.33</td>
<td>1975</td>
<td>57.79</td>
</tr>
<tr>
<td>Hawaii, USA</td>
<td>Water heating for resort hotel</td>
<td>7,855</td>
<td>12</td>
<td>1975</td>
<td>37.83</td>
</tr>
<tr>
<td>Texas, USA</td>
<td>Process heat for a salt works</td>
<td>1,000,000</td>
<td>5.30</td>
<td>1975</td>
<td>16.71</td>
</tr>
<tr>
<td>Miamisburg, Ohio, USA</td>
<td>Heating a swimming pool</td>
<td>2,000</td>
<td>31.60</td>
<td>1981</td>
<td>64.03</td>
</tr>
<tr>
<td>Beit Ha Arava, Israel</td>
<td>Power generation</td>
<td>250,000</td>
<td>18</td>
<td>1984</td>
<td>31.87</td>
</tr>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Research (with evaporation pond)</td>
<td>2,000</td>
<td>84</td>
<td>1986</td>
<td>141.22</td>
</tr>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Research (with evaporation pond)</td>
<td>20,000</td>
<td>52.50</td>
<td>1986</td>
<td>88.26</td>
</tr>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Research (with evaporation pond)</td>
<td>200,000</td>
<td>42.30</td>
<td>1986</td>
<td>71.12</td>
</tr>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Research</td>
<td>2,000</td>
<td>43</td>
<td>1986</td>
<td>72.29</td>
</tr>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Research</td>
<td>20,000</td>
<td>17</td>
<td>1986</td>
<td>28.58</td>
</tr>
<tr>
<td>Columbus, Ohio, USA</td>
<td>Research</td>
<td>200,000</td>
<td>9.50</td>
<td>1986</td>
<td>15.97</td>
</tr>
<tr>
<td>Kutch, India</td>
<td>Supplying process heat to a dairy</td>
<td>6,000</td>
<td>11.51</td>
<td>1987</td>
<td>18.84</td>
</tr>
<tr>
<td>Texas, USA</td>
<td>Producing industrial process heat</td>
<td>210,000</td>
<td>11.3</td>
<td>1991</td>
<td>16.03</td>
</tr>
<tr>
<td>Ancona, Italy</td>
<td>Providing hot water to desalinator</td>
<td>625</td>
<td>44.3</td>
<td>1997</td>
<td>55.63</td>
</tr>
<tr>
<td>Pyramid Hill, Australia</td>
<td>Heat generation for industrial processes</td>
<td>3,000</td>
<td>21</td>
<td>2000</td>
<td>25.16</td>
</tr>
</tbody>
</table>
The effect of pond size on cost is represented in Figure 1.4, and the trend shows that the cost decreases as the size of the pond increases. As most solar ponds are constructed for research and development purposes and are relatively small in terms of size, it could be useful to compare just the small ponds together, as shown in Figure 1.5, which illustrates a similar trend as well.

**Figure 1.4:** The effect of solar pond size on cost.

**Figure 1.5:** The cost of small solar ponds vs. size.
A technique can be more competitive and promising when it becomes cheaper over time, and consequently, it can become more attractive for research and development. Solar ponds have demonstrated a decrease in construction costs over the years, as shown in Figure 1.6, and if the large ponds are excluded (as they play a significant role in the cost comparison), the same decreasing trend is obtained, as illustrated in Figure 1.7.

**Figure 1.6:** The decrease in solar pond costs over time.

**Figure 1.7:** Solar pond cost trend, excluding large ponds, over time.
Amongst the features of solar ponds are the low cost per unit area of collector, their inherent storage capacity, and the fact that they are easily constructed over large areas [39]. In general estimates, the Jet Propulsion Laboratory (JPL) [40] concluded that a small solar pond’s capital cost is between US$ 43 and $ 67/m² depending on 1980 prices. According to the Solar Energy Research Institute (SERI) [41] study conducted in 1985, solar pond construction cost ranged from $ 60/m² to $ 100/m². Hull et al. conducted some solar ponds cost studies, and concluded that these were $ 15 to $ 75/m² in 1989 [33].

1.3.4 Operation and Maintenance Cost Review
Operation and maintenance costs include many factors, such as electricity consumption for instruments and pumping systems, water and salt supplement, equipment repair and maintenance, and the working hours of labours. It can be assumed that the routine operation and maintenance costs are 10% of the capital cost [33].

It was estimated that the O&M costs of Columbus, Ohio 2,000, 20,000, and 200,000m² solar ponds were US$ 13.5/m², $ 6.55/m² and $ 4.85/m² respectively, for the same salt price as above (for 1986) and were $ 9.4/m², $ 3/m² and $ 1.53/m² per year respectively, for free salt cases [33].

The JPL study showed that the O&M cost was about $ 2.5/m² per year based on certain economic assumptions for a 20-year lifetime [40].

1.3.5 Difficulties and Limitations of Solar Pond Use
The saline gradient solar ponds are like any other technology in that they have some limitations but the most common problem in any solar energy application is the absence of sunlight at night and cloudy days. Solar ponds, however, are less affected by this problem as they store heat cumulatively.

The main challenge in using most solar energy applications is heat loss. Therefore, good insulation is vital. The storage zone in SGSP is insulated from the top by the gradient layer, which suppresses convection, but heat loss can still occur from the
sides and the bottom if they are not well insulated. The bottom energy losses can be a serious problem if there is an aquifer beneath.

Most solar ponds are uncovered, and thus they are exposed to dust and impurity fouling. This fouling is an inherent problem in such ponds, which can considerably reduce the irradiation reaching the lower zone. Consequently, the pond’s efficiency will be reduced. Open-surface ponds can be affected by wind shear, which can create waves on the surface of the solar pond; this movement can exacerbate heat loss and increase the evaporation rate. Although rainfall in adequate amounts is desirable to recover the evaporated water, it could adversely affect the pond’s temperature. Moreover, it may dilute the saline water in the pond and cause it to overflow.

The growth of algae on the surface or within the pond is a problem that may impair the transparency of the water of the solar pond. However, Al-Mutaz and Alenezi [37] reported that because the alkalinity of their water had been increased to above pH9, all the algae that had been apparent entirely disappeared from the precipitators, channels and filters in the Salboukh RO Water Treatment Plant. Gasulla et al. [32] reported that both chlorine and copper ethylamine complex can prevent the growth of algae.

One of the most serious problems in a saline gradient solar pond is the upper temperature limit. The temperature in these ponds should not rise up to the boiling point of saline water, otherwise the gradient layer will be destroyed. This problem occurred in El Paso Solar Pond in the early years of construction [13]. This issue can be avoided by continuous heat removal from the storage zone. The boiling temperature of MgCl$_2$ near-saturated water is 117°C [8].

Preparing a concentrated solution (brine), building the layers, and heat accumulation are all time-consuming processes. In El Paso Solar Pond, it took five months to prepare the brine by adding 1,100 tons of salt [45]. In India, a separate system was developed to accelerate the dissolving process, and the dissolving of 3,200 tons of NaCl was accomplished within two and a half months during the first phase. Due to some maintenance works, it was essential to rebuild the layers but further
improvements were made to the dissolving system and the preparation process was reduced to just one month.

Establishing the gradient takes a considerable amount of time [5]. However, due to recent technological improvements, it now takes only a few days. For instance, it took four days in El Paso’s 3,000m² solar pond [13] and 115 hours in the 6,000m² solar pond at Kutch, India. The temperature starts to rise immediately after building the salinity gradient, and the pond’s temperature increases by 1°C per day on average [13]. In an SGSP, the temperature of the storage zone can reach 80°C in about two months [46]. These examples illustrate how much time is needed to rebuild the SGSP layers if any of the layers are destroyed.

Solar pond research and operations have been halted several times in different parts of the world, as they have proved to be uncompetitive with other technologies in commercial projects. Nevertheless, operating solar ponds coupled with other technologies, such as SGSP coupled with MSF or MED for desalination purposes, seems to be more promising.
Chapter 2

Solar Radiation
2. Introduction to Solar Radiation

The sun is a gaseous sphere, mainly consisting of hydrogen and then helium. It emits various electromagnetic waves of differing wavelengths. Those wavelengths vary from fractions of Angstroms to hundreds of metres, as shown in Table 2.1 [42]. The energy radiated by the sun travels through space, about 150 million kilometres, until it reaches the earth, however, about 50% (as an average attenuation) of the extra-terrestrial solar energy is attenuated during its journey toward the earth’s crust, as shown in Figure 2.1. The majority of ultraviolet solar radiation, with wavelengths between 0.2 and 0.3µm, is absorbed by ozone gas which is found in the Ozone layer.

![Diagram of solar radiation distribution](image)

**Figure 2.1**: The distribution of the solar radiation.
Table 2.1: Regions of the electromagnetic spectrum [9].

<table>
<thead>
<tr>
<th>Region</th>
<th>Wavelength (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Rays</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>X-Rays</td>
<td>0.1 - 10</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>10 - 4000</td>
</tr>
<tr>
<td>Visible</td>
<td>4000 - 7000</td>
</tr>
<tr>
<td>Infrared</td>
<td>7000 - 10⁶</td>
</tr>
<tr>
<td>Microwave</td>
<td>10⁶ - 10⁹</td>
</tr>
<tr>
<td>Radio</td>
<td>10⁹</td>
</tr>
</tbody>
</table>

The ultraviolet band is less than 0.2µm, Gamma rays and X-rays are selectively absorbed by the oxygen and nitrogen atoms in the atmosphere. Infrared solar waves, with wavelength longer than 0.7µm, are partially absorbed in the atmosphere by carbon dioxide, ozone, and water vapour. Some of the solar radiation is scattered or reflected back to the sky; the rest is received by earth as a direct beam, and the scattered light is received on the ground as a diffuse beam [43, 44]. It is useful to define some common terms in solar radiation field:

**Irradiation:** The received solar energy per unit area on a surface.

**Solar Constant:** The total amount of solar energy per time per unit of area exposed normally to the sun at mean sun-earth distance outside the atmosphere.

**Direct Beam:** The direct received amount of solar energy without scattering by the atmosphere.

**Diffuse Beam:** The received solar energy after changing its direction due to scattering by the atmosphere.

**Total Solar Beam:** The sum of direct and diffuse beam on a surface.
**Figure 2.2:** Sketch showing the declination and latitude angles.

**Declination Angle** (δ): The angle between True North and the Magnetic North Pole, as shown in Figure 2.2.

**Latitude Angle** (φ): This can be defined as the angle between the earth’s equator and a line linking a point and the earth’s centre, as shown in Figure 2.2.
Solar Altitude Angle ($\alpha$): This may be described as the angle between the centre of the sun’s ray and a horizontal plane, as shown in Figure 2.3.

Solar Zenith Angle ($\theta$): The angle between the centre of the sun’s ray and the zenith, as illustrated in Figure 2.3.

Solar Azimuth Angle ($\psi$): This is the angle measured clockwise between the southern direction and a line from the observer to the sun, projected on the earth.

Surface Azimuth Angle ($\gamma$): This is defined as the angles between the surface of the objective and the southern direction.
2.1 Solar Radiation Behaviour in a Body of Water

When the incident solar radiation falls on a body of water, some of the sunlight is reflected back to the sky and the rest is absorbed by the surface of the water, the energy of which penetrate to over a hundred metres in depth.

2.1.1 Sunlight Reflection

The amount of reflected solar light towards the sky depends on the position of the sun (θ) and the condition of the water’s surface. A rough surface tends to absorb more sunlight and a glass-like surface reflects more, however the roughness of the surface has little effect as long as a wind speed is less than 15.4m/s [57]. When the surface of water is not turbulent or is only slightly turbulent, the surface reflection can be calculated by Fresnel’s equation [58]:

\[ Fr(\theta) = \frac{1}{2} \left[ \frac{\sin^2(\theta - \theta_r)}{\sin^2(\theta + \theta_r)} + \frac{\tan^2(\theta - \theta_r)}{\tan^2(\theta + \theta_r)} \right] \] (2.1)

where \( \theta \) = incident angle in degrees, and \( \theta_r \) = reflective angle in degrees.

The Fresnel reflection (Fr) computes the ratio of the amount of reflected ray to the incident beam. Figure 2.4 illustrates that the reflected ray represents a small fraction, about 2-5%, most of the day and is only high when the sun is near to sunrise and sunset.
2.1.2 Sunlight Transmission

The remaining part of the sunlight, after reflection, penetrates the air-water interface and is refracted into the water medium. This refraction of the incident solar radiation can be predicted by Snell’s Law:

\[
\frac{\sin \theta_r}{n} = \frac{\sin \theta}{n_r} \tag{2.2}
\]

where \( n \) = air refractive index, and \( n_r \) = water refractive index

The solar light travels deeper in the water for many metres depending upon the transparency and clearness of the water. Water impurities may scatter and/or absorb the beam and versa versa; clear water allows it to travel further, and therefore the water should be maintained as clear as possible.
2.1.3 Sunlight Absorption

The propagated light within a medium of water is attenuated by absorption and scattering. The latter is caused mainly by the presence of biological organisms and suspended particles [74], while water molecules themselves cause a minor effect in terms of scattering. It is a useful simplification to consider that the scattering direction is in a forward direction.

The absorption of solar radiation is a complex process, and there is very little available data on sunlight attenuation and transmission in water [90]. Several researchers have attempted to derive formulae to describe it but it has been found that solar radiation absorption in a body of water cannot be described by a single exponential equation, as such absorption varies from one wavelength to another. For example, the near-infrared wavelength can be absorbed within the first decimetre of the water’s surface and most of the visible light band can be absorbed within 10 metres, but short wavelengths may travel up to 150m; none passes further than this depth, even in very clear water conditions [9, 47].

Rabl and Nielsen [9], according to Defant’s observation in 1961, divided the wavelength spectrum between 0.2 and 1.2µm into four bands, and then determined the fraction of solar radiation and average extinction coefficient in each band. They considered that water is practically opaque to wavelengths greater than the infrared range (1µm). This classification is illustrated in Table 2.2.

<table>
<thead>
<tr>
<th>i</th>
<th>η</th>
<th>μ (m⁻¹)</th>
<th>λ (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>3.0</td>
<td>0.75 – 0.9</td>
</tr>
<tr>
<td>4</td>
<td>0.179</td>
<td>35.0</td>
<td>0.9 – 1.2</td>
</tr>
<tr>
<td>5*</td>
<td>0.224</td>
<td>260</td>
<td>&gt; 1.2</td>
</tr>
</tbody>
</table>

* added following Kaushik and Bansal – see below

The total of the solar radiation fractions based on Rabl and Nielsen’s approximation is 0.776, which represents 77.6% of the propagated sunlight in the water. The rest
(22.4%) is assumed to be absorbed within the first few centimetres of the upper layer of the water’s surface, as it is a far-infrared wavelength, i.e. greater than 1.2µm.

Hull [33, 48] also found other absorption data to predict the values of the absorption coefficient and radiation fraction for each band. Although Hull divided the solar radiation spectrum into 40 wavelength bands, he used a 4-part transmission function to calculate the absorbed portion of the radiation. Through this, he found that his method results in values 10% higher than the R-N model, however, it has good accuracy when used for solar absorption prediction in pure water. These data are listed in Table 2.3.

**Table 2.3:** Hull’s absorption data [33].

<table>
<thead>
<tr>
<th>i</th>
<th>η</th>
<th>μ (m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.190</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>0.230</td>
<td>1.75</td>
</tr>
<tr>
<td>3</td>
<td>0.301</td>
<td>0.0656</td>
</tr>
<tr>
<td>4</td>
<td>0.141</td>
<td>0.0102</td>
</tr>
</tbody>
</table>

The data in Tables 2.2 and 2.3 can be used to predict the fraction of the solar radiation at depth (x) by the following equation:

\[
h(x) = \frac{H(x,t)}{H_T(x = 0, t)} = \sum_{n=1}^{4} \eta_n e^{-\mu_n x} \quad (2.3)
\]

This exponential formula was simplified by Bryant and Colbeck [49], and seems to be in very good agreement with the R-N model.

\[
h(x) = 0.36 - 0.08 \ln(x) \quad (2.4)
\]

where \(x\) is the depth in metres

Kaushik and Bansal [50] conducted some comparison studies between the above calculation methods and found that in considering the near-infrared exponential part (greater than 1.2µm), relative to Rabl and Nielsen’s model, Bryant and Colbeck’s model delivers an excellent approximation. This comparative study is summarized in Figure 2.5 and this near-infrared (fifth part) is added to Table 2.2.
Figure 2.5: A comparative study of different empirical equations [90].

2.2 Solar Irradiation Calculations

Solar irradiation data have been widely measured and recorded for almost every region in each country of the world for many years. Nevertheless, predictions and calculations of irradiation are sometimes required to obtain a good approximation of incident radiation.

According to a solar pond’s location, the sun’s path in the sky changes seasonally, and thus the sun’s altitude and azimuth angle as well as the daily sunshine period all vary; this has a great effect on the amount of incident solar radiation and then on the performance of the solar collector. These variations happen when the declination angle is changed due to the earth’s rotation. The declination angle ($\delta$) can be estimated by the following equation:

$$\delta = 23.45^\circ \sin \left( \frac{N - 80}{370} \right) \ast 360$$  \hspace{1cm} (2.5)
where $N$ is the number of the day in the year, which can be obtained from Table 2.4.

**Table 2.4**: Days (and numbers) of a year and the representative day for each month [31].

<table>
<thead>
<tr>
<th>Month</th>
<th>$N$ for $i^{th}$ day</th>
<th>date</th>
<th>$N$ day of year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>$i$</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Feb</td>
<td>$31 + i$</td>
<td>16</td>
<td>47</td>
</tr>
<tr>
<td>Mar</td>
<td>$59 + i$</td>
<td>16</td>
<td>75</td>
</tr>
<tr>
<td>Apr</td>
<td>$90 + i$</td>
<td>15</td>
<td>105</td>
</tr>
<tr>
<td>May</td>
<td>$120 + i$</td>
<td>15</td>
<td>135</td>
</tr>
<tr>
<td>Jun</td>
<td>$151 + i$</td>
<td>11</td>
<td>162</td>
</tr>
<tr>
<td>Jul</td>
<td>$181 + i$</td>
<td>17</td>
<td>198</td>
</tr>
<tr>
<td>Aug</td>
<td>$212 + i$</td>
<td>16</td>
<td>228</td>
</tr>
<tr>
<td>Sep</td>
<td>$243 + i$</td>
<td>15</td>
<td>258</td>
</tr>
<tr>
<td>Oct</td>
<td>$273 + i$</td>
<td>15</td>
<td>288</td>
</tr>
<tr>
<td>Nov</td>
<td>$304 + i$</td>
<td>14</td>
<td>318</td>
</tr>
<tr>
<td>Dec</td>
<td>$334 + i$</td>
<td>10</td>
<td>344</td>
</tr>
</tbody>
</table>

The sunrise or sunset hour angle (in degrees) is given by:

$$\omega_s = \cos^{-1}(-\tan \varphi \tan \delta)$$  \hspace{1cm} (2.6)

where $\varphi$ represents the latitude of the location.

The sunrise or the sunset hour angle can be expressed in hours by the following equation:

$$\omega_s = \pm \frac{24}{360} \left[ \cos^{-1}(-\tan \varphi \tan \delta) \right]$$  \hspace{1cm} (2.7)

The hour angle from the solar noon position is obtained from:

$$\omega = nhn \times \frac{360}{24}$$  \hspace{1cm} (2.8)

where $nhn$ is the number of hours from the solar noon.
The value of $\omega$ is referred to a noontime, where it is negative in the morning and positive in the afternoon.

The incident angle ($\theta$) is achieved from this equation:

$$\cos \theta = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \tag{2.9}$$

As the earth-sun distance varies each season, the apparent extraterrestrial solar irradiation changes during the year. Therefore, the solar irradiation intensity depends on the number of the day in the year. The average daily extraterrestrial solar irradiance is given by:

$$I_o = I_{sc} \left[ 1 + 0.0033 \cos \left( \frac{360N}{370} \right) \right] \tag{2.10}$$

The solar constant ($I_{sc}$) value has been measured by many researchers since the beginning of the 20th Century. Abbot and his team at the Smithsonian Institute, after many researches, proposed a value of 1,353W/m$^2$ as being the value of the solar constant. Many further investigations were made on ground-based and high altitude measurements, and eventually 1,353W/m$^2$ was accepted as being the standard for the solar constant. NASA, after many measurements in space, recommended this value as well [44]. However, it has very recently been published on NASA’s website that the generally accepted value for the solar constant is now 1,368W/m$^2$ (as a satellite-measured yearly average), which is close to the former standard value.

The total daily extraterrestrial radiation on a horizontal surface can be computed by:

$$H_{oT} = \frac{I_{od}}{\pi} \left[ \cos \theta \cos \delta \sin \omega_s + \frac{2\pi \omega_s}{360} \sin \phi \sin \delta \right] \tag{2.11}$$

where $\omega_s$ is expressed in degrees and is derived from Equation 2.7. $I_{od}$ is daily total direct normal extraterrestrial radiation, which can be obtained by yielding the value of extraterrestrial solar irradiation throughout the day, as in the following:

$$I_{od} = 24I_o \tag{2.12}$$

To use these equations for the computation of the monthly daily-average total extraterrestrial radiation on a horizontal surface $\overline{H_{oT}}$, the month’s representative-day, from Table 2.4, should be used in declination angle calculations.
The monthly daily-average total irradiation on a horizontal surface $\bar{H}_T$ is a fraction of the extraterrestrial radiation $\bar{H}_{oT}$ after depletion. This fraction can be determined by the clearness index ($\bar{K}_T$):

$$\bar{H}_T = \bar{K}_T \bar{H}_{oT} \quad (2.13)$$

Page [52] collected measurements from 10 stations and derived a simple formula for identifying the diffuse radiation portion as a function of the clearness index.

$$\frac{\bar{H}_d}{\bar{H}_T} = 1 - 1.13\bar{K}_T \quad (2.14)$$

Page’s correlation was confirmed by further measurements by Choudhury [53], Stanhill [54] and Norris [55]. Lunde [31] recommended it after a little correction to satisfy the standard solar constant value.

$$\frac{\bar{H}_d}{\bar{H}_T} = 1 - 1.096\bar{K}_T \quad (2.15)$$

Thus, the remaining portion can be considered as the radiation beam and is simply given by:

$$\frac{\bar{H}_b}{\bar{H}_T} = 1 - \frac{\bar{H}_d}{\bar{H}_T} \quad (2.16)$$

or:

$$\bar{H}_b = \bar{H}_T - \bar{H}_d \quad (2.17)$$

Liu and Jordan suggested another correlation, which is:

$$\frac{\bar{H}_d}{\bar{H}_T} = 1.390 - 4.027\bar{K}_T + 5.531\bar{K}_T^2 - 3.108\bar{K}_T^3 \quad (2.18)$$

The oldest computation in this issue was introduced by Ångström in 1922, to compute the diffuse irradiation based on sunshine duration, and it has undergone several revisions in the parameter definitions but still the general form has not been changed by Page [52], Garg [44] and Mooley [56].

$$\frac{\bar{H}_T}{\bar{H}_{oT}} = a + b \frac{n}{N} \quad (2.19)$$
where \( n \) = the day length, \( N \) = maximum possible day length over the year, and \( a \) and \( b \) are empirical constants.

### 2.3 Solar Radiation Variability - Recent Decades

Solar radiation is the full frequency spectrum of the electromagnetic radiation that reaches the Earth’s surface from the Sun; this is usually experienced as daylight. Solar radiation can be filtered by the atmosphere, particularly by clouds, and in some parts of the world, climate change has resulted in increased levels of cloud cover, resulting in reduced levels of solar radiation. There are two key variables in terms of resultant/usable solar radiation: latitudinal location and angle of incidence (governed by the seasons); however, there is a further consideration, that of the Sun’s 11-year cycle. Solar radiation levels can be measured by satellite, i.e. before the effects of any filtering have taken place, but solar radiation measured on the Earth’s surface is called global horizontal radiation (sometimes, simply ‘total solar radiation’), which consists of two parts; direct and diffused solar radiation. Direct radiation has not been the focus of much study, and thus there is little understanding of the long-term behaviour of direct radiation [60]. Nevertheless, studies have been conducted into the long-term behaviour of total solar radiation, and these are generally agreed that over recent decades, variability has been in evidence.

Li et al. in 1998 reported a decreasing trend in total radiation from 1961 to 1990 in their study across China[61]. However, they found that this reduction in total surface radiation (on the decadal scale) is not reflected in recorded surface temperature increases in most regions of China. This is supported by Liepert et al. [62] in 1994, who found that from 1964 to 1990, the surface solar radiation data in Germany also exhibited a decreasing trend; they argued that the reduced levels of total radiation were due to changes in cloud cover. However, other studies in China have shown that the observed cloud cover (measured by satellite) exhibits a negative trend from 1984 to 2000 through the satellite measurements [63,64]; these dates are later than those for Lie et al., [61] and the data are in accordance with a more recent positive surface solar radiation trends. These results indicate that cloud and aerosol are crucial in determining the resultant/usable solar radiation. However, the extent to which cloud
cover or aerosol changes are responsible for long-term surface solar radiation changes is still the subject of considerable debate. Nevertheless, the recorded trends in total solar radiation do seem to be correlated (inversely) with the recorded trends in cloud cover. Thus, under clear-sky conditions, the direct aerosol forcing at ground is negative, resulting in reduced levels of solar heating of the surface. Liepert and Tegen in 2002 found an intensified direct aerosol forcing of 7 to 8W/m² in the USA between 1960 and 1990, whereas in Germany, that study found a weakened aerosol forcing of +3W/m² during the same three decades [65].

