OPTIMIZING THERMAL STORAGE EFFICIENCY OF A SALT GRADIENT SOLAR POND USING POLYETHYLENE MEMBRANE

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A Thesis Submitted to the Graduate School in Partial Fulfillment for the Requirements of the Award of Master of Science Degree in Chemistry of Egerton University

EGERTON UNIVERSITY

AUGUST, 2015

DECLARATION AND RECOMMENDATION

DECLARATION

This thesis is my original work and has not been submitted for examination in any other institution.

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ABSTRACT

The need for energy has risen greatly all over the world in recent years. One major source of energy is fossil fuel and most countries get access to this fuel through imports. Besides the rise in cost of fossil fuel, it has serious impacts on the environment which include air pollution and increased greenhouse gases in the atmosphere. Furthermore, this source of energy is nonrenewable and is quickly being depleted. Recently, attention has turned to environmentally benign and sustainable sources of energy. Solar radiation constitutes a vast energy source which is abundantly available all over the earth. Solar energy is in many regards viewed as one of the best alternatives to non-renewable sources of energy. One way to collect and store energy is through the use of solar ponds which can be employed to supply thermal energy for various applications such as process heating, water desalination, refrigeration, drying and power generation. Solar ponds consist of three distinct layers of salt solution stratified by their differences in density, usually called salt gradient solar pond. The bottom layer of the solar pond always has the highest salt content and is thus the heat storage layer. This study aimed at constructing model rectangular solar ponds made from transparent Perspex glass material painted black at the bottom to increase absorption of solar radiation. The rates of diffusion and efficiencies of the salt gradient solar pond and one stabilized by a low density polyethylene was determined and compared by studying the kinetics involved using the hourly temperature rise during the day when there was active solar radiation. This was achieved by measuring the salt concentrations of the layers using a refractometer which measures the refractive index of solutions. The efficiency was calculated using the temperature differences between the start and end of the experiment and was measured using thermocouples connected to a digital thermometer. Results show that the efficiency of a polyethylene stabilized pond rises from 0% to about 69% compared to the traditional solar pond with about 52%. This is attributed to the polyethylene used brings about greenhouse effect where the solar radiation absorbed is trapped and therefore the storage zone heat rises more. The best solar pond system with the highest thermal storage efficiency of 69 % was identified from the various combinations of salt concentration of the layers. The results also show that efficiency of the storage zone increases with increasing salinity and the optimal LCZ concentration was found to be 25% salinity, 10% for NCZ and 0% for UCZ. At these concentrations, there is formation of a clear gradient zone which is stable and therefore hinders convection currents to occur.

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LIST OF ABBREVIATIONS & ACRONYMS

CFCs	Chlorofluorocarbons
HSZ	Heat Storage Zone
IPCC	Intergovernmental Panel on Climate Change
LCZ	Lower Convecting Zone
LDPE	Low Density Polyethylene
NCZ	Non- Convecting Zone
OTA	Office of Technology Assessment
REN	Renewable Energy
SGSP	Salt- Gradient Solar Pond
UCZ	Upper Convective Zone
UV	Ultraviolet

CHAPTER ONE

INTRODUCTION

1.1 Background information

Energy use all over the world has risen tremendously over the past three decades and is expected to continue rising even further in the near future. It is essential for economic growth and improved living standards. The major sectors of the economy spending the majority of primary energy sources include electricity generation, transportation and industrial. The International Energy Agency (IEA) data reveal that the electricity demand almost tripled from 1971 to 2002 (IPCC, 2007). This is due to the fact that electricity is a very “convenient” form of energy to transport and use. The relative share of primary energy for electrical power production in the world increased from about 20% in 1971 to about 30% in 2002 and this is due to the fact that electricity is becoming the preferred form of energy for most applications.

In 2010 the world daily oil consumption had reached an all-time high record of 87.4 million barrels and despite the environmental problems related to energy use, this is expected to increase further in the next years. For many developing countries, much of the energy needed is supplied by imported fuel and with the rising cost of this fuel; these countries are overwhelmed with the challenge of seeking alternative sources of energy. Building dams or power plants to meet the ever increasing demand for electricity could push these nations even deeper into debt (OTA, 1991). On the other hand, continued reliance on fossil fuel as the major source of energy could have serious impacts on the environment. These include air pollution as well as increased atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2) which is the major product of combustion of fossil fuel. International efforts to control greenhouse gas emissions require active participation by developing countries because many developing countries could be adversely affected by climate change much more than many industrialized countries (IPCC, 2007).