This variability was also found by Pinker et al. [66] in 2005, who found a decreasing tendency for radiation (over both land and oceans) from 1983 to the early 1990s but the reverse thereafter. However, this increase after the early 1990s was not apparent in the annual average daily solar radiation data; the trends were all negative, revealing that solar radiation levels decreased 1958 to 1999. The decrease in those daily data were from about 13.4MJm⁻²d⁻¹ in 1958 to about 12.4MJm⁻²d⁻¹ in 1999, representing a reduction in average daily total solar radiation of about 7.5% (1.7% in terms of reduction per decade); this was apparent in the data despite the fact that there had been no change in average daily sunlight hours [66,67].

In 2007, Cutforth and Judiesch [67] studied total solar radiation in seven locations on the Canadian Prairies, finding significant negative trends in the averaged annual and seasonal solar radiation from 1958 to 2005, as in Figure 2.6 below. Their data revealed a decrease in the annual average daily solar radiation from 13.5MJm⁻²d⁻¹ in 1958 to 12.4MJm⁻²d⁻¹ in 2005, which is a reduction of about 8% (1.7% in terms of reduction per decade). In order to assess any variability on the seasonal scale, they divided the year into three seasons, finding that the greatest reduction in solar radiation occurred in the first four months of the year (JFMA); this was a reduction of about 8.6% (1.8% in terms of reduction per decade). MJJA witnessed a reduction of about 7.8% (1.6% per decade), and for SOND, the reduction was about 6.8% (1.5% per decade).
Thus, the Canadian Prairies, which is a region of considerable importance in terms of agricultural production, has witnessed a continuous and significant reduction in daily solar radiation since the late 1950s. However, this is in contrast to the long-term sunshine data, where no general linear trend is evident. It should be noted however that this reduction in total solar radiation over the Canadian Prairies is not apparent on the global scale; many parts of the world have experienced increased levels of solar radiation since the early 1990s. Cutforth and Judiesch [67] argue that increased aerosols and cloud cover were the main factors driving the decreasing trend in total solar radiation.

Liepert and Kukla [68] conducted a study to measure incoming solar radiation at eight stations in Germany. Their findings broadly concur with those of Cutforth and Judiesch [67], in that solar radiation throughout much of the diurnal insolation cycle decreased between 1964 and 1990 at seven stations (Braunschweig delivered an increasing trend), as in the figure 2.7. Their data considered all sky conditions, and
they found statistically significant reductions for cloudy and overcast days, although they did not find any correlation with cloud cover fraction or sunshine duration [68].

Figure 2.7: The annual global solar radiation trends at surface at eight German stations from 1964 to 1990 [68].
In conclusion, although declining trends in solar radiation have been recorded in most parts of the world over recent decades, steady or increasing trends have also been reported in other areas over the same periods. Indeed, the NASA website has published that in recent decades, total solar radiation has increased by approximately 0.05% per decade [69]. Thus, it has generally been found that total solar radiation is subject to a certain degree of variability, which has ramifications for the operational efficiency of solar ponds; increased insolation increases the temperature of a pond but any decrease will result in lowered levels of performance. However, global warming may contribute to an overall increase in temperatures, which in turn would serve to enhance the performance of solar ponds, regardless of location. For example, the average daily temperature in Canada has increased by about 0.25°C every decade, chiefly due to global warming [67].
Chapter 3

Thermal Analysis of Solar Ponds
The performance of a solar pond depends substantially on the amount of solar energy that is inputted into the solar pond and the amount of heat loss from the pond. The solar energy is derived from the incident solar radiation, which can be converted into useful heat by such ponds. The heat behaviour can be described by developing a mathematical model for the solar pond zones, and this may be started by applying the energy balance principles for a body of water, as illustrated in Figure 3.1.

![Figure 3.1: Heat balance in control volume.](image)

In the figure 3.1:

\[
MC_pT \left|_t \right. - MC_pT \left|_{t+\Delta t} \right. - \Delta t Q_u = 0 \quad (3.1)
\]

where

\(Q_u\): the useful heat.

\(t\): Operating time.

\(M\): mass of water.

\(C_p\): water heat capacity.

Dividing Eq. 3.1 by \(\Delta t\) gives us:

\[
\frac{MC_pT \left|_t \right. - MC_pT \left|_{t+\Delta t} \right.}{\Delta t} - Q_u = 0 \quad (3.2)
\]

Finding the limit as \(\Delta t\) approaches zero can be expressed as:

40
Thus, the useful heat represents the gained heat from the solar radiation (into the salinity gradient solar pond) minus the heat loss from the pond. The solar energy absorption process by a body of water (and in a solar pond) was discussed in the previous chapter. The heat losses from a solar pond will be discussed in this chapter.

The use of a one-dimensional model is widely adopted because salinity gradient solar ponds are usually constructed on large scales with large surface area. In such ponds, the horizontal variation of temperature at a given depth is minimal, as compared to the temperature variation with the depth and therefore it is reasonable to assume a one dimensional model for the temperature distribution and neglect the end effects. It is also stated previously that one-dimensional model is sufficient for predicting the performance of solar ponds if the lateral dimensions are sufficiently large with respect to depth [81].

### 3.1 Upper Layer Heat Losses

Heat losses from the surface of a salinity gradient solar pond represent an extremely important issue, as they measurably affect the solar pond’s performance. The heat losses may occur through convection, conduction, radiation and evaporation processes. Although the solar pond is a source of heat, it is found that the surface temperature is usually cooler than the ambient temperature, largely as a result of these significant heat losses. Sodha [51] investigated this fact; the values obtained for the upper layer temperatures $T_u$ and the ambient temperatures $T_a$ are listed in Table 3.1 as a summarization of this report. Alhussieni [91] found that, generally speaking, the surface temperatures are at least (as a minimum) 5% less than the atmospheric ones. Hence, assuming that the upper surface temperature is equal to the ambient air temperature may lead to avoidable errors.
Table 3.1: Surface and upper zone temperatures in a solar pond.

<table>
<thead>
<tr>
<th>Month</th>
<th>Upper zone temperature ($T_u$) [27]</th>
<th>Ambient temperature ($T_a$) [27]</th>
<th>Percentage of the difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>13.30</td>
<td>13.66</td>
<td>-2.64</td>
</tr>
<tr>
<td>February</td>
<td>14.65</td>
<td>15.90</td>
<td>-7.86</td>
</tr>
<tr>
<td>March</td>
<td>19.70</td>
<td>24.35</td>
<td>-19.09</td>
</tr>
<tr>
<td>April</td>
<td>23.60</td>
<td>30.90</td>
<td>-23.62</td>
</tr>
<tr>
<td>May</td>
<td>24.82</td>
<td>32.90</td>
<td>-24.56</td>
</tr>
<tr>
<td>June</td>
<td>25.10</td>
<td>33.85</td>
<td>-25.85</td>
</tr>
<tr>
<td>July</td>
<td>23.30</td>
<td>29.95</td>
<td>-22.20</td>
</tr>
<tr>
<td>August</td>
<td>23.25</td>
<td>30.30</td>
<td>-23.27</td>
</tr>
<tr>
<td>September</td>
<td>23.40</td>
<td>30.50</td>
<td>-23.28</td>
</tr>
<tr>
<td>October</td>
<td>20.55</td>
<td>25.80</td>
<td>-20.35</td>
</tr>
<tr>
<td>November</td>
<td>16.75</td>
<td>19.45</td>
<td>-13.88</td>
</tr>
<tr>
<td>December</td>
<td>13.60</td>
<td>14.20</td>
<td>-4.23</td>
</tr>
</tbody>
</table>

The input and output heat values passing through the upper zone of a solar pond can be briefly described as in Figure 3.2a, and they can be mathematically represented by Equation 3.5. The net heat in the surface layer is thermally fed by the solar irradiation and the conducted heat from the lower zones but part of this heat may be mainly lost by the mentioned four processes.

![Figure 3.2a](image_url)  
**Figure 3.2a**: Heat balance in the upper zone.
\[ Q_{uu} = Q_{sr} + Q_{ub} - Q_{uw} - Q_{uc} - Q_{ur} - Q_{ue} \]  \hspace{1cm} (3.5a)

where:

- \( Q_{sr} \): absorbed heat from solar radiation in the upper zone.
- \( Q_{uw} \): heat loss from the sides.
- \( Q_{ub} \): heat gained from the lower layers.
- \( Q_{uc} \): heat loss by convection.
- \( Q_{ur} \): heat loss by radiation.
- \( Q_{ue} \): heat loss by evaporation.

### 3.1.1 Convection Heat loss

Convection heat transfer from the upper layer to the atmosphere depends mainly on the wind speed and the temperature difference between the atmosphere and the water surface; this can be expressed as in the following equation:

\[ Q_{uc} = h_c A_u (T_u - T_a) \]  \hspace{1cm} (3.6)

where:

- \( h_c \): convection heat transfer coefficient (w/m\(^2\).\(^\circ\)C).
- \( A_u \): upper layer surface area (m\(^2\)).
- \( T_u \): upper layer temperature (\(^\circ\)C).
- \( T_a \): ambient air temperature (\(^\circ\)C).

Several empirical equations have been derived for obtaining the convection heat transfer coefficient. Atkinson [70] suggested the relation below for estimating \( h_c \):
\[ h_c = 0.255 \, f(v_z) \quad (3.7) \]

where \( f(v_z) \) is the wind speed as a function of wind speed measurement height \((z)\).

He then suggested the measurement height to be 2 metres, and used this equation:

\[ f(v_z) = 3.75 \, v_2 \quad (3.8) \]

where \( v_2 \) is the wind speed at height 2 metres in m/s.

Considering the ambient air pressure with wind speed in such predictions was proposed by [71], and accordingly, this equation can be also used:

\[ h_c = 0.0041 \, v \, P_{aa} \quad (3.9) \]

where:

\[ v : \text{wind speed (m/s)} \]

\[ P_{aa} : \text{ambient air pressure (KPa)} \]

A common correlation for calculating the convective heat transfer coefficient was given by McAdams [72], which is:

\[ h_c = 5.7 + 3.8 \, v \quad (3.10) \]

Further details on several correlations for the wind convection coefficient are reviewed by Palyvos in 2007 [73]. Equation 3.10 will be utilized because it can predict both free and forced (mixed) convection heat transfer on flat collectors [95] and it is also validated experimentally [97], thus, it has been used by many
researchers. Moreover, Lior [97] in 1990 stated that this equation is the only calculation way to predict the convection heat transfer over a flat collector until recently.

### 3.1.2 Radiation Heat loss

The solar pond is assumed to behave like a black body radiator, and therefore it emits heat by radiation [70]. The heat transfer between the upper zone and the sky (because of the radiation $Q_{ur}$) is a function of the ambient and water surface temperatures and the upper zone area. Thus, the radiation heat loss equation may be written as the following:

$$Q_{ur} = \sigma E_s A_u \left[ (T_u)^4 - (T_k)^4 \right]$$

(3.11)

where:

- $\sigma$: Boltzman-Stefan constant ($\frac{W}{m^2 K^4}$).
- $E_s$: emissivity of the water surface.
- $A_u$: upper layer area ($m^2$).
- $T_u$: the upper layer temperature (K)
- $T_k$: the sky temperature (K)

The sky temperature value may be found by several equations, such as Swinbank’s formula [75]:

$$T_k = 0.0552 \left( \frac{T_a}{T_a} \right)^{1.5}$$

(3.12)

where $T_a$ is the ambient temperature (K), or by:

$$T_k = T_a (0.55 + 0.61 \sqrt{T_a})^{0.25}$$

(3.13)
where $P_a$ is water vapour partial pressure on the air (mmHg).

### 3.1.3 Evaporation Heat Loss

The heat loss from the surface due to the evaporation phenomenon is considered to be the largest heat loss from the pond [92]. The estimation of the evaporation heat flux is still an issue of intensive research [76] and is still not fully understood. It is very difficult to describe such processes analytically [77], however, several empirical equations have been proposed to predict the behaviour of this phenomenon, for instance, Sodha [51] and Ali [59] used this formula:

\[
Q_{ue} = h_e [C_1 (T_u - T_a) - C_2 (1 - \gamma_h)]
\]  \hspace{1cm} (3.14)

where $C_1$ and $C_2$ are constants and their values are 2.933 and 39.11505, respectively, and where $\gamma_h$ is the relative humidity (widely available for each region).

The evaporation heat transfer coefficient ($h_e$) is a function of wind speed ($v$), and can be given by:

\[
h_e = 8.88 - 7.82v
\]  \hspace{1cm} (3.15)

Kishore and Joshi [93] preferred to use the next correlation, as it includes the wind heat transfer coefficient and the vapour and partial pressure of water.

\[
Q_{ue} = \left( \frac{\lambda h_c}{1.6 C_a P_{atm}} \right) (P_u - P_a)
\]  \hspace{1cm} (3.16)

where:

$\lambda$: water evaporation latent heat ($kJ$ kg$^{-1}$).
$C_a$: humid heat capacity of air ($\frac{kJ}{kg \cdot ^\circ C}$).

$P_{atm}$: atmospheric pressure (mmHg).

$P_u$: water vapour pressure as at the upper layer temperature (mmHg).

$P_a$: water vapour partial pressure in the ambient temperature (mmHg).

The vapour pressure of water at the upper zone ($P_u$) is a function of the upper layer temperature ($T_u$), and this variable can be calculated from:

$$P_u = \exp \left(18.403 - \frac{3885}{T_u - 43}\right) \quad (3.17)$$

The partial pressure of water vapour in the ambient air ($P_a$) is a function of the atmospheric temperature ($T_a$) and relative humidity ($\gamma_h$), and this pressure value may be estimated by:

$$P_a = (\gamma_h) \exp \left(18.403 - \frac{3885}{T_a - 43}\right) \quad (3.18)$$

The Ryan-Harleman model [94] has been widely used in the estimation of the water evaporation process in reservoirs. The heat flux of evaporation is also given by:

$$Q_{ue} = (p_u - p_a) \left[g \left(T_{vu} - T_{va}\right) + b v\right] \quad (3.19)$$

where:

$p_u$: the saturated vapour pressure at the water surface (mbar).

$p_a$: the vapour pressure of the ambient air (mbar).

$g$: constant $= 2.7 \left(\frac{w}{m^2 \cdot mbar \cdot K^{\frac{3}{2}}}\right)$.

$T_{vu}$: the virtual temperature at the water surface (K).

$T_{va}$: the virtual temperature in the ambient air (K).
\[ b: \text{ constant} = 3.2 \left( \frac{v}{m^2 \text{ mbar} \text{ m}} \right). \]

\( v: \) the wind speed at 2 metre above the upper zone (m/s).

The virtual temperature \((T_v)\) is a function of the actual temperature \((T_{act})\), hence:

\[
T_v = \frac{T_{act}}{1 - 0.378 \frac{p}{P_{atm}}} \quad (3.20)
\]

where \(p\) is the water vapour pressure at \(T_{act}\) and \(P_{atm}\) is the atmospheric pressure.

### 3.2 Storage Layer Heat Losses

The heat losses from the storage convecting zone of a solar pond are less, and more controllable, than the upper zone heat losses, and Figure 3.2b may describe these types of heat loss. Actually, the heat losses may occur mainly due to conduction heat transfer. Sufficient insulation to the bottom and sides of this layer may improve the solar pond performance significantly. In addition, the thickness of the non-convecting zone plays an important role in obstructing the upward heat loss from the lower zone to the surface and thence to the ambient region.

\[ \text{Figure 3.2b} : \text{ Heat balance in the storage zone.} \]

The heat balance equation will be:
\[ Q_{su} = Q_{srs} - Q_{st} - Q_{sb} - Q_{sw} - Q_{se} \]  \hspace{1cm} (3.5b)

where:

- \( Q_{srs} \): absorbed heat of solar radiation in the storage zone.
- \( Q_{sw} \): heat loss from the sides.
- \( Q_{sb} \): heat loss from the bottom.
- \( Q_{st} \): heat loss from the top.
- \( Q_{se} \): heat loss by heat extraction.

### 3.2.1 Sides and Bottom Heat Losses

The main heat loss from the lower layer occurs through the bottom or the sides, depending on the solar pond area, i.e., the bottom heat loss may be greater when the pond area is large but in a small solar pond, the side walls could constitute the major heat loss. The distance between the pond bottom and the underground water table or aquifer can affect the amount of heat loss from the bottom, so a short distance leads to more heat exchange between the underground water and the storage zone. This exchange is influenced by the type of soil, as dry soil insulates better than wet. Wang and Akbarzadeh [78] studied ground heat loss through wet soil, and they recommended that the pond should be well insulated, particularly when the ground water level is close to the pond bottom. Davis and his group [79] found that unless the bottom of the pond is insulated, almost 20% of the pond insolation may be lost through the ground.

The early SGSP models completely ignored or underestimated the ground heat loss [80], and thus the results and efficiency estimations were overestimates. Tabor [81] attributed the dissimilarity between the actual (11%) and expected (18%) efficiencies of the Ein Boqek solar pond to heat loss due to the presence of a water table.
The correlations that are used to express the ground heat losses may vary according to the simplifications that could be selected; the models can be 1, 2 or 3 dimensions, and could be steady or unsteady states. For a one-dimensional heat conduction unsteady state model, the following relation can be used:

$$\rho_g C_g \frac{\partial T(x,t)}{\partial t} = K_g \frac{\partial^2 T(x,t)}{\partial x^2}$$  \hspace{1cm} (3.21)

where:

- \(\rho_g\): density of the ground (\(\frac{kg}{m^3}\)).
- \(C_g\): specific heat of the ground (\(\frac{J}{kg \cdot ^\circ C}\)).
- \(K_g\): thermal conductivity of the ground (\(\frac{W}{m \cdot ^\circ C}\)).
- \(T(x,t)\): temperature distribution at time (\(t\)) and depth (\(x\)) measured in \(^\circ\text{C}\).

Hull [82] found that the majority of ground heat loss models consider the soil underneath the pond as either a semi-infinite flat surface or a slab located between the solar pond and a constant temperature heat sink. Hull conducted his study on both steady and unsteady states, neglecting edge effects and horizontal heat flux. It has been found that the ground heat loss is somewhere between steady and unsteady states.

Hull et al. [83] carried out several numerical simulations and compared the results with the Ohio University solar pond (400m\(^2\)) data, and a good agreement was obtained. Consequently, a semi empirical equation was derived to predict the ground heat loss from the storage zone (W/m\(^2\)), as the following:

$$Q_g = \alpha A + \beta P$$  \hspace{1cm} (3.22)

where:

- \(\alpha\) and \(\beta\) are coefficients.
\[ A: \text{pond bottom area (m}^2) \].

\[ P: \text{pond perimetre length (m)} \].

The values of \( \alpha \) and \( \beta \) for selected pond configurations are given in Table 3.2; these values are based on 18m heat sink depth at 40°C difference between the storage zone and the sink temperature. The estimations of this study are carried out based on soil thermal conductivity of 1.00 (W/m°C).

<table>
<thead>
<tr>
<th>Pond shape</th>
<th>Wall type</th>
<th>Wall insulation</th>
<th>( \alpha ) (W/m²)</th>
<th>( \beta ) (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>Vertical</td>
<td>No</td>
<td>2.22</td>
<td>54.8</td>
</tr>
<tr>
<td>Circular</td>
<td>Declined</td>
<td>No</td>
<td>2.20</td>
<td>36.1</td>
</tr>
<tr>
<td>Circular</td>
<td>Vertical</td>
<td>Yes*</td>
<td>2.21</td>
<td>40.4</td>
</tr>
<tr>
<td>Square</td>
<td>Vertical</td>
<td>No</td>
<td>2.22</td>
<td>53.6</td>
</tr>
</tbody>
</table>

* Insulation thickness = 20cm and thermal conductivity = 0.034 (W/m°C).

In this study, the researchers observed that wall insulation for small ponds with radius less than 192m should lessen the storage zone heat losses toward the ground, and it is more effective than bottom surface insulation. It is also found that insulated vertical walls and uninsulated sloping wall ponds are almost thermally equivalent and the latter are better than uninsulated vertical ponds with surface insulation. Extending the wall insulation downward vertically for 1 to 4 metres was recommended to give the most effective insulation. The heat losses from the sides of the storage zone increased slightly when the lower zone depth was enlarged from 1 to 2m.

### 3.2.2 Heat Extraction

Heat extraction is the main aim when constructing a solar pond but it is a form of heat loss as it reduces the storage zone temperature. The following equation may describe the heat removal from the lower convecting layer.

\[
Q_{ex} = \dot{m}_{br}C_p( T_{brw} - T_{brr} ) \quad (3.23)
\]

where:

\[ \dot{m}_{br} \]: brine mass flow rate \( (\frac{kg}{sec}) \).
$C_{pb}$: brine heat capacity ($\frac{J}{kg\cdot{}^\circ C}$).

$T_{brw}$: brine withdrawal temperature ($^\circ C$).

$T_{brw}$: brine return temperature ($^\circ C$).

### 3.3 Shallow Solar Pond Mathematical Model

The shallow solar pond model may be derived through a similar manner to Equation 3.2

\[ MC_p \frac{dT}{dt} = Q_{shu} \quad (3.24) \]

where:

$t$: Operating time.

$M$: Mass of water.

$T$: Hourly water temperature.

The useful heat is:

\[ Q_{shu} = Q_{shr} - Q_{shw} - Q_{sht} - Q_{shb} - Q_{she} \quad (3.25) \]

where:

$Q_{shu}$: Useful heat rate.

$Q_{shr}$: Heat entering the SSP due to solar radiation.

$Q_{shw}$: Heat loss from the sides (wall).

$Q_{sht}$: Heat loss from the top of the SSP.

$Q_{shb}$: Heat loss from the bottom of the SSP.

$Q_{she}$: Heat extracted from the SSP.
As the shallow solar pond is supposed to be well bottom-insulated, the bottom heat loss can be neglected:

\[ Q_{shb} = 0 \]

At the warming up time, the extracted heat is assumed to be zero:

\[ Q_{she} = 0 \]

Assuming that the thermal behaviour of the plastic bag and plastic covers are neglected, and that the temperatures of the water and the plastic bag are equal, consequently, Equation 3.25 will be:

\[ Q_{shu} = Q_{shr} - Q_{shw} - Q_{sht} \quad (3.26) \]

where:

\[ Q_{shr} = (\tau \alpha) A_u H(t) \]
\[ Q_{shw} = U_s A_s [T(t) - T_a(t)] \]
\[ Q_{sht} = U_a A_u [T(t) - T_a(t)] \]

Where \( A_u \) is the upper area and \( A_s \) is the side area. Thus, Equation 3.26 can be written as:

\[ Q_{shu} = (\tau \alpha) A_u H(t) - U_s A_s [T(t) - T_a(t)] + U_a A_u [T(t) - T_a(t)] \quad (3.27) \]

where:

\( \tau \alpha \): hourly optical coefficient.

\( H \): hourly total radiation.

\( C_p \): specific heat of water.
\( U_a \): top loss coefficient.

\( U_s \): side loss coefficient.

\( T_a \): ambient temperature.

Substituting Eq. 3.27 in Eq. 3.24:

\[
MCp \frac{dT}{dt} = (\tau \alpha)A_u H(t) - U_s A_s [T(t) - T_a(t)] + U_a A_u [T(t) - T_a(t)]
\]  
(3.28)

Sometimes, \( M \) can be replaced by:

\[
M = \rho V \quad \text{and} \quad V = AL
\]

where:

\( L \): length (m).

\( \rho \): water density \( \left( \frac{kg}{m^3} \right) \).

\( V \): water volume \( (m^3) \)

As the side area \( A_s \) is very shallow, it can be also neglected, thus;

\[
\rho V C_p \frac{dT}{dt} = A_u ((\tau \alpha) H(t) - U_a [T(t) - T_a(t)])
\]  
(3.29)

And \( U_a \) can be represented by the total \( U \)

\[
\frac{\rho V}{A_u} C_p \frac{dT}{dt} = (\tau \alpha) H(t) - U [T(t) - T_a(t)]
\]  
(3.30)

The irradiation can be considered as constant and can be taken as average hourly total radiation \( H_T \), and thus, the solution for Eq. 3.30 can be performed as the following:
\[
\frac{\rho L C_p}{U} \frac{dT}{dt} = \frac{(\tau \alpha) H_T}{U} - T + T_a
\]

\[
\int_{T_o}^{T} \frac{1}{T - T_a - \frac{(\tau \alpha) H_T}{U}} dT = \int_{0}^{t} \frac{-U}{\rho L C_p} dt
\]

where:

\( T_o \): Initial temperature

\[
\ln \left[ T - T_a - \frac{(\tau \alpha) H_T}{U} \right] - \ln \left[ T_o - T_a - \frac{(\tau \alpha) H_T}{U} \right] = \frac{-Ut}{\rho L C_p}
\]

\[
\ln \left[ \frac{T - T_a - \frac{(\tau \alpha) H_T}{U}}{T_o - T_a - \frac{(\tau \alpha) H_T}{U}} \right] = \frac{-Ut}{\rho L C_p}
\]

\[
\frac{T - T_a - \frac{(\tau \alpha) H_T}{U}}{T_o - T_a - \frac{(\tau \alpha) H_T}{U}} = e^{\frac{-Ut}{\rho L C_p}}
\]

\[
T - T_a - \frac{(\tau \alpha) H_T}{U} = \left[ T_o - T_a - \frac{(\tau \alpha) H_T}{U} \right] e^{\frac{-Ut}{\rho L C_p}}
\]

\[
T = T_a + \frac{(\tau \alpha) H_T}{U} + \left[ T_o - T_a - \frac{(\tau \alpha) H_T}{U} \right] e^{\frac{-Ut}{\rho L C_p}}
\]

Or,
This equation gives the hourly temperature of SSP water, and the hourly transmittance-absorbance \( \tau a \) is given by Lunde [31] as:

\[
\tau a = (\tau a)_n \left\{ 1 + b_o \left[ 1 + \frac{H_b}{H_T} \left( \frac{1}{\cos \theta} \right) - 2 \right] \right\}
\]  

(3.31)

where:

- \( (\tau a)_n \): Optical coefficient at noon.
- \( b_o \): Constant.

The other variables were explained in the previous chapter.

### 3.4 Steady state thermal analysis

Steady state analysis not only provides a good thermal approximation, but it also gives physical insight into parameter variations for a specific design [33]. Kooi suggested that as the thermal change of the environment is very quick, compared with the change inside the solar pond, steady state can be a reliable tool for SGSP thermal analysis. In a steady state salinity gradient solar pond evaluation, it is assumed that the heat insolation inside the gradient layer is completely consumed in building and maintaining the temperature gradient in the non-convecting zone, and thereby the gradient zone can be considered as a slab between the two convecting zones, where the input heat to the gradient zone is equal to the output heat from this zone.

Hence:

\[
Q_{gri} = Q_{gro}
\]  

(3.32)

The steady state model has been widely adopted by the most well-respected researchers in the SGSP field, such as Weinberger, Rabl and Nielsen, Kooi, Ali,
Wang and Akbarzadeh, amongst others. A downward one-dimensional conduction flux model is often used for simplification purposes. The convecting zones (upper and storage layers) are usually assumed to be well thermally mixed regions in a gradient pond, i.e. lumped systems.

The incident solar radiation values, based on monthly average daily amounts can be obtained from the available references for each part of the globe or from the 22-year average values recorded and stored on the NASA website. These values can also be calculated (with good agreement with the published ones) to estimate the solar radiation for a single required input, as developed in this study.

Model validation is possibly the most essential step in the model building stages. Therefore, the model validation in this study is applied to H. M. Ali’s study [23] in Kuwait because the Kuwaiti salinity gradient solar pond is very close to Saudi Arabia in terms of climate, solar radiation and so on, as well as location.

### 3.4.1 Upper Zone Steady State Model

From Equation 3.5, the following relationship can represent the upper zone steady state energy balance:

\[ Q_{uu} = Q_{sr} + Q_{ub} - Q_{uw} - Q_{uc} - Q_{ur} - Q_{ue} \]  

(3.33)

As the one-dimension model is adopted in this study, the side wall effects have limited heat losses, especially for large ponds, and the sides can be also designed with good insulation materials. According to these assumptions, the side wall heat losses can be neglected:

\[ Q_{uw} = 0 \]

The amount of absorbed solar radiation in the upper layer of a pond can be estimated according to the amount of the solar beam attenuation at depth x.
\[ Q_{sru} = \tau A R \quad (3.34) \]

\[ Q_{sruo} = \tau A_u R \sum_{n=1}^{4} \eta_n e^{-\mu_n x_u / \cos r} \quad (3.35) \]

\[ Q_{sru} = Q_{sru} - Q_{sruo} \quad (3.36) \]

where:

- \( Q_{sru} \): input solar radiation to the upper zone.
- \( Q_{sruo} \): output solar radiation from the upper zone at depth \( x \).
- \( Q_{sru} \): absorbed solar radiation within the upper zone.
- \( \tau \): transmissivity of water.
- \( A \): pond surface area.
- \( A_u \): lower surface area of the upper zone.
- \( R \): measured/calculated solar irradiation.
- \( x_u \): depth of upper zone study point.

The transmissivity of water is given by Weinberger [93] as the following:

\[ \tau = 2 N \cos \theta \cos r (c^2 + d^2) \]

where:

\[ c = \frac{1}{(\cos r + N \cos \theta)} \]
and:

\[
d = \frac{1}{\cos \theta + N \cos r}
\]

The measured irradiation \( R \) for Riyadh, Saudi Arabia (24.67 N, 46.69 E) is gleaned from Table 3.3 and, for comparison purposes, a further two locations in the same area (but at different latitudes) are chosen; these are Kuwait City (29.37 N, 47.98 E) and Jerusalem (35.00 N, 31.75 E). The measured values of solar irradiation are taken from [84], however, the measured values for Riyadh irradiation look inaccurate compared with the NASA measurements. For such disagreements and for the absence of some irradiation measured values, a unique single-input computer program has been built for obtaining solar irradiation mathematically. This computer program needs only a latitude value to calculate the local irradiation, and it does so with very good agreement. The measured, the NASA and the program output values for the irradiation are plotted in Figures 3.3, 3.4 and 3.5 for Riyadh, Kuwait City and Jerusalem, respectively.

**Table 3.3:** Irradiation data for three different locations in the Middle East.

<table>
<thead>
<tr>
<th>Month</th>
<th>Riyadh radiation (MJ/m²/day)</th>
<th>Kuwait radiation (MJ/m²/day)</th>
<th>Jerusalem radiation (MJ/m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>NASA</td>
<td>Measured</td>
</tr>
<tr>
<td>January</td>
<td>12.6</td>
<td>13.536</td>
<td>11.16</td>
</tr>
<tr>
<td>February</td>
<td>16.56</td>
<td>16.668</td>
<td>14.76</td>
</tr>
<tr>
<td>March</td>
<td>18.36</td>
<td>19.368</td>
<td>19.8</td>
</tr>
<tr>
<td>April</td>
<td>19.8</td>
<td>22.284</td>
<td>22.32</td>
</tr>
<tr>
<td>May</td>
<td>20.16</td>
<td>25.740</td>
<td>25.56</td>
</tr>
<tr>
<td>June</td>
<td>21.96</td>
<td>28.332</td>
<td>28.44</td>
</tr>
<tr>
<td>July</td>
<td>21.96</td>
<td>27.324</td>
<td>27.0</td>
</tr>
<tr>
<td>September</td>
<td>20.52</td>
<td>22.824</td>
<td>22.32</td>
</tr>
<tr>
<td>October</td>
<td>19.08</td>
<td>19.692</td>
<td>17.28</td>
</tr>
<tr>
<td>November</td>
<td>16.56</td>
<td>15.192</td>
<td>12.24</td>
</tr>
<tr>
<td>Annual (mean)</td>
<td>18.36</td>
<td>20.772</td>
<td>19.8</td>
</tr>
</tbody>
</table>
This script requires only a latitude value to predict sunrise, sunset and sunshine period to compute other equations, as explained in Chapter 2. A new empirical equation has been developed and added to this script to ensure good agreement, and it has been tested for these three locations. Although there could be many and various other factors affecting the accuracy of solar irradiation computation, it can be seen from these three figures that the newly developed single-input method is more accurate than the measured data, when comparing with the NASA 22-year average solar radiation.

Figure 3.3: Plot of three methods for Riyadh solar irradiation data.
Figure 3.4: Plot of three methods for Kuwait City solar irradiation data.

Figure 3.5: Plot of three methods for Jerusalem solar irradiation data.
There is clearly some inaccuracy in the Riyadh measured data, probably due to human or instrument error or to climate change variations in the summer season of that year, for example, dust storms. Therefore in this research, the NASA data are used for the Riyadh, Kuwait City and Jerusalem irradiation values as well as for the Surrey University irradiation values (introduced in Section 3.4.6 below).

The insolation area of each layer is varied because of the wall shading effect, which prevents solar light from reaching some regions close to the walls, particularly when the sun is far from the zenith. The area of the upper zone \( (A_u) \) varies according to the following correlations:

\[
A_u = L_u W_u \quad (3.37)
\]

\[
L_u = L - \frac{H_u}{\tan p} \quad (3.38)
\]

\[
W_u = W - \frac{H_u}{\tan p} \quad (3.39)
\]

where \( L_u, W_u \) and \( H_u \) are the dimensions of the upper zone shading effect.

The profile angle \( (p) \) is expressed by \([31]\):

\[
p = \tan^{-1} \frac{\tan \alpha}{\cos(\psi - \gamma)} \quad (3.40)
\]

The altitude angle \( (\alpha) \) is derived from:

\[
\alpha = \sin^{-1} \cos \theta \quad (3.41)
\]

The solar azimuth \( (\psi) \) is given by:
\[
\psi = \text{sign}(\omega_s) \left| \cos^{-1} \left( \frac{\cos \theta \sin \varphi - \sin \delta}{\sin \theta \cos \varphi} \right) \right|
\]

Surface azimuth \((\gamma)\) is an input value; the other angle definitions and equations were discussed in the previous chapters.

The inlet heat flux to the upper zone coming from the bottom \((Q_{ub})\), based on the steady state gradient zone assumption, is:

\[
Q_{ub} = U_t A \left[ T_s - T_u \right]
\]

where:

\[
U_t = \frac{1}{R_3 + R_c + R_2}
\]

The resistances values can be obtained from:

\[
R_3 = \frac{1}{h_3}
\]

\[
R_c = \frac{x_{gr}}{K_w}
\]

\[
R_3 = \frac{1}{h_2}
\]

where:

\(T_s\): storage zone temperature \(\circ\text{C}\).

\(T_u\): upper zone temperature \(\circ\text{C}\).

\(U_t\): heat transfer coefficient toward the top of the pond \(\frac{W}{m^2 \circ\text{C}}\).

\(K_w\): thermal conductivity of water \(\frac{W}{m^\circ\text{C}}\).

\(h_2\): convective heat transfer coefficient at the boundary between the upper and the gradient zones \(\frac{W}{m^2 \circ\text{C}}\).
\( h_3 \): convective heat transfer coefficient at the boundary between the lower and the gradient zones \( \left( \frac{W}{m^2 \cdot ^\circ C} \right) \).

\( x_{gr} \): gradient zone thickness (m).

The heat loss by convection is given by:

\[
Q_{uc} = h_c A (T_u - T_a) \quad (3.6)
\]

The heat loss due to radiation is calculated by:

\[
Q_{ur} = \sigma E_s A \left[ (T_u)^4 - (T_k)^4 \right] \quad (3.11)
\]

And the selected equation for the sky temperature calculation is:

\[
T_k = 0.0552 (T_a)^{1.5} \quad (3.12)
\]

The evaporation heat loss is given by:

\[
Q_{ue} = \left( \frac{\lambda h_c}{1.6 C_a P_{atm}} \right) (P_u - P_a) \quad (3.16)
\]

And:

\[
h_c = 5.7 + 3.8 v \quad (3.10)
\]

\[
P_u = \exp \left( 18.403 - \frac{3885}{T_u - 230} \right) \quad (3.17)
\]

\[
P_a = (\gamma_h) \exp \left( 18.403 - \frac{3885}{T_a - 230} \right) \quad (3.18)\]
The monthly averaged data for wind speed, humidity and ambient temperature are taken from the NASA website. These values have been also collected as averages of 22-year recorded data.

According to the selected equations, the steady state model for the surface area of a solar pond is:

$$\rho_u C_{pu} A \frac{dT}{dt} = Q_{stru} + Q_{ub} - Q_{uc} - Q_u - Q_{ue}$$  \hspace{1cm} (3.45)

where:

- \( \rho_u \): density of upper layer water \( \left( \frac{kg}{m^3} \right) \).
- \( C_{pu} \): specific heat of upper layer water \( \left( \frac{J}{kg \cdot ^\circ C} \right) \).

### 3.4.2 Lower Zone Steady State Model

The solar radiation is collected and stored as heat in the lower convecting zone, and the extracted heat is usually taken from here. The equation that may represent storage zone heat collection is:

$$Q_{su} = Q_{srs} - Q_{st} - Q_{sb} - Q_{sw} - Q_{se}$$  \hspace{1cm} (3.46)

As one-dimensional conduction heat is assumed and the walls should be insulated, the side heat losses can be neglected. It is supposed that the pond is in warming-up status and for that reason the heat extraction from the storage zone, at this stage of the study, has not yet been started. Thus:

- \( Q_{sw} = 0 \)
- \( Q_{se} = 0 \)

The outlet heat flux from the lower zone toward the top \( (Q_u) \), in the steady state case, is assumed to be equal to the inlet heat flux to the upper zone \( (Q_{ub}) \), and may be similarly expressed by the same equation:

$$Q_{st} = Q_{ub} = U_t A [T_s - T_u]$$  \hspace{1cm} (3.47)
The heat loss from the storage area downward to the ground underneath the solar pond is given by:

\[ Q_{sb} = U_b A \left[ T_s - T_g \right] \]  
(3.48)

And, similar to the non-convecting zone, the overall heat transfer coefficient is computed from the following correlations:

\[ U_b = \frac{1}{R_4 + R_g + R_5} \]  
(3.49)

The resistances values can be derived from:

\[ R_4 = \frac{1}{h_4} \]

\[ R_g = \frac{x_g}{K_g} \]

\[ R_5 = \frac{1}{h_5} \]

where:

\( T_s \): storage zone temperature \(^\circ\text{C} \).

\( T_g \): ground sink temperature \(^\circ\text{C} \).

\( h_4 \): convective heat transfer coefficient at the boundary between the storage zone and the surface of the bottom \( \frac{W}{m^2\,\circ\text{C}} \).

\( h_5 \): convective heat transfer coefficient at the surface of the ground water sink \( \frac{W}{m^2\,\circ\text{C}} \).

\( U_g \): heat transfer coefficient toward the bottom of the pond \( \frac{W}{m^2\,\circ\text{C}} \).

\( K_g \): thermal conductivity of the soil \( \frac{W}{m\,\circ\text{C}} \).

\( x_g \): the depth of ground sink zone (m).
It is found that monthly averaged data are the most convenient method for representing the climatic changes and for the equation computations, as hourly and daily calculations (and measurements) change from one year to another and are too short to give a general impression of the local climate. On the other hand, seasonal and annual readings or obtained values cannot represent the climate computations with sufficient accuracy. Thus, averaged monthly measurements or computations have been adopted in this study.

A Matlab computer software package has been used to build a multi-script program for solving the ordinary differential equations through the finite difference method for steady state models. This program takes into account the changes in the boundary conditions and surrounding factors with time.

The solar pond temperature variation study has been applied on the climate of Riyadh, and the model has been validated with the Kuwait City solar pond (given by H. M. Ali [23, 59, 91]). In addition, the program has been further tested with the temperature behaviour of a cold climate solar pond, and the University of Surrey in the the United Kingdom has been chosen for this investigation. The calculation results of this study are plotted by solid lines in the figures below, while the other findings or measurements are plotted by dashed lines.

The calculations have been made for the Riyadh salinity gradient solar pond, in consideration of the similar constructional conditions of the Kuwait City SGSP; according to Ali [23], the Kuwait City solar pond consists of three layers, where the upper convecting zone is 0.2m, the non-convecting zone is 0.4m and the lower convecting zone is 0.3m. The blackened square bottom of the pond has rectangular vertical walls, giving an area of 2 x 4m. The saline pond’s ground and walls are both made of concrete. The solar irradiation magnitudes were hourly recorded then the monthly daily average values were accordingly computed for a year.

3.4.3 Gradient Zone Steady State Model

The middle gradient zone in the steady state model is supposed to consume the gained heat from the solar radiation into maintaining the temperature gradient profile. This layer works like a solid slap transferring the heat from the lower zone to the upper
zone just by conduction. Thus, the heat transfer equation 3.32 is applied in this zone as explained above.

3.4.4 Riyadh Salinity Gradient Solar Pond

The program has been run to predict the temperature behaviour of the Riyadh solar pond, and this temperature variation during a year is plotted in Figure 3.6. The figure shows, as expected, temperatures rising from January until the middle of the year, and then decreasing gradually until the end of the year. To validate the program’s performance, it has been run for the Kuwait solar pond, on the data supplied by Ali [23], and very good agreement has been obtained. The program output calculation and the actual given data are plotted and illustrated in Figure 3.7. The solar radiation data for Riyadh are taken from NASA and given in Table 3.3.

![Riyadh's Pond Storage Zone Temperature](image)

**Figure 3.6:** Storage zone temperature in Riyadh SGSP.
Figure 3.7: Measured and calculated storage temperature in Kuwait pond.

The slight variations between the actual collected data and the computed temperature in Kuwait (in Figure 3.7) have occurred as a result of assuming a similar average daytime irradiation period throughout the year. Thus, the calculated and the measured temperatures match each other in the moderate periods of the spring and autumn seasons, as these two usually represent the average sunshine hours for one year. However, during the longer sun-path days of summer, the sunlight radiates for longer than the annual average and consequently the computation output has given a lower result for the level of temperature than the actual recorded data. The opposite case is evident in the winter results but in this case, it may be concluded from Figure 3.4 that the measured solar irradiation in the winter period of that year was appreciably higher than the NASA data; this is reflected in the monthly temperature shapes in Figure 3.7.

When the sunshine hours for each month or season are used instead of the averaged yearly irradiation period, the obtained result could be much closer to the actual storage zone recorded temperature, as plotted in Figure 3.8.
Based on these findings, it may be stated that the summer months can be underestimated when the averaged yearly sunshine period is adopted. On the other hand, the average monthly and seasonal solar radiation during daytime can both give good results. Thus, the performance of the Riyadh solar pond has been accordingly estimated and the result is plotted in Figure 3.9. It can be observed from Figures 3.8 and 3.9 that the peak temperature of the salinity gradient solar pond has increased as a result of considering this difference between the average yearly and the average seasonal/monthly period of the total solar irradiation while the solar pond is warming up.
As Kooi concluded, the temperature changes inside a salinity gradient solar pond are considerably limited, relative to the changes in temperature in a day. For example, the ambient temperature may vary about 20°C (from the minimum to the maximum temperature) in a day but the temperature variation in the same day inside a salinity pond may only be 1°C. Consequently, gradient pond behaviour seems to be more accurate if it is represented by a steady state model.

In order to investigate the time required for the solar pond to reach the steady state situation, this study has been extended to involve a second year of the operation process. It can be concluded from plotting both the first and second years of the temperature profile in the storage zone (in Figure 3.10) that, after slightly more than the first two months of the year, the behaviour of the pond is exactly the same.
3.4.5 Riyadh Large Solar Pond

Prediction of thermal behaviour for a typical large solar gradient solar pond is also achieved in this study. The pond is assumed to be constructed in Riyadh, Saudi Arabia, and based on Riyadh climate conditions; the following assumptions are considered in the steady state model:

- The solar pond area is 100 x 100m.
- The pond shape is square and the walls are vertically constructed.
- The upper, middle and lower zone thicknesses are set to 0.2, 1 and 1m, respectively, according to the optimum depths garnered from the literature review.
- Both surface and storage convecting zones are considered to be perfectly mixed.
- The non-covecting zone has a linear gradient of temperature and density.
- The sides are well insulated.
- The temperature of the underground sink is 30°C.
- The depth of the underground water table is 1000 m.
The computer program has been accordingly developed to estimate the storage zone temperature variation during a year, for this typical salinity gradient solar pond, and the results are shown in Figure 3.11. The required variables are also taken from the NASA website and gleaned from Table 3.4. It has been found that such ponds can collect heat to reach temperatures over 104°C, and that the most effective parameter is the thickness of the gradient zone. This effect is investigated by studying 4 different thicknesses of the non-convecting zone, which are 0.4, 0.6, 0.8 and 1 metre, as shown in Figure 3.11. As expected, any increase in the gradient zone thickness can appreciably increase the temperature in the storage zone.

**Table 3.4:** NASA surface meteorology and solar energy for Riyadh.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar radiation (kWh/m²/day)</th>
<th>Ambient temp (°C)</th>
<th>Wind speed (m/s)</th>
<th>Relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>3.76</td>
<td>14.20</td>
<td>3.90</td>
<td>39.00</td>
</tr>
<tr>
<td>February</td>
<td>4.63</td>
<td>16.50</td>
<td>4.23</td>
<td>32.70</td>
</tr>
<tr>
<td>March</td>
<td>5.38</td>
<td>20.80</td>
<td>4.19</td>
<td>31.60</td>
</tr>
<tr>
<td>April</td>
<td>6.19</td>
<td>26.40</td>
<td>3.74</td>
<td>25.50</td>
</tr>
<tr>
<td>May</td>
<td>7.15</td>
<td>31.70</td>
<td>3.93</td>
<td>16.50</td>
</tr>
<tr>
<td>June</td>
<td>7.87</td>
<td>33.90</td>
<td>4.54</td>
<td>12.20</td>
</tr>
<tr>
<td>July</td>
<td>7.59</td>
<td>35.20</td>
<td>4.61</td>
<td>13.10</td>
</tr>
<tr>
<td>August</td>
<td>7.15</td>
<td>35.00</td>
<td>4.45</td>
<td>15.50</td>
</tr>
<tr>
<td>September</td>
<td>6.34</td>
<td>32.30</td>
<td>4.09</td>
<td>15.70</td>
</tr>
<tr>
<td>October</td>
<td>5.47</td>
<td>27.40</td>
<td>3.70</td>
<td>20.70</td>
</tr>
<tr>
<td>November</td>
<td>4.22</td>
<td>21.60</td>
<td>3.84</td>
<td>29.80</td>
</tr>
<tr>
<td>December</td>
<td>3.52</td>
<td>16.40</td>
<td>3.87</td>
<td>39.30</td>
</tr>
</tbody>
</table>
Figure 3.11: The storage zone temperature for different depths of the gradient layer.

However, in the first month, the effect of increasing the thickness of the gradient zone on the temperature of the storage zone is actually reversed; this is a result of the amount of extra solar radiation being absorbed. From the second month until the middle of the year, a rearrangement takes place; this could be for several reasons, affecting the collected heat, such as heat loss conducted from the storage zone into the gradient zone and a decrease in the amount of solar radiation reaching the lower layer. After the mid-point of the year, it is clear that the stored temperature increases with any increase in the thickness of the gradient layer.

3.4.6 The University of Surrey (Cold Climate) Solar Pond

As with the large Riyadh solar pond above, a solar pond is assumed to be built at the University of Surrey (51.14 N, 00.34 W), to study the effect of a cold climate on a solar pond’s performance and to evaluate the computer program results in the context of such a climate. The required climate data are obtained from the NASA website and are listed in Table 3.5.
Table 3.5: NASA Surface meteorology and Solar Energy at the University of Surrey.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar radiation (kWh/m²/day)</th>
<th>Ambient temp (°C)</th>
<th>Wind speed (m/s)</th>
<th>Relative humidity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.77</td>
<td>4.16</td>
<td>6.26</td>
<td>83.80</td>
</tr>
<tr>
<td>February</td>
<td>1.39</td>
<td>4.29</td>
<td>5.76</td>
<td>80.20</td>
</tr>
<tr>
<td>March</td>
<td>2.34</td>
<td>6.42</td>
<td>6.01</td>
<td>76.80</td>
</tr>
<tr>
<td>April</td>
<td>3.59</td>
<td>8.59</td>
<td>5.09</td>
<td>69.80</td>
</tr>
<tr>
<td>May</td>
<td>4.57</td>
<td>12.60</td>
<td>4.65</td>
<td>63.90</td>
</tr>
<tr>
<td>June</td>
<td>4.84</td>
<td>16.00</td>
<td>4.42</td>
<td>60.70</td>
</tr>
<tr>
<td>July</td>
<td>4.80</td>
<td>18.50</td>
<td>4.38</td>
<td>60.10</td>
</tr>
<tr>
<td>August</td>
<td>4.23</td>
<td>18.50</td>
<td>4.34</td>
<td>61.10</td>
</tr>
<tr>
<td>September</td>
<td>2.86</td>
<td>15.50</td>
<td>5.01</td>
<td>66.20</td>
</tr>
<tr>
<td>October</td>
<td>1.73</td>
<td>11.70</td>
<td>5.47</td>
<td>74.00</td>
</tr>
<tr>
<td>November</td>
<td>0.96</td>
<td>7.27</td>
<td>5.90</td>
<td>83.20</td>
</tr>
<tr>
<td>December</td>
<td>0.60</td>
<td>4.93</td>
<td>6.13</td>
<td>85.00</td>
</tr>
</tbody>
</table>

The University of Surrey’s solar gradient pond can produce about 56°C, as shown in Figure 3.12. The collected temperature can be further raised when the gradient layer is increased to 1.5m, and the storage zone thickness is reduced to 0.3 m. With these changes in the layers’ thickness, almost 80°C can be obtained, as plotted in Figure 3.13. Furthermore, even higher temperatures than this can be achieved and then extracted using good insulation materials.
Figure 3.1: Surrey storage zone (1m thick) temperature at 1m depth of the gradient zone.

Figure 3.12: Surrey storage zone (1m thick) temperature at 1m depth of the gradient zone.

Figure 3.13: Surrey storage zone (0.3m thick) temperature at 1.5m depth of the gradient zone.
Although a salinity gradient solar pond located in a sunny climate receives more solar radiation than one located in a cold climate, the heat loss through evaporation in a hot climate is also higher. The heat loss due to the evaporation usually represents an average of 50% of the total heat loss [88]. In this study, that evaporation loss is computed to be about 52.3% in the Saudi Arabian SGSP, while it is about 46% of total heat loss in the Surrey solar pond. In addition, we find that although the input radiation in the Saudi Arabian solar pond is 240% higher than in Surrey, the evaporation heat loss is also higher, by as much as 350%. Therefore, utilising solar ponds in cold climate regions can be highly recommended. The other heat losses in hot climates such as radiation, convection and heat removal represent average of 33.4, 5.7 and 8.6% respectively.