Energy is considered as the most significant factor in economic development. After the oil crisis, at the early nineteen seventies, the concern was on the cost of energy, during the past two decades however the problems associated with environmental degradation are more apparent. This energy related environmental problems are due to a combination of several factors such as the increase of the world population and the consequent energy consumption, and the expansion of the industrial activities. Many scientists now realize that the possible solutions to environmental problems would require long-term actions for sustainable development. As part of this, the dependence on renewable energy resources appears to be the most effective solution. Another parameter to be considered is the world population. By the end of 2011 the world population reached 7 billion and with the current rate of increase it is expected to double by the middle of this century. As economic development will continue to grow, the global demand for energy is expected to increase.

Until recently, only conventional pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulates, and carbon monoxide (CO) were considered in environmental analysis. Recently however, carbon dioxide (CO_2) and hazardous air pollutants, which are toxic chemical substances which are harmful even in small doses, are considered in such analysis. In fact carbon dioxide, which is a greenhouse gas, plays a vital role in global warming, being responsible for about two-thirds of the greenhouse effect as fossil fuel combustion is the most significant contribution to the CO_2emittedto the atmosphere. If humans keep degrading the environment, the future of our planet and of the generations to come will be negatively impacted. The three environmental problems that are today well known are:

- **Global climate change:** This is brought about by greenhouse effect which refers to the role of the atmosphere to keep the surface of the earth warm. During the last years however, it is increasingly associated with the contribution of various gases such as CO_2, CH_4, CFCs, N_2O, ozone and peroxyacetylnitrate in rising the earth's temperature. These are produced by the industrial and domestic activities. Increasing atmospheric concentrations of these gases, called greenhouse gasses, increase the amount of heat trapped by decreasing the heat radiated from the earth's surface, so as the surface temperature of the earth is raised. Today there is an agreement among the world’s leading climate scientists that global warming is caused mainly by CO_2 and other gases emitted by human activities, such as from fossil fuel combustion, methane emissions and CFC releases.
- **Ozone layer depletion:** The ozone that exists in the stratosphere plays a natural equilibrium-maintaining role for the earth, through absorption of ultraviolet (UV) and infrared radiation. A global environmental problem the planet is facing today is the depletion of the stratospheric ozone layer caused by the emissions of CFCs, and NO_x. The depletion of ozone layer can lead to increased levels of damaging UV radiation reaching the ground, causing eye damage to humans

and increasing the rates of skin cancer. Energy related activities are directly or indirectly responsible for the emissions which lead to stratospheric ozone depletion. CFCs have the most significant role in ozone layer depletion, mainly used as refrigerants in air conditioning and refrigerating equipment, as well as NO_x emissions produced mainly by fossil fuel combustion.

- **Acid rain:** This is a form of pollution in which NO_x and SO_2 produced by the combustion of fossil fuels are moved over long distances in the atmosphere and precipitated on the earth as acid rain. Therefore, the solution to the problem of acid rain requires the control of NO_x and SO_2. These kinds of pollutants cause both regional and trans-boundary problems and energy-related activities are the major sources of acid precipitation. As acid precipitation depends on energy consumption, the easiest way to reduce its effect is by reducing energy consumption.

The idea of seeking alternative sources of energy is not a new phenomenon but started way back in 19th century when whale oil was the dominant form of lubrication and fuel for lamps. The depletion of the whale stocks by mid-century caused whale oil prices to skyrocket setting the stage for the adoption of petroleum which was first commercialized in Pennsylvania in 1859. Alexander advocated ethanol as an alternative to coal and oil stating that the world was about to deplete these fuels. By 2007, there were 35000 oil filling stations throughout Brazil with at least one ethanol pump (Daniel and Paulo, 2007).

Attention has now been turned to renewable and ecologically friendly sources of energy. This is energy which comes from natural sources such as sunlight, wind, water, tides and geothermal heat. In 2008, about 19% of global energy consumption came from these sources. Solar energy accounts for most of the available renewable energy on earth since it is abundantly available on all parts of the earth. Solar energy is in many regards one of the best alternative to non-renewable sources of energy (Dincer and Rosen, 1998). It has been harnessed by humans since ancient times using a range of ever-evolving technologies. These include greenhouses for agriculture and horticulture, solar lighting, solar water heaters, water treatment, solar cookers, solar panels, solar vehicles and solar ponds (REN 21, 2010).

There has been an increase in the efforts to promote renewable energy in developing countries. Solar pond is one such technology which has been adopted in various countries across the world and is also appropriate and relevant in the Kenyan context as the country lies within the tropics where incident solar radiation intensity is high. A solar pond is a pool of saltwater which acts as a large scale solar thermal energy collector and is essentially a low cost solar collector with integrated storage; it is a cheaper alternative to flat plate collectors system when in suitable location (Kishore and Kumar, 1996; Murthy and Pandey, 2003).

Solar pond's temperature effect was first observed in Transylvania in early 1900s. It was observed that temperature increased with depth in salt lakes. This effect was due to the salts in the lakes' water which created a density gradient that prevented natural convectional currents (Anderson, 1959). Rudolph proposed this after he came across reports of lakes in Hungary in which temperature increased with depth. A prototype pond was constructed on the shores of the Dead Sea near Jerusalem (Halacy and Daniel, 1973). From then onwards up to today, artificial ponds have been constructed all over the world.

Solar ponds were generally designed for electricity production but they were not cost-competitive compared to other conventional technologies (Tabor and Matz, 1965), and so they were largely abandoned in 1975 (Dickinson and Cheremisinoff, 1980). However, in 1974, research on solar ponds as long-term heat storage devices began in the USA at Ohio University. Initially, theoretical studies were conducted on space heating (Rabl and Nielsen, 1975) and soon after, some experiments were successfully completed (Nielsen *et al*, 1977). Another solar pond was established in the USA at the University of New Mexico in 1975 (Zangrando and Bryant, 1976). 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. The measurements taken at El Paso Solar Pond recorded temperatures reaching about 90 ^{o}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 (Lu *et al.*, 2001). In the Gulf, a small pond with an area of $8m^2$ was constructed in Kuwait during the mid-1980s, and temperatures of more than 80^{o}C were reported in summer (Ali, 1986).

The solar ponds are designed such that they consist of three distinct zones; the lower convective zone (LCZ) has the highest temperature and density because it has the highest salt concentration (at saturation) and is the region where solar radiation is absorbed and stored. The upper convective zone (UCZ); mainly of pure water has the lowest temperature and density. This zone is mixed by surface winds, evaporation and nocturnal cooling. These two layers are characterized by almost homogeneous temperature and concentration due to convection. The intermediate zone whose salt content is in between the upper zone and the lower zone is called the non-convective zone (NCZ) (or the gradient zone) because no convection occurs here. Temperature and density decrease from the bottom to the top in this layer, and it acts as a transparent insulator. It permits solar radiation to pass through but reduces the heat loss from the hot lower convective zone to the cold upper convective zone. Heat transfer through this zone is by conduction only. At the very bottom of the pond is a dark layer that can absorb heat energy from the sun (Srinivasan, 1985). The salts used in these ponds include; natural brine, fertilizer salts, magnesium chloride and sodium chloride. In most cases, sodium chloride is used because it is affordable and easily available.

If the water in the pond is translucent enough, its bottom with high optical absorption, then nearly the entire incident solar radiation will go into heating the bottom layer. This means that the temperature at the bottom can rise up to 90 ^{o}C while that at the top of the pond can be around 30 ^{o}C. The heat trapped in the salty bottom layer can be used for many different purposes such as process heat, desalination, dairy industry, refrigeration and power production (Nielsen *et al.*, 2005).

Despite advances in the development of solar ponds not many last long. Not all ponds which were constructed are still operational. Many have closed down due to operational problems. The major problem is mixing of the salt layers. Some mechanisms have been devised to counter this; the simplest method was to make the lower layer denser than the upper layer by adding salt in the lower layer (Srinivasan, 1990). This could not work because of solubility problems where salt crystallized at the bottom during cold seasons and then reflecting solar radiation instead of absorption. There are other ways to prevent mixing between the upper and lower layers. One of them is the use of a transparent honeycomb structure which traps stagnant air and hence provides good transparency to solar radiation while cutting down heat loss from the pond. The honeycomb structure is made of transparent plastic material (Ortabasi and Dyksterhuis, 1985). The other one is the use a transparent polymer gel as a means of allowing solar radiation to enter the pond but cutting down the losses from the pond to the ambient (Wilkins and Lee, 1987). But these mechanisms are unpopular because they are not readily available all over the world.