3.6 Covering Solar Ponds

The heat loss from the surface of any body of water, including a salinity solar pond, results from evaporation, radiation, convection and conduction. The main factor affecting a solar pond’s performance in terms of its ability to collect heat energy is heat loss, and among these loss factors, the major thermal loss occurs due to surface layer evaporation. As the upper layer is appreciably shallow, the heat loss due to conduction is limited, and thus it can be neglected, while the evaporation, convection and radiation effects can be greatly reduced by covering the solar pond. The evaporation heat loss and the effect of covering the SGSP are plotted in Figure 3.14. It can be seen from this figure that the average peak temperature has been increased from 76.6°C in an open surface pond to 93.3°C as a result of eliminating the evaporation effect, and this represents an increase in the temperature in the lower zone of the pond by about 22%. Covering the surface of the solar pond can eliminate most of the surface heat loss, thereby raising the temperature accordingly from 76.6 to nearly 100°C, which results in a 30% improvement in the solar pond’s ability to collect heat energy.
Figure 3.14: The effect of evaporation heat loss and covering the pond.
Chapter 4

Salinity Gradient Solar Pond
Stability
4.1 Introduction

The most essential factor in gradient solar pond stability is maintaining the gradient profile in the non-convecting middle zone of the pond. A salt gradient solar pond (SGSP) cannot operate efficiently without an internally stable non-convecting zone (NCZ). The main design consideration for the successful operation of an SGSP is to maintain the stable state of the NCZ boundaries and level of salt gradient. Moreover, the state of the NCZ can be affected by the UCZ and LCZ, causing erosion to the integrity of its boundaries; erosion leads to a reduction in the thickness of the NCZ and, ultimately, the destruction of the pond.

This aim of stability will not be achieved unless the slat concentration gradient is faultlessly built, and the salt diffusion inside a nonconvecting solar pond is successfully controlled. The density of this highly saline water is a function of salt concentration and temperature. The saline concentration and temperature should both increase downward and, although the solution density decreases as temperature increases, the direct proportion with salinity concentration has a greater effect. There are several internal and external factors that can affect solar pond stability or could destroy the gradient zone of the SGSP. The minimum requirement for gradient pond stability is that the salt density in the gradient layer increases downward to avoid any gradient mix or overturn.

For stability considerations, it may be useful here to describe the filling approach of a SGSP and the creating of the gradient zone. The piece of equipment playing the essential role in filling and maintaining an SGSP is the diffuser. This diffuser can also accomplish brine circulation for out-pond heat extraction purposes. It usually consists of a large pipe ending with two plates with a gap of 2-3 millimetres, as shown in Figure 4.1. A velocity of water flow of 2.6m/s has been successfully achieved in several gradient ponds [105].
4.1.1 Filling with Concentrated Brine

The most commonly used salt in solar ponds is sodium chloride. This salt is mixed with water to produce brine. Usually this process is done externally (away from the pond), as sometimes it becomes difficult to dissolve the salt in the pond if it consists of insoluble dirt but it can be done in the solar pond as well. However, one disadvantage of conducting this process inside the solar pond is that the excess salt might take many years to clear up [103].

Collins [104] conducted experiments to quicken this process; he used a lixator to dissolve the salt. This dissolver is comprised of a pit and a filter mechanism. The pit is full of salt crystals and when fresh water is mixed with these crystals, they become saturated. However, the filter mechanism ensures that there are no insoluble particles left in the final solution.
4.1.2 Creation of the Salinity Gradient

The technique developed by Zangrando [105] gives a great deal of insight into creating a salinity gradient. The author states that the simplest method to establish a salinity gradient in a solar pond can be achieved in three steps. Firstly, concentrated brine should be poured to fill the depth of the lower convective zone, and approximately half the depth of the gradient zone. Secondly, fresh water should be added to the brine solution in specific quantities to form layers. This step will dilute the concentration of the initial brine solution and will create a gradient. The final step is to add another layer to fresh water to fill the upper zone. This method has been recognized as the accepted method of filling solar ponds and is widely used. Alternatively, a slight variation to this method is practiced in Melbourne, where the fresh water is simply added to the brine solution [99, 101].

Furthermore, Nielsen [86] suggested another method for mixing the brine solution and fresh water: mix by pumping water from the bottom using a mixing valve. In this case the gradient layer can be configured by controlling the mixing valve. Unlike Zangrando’s method, this method is not influenced by the rate of flow of fresh water. The former is significantly affected by the flow rate of the fresh water and requires the brine to be uniformly concentrated between the surface and the distributor. Hence, it is recommended to monitor the salinity distribution at the time of gradient construction.

4.1.3 Maintaining the Salinity Gradient

It is imperative to maintain the salinity of the gradient layer in order to sustain the system of the solar pond. One of the methods for achieving this is by using artificial gradient strengtheners at the upper boundary of the NCZ, which will prevent the thickness of the surface zone to expand considerably. Similarly, it is important to keep the gradient strong at all depths to ensure internal stability; localized injections can be used to fulfil this purpose [100, 102, 106, 130]. In some cases, the extraction of a layer at a given level becomes necessary in an attempt to strengthen the overall gradient layer.
Tabor [7] has proposed another method for maintaining the gradient of the solar pond. This method is called the ‘falling pond method’. In this method, a hot brine solution is acquired from the lower convecting zone and is passed through a flash evaporator to produce steam and concentrate; this is an effective procedure for extracting water from the brine solution. The resulting brine solution is naturally of a higher concentration than the one which was initially extracted. These quantities of highly concentrated brine solutions are returned to the pond’s lower zone and subsequently fresh water is added to the top.

4.1.4 Control of the Surface Zone Boundary

If the boundary conditions of the surface zone are not controlled, then the wind may cause the thickness of the zone to increase; this will deteriorate the performance of the solar pond but the technique and the reasons are not fully understood [33]. One of the methods to control this is to decrease the depth of the surface zone by appropriately injecting brine from the surface-zone boundary; this method has been successfully tested in Israel but the procedure has not been published [33]. Normally, it is recommended to perform this action not more than twice a year; however, Zangrando used a similar procedure but she made corrections to the surface-zone layer much more frequently than the recommendation. [130].

Alternatively, the solar pond can be operated as a rising pond to achieve the same purpose. The concept is to maintain a net volume of brine input to the lower zone so that the gradient layer is made to rise by the same rate as boundary would push downward due to erosion[33].

4.1.5 Control within the Gradient Zone

Normally, moderate temperatures produce the strongest gradient layer, and correspondingly a stable system. However, if variation in temperature (usually when temperature values are high) is observed, then there is a strong possibility that an internal convective zone may be produced. One method of controlling this is to increase the gradient near the upper boundary of the NCZ to restrict the growth of the surface zone. This process is done through a combination of fresh water injection and the rising pond principle.
In the event that convection is evident in this zone, restoring the vertical dimensions of the gradient becomes difficult. Hence, in this case, redistribution of the layer becomes the only feasible option. In order to rectify the instability in the system, fresh water can be added from the top, or concentrated brine can be added from the bottom, for the cases of strong gradient above or below the instability, respectively. For the case of complete breakdown of the gradient, hot brine with added salt is passed into the solar pond. This process increases the salinity and stability of the system, however, the temperature of the system may also be slightly reduced.

4.1.6 Control of the Lower-Zone Boundary

Monitoring the heat extraction rate is the most efficient procedure for controlling the lower boundary of the gradient zone [130]. When the conditions of the lower-zone boundary are not met, erosion in the layer occurs. These conditions can simply be maintained by maintain higher temperatures within the storage zone in the pond to avoid changing the temperature profile due to the heat removal or climate temperature decrease.

4.2 Static Stability

The internal stability of a solar gradient pond is based on salt diffusion from the storage zone toward the upper zone of the pond. Diffusion can be defined as the movement or migration of an individual component within a mixture solution medium. The primary cause of diffusion is the different concentrations or the concentration gradient of a component in a fluid. Such fluids attempt to become internally stable through equalizing the concentrations, and consequently the molecules travel from the high concentration area to the lower one. If there is no applied pressure or forced diffusion in a binary or multi-component fluid, the mass flux in the mixture is primarily dependent on the concentration difference and the temperature gradient. The former is known as molecular (ordinary) diffusion and the latter may be expressed by thermal diffusion or Soret effect. Unfortunately, both molecular and thermal diffusion work against the stability of any salinity gradient solar ponds. Therefore, the salt management is absolutely essential for monitoring and operating a gradient solar pond.
4.2.1 Molecular Diffusion

Molecular diffusion happens mainly as a result of the concentration gradient in a solution, and this kind of diffusion occurs according to Fick’s law in 1955. A substance diffusion is the primary type of mass transport, which can be represented in the form of salt diffusion inside a solar pond. The salt concentration in a bottom zone of a salinity solar pond is about 230g/l of sodium chloride (NaCl), and this amount of salt may represent 20% of the lower zone’s saline water, while the upper zone may contain between 0 and 2% salinity [33, 108].

If the molecular diffusion is only considered in a solar pond study, then Fick’s law can be expressed as the following:

$$ J = K_s \frac{dc}{dx} $$  \hspace{1cm} (4.1)

4.2.2 Thermal Diffusion

Thermal diffusion was first discovered and reported by Carl Ludwig (Fick’s mentor) in 1856. The observation was based on an experiment in which a tall column of uniformly distributed saline water was cooled from the bottom and heated from the top. At the beginning, the salt concentration was uniform but shortly after the concentration was greater at the lower cooled end, and a gradient concentration was evidently formed. Two decades later, further experimental works were carried out by Charles Soret, after whom this thermal diffusion has been known as the Soret effect [148, 154].

4.2.3 Static Stability Criteria

The salt density gradient resulting from salt concentration difference magnitude in a solar pond is sometimes called a positive gradient, as it contributes to forming the desired shape of the gradient profile inside a non-convecting layer within a solar pond, i.e. the salinity gradient is concentrated downward. On the other hand, the density gradient may create a reversed profile in the salinity gradient due to the Soret effect; this is not actually desired and it may be called a negative gradient. These counter effects of positive and negative density gradient should be investigated to predict the static stability in a gradient pond, and if a negative stratification dominates
the positive gradient, convection may gradually take place inside the gradient zone; this gradient will then be destroyed or at least the performance of the pond will be reduced. In other words, the net concentration value at any point in a salinity gradient pond must be lower than at any point underneath in order to suppress vertical convection in the gradient zone [109]. This stability condition was first suggested by Weingerger [93], and it has been widely accepted and adopted by the most researchers. The condition can be expressed by the following formula [93]:

\[
\frac{dT}{dx} \leq \frac{dS}{dx} \quad (4.2)
\]

and:

\[
\alpha = -\left.\frac{1}{\rho} \frac{d\rho}{dT}\right|_s \quad (4.3)
\]

\[
\beta = \left.\frac{1}{\rho} \frac{d\rho}{dS}\right|_T \quad (4.4)
\]

where:

\[\frac{dT}{dx}\]: temperature gradient with depth (°C/m).

\[\frac{dS}{dx}\]: salinity gradient with depth (kg/m^4).

\[\rho\]: density (kg/m^3).

\[\alpha\]: thermal expansion coefficient (1/°C).

\[\beta\]: salinity expansion coefficient (m^3/kg).

Consequently, the density change with depth must satisfy this equation to indicate that a solar pond is sufficiently stable:

\[
\frac{d\rho}{dx} = \alpha \frac{dT}{dx} + \beta \frac{d\rho_s}{dx} > 0 \quad (4.5)
\]

Alternatively, the above correlation can be expressed by a finite different approach:
\[
\frac{\Delta \rho}{\Delta x} = \alpha \frac{\Delta T}{\Delta x} + \beta \frac{\Delta \rho_s}{\Delta x} > 0 \quad (4.6)
\]

where:
\[\frac{dp}{dx} : \text{the net density gradient with depth (kg/m}^4).\]
\[\frac{dp_s}{dx} : \text{the density gradient with depth caused by salt concentration (kg/m}^4).\]

The stability criterion can be also viewed by another formula based on thermal and saline Rayleigh number. It is a dimensionless number resulted by multiply Grashof number, which expresses the relation between buoyancy and viscosity in a fluid, by Prandtl number, which describes the relationship between momentum and thermal diffusivities. Thus, the Rayleigh number may be considered as the product of the ratio of buoyancy and viscosity forces and the ratio of momentum diffusivity and thermal diffusivity. Hence;

\[R_a = G_r \cdot P_r \quad (4.7)\]

Garg [90] stated that convection takes place only when the Rayleigh number \((R_a)\) in the above relation is higher than 2000.

The thermal Rayleigh number \(R_T\) is:

\[R_T = \frac{g\alpha\Delta T d^3}{\nu K_T} \quad (4.8)\]

and the saline Rayleigh number \(R_s\) is:

\[R_{s1} = \frac{g\beta\Delta S d^3}{\nu K_s} \quad (4.9)\]

The saline Rayleigh number can be simplified in a double-diffusive (thermohaline) fluid by using \(K_T\) instead of \(K_s\), and it is more usual [33]:

\[R_s = \frac{g\beta\Delta S d^3}{\nu K_T} \quad (4.10)\]
where:

\( g \): gravity acceleration (m/s\(^2\)).

\( \alpha \): thermal expansion coefficient (1/°C).

\( \Delta T \): temperature change across a certain depth \( d \) (°C).

\( K_T \): thermal diffusivity (m\(^2\)/s).

\( \beta \): salinity expansion coefficient (m\(^3\)/kg).

\( \Delta S \): salinity change across a certain depth \( d \) (kg/m\(^3\)).

\( K_s \): solutal diffusivity (m\(^2\)/s).

\( \nu \): kinematic viscosity (m\(^2\)/s).

The density ratio of the thermal and salinity Rayleigh number \( (R_\rho) \), which may determine the stability behaviour, can be represented by the following correlation [33, 90, 109]:

\[
R_\rho = \frac{R_S}{R_T} = \frac{\beta \Delta S}{\alpha \Delta T} \tag{4.11}
\]

### 4.3 Dynamic Stability Criterion

When the above static stability condition is obtained and the salinity gradient is sufficiently concentrated to suppress vertical convection, the solar pond tends to be stable. However, there are several external perturbation factors, such as wind, falling particles, rainfall, evaporation, heat loss, etc., which may support the Soret thermal gradient to rebel against the salinity gradient suppression force. This may occur due to the potential energy stored into the inverted temperature profile and, if the transmitted external energy together with the profile potential energy is stronger than the viscous damping, then vertical convection will be initiated and will grow with time, leading to the mixing of the solar pond layers. It has been found that heat diffusivity is 100 times faster than salt diffusivity [33, 109]. In a laboratory
experiment, the internal oscillation was identified as having a very small value but
then it grew gradually until it was ultimately supported by convection; shortly
afterwards, the saline gradient was debilitated by the mass transfer resulting from this
oscillation [110, 111, 163].

The dynamic stability condition equation for a gradient solar pond was introduced by
Weinberger [93]. The proposed formula can maintain the gradient sufficiently to
avert any oscillatory movement effects developing with time, and this condition may
be expressed by the following relationship:

\[(v + \alpha_T) \frac{\partial \rho}{\partial T} \frac{\partial T}{\partial x} + (v + \alpha_S) \frac{\partial \rho}{\partial S} \frac{\partial S}{\partial x} \geq 0 \quad (4.12)\]

where \(\alpha_T\) and \(\alpha_S\) are thermal and salinity diffusion coefficients, respectively. The
above equation can be rewritten in another suggested way [112]:

\[\frac{\Delta T}{\Delta x} < \left( \frac{P_r + \tau}{P_r + 1} \right) \left( \frac{\rho}{\alpha} \right) \left( \frac{\Delta S}{\Delta x} \right) \quad (4.13)\]

where the Prandtl number \((P_r)\) and the Lewis number \((\tau)\) are:

\[P_r = \frac{\nu}{K_T} \quad (4.14)\]

\[\tau = \frac{K_S}{P_r} \quad (4.15)\]

The above equations have been adopted by most investigators, and they have been
used widely to investigate gradient solar pond stability. Equation 4.13 is employed to
carry out the stability calculation from the top to the bottom of a solar pond, including
both convecting and non-convecting zones. In the case of one-dimensional
instability, Schladow [114] suggested a simplification of the above equation:

\[R_p = \frac{P_r + \tau}{P_r + 1} \quad (4.16)\]
The mathematical analysis of thermohaline (double-diffusive) diffusion in a gradient study may predict the marginal stability, and can be represented in this equation [115]:

\[ R_T = \frac{v + K_s}{v + K_T} R_s + \left( 1 + \frac{K_s}{K_T} \right) \left( 1 + \frac{K_s}{v} \right) \left( \frac{27\pi^4}{4} \right) \]  

Equation 4.17

The salinity and thermal Rayleigh correlations have an effect much larger than the second term in the left hand side of Equation 4.17; hence, the latter term can be neglected, leading again to the Weinberger dynamic stability criterion in Equation 4.12; this simplification is commonly assumed. For a typical salinity gradient solar pond, Hull [115] stated that the Lewis number usually varies from 30 to 140, and that the Prandtl number is expected to be between 3 and 10. It was confirmed in the same report that the salt concentration gradient should be far greater than that obtained through the dynamic stability correlation in order to ensure that the marginal stability is strong enough to keep a gradient zone in a fixed position.

4.4 Instability sources

Although the internal behaviours of the three parts of a solar pond are not fully understood [33], including the gradient zone and boundary erosion, there are several factors believed to cause destabilization issues in an SGSP. The following factors may cause static or dynamic instability issues.

4.4.1 Mass Flux

In solar gradient pond studies, the water inside a pond is usually considered as a binary system (a single solute substance in an aqueous solution). There is a significant lack of information about the diffusion coefficient of a ternary system [33], not to mention multi-component saline water. However, the stability of the system significantly depends on the mass transport rate. The mass transfer rate per unit area
in a uniform temperature binary solution depends on the concentration gradient and the molecular diffusivity. Thus, the upward salt migration from the rich salty lower zone to the surface layer would contribute to gradient pond destabilization. This mass transport can be represented as the following:

\[
\frac{\partial S}{\partial t} = K_s \frac{\partial^2 S}{\partial x^2} \quad (4.18)
\]

At steady state assumption, there is no change with time at a certain point in the non-convecting zone. Thus, if integration is achieved:

\[
q_s = K_s \frac{dS}{dx} \quad (4.19)
\]

The above relationship is typically adopted and used by the vast majority of solar pond researchers, and it relies on assuming that the salt mass transfer is only driven by the concentration gradient.

4.4.2 Salt types

The salt type contribution to SGSP stability should be appreciably considered. A typical salt for a gradient pond must have the following essential features to enhance the pond’s performance and stability [90, 117-121]:

- The salt solubility value must be high enough to meet the highest level of solution density required.
- The salt solubility should not change significantly with solar pond temperature variations.
- When the salt is dissolved in water, the solution must be sufficiently transparent to permit solar irradiation to the bottom of the pond.
- It must be environmentally friendly.
- It must not cause any contamination to the ground water.
- For cost considerations, it should be cheap and abundant, and near to the pond’s location.
- The salt molecular diffusivity $K_s$ should be low.

The firmness of salt solubility against solar pond temperature variation with time and with position in the pond (depth) is quite important for solar pond stability. Different types of salt exhibit various solubility behaviours with temperature change in water, which are summarized in Figure 4.2. It can be seen that the top three salts in terms of stability with temperature are sodium chloride (NaCl), magnesium chloride (MgCl$_2$) and sodium sulphate (Na$_2$SO$_4$).

![Figure 4.2: Solubility of three salts with temperature variation [90].](image)
The salt diffusivity value is another important factor in terms of enhancing SGSP stability. Generally, the molecular diffusivity of a salt is a function of salinity and temperature, as the solvent viscosity decreases with rising temperature. For example, the solubility of sodium chloride (NaCl) at 90°C is 5 times greater than its solubility at 10°C [116]. On the other hand, the molecular diffusivity $K_s$ may vary less than 10% with the salinity percentage variation at between 0 and 20 at a certain temperature [33]. The molecular diffusivities of different types of salt at room temperature are given in Figure 4.3. Hull et al. reported that the diffusivities at other temperatures have not been investigated [33] but it is understood that the diffusion coefficient usually increases at higher temperatures, which leads to raising the upward salt flux.

![Figure 4.3: Salt molecular diffusivities with salinity variations at 25°C [33, 117-121].](image-url)
According to the above information, it is not surprising that it is said that sodium chloride is the most effective salt by far for filling and operating solar ponds all over the world. Sodium chloride also represents the largest proportion (77%) of sea and ocean water salts, and it is one of the most stable salts with temperature variation. Moreover, the transparency of sodium chloride brine is appreciably high, and it is one of the cheapest salts in the world. This salt has the ability to be dissolved in water up to 27-30% before reaching saturation, which is relatively low, as illustrated in Figure 4.4. The vast majority of the US SGSPs have been using sodium chloride [33, 81, 122].

However, another commonly used salt in salinity ponds is magnesium chloride (MgCl$_2$), which is considered the second largest salt constituent of sea and ocean water, although it is the largest proportion of salt in the Dead Sea (as well as in some saltworks brines). This salt is exceptionally stable during operation; it also exhibits great solubility in producing brine with high density, as it is able to dissolve between 35 and 40% according to the solution temperature (plotted in Fig. 4.5). This salt has been used in two ponds in Israel and a large pond in the USA [33, 81, 123]. In comparison with sodium chloride, magnesium chloride is able to produce higher salinity brine, and is more stable during the solar pond’s operation. However, it is much more expensive than sodium chloride.

The brine most widely used in Israeli gradient ponds is Dead Sea brine, as it is costless and can be drawn directly from the Sea. The Dead Sea is unlike other seas and oceans as magnesium chloride represents the major salt in percentage terms, at about 13%, while NaCl stand for only 8%. MgCl$_2$ is the most dense brine in the world; its average density is about 1230kg/m$^3$. 
Figure 4.4: Density-temperature variation for NaCl solution [33].
4.4.3 Heat Flux

Heat transport from a solar pond to the surrounding area affects the saline water density, which in turns affects the stability of the gradient pond, as explained above. The heat within a water medium is influenced by radiation, convection and evaporation. The latter represents the primary mechanism of solar pond heat losses and represents the main process in concentrating the upper layer of a pond. Surface water cooling, by either evaporation or any other processes, and concentrating the upper zone solution increase the density of the water. This increase in water density correspondingly results in a rise in convection motion, which may affect the stability of the gradient zone and its upper boundary. It may also erode the upper zone and raise the upper-middle zone boundary. This is what was reported by [124] in an investigation that followed a considerable period of surface layer evaporation in the Ohio State University solar pond. It was found that the gradient had expanded upwards by 10cm, representing a weak gradient extension.

Figure 4.5: Density-temperature variation for MgCl\textsubscript{2} solution [33].
The convection circulation (overturn) in a thin layer is one of the causes which may encourage the turbulent kinetic energy to take place and may grow with time. Schladow [125] suggested an equation to predict the velocity associated with upper zone convective overturn ($\omega_{co}$), which is:

$$\omega_{co} = \frac{\alpha g z H_{cr}}{\rho C_p} + \beta g z \omega_{vr} S \quad (4.20)$$

where:

- $\omega_{co}$: velocity associated with convective overturn (m/s).
- $\alpha$: thermal expansion coefficient (1/°C).
- $g$: gravity acceleration (m/s$^2$).
- $z$: upper zone depth (m).
- $H_{cr}$: surface cooling rate (w/m$^2$).
- $\rho$: density of the surface water (kg/m$^3$).
- $C_p$: heat capacity of the surface water (J/kg.°C).
- $\beta$: salinity expansion coefficient (m$^3$/kg).
- $\omega_{vr}$: volume loss rate of water per unit of area due to evaporation (m/s).
- $S$: upper layer salinity (kg/m$^3$).

The heat flux from the lower zone at high temperatures may lead to the boiling point being reached; consequently, one of the worst instability cases will occur because the gradient zone with all boundaries may be entirely destroyed. This solar gradient pond disaster has been observed in a few ponds and it seems that the presence of air bubbles was the main factor in these ponds becoming mixed.

The above salt diffusion equation (4.18) is used when the diffusion calculations only consider the molecular diffusion in the solar pond mass flux, but when the temperature gradient effect in a steady state model is involved in the calculation, the Soret effect term must be added to that equation, as in the following:
\[ q_s = K_s \left[ \frac{dS}{dx} + K_{ST} S \left( 1 - \frac{S}{\rho} \right) \frac{dT}{dx} \right] \quad (4.21) \]

where:

- \( K_s \): Soret coefficient (m²/s)

Only a limited number of studies have been carried out on the Soret coefficient; its value is not well known, particularly at high concentrations and temperatures. However, it is thought to be in the order of \(1 \times 10^{-3}\) to \(3 \times 10^{-3}\) and is a positive value for sodium chloride. Rothmeyer in 1980 estimated the Soret diffusion’s magnitude in the University of New Mexico solar pond, according to the best available data, and it was found that the diffusion due to the Soret effect was 70% as large as the one that resulted from the concentration diffusion when the marginal stability was just before being damaged (at about \(80^\circ\)C). On the other hand, according to Nielson’s observation in the Ohio State University SGSP, the difference between the total salt diffusion calculations with and without considering sort term, is less than 10%; Hull in 1989 supported this findings by stating that the sort-term effect can be neglected [33, 126-129].