In this work, a low density transparent polyethylene paper was used to separate the LCZ and NCZ in the traditional solar pond with UCZ, NCZ and LCZ. The polyethene paper has good optical properties as it allows solar radiation to reach the LCZ and less radiation is lost back to the adjacent NCZ. The polyethylene paper also does not allow upward salt diffusion from the LCZ.

1.2 Statement of the problem

Solar ponds are designed to have three distinct layers of salt solution stratified by density. These layers form a step-like concentration profile. But because of diffusion of salt from the lower zone with the highest salt concentration, this step-like is gradually converted to a linear profile and with time if diffusion is not controlled, the profile becomes uniform. This allows convection currents to occur and therefore the rate of energy loss by convection is increased. This destabilizes the performance and efficiency of the ponds and makes the cost of operation to be expensive forcing closure of some ponds. There is need therefore to check this molecular diffusion to stabilize performance and improve the efficiency of a solar pond for diverse uses. This study was aimed at minimizing molecular diffusion to optimize efficiency of a solar pond by using a low density transparent polyethylene membrane with good optical and thermal insulation properties to separate the salt layers therefore minimizing diffusion and identifying the best solar pond system that yields optimum efficiency.

1.3 Objectives

1.3.1 General objective

To fabricate a model solar pond and optimize its thermal storage efficiency by minimizing molecular diffusion using polyethylene membrane.

1.3.2 Specific objectives

i. To determine and compare the rates of diffusion of salt in a salt gradient solar pond and a polyethylene stabilized one using a model solar pond.

ii. To determine and compare the thermal storage efficiency of a salt gradient solar pond to a polyethylene stabilized one using a model solar pond.
iii. To identify the optimum combination of salt concentration of the layers for optimum thermal storage efficiency.

1.4 Hypotheses

i. There is no significant difference in rates of diffusion of salt layers in both salt gradient solar ponds and polyethylene stabilized one.

ii. There is no significant difference in thermal storage efficiency of a polyethylene stabilized solar pond and a salt gradient one.

iii. There is no significant difference in thermal storage efficiency between the different salt concentrations of the layers.

1.5 Justification

In the solar pond, the layer with the highest salt content is at the bottom and is the heat storage layer. The intermediate layer is the insulating layer to the heat storage layer by establishing a density gradient that prevents heat exchange by natural convection. When solar radiation is absorbed at the bottom, the temperature of the bottom layer rises and the rate of diffusion is increased causing the layers to mix and become uniformly concentrated overtime. The only methods which have been used to prevent mixing of the layers are a transparent plastic with honeycomb structure and transparent polymer gel but these methods have not been universally adopted because the materials are expensive and not readily available besides the plastic is not environmentally friendly. Polyethylene is an affordable and readily available material that allows transmission of solar radiation and prevents much of the trapped heat from being lost to the surrounding. Solar ponds are economically viable and can aid in provision of alternative energy since solar energy is an abundantly available renewable energy. This will help ease over dependency on fossil fuel whose impact on the environment is bad.