### 4.4.4 Heat Extraction System

The potential for a gradient pond to become unstable due to the brine withdrawal process from the lower convecting saline region is logically to be expected. Harsh suction and/or reinjection procedures through a turbulent flow mechanism coupled with an improper diffuser system design would definitely increase the middle zone erosion risk. This happened in the 400m² OSU and the 2000m² Miamisburg Ohio solar ponds, where uneven returning flow was the reason given for gradient erosion in the former pond, while the problem was caused as a result of the high suction rates in the latter SGSP [131].

Actually, many solar pond monitoring cases have confirmed that brine withdrawal for heat extraction is not a problem if an appropriately designed system is employed [130]. The withdrawal point should be several centimetres just below the top of the
storage convecting zone, and the returned colder brine should be re-injected at a lower level of this bottom zone. It is also recommended that the returned fluid temperature should be well below the storage zone temperature, otherwise a rapid erosion may be caused to the gradient zone above in such cases [33]; although there was not a given reason, it can be interpreted that this system is recommended to satisfy the natural convection phenomenon, as the colder pumped molecules, which are heavier, would tend to flow toward the bottom. A high suction rate of 1000w/m² for obtaining energy was utilized in the 40,000m² Israeli solar gradient ponds with a suitable diffuser set-up, and there was some noticeable erosion. Another example of such accurate operational investigations was reported on the 156m² Wooster SGSP, which had a heat energy extraction rate of 112w/m² [131].

It has been found that, in both laboratory examinations and field observations, that the prediction of how extend the withdrawal and injection can be restricted to the diffuser level is a strong function of the Froude number \( F_r \). Tabor [81] stated that extraction can be stably circulated when the Froude number equals 1. This number can be defined as the following:

\[
F_r = \frac{V}{d} \left( \frac{2\rho}{g \frac{d\rho}{dx}} \right)^{\frac{1}{2}} = 1 \quad (4.22)
\]

where:

\( V \): bulk volumetric flow-rate per unit width of the SGSP (m²/s)

\( d \): thickness of mixed flowing area (m)

\( \rho \): density of the lower layer (kg/m³)

\( \frac{\partial \rho}{\partial x} \): density gradient inside the gradient zone (kg/m⁴)

and:

\[
Q_{ex} = \frac{V\rho C_p \Delta T}{L} \quad (4.23)
\]
where:

$Q_{ex}$: energy extracted per area of the SGSP (w/m$^2$)

$\Delta T$: temperature drop in the heat exchanging process (°C)

$L$: length of the pond (m).

$C_p$: heat capacity of the brine (J/kg.°C).

When the above two equations are combined, the thickness of the mixed flowing layer (d) can be obtained from:

$$d = \left[ \frac{Q_{ex}L}{\rho C_p \Delta T \left( \frac{2\rho}{g \frac{d\rho}{dx}} \right)^{1/3}} \right]^{1/3}$$  \hspace{1cm} (4.24)

A simple condition has been set as a criterion for investigating the smoothness of the fluid return with respect to the stability of the gradient zone boundary. If the velocity of a returned flow is $v$, then the criterion will be:

$$\rho v^2 < |2\Delta \rho g \Delta x|$$  \hspace{1cm} (4.25)

and:

$$\Delta \rho = \left. \frac{d\rho}{dT} \right|_{\Delta T} $$  \hspace{1cm} (4.26)

Zagrando and Johnson [41] concluded from their review of different solar pond works that the Richardson number can be utilized to ensure that the boundary between the lower and middle zones is safe, according to the following criterion for suction and reinjection flow rates:

$$Ri_b = \frac{g \frac{d\rho}{dx} \rho^4}{\rho V^2} > 10^9$$  \hspace{1cm} (4.27)
\[ Ri_d = \frac{g}{\rho V^2} \frac{d\rho}{dx} z^4 > 500 \]  \hspace{1cm} (4.28)

where:

\( Ri_b \): bulk Richardson number.

\( Ri_d \): difusing Richardson number.

\( g \): gravity acceleration (m/s\(^2\)).

\( \frac{d\rho}{dx} \): density gradient at a lower level of the gradient zone (kg/m\(^4\)).

\( \rho \): density of the storage zone ((kg/m\(^3\)).

\( Z \): thickness of the lower layer (m).

\( z \): the distance between the extraction position and lower-middle zone interface (m).

\( V \): bulk volumetric flow per width unit (m\(^2\)/s).

Angeli and Leonardi [96] introduced an additional term to the double-diffusive equation in order to include the effect of heat extraction on the density gradient. Therefore, the following equation was proposed in their study:

\[ q_s = K_s \left[ \frac{dS}{dx} + K_{ST} S \left( 1 - \frac{S}{\rho} \right) \frac{dT}{dx} \right] - \nu S \]  \hspace{1cm} (4.29)

where:

\( \nu \): velocity of the brine injection (m/s).

### 4.4.5 Evaporation

As mentioned above, the evaporation effect on a solar pond’s stability and performance is extremely important. Usually, the greatest proportion of lost heat from a solar pond heat occurs as a result of evaporation, and this heat loss cools the
pond, particularly the surface layer. Thus, as explained in Chapter 3, the surface layer recorded temperatures are usually less than the ambient temperature; the evaporation equations were given in the previous chapter. Daily evaporation lessens the amount of water in the upper zone, and consequently the salt concentration increases. Both losses of heat and water are not desired in any SGSP operation, as these will act as instability factors, as discussed above. Therefore, some fresh water must be added to compensate for the evaporated water and to maintain the gradient stability. The required amount of fresh water is directly dependant on the evaporation rate, which in turn is usually affected by the prevailing weather conditions. According to different Israeli SGS ponds, it is reported that each 1 m$^2$ of pond area needs about 1.8 m$^3$ every year of fresh water for this purpose; the average salinity in the upper zone rises to around 2% (at most) in this timeframe [33].

### 4.4.6 Wind

The air current blowing parallel to the top surface of a water body generates wind shear; the water becomes wavy (according to the wind speed) and the water then resists this action. In fact, the mechanism of the wind-water interaction is quite complex. Van Dorn in 1953 carried out several experiments in an artificial pond to investigate the effect of wind stress on the pond, finding that the effects of friction drag for a body of water are directly proportional to the square of the wind speed and to air density. It was also noticed that this drag action is not generated unless the wind is blowing at higher than a certain speed. The relationship below was obtained [41, 133]:

$$\tau_w = C_D \rho_a v_w^2$$  \hspace{1cm} (4.30)

where:

- $\tau_w$: wind stress (N/m$^2$).
- $C_D$: dimensionless wind drag coefficient.
- $\rho_a$: density of air (kg/m$^3$).
- $v_w$: wind speed (m/s).
In a comparison with other findings regarding wind shear estimations, Van Dorn concluded that the differences were a result of the height at which the wind speeds were measured. Francis in 1954 found that the drag coefficient is only constant as long as the wind speed is not higher than (nearly) 4.12 m/s, but that with faster winds, it becomes a function of wind speed. Thus, this relationship can be represented by the following equation [134]:

$$C_D = 0.00013v_w$$  \hspace{1cm} (4.31)

However, the coefficient suggested by Van Dorn has been used in most of the references. Recently, the height of speed measurement has been standardized at 10m, and this level has been adopted by NASA; data for the entire world has been collected and stored on its website.

Fortunately, Saudi Arabia has been classified by the World Health Organization (WHO) as having a low level of wind speed hazard; the wind speed distribution map is illustrated in Figure 4.6. Moreover, the wind effect may be suppressed by installing a wind suppression system, as explained in Chapter 1 and illustrated in Figure 4.7. The wind speed can be obtained from the NASA database, and the average monthly wind speed values at a height of 10m are given in the following table:

**Table 4.1**: Averaged monthly wind speed in Saudi Arabia.

<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>$v_w$</td>
<td>3.90</td>
<td>4.23</td>
<td>4.19</td>
<td>3.74</td>
<td>3.93</td>
<td>4.54</td>
<td>4.61</td>
<td>4.45</td>
<td>4.09</td>
<td>3.70</td>
<td>3.84</td>
<td>3.87</td>
</tr>
</tbody>
</table>
Figure 4.6: Wind speed hazard distribution in Saudi Arabia [167].

Figure 4.7: Floating pipe wind suppression system in a Canadian solar pond [33].
4.5 Proposed Saudi Arabia SGSP Stability

The stability of the proposed salinity gradient solar pond in Saudi Arabia has been analysed to investigate the effect of double-diffusive action on the pond. Neither concentration gradient force nor thermal diffusion resistance are a serious problem as long as the bottom zone of the pond is frequently recharged with 40kg of salt per each square metre of the pond's area in a sunny location (on a seasonal basis) during the year, and the surface layer is kept supplied with fresh water from time to time, according to the evaporation rate and upward salt diffusion. Moreover, if the out-pond exchanging method is adopted, an appropriate diffuser design and circulation should be used to keep the brine flow rate under control.

The above static stability equations can be employed to predict the salinity profile and the gradient stability. Xu [107] conducted several investigations to develop more convenient and accurate equations for predicting the salinity shape and stability criterion. The correlations can indicate thermohaline diffusion with accuracy better than 0.03% in most of the solar pond salinity and temperature values. The density profile equation can be expressed as:

$$\rho(S,T) = a_1 + a_2 T + a_3 T^2 + a_4 T^3$$

(4.32)

and:

$$a_1(S) = 999.9 + 7.6374 S + 7.3624 \times 10^{-4} S^2 + 4.7088 \times 10^{-4} S^3$$

$$a_2(S) = 0.02592 - 0.033946 S + 7.7952 \times 10^{-4} S^2 - 9.3073 \times 10^{-6} S^3$$

$$a_3(S) = -5.9922 \times 10^{-3} + 3.7422 \times 10^{-4} S - 1.0436 \times 10^{-5} S^2 + 1.4816 \times 10^{-7} S^3$$

$$a_4(S) = 1.5332 \times 10^{-5} - 9.386 \times 10^{-7} S + 3.2836 \times 10^{-9} S^2 + 4.0083 \times 10^{-10} S^3$$

where:

\( \rho \): density of SGSP water as a function of concentration and temperature \( \text{ (kg/m}^3 \text{)} \).

\( T \): temperature of SGSP water \( \text{(°C)} \).

\( S \): salinity of SGSP water \( \text{( %) } \).
The previous solar pond thermal performance Matlab program in the preceding chapter has been improved in order to utilize the pond temperature values in the thermal diffusion effect. The salt concentration gradient from the bottom layer to the top layer of the Saudi Arabia SGSP is also involved.

As the model needs to be validated and as there is no available data regarding the salinity gradient profile in the Kuwaiti solar pond, the Matlab model can be checked against the available data for salt density behaviour in a solar pond. Hull and Nielson [33] provided various values for sodium chloride density, which varied according to NaCl concentration and solution temperature. These values can be utilized to compare the solar pond salinity behaviours as long as the salt used is sodium chloride; this is regardless of solar pond location, as the weather changes can be expressed by the temperature values. Therefore, the average salinity of the Saudi Arabia SGSP for a year has been obtained and compared with the data provided by Hull and Nielson for the solar pond’s average temperature. This comparison is illustrated in Figure 4.8, and it can be seen from the graph that the obtained profiles are in good agreement, particularly the average temperature which is located in the middle of the graph.

![Figure 4.8](image.png)

**Figure 4.8:** Salinity profile at a certain average temperature compared with given data.
Based on the good agreement obtained for a certain average temperature, the study has been extended to involve several months of salinity profile, including the temperature variation effect, according to the steady state model; the results for a selected month from each season are plotted in Figure 4.9. It can be observed from this graph that the steady state salinity profile is linear, increasing from the top of the gradient zone down to its bottom; this represents static stability. It may be also noticed that during the high temperature months (such as July), the solution density magnitude becomes lower than the cold months; this could be due to the contribution of the Soret effect in the density profile formation. The density reduction due to temperature increase between January and July at the lowest level of the gradient zone is only 2.3% (28 kg/m³). There is no significant change in the density value either in the upper part of the gradient layer or in the surface layer because the temperature variation during the seasons is limited, relative to the remarkable seasonal temperature difference in the lower part of the SGSP.

Figure 4.9: Seasonal density change within the salinity gradient solar pond.

The dynamic stability factors for a double-diffusive system may affect the solar pond’s stability, and this effect can be measured by the following dynamic criterion, with symbols defined as above:
\[
\frac{dS}{dx} = R \frac{dT}{dx} \tag{4.33}
\]

and:

\[
R = \frac{\alpha (v + K_T)}{\beta (v + K_S)} \tag{4.34}
\]

Alternatively, it can be obtained from the stability criterion given by Elwell et al. in 1977 [109]:

\[
\Delta T < \left( \frac{P_r + \tau}{P_r + 1} \right) \left( \frac{\beta}{\alpha} \right) \Delta S \tag{4.35}
\]

The data provided by Xu is utilized to check the dynamic stability of this thermohaline system with temperature and salinity variation in the Saudi Arabia solar pond, and the results with and without the stability line are presented in Figures 4.10 and 4.11, respectively. The salinity variation represents the change in the salt concentration in weight percentage driven by the temperature variations. From the first figure, it can be concluded that all the salinity and temperature changes vary within the stable region of the graph. The second figure has been plotted to focus on the behaviour of the salinity during the different seasons, and it can be clearly seen that the effect of temperature increases with its thermal expansion from January to July, raising the salinity profiles upward. This marginal instability increases as the temperature increases, and yet it is appreciably well below the unstable area. The only change due to monthly temperature variation is about 5%.
Figure 4.10: Seasonal concentration instability profiles within the stable region.

Figure 4.11: Seasonal concentration instability profiles.
Chapter 5

Using Solar Pond Heat
for Desalination Purposes
5.1 Solar Pond Heat Removal

A salinity gradient solar pond can be expected to reach boiling point, particularly in a location with abundant solar irradiation and low potential for ground heat loss, such as Saudi Arabia. At least one solar pond boiled to over 113°C in Israel [33], and the one in El Paso in the USA reached about 106°C [13]. When a solar pond boils, the gradient zone will be destroyed; vapour bubbles will be present and the transparency of the solar pond will be impaired. Consequently, a solar pond’s heat must be immediately removed when the lower layer temperature reaches just over 100°C; thus, the pond should be constantly monitored. The optimum heat extraction rate is achieved when the solar irradiation heat energy input into a solar pond is nearly equal to the heat energy extracted from the pond [115, 130].

5.1.1 Types of Heat Extraction

There are two common heat extraction methods; the submerged heat exchanger and the brine withdrawal method. Both of these methods have been practically tested and have produced acceptable results. These methods are elaborated below:

5.1.1.1 Submerged Heat Exchanger

This internal method for the extraction of heat is designed such that the thermal energy can be deployed for multiple uses. The process involves circulating water, glycol or any required fluid through pipes into an internal heat exchanger, which is placed at the bottom of the solar pond. The heated liquid is then passed on to an external heat exchanger placed at a distance (usually 200m), which then provides heat to an attached application [33,115]. The choice of pipe material has an impact on the efficiency of this system. For the case of using metallic pipes, the intensity of the natural convection process would directly influence the rate at which heat can be extracted. On the other hand, plastic pipes have a higher resistance towards heat extraction amount. This choice of material is driven by both efficiency and cost considerations and thus is implemented accordingly. A plastic in-pond heat
The exchanger was successfully used in the ANL solar pond, and the average rate of heat extraction was close to 100W per m² [140].

This method experiences ‘temperature stratification’. Temperature stratification is a natural phenomenon where a less dense layer of fluid overlays a denser, colder layer of fluid, which is not a desired case in a solar pond, as the lower layer should be both denser and hotter. The temperature stratification occurs in the lower portion of the NZC because it is experiencing loss of temperature through conduction, down towards the heat exchange pipes due to the temperature difference. This in turn, increases the size of the LCZ; there is an acceptable level of NCZ erosion and the system should remain stable. Temperature stratification also takes place at the bottom of the LCZ due to natural heat transfer through convectional currents. The cooler fluid moves towards the bottom and the warmer to the top of the layer, resulting in stratification. This lower-temperature fluid at the bottom also results in lowering any ground heat losses. Another advantage of this method is that it can be free of any metallic corrosion problems if plastic components are used.

Temperature stratification can also cause problems if the heat exchanger is placed at the bottom of the LCZ instead of at the top. This would restrict the heat exchanging capabilities of the system according to thermal conductivity of the LCZ.

Apart from unforeseen technical difficulties, the heat exchanger system in a solar pond will probably have a number of maintenance issues, such as growth of algae or salt pollution. The growth of algae would sully the transparency of the system and the efficiency of the heat exchanger would decrease. Al-Mutaz and Alenezi [32] stated that the algae can be treated by raising the water’s pH value to 9. The effects of salt precipitation on the heat exchanger pipes can be controlled by adding chemical agents. However, in case there is leakage or invasive maintenance work is required, months of warming-up time may be lost.

### 5.1.1.2 Brine Withdrawal Method

This method involves pumping hot brine directly from the storage zone by using an extraction diffuser. The brine, once its heat energy has been extracted, is then returned to the bottom of the pond by using a return diffuser. This is considered more
effective than the method discussed above, and hence it is practiced more often. For
greater efficiency in this method and to maintain the solar pond gradient, the suction
diffuser should be at a level just underneath the gradient layer and it is advised that
the return stream be injected at the opposite side of the extraction line and close to the
pond’s bottom. The advantage of using this circulation method is that it reduces
ground heat losses, as this method ensures that the cooler brine is always at the
bottom. However when a solar pond is relatively large, both diffusers (return and
extraction) can be in close vicinity. This extraction configuration has been
successfully applied in Israel, with a pond size of 210,000m². In another example
with a withdrawal heat extraction design, a 40,000 m² pond has a capability of
producing up to 2 million Watts of thermal energy, delivering 1000W/m² [33].

Although this method is the most commonly used one for extracting heat from
gradient solar ponds, it has a few disadvantages. The primary problem is that it is
easily exposed to corrosion; this method is more vulnerable to corrosion than other
due to the impact of the hot brine. The metal parts of the heat exchanger system that
come into contact with the hot concentrated brine are likely to corrode but for smaller
solar ponds, this problem can be overcome by using plastic instead of metal. Also, a
few precautions must be taken to keep the operation of the system running smoothly.
Firstly, the injection and withdrawal of hot brine should be such that it does not erode
the lower boundary of gradient layer. Secondly, if there is an air leak in the external
system, air bubbles may be introduced into the lower zone, and these bubbles will
result in increasing the corrosion of the system and may also destabilize the gradient
of the NCZ. Lastly, heat extraction can produce temperature stratification within the
LCZ [141].

5.1.2 Studies on Solar Pond Heat Extraction

The thermal efficiency of a solar pond has been defined as the ratio of total thermal
energy extracted to the total solar radiation that falls on the pond’s surface, within a
specified interval. The interval observation should be selected such that it provides
enough time to omit the factor of heat loss from the solar pond. This omission can
result in a few discrepancies in the calculations but if the interval is carefully selected,
the difference would not be too great. Researchers have conducted a number of
experimental and theoretical heat extraction investigations to evaluate the thermal efficiency of solar ponds with the greatest possible degree of accuracy. Wang and Akbarzadeh [143] carried out a computational analysis to evaluate the thermal energy storage and extraction efficiency of salinity gradient solar ponds under changing conditions. The results showed that solar ponds are capable of being 15% efficient at an average temperature of around 85°C and 20% efficient at an average temperature close to 65°C.

The studies of Wang and Akbarzadeh proved that heat extraction efficiency is a variable of environmental temperature; one experiment was conducted in summer and the other in winter [142]. Jaefarzadeh [143] made a series of investigations to determine the influence of temperature and climate on the heat extraction process of a salinity gradient solar pond [33]. The summertime experiment to investigate the influence of weather on heat exchange was conducted from 30 May to 6 June 2000. The average temperatures of the lower convective zone were noted, along with the outlet and inlet temperatures of the heat exchangers. The normal temperature in the LCZ before the heat extraction process started was 59°C. After an initial drop, the LCZ temperature remained constant for most of the experiment. No significant effect in terms of environmental temperature on the LCZ was noted, although a significant impact of the inlet and outlet temperatures of the heat exchanger was observed; this could reach 9°C. The winter season investigation to determine the influence of winter weather conditions on the heat removal process from a solar pond was conducted on 6 November 1998 and lasted for a couple of months. The average LCZ temperature, along with the temperatures of the inlet and outlet valves of the heat exchanger, was maintained. Initially, it was observed that the environmental temperature had a significant effect on the temperature of the LCZ (it increased steadily, irrespective of the ambient conditions). The inlet and outlet valves of the heat exchanger showed a similar initial increase in temperature but it became stable after the process reached its steady state stage [143].

The suggested solar pond heat extraction system using an air external exchanger is given by Jaefarzadeh in 2006, and it can be seen in Figure 5.1 [143].
This suggested system consists of the following elements:

1. The internal system is made of polyethylene pipes, having an external diameter of 20mm and an internal diameter of 16mm. The length of the pipe is in the region of 15m and is fixed 0.3m above the bottom of the pond.

2. A pump is used to circulate the water.

3. The external system is made of copper pipes and resembles a car radiator.

4. An orifice meter to measure the flow rate.

5. Four thermal sensors strategically placed as shown in the figure above.

6. A valve to control the amount and speed of discharge.

5.1.3 Unconventional methods of heat extraction

A number of researchers have adopted other heat extraction methods in order to utilize the heat in a number of different applications. Jaefarzadeh introduced an alternative heat exchanging method. In this investigation, Jaefarzadeh made use of a 2m wide and 1.1m deep solar pond. This system consists of an internal heat exchanger, placed within the LCZ, and an external heat exchanger, placed a few metres away. Fresh water is circulated through the pond to transfer the thermal energy from the internal to the external heat exchanger. He concluded that salinity
gradient solar ponds could transfer heat both continuously and intermittently. However, the efficiency of the continuous heat exchanging system is significantly lower than the efficiency of the intermittent system [143].

Andrew and Akbarzadeh suggested a method with high heat exchanging efficiency. The process suggested makes use of both the LCZ and the NCZ. It is found that this method can potentially increase the thermal efficiency of the system by as much as 50%, when compared with traditional heat extraction methods, which use only the LCZ. There are two assumptions made in this analysis: the working fluid consists mostly of fresh water and, much like other heat extraction methods, this method uses a single-phase heat transfer as well. Andrew and Akbarzadeh realized that this method suffers from a couple of constraints that hamper its efficiency. Firstly, a single-phase heat exchanger is enormous in size and weight, and it needs to work at a high flow rate in order to transfer a large amount of heat from the salinity gradient solar pond. Secondly, the circulation of fresh water to the internal heat exchanger requires a huge amount of pumping power. These power requirements cannot always be fulfilled in remote locations [144].

In order to improve the heat extraction system, many researchers have suggested using a two-phase heat transfer system. Lee et al. based the theoretical feasibility of their system on the latent heat of evaporation of fresh water. They found that as the fluid takes a passive role in the exchanging operation, a higher transfer of heat can be expected with a smaller system size. Unfortunately, this model still exists in theory and it has not yet been tested and implemented for heat exchanging in salinity gradient solar ponds. In that respect, the literature by Lee et al. only investigates the potential of this thermal energy exchange system by using a two-phase assisted thermosiphon in the form of a heat exchanger [145].

To further enhance the efficiency of a heat extraction system, Jaeferzadeh suggested an alternative method, by extracting heat from the NCZ of the solar pond. This method is still not widely tested and does carry some implications. Heat extraction from a non-convecting zone can be utilized as the difference in temperature between the pond’s brine and the heat transfer fluid is minimal. This makes it a suitable method where it is required to heat the fluid from an ambient temperature to nearly
the temperature of the lower convecting zone. The size of the heat extraction system needs to be either medium or large.

Andrews and Akbarzadeh observed another implication in the process of extracting heat from the NCZ, which relates to the stability of the salinity gradient (horizontal and vertical). The authors noted that this process would require more trial experiments to gauge the efficiency of brine re-injection and withdrawal at multiple levels. Lastly, an economic analysis of this alternate process needs to be conducted in order to determine if the increase in thermal efficiency justifies the corresponding increase in the operating costs of the heat extraction system [144].

5.1.4 Selecting a Heat Extraction Method

The different possible methods of heat extraction have been explained above and the researchers’ studies have been reviewed. In brief, the heat extraction can be internal (in-pond) or external (out-pond). The former extraction approach may be accomplished in a storage zone, gradient zone or in both layers but the latter must be performed only in the storage layer of a salinity gradient pond. The two-phase method has been successfully used in various applications, such as power generation in Israel, however, it has not been proposed for desalination purposes.

The brine withdrawal method has several advantages over the other methods, and these include [33]:

- Heat exchanger is more accessible and convenient.
- Heat exchanger maintenance does not affect the solar pond performance.
- The brine heat capacity is higher than the feed water, and therefore the thermal load will be more; also, heat loss is less during circulation.
- No chance for algae growth on the exchanger.
- The required area is low.
- More stability against temperature fluctuation during circulation.
- More stability for operation temperature.
Based on the above features, it is concluded that the brine withdrawal heat removal technique is the most - if not the only - suitable one for multi-effect evaporator (MEE) desalination. The horizontal and vertical falling film method needs a hot tube to spray water onto it in order to accomplish the evaporation process. The proposed method of heat extraction for this study is simply sketched in Figure 5.2.

![Figure 5.2: Simple sketch of heat extraction method for MEE desalination technology.](image)

5.2 Desalination

Humans and other life forms have always been dependent on clean, fresh water but in modern times, industry has noticeably increased the demand for water. Water is a vital driver for sustainable growth as it is used in energy, agriculture, transport and industry. Porteous [147] ascertained that to produce a ton of industrial products, over 200 tons of water must be consumed. The author has stated that without the availability of abundant clean water, industrial development would never have been possible. The increase in demand for clean water has led to a corresponding rise in the cost of water production and desalination. For instance, the price of water in the UK is increasing due to the rising costs of reservoirs and distribution systems [3].