CHAPTER TWO

LITERATURE REVIEW

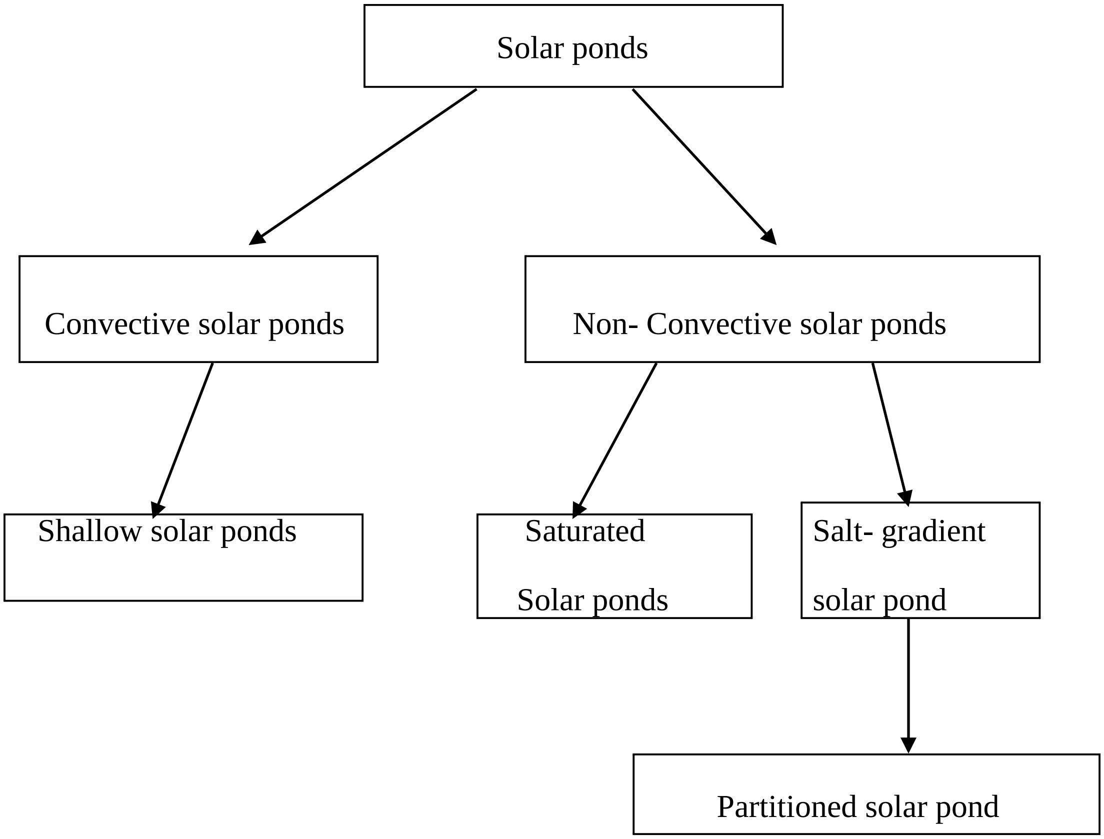
2.1 History of solar ponds

The concept of solar lake was discovered by Kalecinsky who found that Medve Lake in Transylvania was showing a maximum temperature of 70 ^{o}C at a depth of 1.32m at the end of summer. This followed the identification of similar solar natural lakes in other areas like Orovilve in Washington State (Anderson, 1959); Vanda in Antarctic (Wilson and Wellman, 1962) and Eilat in Israel (Cohen *et al*, 1977).The idea of creating artificial solar ponds were proposed by Bloch Rudolph (Tabor and Matz, 1965). A serious research effort was initiated in Israel by Tabor (1965) established the mechanism underlying solar ponds through a series of fundamental research papers. However, it received a setback in 1966 when fuel oil was competitively cheaper than that available from solar ponds. It was later revived in 1973. The interest in solar pond research subsequently spread to other countries like Australia, United States of America, Canada, India etc. (Tabor, 1981; Njoku *et al*., 2009).

Solar ponds have been studied by many researchers because of their excellent heat collection and storage performance. There have been considerable studies on solar ponds both theoretical and experimental. Theoretical studies have concentrated on modeling and predicting pond performance (Hull, 1980; Rajput, 2005). Early studies of this type were performed on one dimensional model but did not account in detail the way for dynamical thermal interactions between the solar pond and the environment. Later, researchers developed more detailed models which account for two dimensional interactions within the soil (Atkinson and Harleman, 1987) and many experimental solar ponds have been constructed, instrumented, operated and various numerical models have been developed for analyzing the performance of salt gradient solar pond (Tahat *et al.*, 2000; Hassari *et al.*, 2001).

2.2 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). Based on the convection behavior of the saline solution in solar ponds, they may be classified into two main categories: non-convecting and convecting solar ponds (Garg, 2000).



Scheme1: A scheme showing different kinds of solar ponds.

2.2.1 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 been classified in varying ways, for example, Kreider and Kreith (1982) categorized these ponds according to depth, differentiating between shallow and deep salt less solar ponds. 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.