The most abundant source of water is from the seas and oceans but it needs to be desalinated before use; even water from lakes and rivers needs to be purified first. The amount of ‘total dissolved solids’ (TDS) in water determines the usability of water. Seawater has about 35000ppm of TDS. Brackish waters have a TDS count of
over 1000ppm. In the same publication by Porteous, the author stated that humans can only tolerate water with a TDS count of less than 500ppm. Even the tolerance of animals is only marginally higher than this value. As seawater is the most significant source of water, there is an imperative need for cheap desalination methods to meet the large-scale clean water demands of people, livestock and industry [147].

In recent times, the technologies for desalination have been evolving, and using salinity gradient solar ponds to heat the raw water (seawater, industrial waste water and brackish ground water) represents one of the most promising technologies for desalination. The two most commonly employed thermal desalination processes are the multi-effect evaporator or distillation (MED or MEE) techniques as well as the multi-stage flash distillation (MSF) technique. Mesa et al. in 1996 stated that as much as 70% of all seawater desalination is conducted by using these two methods. However, they consume a great deal of energy; thermal desalination energy consumption is approximately 1.3 kWh (3%) electricity and as much as 48.5 kWh (97%) heat for every cubic metre of the product water. The high-energy requirements for these methods have resulted in them failing to become cost-effective, and so the use of solar energy for the thermal desalination process has become imperative [2,3].

After reviewing the available options for solar energy, Howe was able to deduce that salinity gradient solar ponds provide the most inexpensive and convenient method for thermal desalination. Choosing SGSP is significant for both economical and environmental purposes. Furthermore, the heat storage system of an SGSP allows the desalination process to continue at night or during rainy weather [148,164].

The MSF and MED methods for thermal desalination will be demonstrated in this section with respect to SGSP. The structure of this section will include a review of the literature, elaboration on the MSF and MED methods, and their performance will be illustrated and analysed [164].
5.2.1 Literature Review

According to a research by the World Health Organization (WHO) and other water authorizations, the acceptable level of salinity for water is around five hundred parts per million, although due to the differing regulations of national authorities worldwide, the WHO has recently raised this threshold to 1000ppm. However, most seawater salinity has up to tenth of thousand parts per million. Hence, any desalination process must be both effective and efficient in delivering clean water, i.e. below 1000ppm. Garman and Muntasse studied the various desalination methods, and because of the increase in the cost and demand for desalinated water, their study was focused on the energy needs of the desalination process [28]. According to several estimations, to produce 22-25 million m$^3$ of desalinated water per day would require 204-230 million tons of oil per year [135,147]. In this regard, Posnansky in his research had already suggested the use of the solar pond technique to satisfy the energy needs of the thermal desalination process, as it was recognized as an effective and inexpensive method for generating heat [150].

Other researchers conducted studies on adopting solar ponds for the thermal desalination process in the mid-1990s. This involved rigorous testing to evaluate the functionality of solar pond technology coupled with thermal desalination. During the testing phase, the multi-stage flash (MSF) distillation units were used intermittently in 1987-88 and 1990-2. In 1992, the multi-effect, multi-stage (MEMS) distillation method was also tried [13]. Lu and Swift found that solar ponds can provide heat of around 100°C and therefore can be considered ideal for the thermal desalination process. Furthermore, the ability of solar ponds to store thermal energy also makes these well suited for desalination. One method of heat extraction from an SGSP uses hot brine, and thus, if the solar pond were to be coupled with the desalination plant, then the waste brine could then be used as a source for salt in the SGSP. This method would not only perform desalination, but additionally would prevent waste concentrated brine from being disposed of in the environment [13].

Suarez conducted a research that would use an SGSP to provide thermal energy to a desalination plant. The author mentioned that the most important benefit of this system is that the costs are negligible, as a renewable source of energy would be being
used to power the system, and it could operate continuously without break. Furthermore, it has been found that the zero-discharge process that enables the system to work uses the salt extracted from the seawater to readjust the layers of the solar pond. It is estimated that if a solar pond has a surface area of one acre, it could produce up to three acres feet of clean water in one year [151]. The initial experiments were conducted inside a laboratory, using a small-scale unit (400 gallon tank), where fibre optic temperature sensing units were utilized to monitor the desalination process. The laboratory experiments were deemed a success by the group, but it was suggested that to evaluate the effectiveness of the system, tests must be carried out in a natural lake. It was also concluded that the efficiency of the system could be increased [151].

Agha observed that one of the obstacles that led to a delay in the shift from non-renewable to renewable resources for thermal desalination was the necessity of building large-scale desalination plants. A solar energy based desalination plant would therefore require a considerable land area but in those earlier days, even a large plant was only capable of delivering relatively small volumes of clean water [152].

The MSF method for desalination has recently gained in popularity, and several medium- and large-sized plants are being used. On the other hand, MSF can be powered by parabolic troughs. Block in 1989 evaluated that MSF can potentially produce 6 to 60L/m² a day, as opposed to the production of normal solar stills, which is only 3-4L/m² a day. The success of medium-sized desalination plants resulted in small-scale units being produced for commercial use. These small-scale MSF plants powered by parabolic troughs have been also studied; on average, a small unit produces 450L a day using energy at just under 50kW [153].

The zero discharge system has also been studied; this system consists of a solar pond as a heat source and a desalination unit to produce fresh water and waste brine, which can then be used in an evaporation pond for concentrating that brine to provide saline water for the solar pond (or to produce commercial salt). Abu-Jabal et al. suggested the system shown in Figure 5.3.
After the economic and initial performance tests on the multi-effect, multi-stage (MEMS) flash desalination units based on thermal energy had been completed, this attracted attention in determining the thermodynamic performance of these systems. For this purpose, an MEMS system in the El Paso SGSP was investigated in 1997. Many tests and operational data were collected on the MEMS unit and other researchers were able to provide definitive information regarding the technical performance of the SGSP coupled with thermal desalination [153].

According to the report by Posnansky, the most satisfying aspect of using this system is the positive impact it has on the environment; it eliminates the emissions caused by burning fossil fuels. In addition to this, the report suggested that the performance ratio of the system is between 0.84 to 1.85 litres of clean water per 292 watts of energy provided. This makes the system very efficient and researchers of that study recommended it for commercial use [154].

Posnansky also found that SGSPs to be the most commonly used solar collectors for MSF desalination plants. As an example, the desalination system in Margarita de Savoya uses an SGSP, the plant for which has a capacity of 50-60m$^3$ of desalinated
water a day. Another example is the El Paso plant in Texas, which has a production of 19m$^3$ a day [154].

Szacsvay et al. in 1999 conducted experiments using a small-sized desalination system, coupled with a SGSP as a source of heat, although the system used a slightly modified version of the MSF process. The data were automatically collected and inputted into a computer simulation, which generated results and compared them with results of previous experiments. The studies were carried on and verified against the Switzerland solar pond. The study period covered 9 years of continuous operation, resulting in the researchers being able to raise the production capacity of small-sized units to 300m$^3$ a day [155].

Medium-sized MEE plants are also being produced worldwide. El-Nashar and Samad reported on the results of an operational solar-collector desalination plant (that included a medium-sized MEE plant) that produced up to 120m$^3$ of water a day. The system was capable of desalting seawater with salt levels of 55,000ppm. The plant performance was analysed over a period of 13 years, and the MEE had 18 ‘effects’ (or stages) in total. The authors determined that the plant consumed 44.0kcal/kg [156]. According to the study, the MEE plant worked well but the maintenance of the pumps cause some difficulties. It was advised that regular silt removal and acid cleaning would be imperative for the plant to perform to its full potential [156].

Schwarzer, Eugenia, Faber and Muller in 2001 studied a small-scale solar desalination system working on the MED principles in order to gain knowledge about the operational features of such a distillation plant. The design used a series of flat plate trays as effects, and oil was used as a heating source (the oil circulates by a process of natural convection between the first effect and the solar collector). The results of the experiment were processed using a numerical simulation code. The results of the simulation showed that the rate of production could easily rise to 25L/m$^2$ a day for a solar radiation value of 4.8kWh/m$^2$ [157].

In addition to the above works, other researchers have discussed the practicality of desalination units in terms of scale. Abu-Jabal, Kamiya and Narasaki in 2001 analysed a three-effect MED system, which was paired with an SGSP to provide
energy. This plant was manufactured in Tokyo and the samples were tested in the University of Gaza. The results concluded that the plant was able to produce between 85 and 204L/d [158].

The research conducted by Posnansky aimed to provide an estimate of the costs of running an MED-based solar powered thermal desalination plant. The capacity of the simulated plant was varied between 500 and 5000m$^3$ of water produced a day. The report demonstrates production costs can be reduced by enhancing the productivity of the plant. For instance, for a capacity of 500m$^3$, the production costs were $3.3/m^3$, whereas for a capacity of 5000m$^3$, the production costs fell to just $2/m^3$ [150].

Thomas in his publication reports that both the MSF and the MED methods can experience difficulties whilst operating in variable conditions. This report was based on his analysis of an MED and an MSF plant in Kuwait. It was concluded that self-regulating MSF plants possess the ability to cope better than MED plants in variable conditions. Intriguingly, it was additionally found that both MED and MSF should not be considered for the large-scale production of potable water [159].

Garman and Muntasse in 2007 reviewed the performance of an MED plant coupled with an SGSP. Naturally, the first observation about this system declared that the total number of effects determined the capacity of the desalination unit. In these experiments, the performance of a 4-effect plant was observed, and it was discovered that the amount of thermal energy required is proportional to the surface area of the solar pond. Furthermore, the thickness of upper convecting zone (UCZ), lower convecting zone (LCZ) and non-convecting zone (NCZ) should be maintained at proportionate levels in order to maintain high performance. The experiments concluded that under optimal conditions the plant performs efficiently and produces 6000m$^3$ of distilled water a day [28].

Ophir and Lokiec in 2005 conducted certain experiments in Israel to determine the economic viability of MEE, and evaluated which desalination process would be economically the most appropriate. It was identified that low temperature multi-effect evaporators operating at approximately 70$^\circ$C are ideal for an efficient operation. The authors deduced that the energy requirements and the use of inexpensive building

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materials make MED the most inexpensive distillation plant. The report by Ophir and Lokiec found that an MEE plant with five effects can produce distilled water at a rate of $0.54/m^3$ and that each of the five effects can potentially produce 20,000m$^3$ a day [160].

Cipollina et al. observed a few notable trends in the market for thermal desalination, with respect to the MSF and MEE methods. They reflected on the recent developments designed to assist the thermal desalination process to becoming more competitive. Firstly, there have been vast improvements in the production capacity of both MED and MSF units. Corresponding with increase in unit capacity, the production costs have reduced. Secondly, the process has been optimized and a great deal of expensive and redundant equipment (such as by-passes, controls, pumps, valves, etc.) has been eliminated. Lastly, different construction materials are being used in order to enhance the performance of these systems. For instance, the ‘316L’ stainless steel has made way for ‘Duplex’ stainless steel, as it affords superior resistance to corrosion. Similarly, using titanium tubes instead of copper ones would deliver better performance in the low-temperature sections of MED and MSF [161].

Al-Shammari and Safar conducted a survey of operational multi-effect distillation plants around the world, including some under construction. Their study showed that the ‘thin falling film’ evaporator design is the most common one utilized in MEE plants, as it can reduce scaling significantly and can raise several desirable factors contributing to performance enhancement; HTC is an example. The survey findings are summarized in Table 5.1, and it can be seen from the table that the Southern California plant is able to produce 283,900m$^3$/day (75 million gallon daily) by using a falling film ME stack, with a gain in the output ratio reaching 23.
Table 5.1: MEE survey summary; Al-Shammari and Safar in 1999 [146].

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<th>Cap. Mgd</th>
<th>Design Type</th>
<th>No. Eff.</th>
<th>GOR</th>
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<td>LT-MES-TVC-SF</td>
<td>14</td>
<td>9.4-14</td>
<td>1988</td>
<td>Spain</td>
</tr>
<tr>
<td>PSA-II</td>
<td>69</td>
<td>0.019</td>
<td>LT-MES-ABS-SF</td>
<td>14</td>
<td>24</td>
<td>1994</td>
<td>Spain</td>
</tr>
<tr>
<td>S. California</td>
<td>110</td>
<td>75.0</td>
<td>HT-MES-VTE-FF</td>
<td>30</td>
<td>23</td>
<td>1997</td>
<td>S. California</td>
</tr>
<tr>
<td>Nagoya</td>
<td>110</td>
<td>0.264</td>
<td>HT-MES-FF</td>
<td>-</td>
<td>6</td>
<td>1974</td>
<td>Japan</td>
</tr>
</tbody>
</table>

Here are some details about the terms used in the above table:

- **LT**: Low Temperature
- **HT**: High Temperature
- **MVC**: Mechanical Vapour Compressor
The greatest number of effects used so far is 55, constructed in Al-Ain in the United Arab Emirates; however, it is designed to produce only 500m$^3$ daily (0.1319 million gallons per day). The most recent low-temperature multi-effect distillation plants are able to work under 60$^\circ$C, and it is reported that Eilat plant in Israel and the Trapani plant in Italy have been successfully working at 55$^\circ$C since 1992. Other plants in the United Arab Emirates, such as Mirfa, Jebei Dhanna and Sila, are designed to produce desalinated water at top brine temperature (TBT) of 58.5$^\circ$C [146].

5.2.2 Multistage Flash Desalination Method

The multistage flash (MSF) desalination method is a widely used procedure, comprising of 60% of market share, i.e. of the total production of potable water from seawater in the world [162]. This method exploits evaporation; the process begins by heating seawater until it evaporates into a vacuum evaporator, and the collected vapours are then condensed to form fresh water. The efficiency of the system is dependent on the ability to recover the latent heat of condensed vapour [162].

The thermal energy needed to raise the temperature of seawater (or brine) to its boiling point is usually delivered as steam generated by power from an electricity power plant but it could be from any other heat energy source. The MSF plant is divided into stages, in which each stage is a closed chamber where the process of evaporation and condensation takes place. The MSF process can be employed by three different methods. The first uses brine recirculation (MSF-RE), the second uses
multiple flash units without any recirculation, called the ‘once through’ method (MSF-OT), and the third uses a brine-mixing technique (MSF-M) [162].

In a traditional MSF plant, the first stage consists of brine being heated in the heater until it reaches its saturation temperature. The heated brine is passed through an orifice, where the pressure is reduced from approximately 6 bars to 2 bars. When the brine has reached its high-pressure saturation point, at a lower pressure it then starts to flash. This results in the formation of vapours, which are raised through the demisters, ensuring that no entrained brine droplets are carried to the product water. Finally, the vapour reaches the top and touches the tube surface, where it condenses. This condensate is the product of the process. The remaining brine is sent forward to the next stage; from the last stage, it is pumped back to the brine heater through a series of tubes. Because the tubes are warm, some thermal energy is transferred from the tube to the brine, hence reducing the level of thermal energy needed in the heater. It can be observed from Figure 5.4 that the MSF method can have multiple stages, so that this process can consistently repeat itself. Un-evaporated water would be able to undergo the same process in the subsequent stages [162].

![Figure 5.4: MSF Units: SIDEM-desalination [171.]](image-url)
The most important component of any MSF plant is the brine heater. It is the only interface between the heat source and the desalination units. Its components should ideally maintain a smooth operation for the MSF plant to perform well.

MSF plants have undergone constant experimentation and improvements, and as a result, MSF output capacity has been significantly increased. Correspondingly, MSF plants have become more cost efficient. According to Cipollina et al., the desalination capacity of a MSF-based system can reach up to 75,000 m$^3$ per day. Most MSF plants have been built in the Gulf countries, as that region suffers from a shortage of fresh water sources, such as rain, rivers or lakes, but has an abundant supply of fossil fuel [163].

The features of the MSF method are listed below:

- This method can be employed on a large scale. There are examples of many large-capacity plants that work just as efficiently as small-scale plants. According to Szacsvay, the production capacity of large MSF plants has reached over 76,000 m$^3$ daily [155].
- The hot brine droplets passing through the tubes help raise the temperature of the tubes. This illustrates the heat recovery properties of this method, as less thermal energy is now needed in the brine heater [155].
- Szacsvay states that this is the most reliable method, as the effectiveness of this method is not affected by turbidity or salinity, thereby providing consistent performance [155].
- There is potential to increase the performance of the MSF method. The primary advantage of having multiple stages is to enhance the system’s performance.
- It is the most widely employed method for thermal desalination.

5.2.3 The Multi-Effect Evaporators

The multi-effect distillation/evaporator (MED/MEE) is an effective method for distillation. Similar to MSF, it also uses an evaporation process for desalination to produce fresh and distilled water. The market share among all thermal desalination
processes is significantly less than that of MSF. According to a report by Cipollina et al., the market share of MED is approximately 12.5% [163]

An MED plant consists of particular components, called ‘effects’. An electrical power plant or an SGSP can act as the source for thermal energy for the first effect of the MED system. The next and all the following effects are supplied with heat from the previous effect. The process of evaporation is repeated in all the effects.

There are three types of MED, based on the shape of the heat-transferring unit. They are the Vertical Tube Evaporator (VTE), the Multi-Effect Plate (MEP) and the Horizontal Tube Evaporator (HTE) [28]. The most commonly used MED procedure employs the HTE, as statistically it is the most efficient system, in terms of heat transfer. The MED plant shown in Figure 5.5 can be viewed as series of closed spaces, partitioned by the walls of the tube.

The plant comprises of just one heat source and a heat sink at the opposite end. The MED operates with the vapours from the first effect being passed through a tube towards the second effect. This causes the vapours to condense in the second effect, and the heat produced (released during condensation) is used to boil the fluid in the second effect. Each effect is maintained at a different pressure, which leads to a different boiling point for the fluid in each boiler. Furthermore, the temperature of the saline water should be lower than the temperature of the condensing steam. These two conditions are essential for the proper functioning of the MED operation; otherwise, the second effect (or any other subsequent effect) would not receive any sufficient thermal energy to complete the process [28]. The pump delivers the distilled water at atmospheric pressure, as the system works very low pressures. With the addition of each effect, the ability to produce fresh water increases. However, this would require a higher level of investment, and thus a trade-off should be determined.
MED plants are mostly employed in the Middle East. These systems do not achieve desalination capacities comparable with MSF plants but this region does not require such high capacity units. Also, the energy requirements for this process are significantly less than the thermal energy needed for MSF units, and this is another reason for their extensive deployment in the Middle East [28].

**Features**

- MED is considered to be one of the most high-performing desalination methods. The evaporation and condensation take place simultaneously within the heat exchanger and different effects.
- The power consumption of MED relatively low (less than 1kWh/m³); it requires the least amount of power amongst all desalination methods.
- It can work with low temperature heat sources such as solar energy collectors.
- It can tolerate various conditions in the saline fluid.
- It operates at low temperature to avoid scaling and corrosion.
- This process is not affected by changes in seawater quality (such as salinity or turbidity); thus, it provides stable and reliable performance and operation [13].

*Figure 5.5: MED Unit: Dabbagh *et al.*, [98].*
5.2.3.1 MEE Evaporators

Evaporation is the most significant process in multi-effect desalination. The process is mainly carried out by the evaporators. The evaporators can be classified into three types, according to the method of the heat exchange between the hot fluid and the feed water within the effects, and these types are: submerged, ‘falling films’ tubes and plate evaporators. These three types are described as follows [163]:

A- Submerged Evaporator

These evaporators are similar in method to those commonly used in electronic equipment in households, such as electric kettles and humidifiers. A process diagram of a two-effect submerged evaporator is sketched in Figure 5.6. The process starts in the first effect, where the hot steam condenses on the inside wall of the tube. In doing so, it releases the contained latent heat and a thin layer of liquid is formed on the outside of the tube. Vapour bubbles rise through the layer of liquid into the vapour space. These vapours are then transferred to the second effect, where a similar process takes place (condensing on the walls of the tube, transferring heat to another evaporation process). The quantity of vapour produced in the second effect is naturally less than the vapour released in the first effect, and a sequence of effects may be added to repeat the process for obtaining a higher distillate production rate and less blow-down [163].

This process was used in small industrial desalination plants in the early parts of the twentieth century; however, it did not prove to be cost effective, as it was hampered by constant scaling and fouling on the outside surface of the tubes. Furthermore, the works of Cipollina et al. also show that this process was not energy efficient.
Figure 5.6: Two-effect submerged evaporator; Cipollina et al., [161].

B- Falling Film

The second type of evaporator is called the falling film. This configuration is much more advanced than the submerged tube, and it eliminates some of the drawbacks of using submerged tube evaporators. This process is controlled by two heat-transfer mechanisms: convection or conduction across the films. The evaporation occurs by flowing or spraying the liquid down, while subjecting it to heat, to form vapour. There are two categories of falling film evaporator: vertical and horizontal arrangements. These two arrangements are shown in Figure 5.7 [163].

The horizontal arrangement maintains a higher energy coefficient than that of submerged tube evaporators; however, this process is also hampered by the scaling of tubes. The effect of scaling can be restricted by operating the horizontal tube falling film evaporator unit at temperatures below 70°C. This arrangement is mostly employed in the MED units for desalination purposes [163].

The vertical tube arrangement is characterized by multiple thin falling films for the seawater to flow down. The formation of films is relatively more complicated to control than in the horizontal arrangement, which leads to scaling, formation of dry patches and uneven tube expansion. However, it may operate at higher temperatures than the horizontal tube falling film arrangement.
C- Plate Evaporators

A plate evaporator works in two parts, and comprises of steam passing to condense on one side of the plate, and water evaporates from the other side, as shown in Figure 5.8. The advantages of using plate evaporators are that they occupy small spaces, have a good heat coefficient, are lightweight and have a relatively high capacity. However, these evaporators are currently only limited to prototype and experimental units, and are yet to be produced for commercial use.

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**Figure 5.7**: Horizontal and vertical tube falling film arrangement; Cipollina et al., [161].

**Figure 5.8**: Plate evaporators; Cipollina et al., [161].
5.2.3.2 Single-Effect Evaporation

The main elements of a single-effect horizontal tube falling film evaporation system are the pre-heater, evaporator, pumping units and vacuum system. The structure of this evaporation system is shown in Figure 5.9.

The process begins when seawater, along with cooling water, is introduced into the pre-heater unit of the system. The purpose of driving the cooling water in the condenser is to eradicate any excess heat from the evaporator. The thermal energy provided by the pre-heater is supplied by the condensing vapours from the evaporator unit. This not only enhances the energy coefficient of the system, but also removes excess heat from the system [163].

Figure 5.9: Single-effect evaporation desalination process; Cipollina et al.,[161].

As the feed water (seawater) enters the evaporators from the top through tubes, it falls in the form of thin films. The feed water evaporates after receiving heat from the
heating steam as it condenses, releasing its latent heat. The resulting salt-free vapours are then passed through a ‘demister’ to remove the entrained brine particles. This is an important step, as it protects the tubes from exposure to brine droplets, which may cause scaling.

5.2.3.3 Methods of MEE feeding:

A single evaporator approach is wasteful of heat energy because the latent heat of vapour is not properly used; however, most of the latent heat may be recovered by using a multi-effect configuration. There are three types of MEE configuration based on the effect feeding method:

A- Forward-feed evaporators:

Forward multiple-effect feeding is the most commonly used method, as it delivers a good production rate and can significantly reduce the number of pumps, consequently lessening the energy consumed for pumping duties. As can be seen from Figure 5.10, the feed water initially enters the first effect, and then flows to the next effect without using pumps, as each other evaporator in the series has a lower pressure than the one before. Another main advantage of using this method is that it extracts more of the product fluid than the other methods and it concentrates the blow-down discharge.

![Figure 5.10: Sketch of forward-feed MEE.](image-url)
B- Backward-feed evaporators:

The backward multiple-effect evaporator feeding technique is rarely constructed in desalination plants, however it is a relatively common method in other evaporator applications, particularly when the concentrated discharge is highly viscous and when the feed is relatively cold. This reverse feed method is designed to pump the feed into the last effect while the brine is collected from the first boiler unit, as illustrated in Figure 5.11. Unlike the forward feed method, there should be a pump between every two effects to overcome the pressure increase.

![Sketch of backward-feed MEE.](image)

**Figure 5.11:** Sketch of backward-feed MEE.
C- Parallel-feed evaporators:

The parallel feeding approach is commonly installed in multi-effect desalination plants, and it is set up to allow each effect to operate by the once-through operation method described above; it is sketched in Figure 5.12. The raw water is directly pumped into each boiler, ensuring that there is no transfer of water between any two effects; the brine is also withdrawn from each unit. This method is widely used when there is an abundance of raw liquid, and the concentrated stream is rejected or returned to the intake source.

![Figure 5.12: Simplified sketch of parallel-feed MEE.](image)

### 5.3 Comparison Between MED and MSF Plants coupled with SGSP

The following comparison was conducted by Ophir and Lokiec to determine the most efficient desalination process available today. The comparison was conducted between MED and MSF plants of equal production (100,000m³ per day). To achieve an equal level of daily distilled water production, a five-effect MED plant and a two-
stage MSF plant were observed. This is represented in Table 5.2 [160] and it was found that the construction cost for the MEE plant was lower by 10.5% than for the MSF. In addition, the MED plant cost less in term of chemical agent use, labour rate and electricity consumption. For example, the MSF plant consumed $0.175/m$\textsuperscript{3} in terms of its power requirements, while the MEE required only $0.06 to cover its electricity consumption for each cubic metre of distillate water production, i.e. the MSF was higher by about 192% than the MEE in term of the cost of power. The comparison clearly illustrates the superior performance of the MED plant in terms of energy consumption and cost per cubic metre production over the MSF plant. Moreover, a Low-Temperature MEE (LT-MEE) has a further advantage over both a High-Temperature MEE (HT-MEE) and an MSF, which is its ability to reduce the potential of scaling on the plant units during operation, which in turn reduces the maintenance costs and the chemical agent consumption.

Table 5.2: Comparison between MED and MSF plants.

<table>
<thead>
<tr>
<th>Units</th>
<th>MSF</th>
<th>MED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Configuration of Plant</strong></td>
<td>2 units</td>
<td>5 effects</td>
</tr>
<tr>
<td>Daily production m$^3$ per day</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Equipment costs USD (millions)</td>
<td>95</td>
<td>85</td>
</tr>
<tr>
<td><strong>Operating Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity cost USD/m$^3$</td>
<td>0.175</td>
<td>0.060</td>
</tr>
<tr>
<td>Chemical USD/m$^3$</td>
<td>0.070</td>
<td>0.050</td>
</tr>
<tr>
<td>Labour USD/m$^3$</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Extra parts USD/m$^3$</td>
<td>0.050</td>
<td>0.031</td>
</tr>
<tr>
<td>Desalted water cost USD/m$^3$</td>
<td>0.60</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>Electricity Consumption kWh/m$^3$</strong></td>
<td>3.5</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio of economy (distilled water/steam) Ton/Ton</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Steam consumption Ton per hour</td>
<td>520</td>
<td>520</td>
</tr>
<tr>
<td>Steam temperature °C</td>
<td>120-150</td>
<td>70</td>
</tr>
</tbody>
</table>
5.4 MEE Process Modelling

The Forward Feed Multiple Effect Evaporation process (MEE-FF) is selected for coupling to the salinity gradient solar pond in this study, although other MEE types can be also used. In fact, the modelling of MEE studies is limited and coupling an MEE with a SGSP is rarely found. Therefore, the suggested evaporator solutions offered by Geankoplis [137] and El-Dessouky and Ettouney [138] are adopted, and are then improved to meet the requirements of this study. In addition to the solar pond hot water, the system includes a series of evaporators, a pre-heater and a mechanical vapour compressor, as illustrated in Figure 5.13. The number of evaporators is initially set to 4, and mass and heat balance have been used to build a Matlab code to solve this model through iteration approaches. The aim of this system is to produce 1kg/s of distilled water with the assistance of mechanical vapour compression. The assumptions for using a salinity gradient solar pond coupled with an FF-MEE desalination system are the following:

The thermal loads in the effects are equal.

The heat transfer areas are equal and constant in all evaporators.

Constant specific heat.

Demister thermal effect is limited, hence it can be neglected.

The feed (sea or brackish) water is preheated before being introduced into the first evaporator.

The non-condensed gases effect can be ignored, as there is no need for a condenser unit with the presence of a mechanical vapour compressor.
Figure 5.13: The SGSP-MEE coupling system
5.4.1 Mass and Heat Balance Equations

\[ M_f = M_d + M_b \]  \hspace{1cm} (5.1)

Concentration balance for the first effect can be obtained from:

\[ X_f M_f = X_b M_b \]  \hspace{1cm} (5.2)

and for the other effects:

\[ X_i M_{b_i} = X_{i-1} M_{b_{i-1}}, \hspace{0.5cm} i = 2 - n \]  \hspace{1cm} (5.3)

where:

\[ M_f : \text{Feed flow rate (kg/s)} \]
\[ M_d : \text{Distilled flow rate (kg/s)} \]
\[ M_b : \text{Brine flow rate (kg/s)} \]
\[ X_f : \text{Feed concentration (ppm)} \]
\[ X_b : \text{Brine concentration (ppm)} \]

The total distillate water is the summation of each effect product, therefore:

\[ M_d = M_{d_1} + M_{d_2} + \cdots + M_{d_n} \]  \hspace{1cm} (5.4)

As the required thermal load is assumed to be the same and constant, the heat load \( Q \) will be:

\[ Q_1 = Q_2 = Q_3 = \cdots = Q_n \]  \hspace{1cm} (5.5)

where \( Q_1 \) for the first effect is:

\[ Q_1 = M_s \lambda_s \]  \hspace{1cm} (5.6)
and $Q_i$ for the other effects will be:

$$Q_i = M_{di}\lambda_i$$  \hspace{1cm} (5.7)

where:

$Q_i$ : Thermal load for $i$ effect (kJ/s).

and $i$ is the number of effect = 2, 3 … $n$

$M_s$ : Steam/storage zone water flow rate (kg/s).

$M_d$ : Distillate flow rate (kg/s).

$\lambda_s$ : Steam/storage water latent heat (kJ/kg).

$\lambda_i$ : Latent heat formed in $i$ effect (kJ/kg).

In each effect (from Effect 2 to Effect $n$), the thermal load can be considered to be the previous effect’s thermal heat carried by the vapour, so:

$$M_{di}\lambda_i = M_{d(i-1)}\lambda_{i-1}$$  \hspace{1cm} (5.8)

In the same way:

$$M_{d2} = \frac{M_{d1}\lambda_1}{\lambda_2}$$  \hspace{1cm} (5.9)

$$M_{d3} = \frac{M_{d2}\lambda_2}{\lambda_3}$$  \hspace{1cm} (5.10)

The first effect may be used as a reference, and the equations can be expressed in terms of $M_{di}$:

$$M_{di} = \frac{M_{d1}\lambda_1}{\lambda_i}$$  \hspace{1cm} (5.11)

where $i$ is the number of the effect; it starts from 2 and proceeds to the last effect number, which is $n$. If the above equation is used in Equation 5.4, this will lead to:
Then, Equation 5.1 is utilized to find the product flow rates (distillate rates) for the rest of the evaporators. The brine flow rate from the first effect can be estimated by:

\[ M_{d1} = \frac{M_d}{\lambda_1 + \frac{\lambda_1}{\lambda_2} + \ldots + \frac{\lambda_1}{\lambda_n}} \quad (5.12) \]

The latent heat can be taken from the steam table, which is available in most of the references or can be calculated from this equation, which is given by El-Dessouky and Ettouney:

\[ \lambda_i = 2499.5698 - 2.204864 T_i - 2.304 \times 10^{-3} T_i^2 \quad (5.15) \]

The above equation is accurate enough to be reliable, and is more convenient than the steam tables or graphs, particularly in programming and in the calculations as long as the temperature is between 5 and 200°C, which is within the range of the solar pond and desalination system conditions. The comparison between steam table latent heat and calculated latent heat shows that the error is less than 0.026%, and these results are plotted in the following figure:
However, the latent heat is a function of the temperature, and to be obtained, the temperature of each effect should be calculated.

The heat load in each evaporator can also be estimated in terms of the evaporator heat transfer area, the temperature driving force and the overall heat transfer coefficient in each evaporator by the following equation:

\[ Q_i = A_i U_i \Delta T_i \]  \hspace{1cm} (5.16)

where:

- \( A_i \) : The heat transfer area for the \( i \) effect (m\(^2\)).
- \( U_i \) : The overall heat transfer coefficient for the \( i \) effect (W/m\(^2\)°C).
- \( \Delta T_i \) : The temperature driving force in the \( i \) effect (°C).

As the heat transfer areas in each evaporator are equal, Equation 5.16 will be:

\[ \frac{Q_1}{A_1} = \frac{Q_2}{A_2} = \cdots = \frac{Q_n}{A_n} \]  \hspace{1cm} (5.17)
and:

\[ U_1 \Delta T_1 = U_2 \Delta T_2 = \cdots = U_n \Delta T_n \]  \hspace{1cm} (5.18)

or:

\[ U_1 \Delta T_1 = U_2 \Delta T_2 \]  \hspace{1cm} (5.19)

\[ \Delta T_2 = \frac{U_1 \Delta T_1}{U_2} \]  \hspace{1cm} (5.20)

\[ \Delta T_3 = \frac{U_2 \Delta T_2}{U_3} \]  \hspace{1cm} (5.21)

If \( \Delta T_i \) is taken as a reference temperature drop, then:

\[ \Delta T_i = \frac{U_1 \Delta T_1}{U_i} \]  \hspace{1cm} (5.22)

The overall temperature drop in the system is the difference between the steam/storage zone temperature \( T_s \) and the last effect vapour temperature \( T_n \), and this drop can be represented by this equation:

\[ \Delta T_t = T_s - T_n \]  \hspace{1cm} (5.23)

This overall temperature drop can be also represented by the summation of the temperature drops in each evaporator:

\[ \Delta T_t = \Delta T_1 + \Delta T_2 + \cdots + \Delta T_n \]  \hspace{1cm} (5.24)

Substituting Eq 5.22 in Eq 5.24 will give:
The temperature in the first effect is estimated by:

\[ T_1 = T_s - \Delta T_1 \]  \hspace{1cm} (5.26)

and the temperatures of the other effects are given by:

\[ T_i = T_{i-1} - \frac{U_i \Delta T_1}{U_i} \]  \hspace{1cm} (5.27)

### 5.4.2 Heat Transfer Areas

In iteration solutions, the heat transfer area is needed to check the models’ initial assumptions; this is in addition to the requirement of obtaining such areas for studying the effect of the heat area on a system’s design and performance. The area of the first effect is given by:

\[ A_1 = \frac{M_{d1} \lambda_1}{U_1(T_s - T_1)} \]  \hspace{1cm} (5.28)

Also, for boilers 2 to \( n \), it may be expressed by this correlation:

\[ A_i = \frac{M_{di} \lambda_i}{U_i(T_i - \Delta T_{loss})} \]  \hspace{1cm} (5.29)

The temperature drop due to the thermodynamic losses (\( \Delta T_{loss} \)) in each evaporator in the system can vary between 0.5 and 3°C [138].

The condenser heat transfer area may be calculated by:

\[ A_c = \frac{Q_c}{U_c(LMTD)_c} \]  \hspace{1cm} (5.30)

and \( (LTMD)_c \), can be computed by:
where:

\( A_c \): The condenser heat transfer area (m\(^2\)).

\( Q_c \): The condenser heat load (W).

\( U_c \): The condenser heat transfer coefficient (W/m\(^2\)°C).

\( T_f \): The feed temperature (°C).

\( T_{cw} \): The intake temperature (°C).

\( T_n \): The last effect temperature (°C).

To use the above logarithmic mean temperature equation, it is advised to consider the following assumptions [139]:

- The overall heat transfer coefficient (U) is constant.
- The specific heat of both hot and cold fluids is constant.
- The thermal exchange with the ambient is neglected.
- The fluids’ flow rate is at steady state.

The specific heat transfer area \( sA \) is given by:

\[
sA = \frac{\sum_{i=1}^{n} A_i + A_c}{M_d} \tag{5.32}
\]

### 5.4.3 Iteration and Convergence Criterion

If the above model is applied, a new iteration may start by using the obtained Area in Equation 5.28 and Equation 5.29 to obtain the temperature drop in the effects based on the this formula:

\[
\Delta T_i = \Delta T_i \frac{A_i}{A_m} \tag{5.33}
\]

where \( A_m \) is the mean heat transfer area, and is given by:
Then, the model steps can be repeated until the convergence condition is reached. The convergence criterion can be checked by investigating the maximum difference between the effects’ heat transfer areas according to this correlation:

\[ \Delta A_{\text{max}} = \text{Max}(A_{i+1} - A_i), \quad \text{where } i = 1, n - 1 \]  

(5.35)

\[
A_m = \frac{\sum_{i=1}^{n} A_i}{n} \quad (5.34)
\]

5.4.4 Performance Parameters

The performance ration may be described as the product (distillate, \(M_d\)) flow rate to the vapour generator steam/hot water (\(M_s\)), and this will be expressed by this relationship:

\[ PR = \frac{M_d}{M_s} \quad (5.36) \]

The condenser thermal load is given by:

\[ Q_c = M_{dn} \lambda_n \quad (5.37) \]

and:

\[ Q_c = (M_f + M_{cw})C_p(T_f - T_{cw}) \quad (5.38) \]

5.4.5 System Model Validation

As a similar model does not exist, at least in the available references, the model’s validation is initially checked against the Forward Feed Multiple Effect Evaporator (MEE-FF) system given by El-Dessouky and Ettouney [138]. The plant consists of 6 evaporators and the intake water is pumped at 25°C with total dissolved solid (TDS) being 42,000ppm. The motive steam is circulated at about 100°C to produce in total 1kg/s of salt-free drinking water, and the brine is rejected with a salinity level of
70,000 ppm. The overall heat transfer coefficient in the first unit is set to 2.4 kW/m^2. A summary of the temperatures, flow rates and concentrations is given in Table 5.3.

A Matlab code has been programmed to simulate the above study and the data and assumptions, which are similar, are adopted to investigate the model’s validation. The obtained outputs are presented in Table 5.3, and a good agreement has been reached.

**Table 5.3:** The model outputs compared with the model given by [138].

<table>
<thead>
<tr>
<th>Effect No.</th>
<th>Temp °C</th>
<th>Distillate kg/s</th>
<th>Brine kg/s</th>
<th>Conc. ppm</th>
<th>Area m^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.67</td>
<td>0.1708</td>
<td>2.3292</td>
<td>45078.9</td>
<td>22.1446</td>
</tr>
<tr>
<td>2</td>
<td>84.96</td>
<td>0.1693</td>
<td>2.16</td>
<td>48611.5</td>
<td>22.1445</td>
</tr>
<tr>
<td>3</td>
<td>76.84</td>
<td>0.1677</td>
<td>1.9922</td>
<td>52704.4</td>
<td>22.1445</td>
</tr>
<tr>
<td>4</td>
<td>68.29</td>
<td>0.1662</td>
<td>1.826</td>
<td>57501.2</td>
<td>22.1446</td>
</tr>
<tr>
<td>5</td>
<td>59.29</td>
<td>0.1646</td>
<td>1.6614</td>
<td>63198.6</td>
<td>22.1446</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>0.1614</td>
<td>1.5</td>
<td>70000</td>
<td>22.1446</td>
</tr>
</tbody>
</table>

**This study output**

<table>
<thead>
<tr>
<th>Effect No.</th>
<th>Temp °C</th>
<th>Distillate kg/s</th>
<th>Brine kg/s</th>
<th>Conc. ppm</th>
<th>Area m^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.6724</td>
<td>0.1702</td>
<td>2.3298</td>
<td>45069</td>
<td>22.1435</td>
</tr>
<tr>
<td>2</td>
<td>84.9592</td>
<td>0.1690</td>
<td>2.1607</td>
<td>48595</td>
<td>22.1434</td>
</tr>
<tr>
<td>3</td>
<td>76.8400</td>
<td>0.1675</td>
<td>1.9932</td>
<td>52699</td>
<td>22.1435</td>
</tr>
<tr>
<td>4</td>
<td>68.2934</td>
<td>0.1660</td>
<td>1.8272</td>
<td>57495</td>
<td>22.1435</td>
</tr>
<tr>
<td>5</td>
<td>59.2971</td>
<td>0.1644</td>
<td>1.6628</td>
<td>63186</td>
<td>22.1435</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>0.1618</td>
<td>1.5000</td>
<td>70000</td>
<td>22.1435</td>
</tr>
</tbody>
</table>

After 8 iterations, the above results are obtained and it is clear that the results of this study are very close to the ones given by [138]; the model has been since improved to meet the requirements of this study. These improvements include using a mechanical vapour compressor, regenerative line and utilizing the salinity gradient solar pond as a source of the heat.
5.5 Multi-Effect Evaporators with Vapour Compression

The relationship between multi-effect boilers and vapour compressors has a long history, going back to the WWII [147]; when troops needed fresh water on isolated islands, there was a pressing need to improve MEE performance.

Multi-effect units can work independently or with vapour compressors; however, since the last decade of the 20th Century, it has not been common to construct an MEE plant without a vapour compressor. Studies have shown that the performance ratio (kg product/kg heating fluid) may be duplicated when an MEE plant is designed with a vapour compression unit. Temset et al. in 1996 found that a 12-effect MEE plant’s performance ratio is about 8, but when an MEE is used with a vapour compressor, the PR value reaches about 16 [166].

About 2,257kJ of heat energy is required to evaporate 1kg in an evaporator at atmospheric pressure, using steam (at 100°C). This saturated vapour is at about 100°C, and when it is adiabatically compressed, for example, by a Mechanical Vapour Compressor (MVC) to 1.7atm, the process consumes 95.3kJ of electric power. After this compression, the saturated vapour becomes superheated and that raises the temperature to 150°C. To recover this energy, the superheated vapour needs to be cooled to the saturation temperature, which is 100°C, and therefore 73kJ can be collected; the condensation latent heat then needs to be given out which is 2212kJ. Thus, the total energy produced due to the compression process is 2212 + 73 = 2285kJ, while the required evaporation energy for another 1kg of water is only 2257kJ. Consequently, this obtained heat energy can be used to evaporate another kilogram of water, and even then there is excess heat energy of about 30kJ; this can be expressed as the temperature difference between releasing the evaporation enthalpy at two different pressures (16°C in this example) [136].

The purpose of vapour compression is not only to raise the obtained heat energy but also to raise the heat to the desired temperature and pressure for heat exchanging, and this can be accomplished and adjusted automatically.
5.5.1 Types of vapour compression

There are four known types of vapour compressor that can work with MEE, and these types include Mechanical Vapour compressor (MVC), Thermal Vapour Compressor (TVC), Absorption Vapour Compressor (ABS) and Adsorption Vapour Compressor (ADS). The first two compressors are the ones most widely used with MEE, although the last two are promising; El-Dessouky and Attouney [138] presented outcomes from a mathematical model showing that an MEE-ABS plant can operate with a performance ratio of 25 with top brine temperature of 110°C by using 12 effects. However, ABS and ADS can be classified as new combination proposals, and therefore only MVC and TVC are considered in this study.

Selecting a vapour compressor depends on the cost and the required thermal or mechanical energy to operate a vapour compressor in a desalination plant. The required energy depends on two main factors, which are the vapour temperature/pressure rise and the thermodynamic/mechanical efficiency of the selected VC.

A- Mechanical Vapour Compressor (MVC)

The mechanical vapour compressor is the most attractive method for combining with multi-effect evaporators, compared with the other compression units described above. An MVC usually consists of bearings, seals and rotating parts, and is similar in principle to a centrifugal blower (but a little more advanced). It requires a steam turbine or electric power to compress the vapour and thermal energy is not needed to accomplish this, as illustrated in Figure 5.15. A turbo-compressor is preferred over other types of compressor for handling large quantities of vapour, i.e. to compress the steam, particularly when flow rates are higher than 5000m³/h [165, 166,].

The development of the turbo-compressor also originates in the WWII. Initially, a simple MEE operating at above 100°C could produce about 35kg of distilled water by burning 1kg of fuel in a diesel engine but after developing the turbo compressor, more than 260kg of fresh water was produced per 1kg of fuel [147]. This considerable improvement in MEE productivity and in MEE plant performance contributed notably
to the increased adoption of MEE around the world, particularly in arid and semi-arid areas such as the Middle East.

\[ W = \frac{\gamma}{\eta(\gamma - 1)} P_i V_i \left[ \left( \frac{P_o}{P_i} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \]  

(5.39)

where:

- \( W \): Specific power consumption (kWh/m\(^3\))
- \( \gamma \): The isentropic efficiency.

**Figure 5.15:** Simple sketch of a mechanical compressor and pressure-velocity diagram.
η: MVC efficiency.

Vi: Vapour specific volume (m³/kg).

Pi: MVC inlet pressure (kPa).

Po: MVC outlet pressure (kPa).

B- Thermal Vapour Compressor (TVC)

Thermo-compressors compress vapour thermally by high pressure steam ejectors without any moving parts. As described in Figure 5.16, a thermal compressor usually consists of a steam nozzle, suction chamber, throat and diffuser. The primary motive steam (at high pressure) passes through the nozzle, changing its internal energy into kinetic energy with more than supersonic velocity; this creates a vacuum in the effects in addition to compressing the vapour to the required temperature and pressure. In general, it is found that in a thermal compressor 1kg of steam can evaporate 1kg of desalinated water without any supportive process such as preheating [147].

As steam ejectors do not have any moving parts, they require little attention or maintenance, and they are considered reliable compressors. However under some operational conditions, thermal vapour compressors need to be made of corrosion resistant materials to protect the ejector parts from the effects of corrosion, which would cost a considerable amount of money. Moreover, these ejectors are not as commonly used as before because the cost of steam has been rising constantly; in many applications, a TVC may be replaced by an MVC, as the latter consumes much less energy for the same work [139].

The performance of a thermal compressor can be predicted by the entrainment ratio (Ra), which may be defined as the mass of motive steam per entrained vapour unit mass, and it is given by:

\[
R_a = 0.296 \left( \frac{PCF}{TCF} \right) \left( \frac{P_s}{P_{ev}} \right)^{1.19} \left( \frac{P_m}{P_{ev}} \right)^{0.015} \quad (5.40)
\]

In the above equation, the pressure correction factor (PCF) and the temperature correction factor (TCF) can be found by:
\[ PCF = 3 \times 10^{-7} (P_m)^2 - 0.0009 (P_m) + 1.6101 \]  
\[ TCF = 2 \times 10^{-8} (T_{ev})^2 - 0.0006 (T_{ev}) + 1.0047 \]

where:

- \( P_m \): The motive steam pressure (kPa).
- \( P_s \): The mixture steam pressure (kPa).
- \( P_{ev} \): The entrained vapour pressure (kPa).
- \( T_{ev} \): The entrained vapour temperature \(^\circ\)C.

These correlations are valid when they satisfy the following conditions:

- \( R_d \leq 4 \)
- \( 100 \leq P_m \leq 3500\) kPa
- \( 10 \leq T_{ev} \leq 500\) \(^\circ\)C
- \( \frac{P_s}{P_{ev}} \geq 1.81 \)

**Figure 5.16:** Simple sketch of a thermal compressor and pressure-velocity diagram [138].
5.5.2 Boiling Point Elevation (BPE)

The boiling temperature of a solution is higher than that of pure water at a given pressure, and this difference between the boiling point temperatures is known as Boiling Point Elevation (BPE) or Boiling Point Rise (BPR). This boiling elevation in an aqueous solution depends on the concentration magnitude. The BPE can be very small in dilute solutions and very high in some concentrated solutions, for example, it could be about 80°C for some inorganic salt solutions, while less than 1°C for seawater with a TDS of 30,000ppm [139, 168].

The BPE can be calculated by the Duhring rule, which states that the boiling point of an aqueous solution is a linear function of the boiling point of pure water at the same pressure [139]. Therefore, straight lines should be obtained when the BP of a solution is plotted against the BP of pure water at the same pressure, and different concentrations would offer different lines, as shown in Figure 5.17 for a sodium chloride solution.

![Figure 5.17: Duhring diagram for the boiling point of sodium chloride solutions [169].](image)

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El-Dessouky and Ettouney [138] gave an empirical equation to compute the BPE of seawater as a function of concentration and temperature. The equation is presented below and it is valid when the concentration is between 1 and 16% and when the temperature ranges from 10 to 180°C; both conditions are compatible with thermal desalination operating conditions:

\[ BPE = AX + BX^2 + CX^3 \]  

(5.43)

Also:

\[ A = 8.325 \times 10^{-2} + 1.883 \times 10^{-4} T + 4.02 \times 10^{-6} T^2 \]

\[ B = -7.625 \times 10^{-4} + 9.02 \times 10^{-5} T - 5.2 \times 10^{-7} T^2 \]

\[ C = 1.522 \times 10^{-4} - 3 \times 10^{-6} T - 3 \times 10^{-8} T^2 \]

where:

T: Solution temperature (°C).

X: Salt concentration percentage (wt%).

5.6 Coupling SGSP with FF-MEE-MVC Case Study

Recent advances in desalination technologies has resulted in the competition becoming extremely fierce, for instance, the reverse osmosis (RO) desalination plants used to be constructed mainly for treating brackish water, as the membranes were very sensitive to impurities; they also needed costly pre-treatment procedures and frequent washing and cleaning (chemically and physically). However, recently RO technology has broken into the seawater desalination field and many of the pre-treatment chemicals have been eliminated. Moreover, RO bundles were used to operate at high pressure (17 bars) but now they are able to produce water at about 11 bars, which means a considerable reduction in energy costs. Likewise, multi-stage flash distillation has been improved, and it has been a leader of thermal and seawater desalination for decades due to the high production rates that it can provide.
The aim of this study is to utilize solar pond technology to exploit a source of energy that is free, i.e. the sun, to improve the performance of multi-effect evaporators and to greatly reduce the energy costs, as MEE is the only commercial thermal desalination technique that can operate at low temperatures; this matchless feature makes it suitable for solar ponds. Thus, coupling a solar pond with MEE would efficiently provide drinking water to cities and villages from seawater or brackish water sources at reasonable cost. The ability of MEE to work stably under operating conditions that fluctuate makes this an ideal coupling, as there will undoubtedly be frequent changes in operating conditions due to the weather. This SGSP-MEE coupling system will reduce the need for conventional energy sources, which will substantially contribute to reducing any greenhouse gas emissions; huge amounts of fossil fuel are burned to produce millions of cubic metres of fresh water all over the world on a daily basis.

After validating the model, the above model has been improved to satisfy the aim of this chapter, which is to use a salinity gradient solar pond to provide heat for an MEE plant under Saudi Arabian weather conditions. The forward feed method has been selected because of the lack of water sources in Saudi Arabia and to make the brine as concentrated as possible in order that it can be reused in the solar pond. The horizontal falling film configuration is adopted, as it offers a high heat transfer coefficient, which in turn should improve the system’s performance. The mechanical vapour compressor (MVC) has been chosen to support this system for the following reasons:

- The mechanical vapour compressor needs only a moderate capital cost.
- The turbo-compressor has a proven reliability for a long operational lifespan.
- It does not consume much energy.
- It does not need heat and steam to operate.
- It can work for high production rates.

Based on the above features, the system has been configured as shown in Figure 5.12, and it is initiated with 4 evaporator units. The feed water is initially pre-heated through the condensers and then sprayed on the horizontal tubes in the first effect, to form a thin falling film on the outside area of the tube, while inside this horizontal falling film tube, there is hot water pumped from the storage zone of the solar pond at varying flow rates and temperatures. The hot water temperature is governed by the
solar pond performance, which is related to the weather changes; the evaporators and the other units in the MEE plant will operate accordingly. Once sufficient heat is provided to the first effect, the sprayed feed water starts to evaporate inside the first evaporator, and the vapour rises and passes through a demister toward the top of the evaporator. The demister is fixed to prevent any impurities that may be associated with the vapour from polluting the product. Any inlet water that is not evaporated in the first effect, i.e. brine, is pumped or driven by gravity to be sprayed into the second effect, and the resultant vapour from the first effect is used to evaporate this brine. The second effect must be under further vacuum to ensure that the evaporation in it can be achieved, and the vapour latent heat should be released to evaporate the falling brine outside the tube and to condense the previous effect’s vapour inside it. In other words, each effect (except the first effect) should operate at a lower pressure than the one before and should use the previous effect’s vapour to evaporate its inlet sprayed feed water. In the forward feed multi-effect evaporator (FF-MEE) method, the inlet feed is the blow-down from the previous unit. The other effects operate as the second effect, and finally the last effect’s vapour can be used in various ways but here it is compressed by the MVC up to the required temperature and pressure. This compressed vapour will enhance the hot water (which comes from the solar pond) by providing further heat energy, and will assist in generating low-pressure conditions in the MEE units. The condensed product water and the brine in each boiler are utilized in preheating the feed water.

The concentrated blow-down can be conveyed to the solar pond to compensate for the daily evaporation process to the environment, or may be sent to an evaporation lagoon to collect free salt; both processes could accomplish a zero discharge technology, i.e. this technology is environmentally friendly.

A steady state Matlab script has been programmed to obtain the temperature values from the similar solar pond’s Matlab script in Chapter 3, but with different dimensions to improve the SGSP performance (to give more insulation to the storage zone, the gradient zone in this SGSP has been increased to 0.9m, and the upper layer and the storage zones are 0.2 and 0.3m, respectively). These output temperature values and the above FF-MEE-MVC falling film module can be used to estimate the
performance of a multi-effect evaporator plant assisted by a salinity gradient solar pond on hourly, daily or monthly bases, although the daily-averaged monthly method is adopted in this study. The effects of the variables will be studied from two main perspectives, which are the operating temperature and the heat transfer area.

5.6.1 Effect of Solar Pond Temperature

The SGSP-MEE system is heavily dependent on the storage zone temperature in the solar pond. The temperature varies according to the weather conditions, and this can be seen in the monthly temperature profile in Figure 5.18. The pond is able to collect sufficient solar energy to raise the temperature of the storage zone to 116°C in summer, and fortunately this summer temperature is sufficiently dependable to support the plant’s operation.

![Figure 5.18: The temperature profile during a year.](image)

However, the SGSP may not provide enough heat to operate the MEE plant in the winter, as the storage zone temperature is gradually reduced to as low as 23°C (under
this study’s conditions). Thus, the system may need to be assisted by an electric heater or any other heating device during the winter months in order to maintain the temperature of the storage zone at a sufficiently high level to allow the plant to continue operating; such low performance for any solar energy application in the winter season is only to be expected. The annual maintenance, however, could be scheduled for the coldest month, when the water demand would be at the lowest level.

As investigated in Chapter 3, it is not accurate to include the start-up season temperatures, and a more realistic temperature for January can be roughly assessed by calculating the mean temperature value for January and December at the end of the first year. The second month’s temperature, which is February in this study, may be raised by 8% to make it closer to the steady state temperature. Alternatively, the second year of the SGSP’s operational period could be adopted for more accuracy, particularly for the first 2 or 3 months, but the other months of the first and the second years are approximately the same. The solar pond’s temperature can also play a key operational role in the operating temperatures within each evaporator. The performance of the SGSP over two years of operation is illustrated in Figure 5.19.

![Figure 5.19: Two years of pond performance.](image-url)
5.6.2 Effect of Top Brine Temperature

The top brine temperature depends mainly on three operational factors, which are the gained temperature, the feed salt concentration and the pressure in the first effect. The temperature depends on the amount of heat transmitted to the feed water in the first evaporator, which is in turn affected by the solar pond’s storage zone temperature, the hot water flow rate, the regenerative steam temperature and flow rate, the heat exchange area and the tube heat transfer coefficient. The amount of total dissolved solids (TDS) in the plant’s input feed water varies according to the source of that feed water, which can be brackish, seawater or brine; a TDS value of 30,000mg/l (3%) is assumed in this investigation. The feed concentration of the second effect and onwards will be affected by the evaporation percentage in the previous boiler. TBT changes markedly with vapour pressure in a direct relationship, as shown in Figure 5.20 for some common boiling point temperatures in MEE plants. Consequently, the vacuum created by a vapour compressor can significantly affect the boiling point temperature, as the VC usually controls the pressure magnitudes in the MEE units.

Greco et al. [170] reported that the Trapani MEE plant operates efficiently with a top brine temperature (TBT) at 55°C with a gain output ratio (GOR) of 16.6%. In this research, it is assumed that the minimum top brine temperature is 60°C, and if there is any shortage in the coldest months, an auxiliary source will provide further heat to increase the temperature up to 60-65°C in order to ensure continuity in MEE operation.

In the MEE plant design stage, the heat transfer area of the evaporators and condensers depends heavily on the top brine temperature and it is clear from Figure 5.21 that the required heat transfer area to produce 1kg of distilled water decreases as the TBT increases. This inverse relationship shows that if the temperature is increased from about 70 to 80°C, the heat transfer area could be reduced by nearly 51% (for a 1kg production rate of fresh water); indeed, 269% of the area could be saved by operating between the minimum and maximum TBT.
Figure 5.20: The boiling point temperature to pressure relationship.

Figure 5.21: The relation between the required area and the top brine temperature.
This difference in the heat transfer area values may be taken into account in the capital cost considerations but in cases when the MEE plant is to operate for decades, this cost can be disregarded; it is not significant relative to the running costs and the environmental considerations, in terms of lower emissions, are more important. Therefore, it would be appropriate to design the plant to operate at the lowest possible temperatures. Both plant operational and solar pond temperatures (in addition to the minimum operational temperature) are shown in Figure 5.22.

![Figure 5.22: Solar pond and MME operating temperatures.](image)

### 5.6.3 Effect of Evaporator Heat Transfer Area

The relationship between the heat transfer area and the operating temperature is explained and plotted in the above section but the thermal transfer area is also connected to other operational factors, such as feed and intake temperatures as well as flow rates.

If the main effect temperature is set to 60-65°C, the relationship between productivity (in kilograms per second) and area (in square metres) is linear, as in Figure 5.23. For example, the required heat transfer area increases from about 40 to 80m² when the
productivity rises from 1 to 2kg/s, and the other assumed production rates and the obtained heat transfer area are likewise, in terms of increment percentage.

\[ \text{Figure 5.23: The effect of production rate increase on the required heat transfer area.} \]

### 5.6.4 Effect of the Mechanical Vapour Compressor

The mechanical compressor can raise the last effect’s product vapour to the required temperature and pressure, to be used in heating the first effect. The MVC in this study has an efficiency of 0.589, while its isentropic efficiency is set to 1.32. By running the program module at the given conditions with these efficiency values, it is found that the turbo-compressor requires 3.5 to 3.6kWh to elevate one cubic metre of water vapour by 1°C via the vapour compression process.

The compressed vapour is normally converted to superheated vapour immediately after the compression process, and this superheated vapour is preferable to the saturated state for rotating turbine blades for power generation purposes, as it has a lower moisture content and fewer water drops, but the saturated vapour may cause serious corrosion inside the turbines. Thus, some of the MVC output vapour can be efficiently utilized for power generation; this also is in the interests of clean energy.
usage, as conventional power stations and desalination plants burn crude oil in their operations, which has serious ramifications for the environment.

A significant advantage to using a vapour compressor unit in a multi-effect plant is utilizing the latent heat difference between the last effect and the first effect. In this module, the last evaporator latent heat is about 2393.5kg/kJ, while the required heat for the first effect’s optimal operating conditions is only 2359kg/kJ. The latent heat differences between the first and last effects at 60 and 100°C operational temperatures, respectively, are presented in Figure 5.24; this drop in temperature and change in latent heat from the last to the first effects may vary according to several factors, such as the number of effects. At a certain top brine operation temperature, the increment in the latent heat increases as the temperature difference increases between a first and last effect in an MEE plant.

As superheated steam does not add much heat to the feed water, it is widely accepted in desalination to use a compressor to raise the temperature by 5-10°C, as assumed in this module.
5.6.5 Thermal Load in the System

There are two main sources of thermal load in the first effect; the solar pond circulation line heat and the regenerative line latent heat, in addition to the auxiliary heat source when it is required. The first boiler is supposed to operate at 60°C and the feed water can be pumped at around 35°C for the evaporation process, but to achieve this evaporation, about 342.6kJ of heat energy is required for each kilogram of feed water, based on the current system’s conditions. When the feed water is at 40°C, the required heat for evaporating 1kg of the raw water is reduced to 321.7kJ. This means every 5°C of feed water temperature represents about 21kJ for each kilogram of saline water. Thus, the boiler’s required thermal load depends essentially on the feed temperature, which is obtained by adding the raw water temperature to the temperature gained from the heat exchange process between the product and the brine in the condenser unit (heat exchanger).

5.6.6 Condenser and Pre-heater Heat Transfer Area

The heat transfer area and the quality of the condenser or the heat exchanger should be carefully considered during the plant design stage, although the presence of a mechanical vapour compressor may reduce the importance of the condenser in some cases. The module has been designed to investigate the feed temperature increase with and without the MVC; it is essential to have a condenser in the case of a multi-effect plant operating without a MVC.

Three different last boiler temperatures have been assumed in order to investigate the effect of the discharge temperature on the heat transfer area of the condenser in reaching various feed temperature values, and the results are plotted in Figure 5.25. The three temperature values are 46, 56 and 66°C, and it is found that to elevate the feed water up to 40°C, the system with a last effect temperature of 66°C needs a condenser with a heat transfer area of about 9.7m², but when the last effect produces water at the other two temperatures, the heat transfer area needs to be increased by about 242.3% and 54.6% for 46 and 56°C, respectively.
Another substantial advantage to the use of a mechanical compressor in a desalination plant is that the plant can work without a condenser; this would reduce both the capital and maintenance costs. However, in this module a heat exchanger is used to increase the temperature of the intake water by gaining the heat from both the brine and distillate water.

Most heat exchangers are unable to bring the exit stream temperature very close to the hot inlet fluid temperature but the majority of them can exchange the heat to a considerable degree of temperature convergence. A pre-heater with high exchanging performance is usually quite expensive and it needs a considerable heat transfer area. There are other factors that may affect the required heat transfer area, such as fluid flow rates and temperatures, heat transfer coefficient, etc.

The MEE output fluids are produced with an average temperature of about 56°C, assuming that the top brine temperature is operating at about 60-65°C. The result is plotted in Figure 5.26 for this average operational temperature in addition to ±10°C, which has been added to illustrate the effect of these changes in the heat of the feed water and the operational temperatures on the required heat transfer area. The MEE feed water temperature is set to vary from 30°C to less than the average value of the

Figure 5.25: The effect of last effect temperature on condenser heat transfer area without MVC.
boiler temperatures, but the other exchanger streams are assumed to have constant temperatures in order to investigate the effect of any feed temperature increase on the pre-heater heat exchange area.

It is found that to reach a certain feed water temperature, the required heat transfer area (in a pre-heater) increases as the average operation temperature increases, and also the required area rises if the feed water temperature is elevated. This increasing trend is respected as long as the temperature driving force of the MEE discharge water is higher than the cold stream temperature driving force. It should be noted that the logarithmic mean temperature method in Equations 5.30 and 5.31 is not valid if the temperature differences are equal at both ends of the heat exchanger; the average difference temperatures can be used as an alternative solution.

![Figure 5.26: The relationship between the inlet temperatures and the required HTAs.](image)

In a similar way, the effect of the exchanger discharge temperature on the pre-heater required heat transfer area has been studied and is sketched in Figure 5.27. Any increase in the exchanger output temperature (MEE product pipes) leads to a remarkable decrease in the required area for the heat exchanging process at a certain average operational temperature. A higher-than-average boiler temperature requires less transfer area at a lower exchanger output temperature, however when this output
temperature rises considerably, the required heater area will be more than at lower operational temperatures. This is because of the effect of the temperature driving force changes on the pre-heater heat load and on the log mean temperature as a result of changing the cooler inlet and outlet stream temperature (MEE outputs). The exchanger thermal load is reduced by 45% due to a 10°C incremental drop in the output temperature at the boilers’ average temperature of 46°C, but at 66°C MEE average temperature, the heat load is reduced by 22.5% as a result of the effect of the same increment. At the same time, the log mean temperature would affect the calculation for the required heat transfer area because of the raising of the pre-heater blow-down stream temperature by 10°C, and this is apparent in the increase by 186.7% and 118.2% in the log mean temperature when the evaporation is achieved at 46°C and 66°C operation temperatures, respectively.

Figure 5.27: The relationship between the outlet temperatures and the required HTAs.

5.6.7 Solar Pond Recirculation Flowrate

To commence the evaporation process based on the given SGSP-MEE-FF system, each single kilogram of raw water requires about 351.2kJ of heat energy. The main source of this required heat energy is the storage zone of the solar pond but it would be supported by a mechanical vapour compressor, and, when it is needed, the system is further enhanced by an external heat source in the winter season. The storage zone
temperature drop as well as the zone’s stability must be monitored during the heat extraction process to avoid any damage to the solar pond’s performance or overall integrity. A proportion of the storage zone’s hot water is withdrawn and circulated to provide the first effect with the heat energy required to start the evaporation process. It is found that to transmit this magnitude of heat, the hot water recirculation flow rate should be about 16.73kg/s in the case of the feed water being preheated to 35°C and the regenerative tube has not yet begun working. Once the regenerative system is working, the required heat from the solar pond is reduced to 115.5kJ/kg for the feed, i.e. a 67.1% heat reduction, and the SGSP hot water flow rate will be lessened to 5.5kg/s (18m$^3$/hr). This would result in only a 5°C drop in the storage zone temperature. Consequently, at steady state operation, the system is expected to collect 67.1% of the required heat from the vapour circulation and 32.9% of the thermal energy needed from the pond, although the latter heat percentage is supported by an auxiliary heat source during some winter months.

The effect of the MEE steady state operational mode on the storage zone of the solar pond temperature for 2 years is plotted in Figure 5.28. It can be seen from this figure that the drop in temperature is limited by employing the recirculation line. Also, the solar pond heat can be utilized in winter to raise the feed water temperature by between 5 and 10°C, which should reduce the level of electric energy consumption (by using this renewable harmless energy).

![Figure 5.28: Effect of MEE operation on the solar pond temperature.](image-url)
## 5.7 Summary

The results of SGSP-MEE system for different numbers of evaporators have been summarized and are detailed in the table below.

**Table 5.4: SGSP-MEE summary.**

<table>
<thead>
<tr>
<th>No. of Effects</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBT °C</td>
<td>59.70</td>
<td>62.13</td>
<td>63.56</td>
</tr>
<tr>
<td>Each area m²</td>
<td>45.38</td>
<td>50.84</td>
<td>57.57</td>
</tr>
<tr>
<td>Thermal load kJ/kg</td>
<td>421.20</td>
<td>351.28</td>
<td>309.35</td>
</tr>
<tr>
<td>Pre-heater area m²</td>
<td>22.46</td>
<td>15.09</td>
<td>10.92</td>
</tr>
<tr>
<td>SGSP req. heat kJ/kg</td>
<td>106.13</td>
<td>115.55</td>
<td>121.14</td>
</tr>
<tr>
<td>SGSP water flow rate kg/s</td>
<td>5.05</td>
<td>5.5</td>
<td>5.77</td>
</tr>
<tr>
<td>Effect Temperature °C</td>
<td>59.70</td>
<td>62.13</td>
<td>63.56</td>
</tr>
<tr>
<td>effect distillate kg/s</td>
<td>0.33572</td>
<td>0.25179</td>
<td>0.2013</td>
</tr>
<tr>
<td>Effect Brine kg/s</td>
<td>2.1643</td>
<td>2.2482</td>
<td>2.30</td>
</tr>
<tr>
<td>Effect Brine Conc. ppm</td>
<td>48514.96</td>
<td>46703.87</td>
<td>45678.91</td>
</tr>
</tbody>
</table>
6. Conclusions

This study has utilized one-dimensional study state model to predict the performance of a salinity gradient solar pond in sunny climates such as Saudi Arabia. A specially designed code has been developed utilizing a predicted equation to use a single input data for calculating the solar radiation at any sunny part in the world with a good result. The monthly averaged daily solar irradiation method have been used for these computations. Predicting the solar pond performance in a cold climate has been investigated and a comparison with Saudi Arabia's solar pond in terms of the input heat and the major heat loss. Coupling the salinity gradient solar pond with Multi-effects desalination plant for a large pond in Saudi Arabia has been studied. The following results have been concluded;

Salt gradient solar pond technology is ideally suited to arid and semi-arid areas such as Saudi Arabia owing to the abundance of solar radiation, the thermal energy from which can then be employed to generate power for desalination purposes. Coupling a solar pond with a desalination unit could assist in addressing the single major issue in such areas, that of providing fresh potable water to the inhabitants. This combination could also work efficiently in cold climate countries to provide space heating.

Fortunately, the costs involved in solar pond construction are quite reasonable given a lifespan of decades, and these ponds are on the whole ideal when specifically designed for use with desalination plants. Furthermore, the costs involved in building solar ponds are relatively cheaper in Saudi Arabia because salt, concentrated saline water and land are all plentiful and almost free.

As expected, the greatest heat loss from the upper layer is a result of evaporation heat, and therefore covering the solar pond could significantly reduce this loss and may even improve the solar pond’s performance. It has been found that covering an SGSP can raise the average temperature by 30%, i.e. from 76.6°C to 100°C, for example.
The thickness of each of the three layers in a solar pond is critical to its performance, and must be carefully determined. It has been proved that the upper convecting zone should be 0.2-0.3m, the non-convecting gradient zone around 1m and the lower convecting storage zone 0.3-1m.

The cleanliness and transparency of a solar pond is also an extremely important issue, as impurities in the saline solution may scatter the solar radiation, thereby reducing the efficiency of the storage zone, which is certain to reduce the solar pond’s performance.

The predictive empirical equations for solar irradiation calculations have been examined for three different locations in the Middle East through building a unique computer program, and these equations for computing solar irradiation have been utilized through single input data. This program has provided good predictions, which compare well with the NASA (22-year average) data.

Time-dependent steady state model has been developed to predict the behaviour of solar pond temperatures. It has been found that the steady state model offers good accurate solutions in this study. It is also found that the pond can reach the steady state case between the second and the third month of the pond’s operation. Thus, the second year of operation can be recommended or the first month can be calculated as the average of the first and the last month values, while the second month may be increased by about 8% to represent more accurate temperatures.

Constructing a solar pond in Saudi Arabia with an area of 100 x 100m and with a gradient zone thickness of 1m may be considered to be the ideal dimensions for a pond, as it can provide hot saline water with a temperature exceeding 100°C. Moreover, if this pond is covered, the temperature may be increased by 30%.

The solar pond can work effectively and can provide considerable heat in a cold climate region such as at the University of Surrey, UK, and using an SGS pond can supply heated water with a temperature reaching more than 80°C. Utilising such heat in space heating in the university buildings could save a considerable amount in energy consumption for the university.

It is estimated that the input irradiation in a solar pond located in a sunny region such as Saudi Arabia is higher by 240% than a pond in a cold weather location.
Unite Kingdom is an example. However, the major heat loss occurs as a result of evaporation and it is also found that the evaporation heat loss in Saudi Arabia's solar pond is as much as 350% higher than the one in UK, Surrey. This can support and explain that a salinity gradient solar pond can work in a good performance even in the cold climate countries.

The stability of an SGSP can be determined by the appropriate static and dynamic stability criteria, and this stability is influenced by several factors, such as the upward salt diffusion, the type of salt used, the heat flux, the rate of heat extraction, and the amount of evaporation and wind. However, the stability is not of concern if the pond is seasonally supplied with about 40kg of salt for each square metre of the pond’s surface area and its surface layer is kept provided with fresh water to compensate for evaporation.

Direct extraction from the lower zone of the solar pond is the most convenient heat removal approach for falling film multi-effect evaporators (FF-MEE). The design of the heat extraction system should ensure that the withdrawal of heat is performed as smoothly as possible. If the pond is small, the suction and re-injection of hot brine should be in opposite directions, however for large solar ponds the heat removal circulation system can be located on one side. The extraction point should be few centimetres below the gradient layer while the level of the return diffuser is advised to be a few centimetres higher than the solar pond’s base.

It has been found that an SGSP can be successfully coupled with Multi-Stage Flash distillation (MSF) and Multi-Effect Evaporators (MEE). However, the MEE is more convenient than MSF as it operates more smoothly with variations in feed temperature, requires a lower top brine temperature, and costs less in terms of construction and operation. It has been reported that several MEE plants have been successfully operating with a top brine temperature of 58.5°C.

Recently, vapour compressors have been adopted in MEE plants, and thus it is essential to utilize a VC in this system; both mechanical and thermal vapour compressors can be used in these couplings. It is estimated that an MVC needs about 3.5kWh of electricity to elevate the vapour temperature by 1°C for each 1m³ of fresh water product. The compression is usually used to raise the last effect’s
temperature by between 5 and 10°C but it could be considerably higher if the vapour were used for turbine blade rotation (for power generation purposes) in this system. The existence of the MVC eliminates the need for a condenser unit. Regenerative circulation is essential for reducing the required heat load; it is found that the use of this circulation system can provide about 67.1% of the required heat for the first effect of the plant, and it can reduce the SGSP’s required hot water circulation flow rate from 16.73kg/s to 5.5kg/s.

Although solar ponds, like all solar energy techniques, suffer from variations in the energy source due to weather fluctuations, their unique feature is that they can provide heat for the majority of months in a year. The published SGSP reports have recorded 70°C as a minimum average temperature, such as at the El Paso solar pond in Texas, USA. However, in case of any shortage in the heat required, the SGSP-MEE system can be assisted by an auxiliary heat provider, powered by electricity.

The required heat for delivering 1kg of distillate water through a vacuum evaporation process at 60°C is 2359kJ/kg. In this 4-effect system, the first effect requires 351kJ for each 1kg of feed water (pumped at 35°C). Raising the feed water temperature from 35 to 40°C may save about 21kJ/kg of the heat energy requirement.

The evaporators’ required heat transfer area decreases as the top brine temperature increases, and thus it is estimated that if the temperature is increased from about 70 to 80°C, this would reduce the heat transfer area of the evaporators by nearly 51% for a 1kg production rate of fresh water, and 269% of the area can be saved by operating between the minimum (60°C) and maximum (105°C) top brine temperatures in this study’s conditions.

The SGSP-FF-MEE plant proposed in this study was initiated with 4 evaporators but then extended to cover 3 and 5 effects. As the number of evaporators increases, the required heat transfer area for each evaporator and the top brine temperature, withdrawal circulation flow rate, and the product per each effect all increase, while, for producing the same amount in terms of plant capacity, the preheater heat transfer area and the required thermal load both decrease accordingly.
7. Future work

The following points require further investigations;

- The transient model for a salinity gradient solar pond needs to be investigated for both hot and cold climate solar ponds.
- Covering the solar pond in different transparent cover materials and the covering effect on the solar pond performance should be studied in details.
- There is a shortage in the information about the convecting salt and saltless solar ponds, thus searching such subject may bring further knowledge and understanding about the convecting solar pond.
- Coupling a salinity gradient solar pond and shallow solar pond may support the gained heat by two heating steps; preheating by the gradient pond and further insolation by the shallow solar pond. It could useful of this coupling performance can be researched.
- The salinity gradient pond works by the concept of preventing the convection inside the pond. Thus, it may be interesting to study the level of saturation in which the saline solution can be heavy enough to prevent the convection in the whole pond.
- There are many points in the solar pond performance and the stability of the pond have not been fully understood yet such as the marginal stability, the dynamic stability factor effects and this fact has been stated in the majority of the references. It can be useful to investigate such points.
- Further study about using the SGSP for the desalination is required such as using two phases heat extraction method to utilize the latent heat, using multi-flash desalination technique with this coupling.
- This coupling can be also utilized in generating electricity power by superheating the vapour through the mechanical vapour compressor to rotate a turbine blades for generating power. The study of such integrated system for power generating and water desalination may be suggested to studied. The membrane technology may be also included in such research.
8. References


[26]- Enersalt website (2011) Solar pond. Available at: 