2.2.2 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 saline water temperature. Naturally, when the sun’s ray’s 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 and lighter 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 ^{o}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 (Dincer and Rosen, 2007).

2.2.3 Salt - gradient solar pond

A solar pond is a simple and low cost mean to collect and store solar thermal energy in form of hot high- density salt water. It is artificially constructed to contain three distinct zones stratified by density differences. Significant temperature rises are realized at the bottom which has the highest salt content by preventing the occurrence of natural convection currents. This is done by establishing a salinity gradient which forms a density gradient that increases with depth, and this counteracts the temperature gradient, thus preventing heat in the lower layers from moving upwards by convection and leaving the pond. The figure below shows a typical salt gradient solar application.

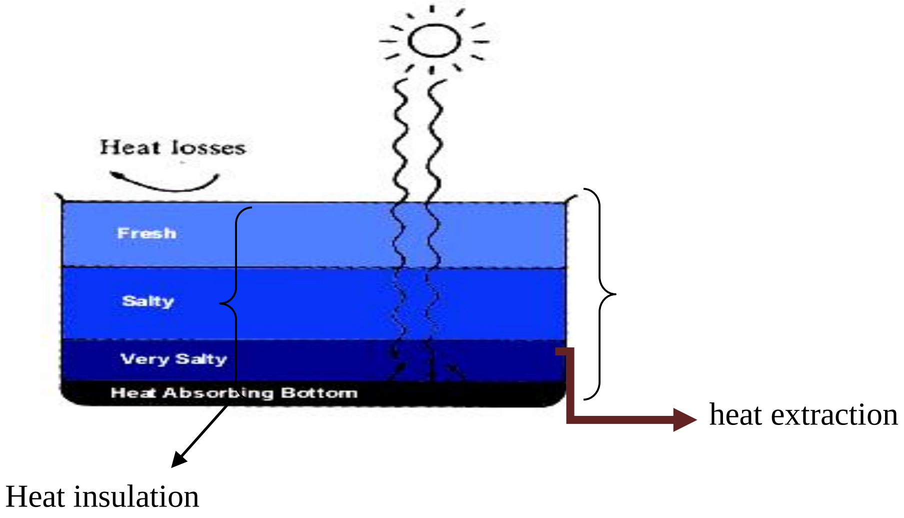


Figure 2.1: A laboratory salt- gradient solar pond

In general, a salt- gradient solar ponds are composed of three zones: The first zone called the upper convective zone (UCZ) is the fresh water layer at the top of the pond. This zone is fed with fresh water of a density near to the density of fresh water in the upper part to maintain the cleanliness of the pond and replenish lost water due to evaporation. It is also used to limit wind effects however; the increase in the thickness of this zone reduces the attainable radiation that reaches the lower convecting zone. Therefore its thickness is minimized.

Thermodynamically, thermal (energy) efficiency (η) for the upper convective zone (UCZ) is generally expressed as;

$$\eta = \frac{Qnet}{Qin} \tag{2.1}$$

Where Q_{net} is the net heat addition to the pond and equals Q_{stored} where

$$Q_{stored} = Q_{in} - Q_{out}$$

$$Q_{stored} = (Q_{solar} + Q_{down}) - (Q_{side} + Q_{wa)} \tag{2.2}$$

Q_{stored} is the net heat stored in the UCZ, Q_{solar} is the amount of net incident solar radiation absorbed by the UCZ, Q_{down} is the total heat transmitted to the zone from the zone immediately below, Q_{side} is the total heat loss to the side walls of the pond, and Q_{wa} is the total heat lost to the surroundings from the upper layer via evaporation (Kayali *et al*., 1998; Karakilcik *et al*., 2006; Njoku *et al*., 2009).

Substitution of Eq. (2) in Eq. (1) for the UCZ yields the following expression for the energy efficiency;

$$\eta_{UCZ} = 1 - \frac{(Q_{side} + Q_{wa})}{(Q_{solar} + Q_{down})} \quad (2.3)$$

$$Q = mCp\Delta t$$

Where Q is the heat, *m* is the mass of substance, *Cp* is the specific heat capacity and Δt is the change in temperature.

The second (middle) zone is the insulation zone between the lower convective zone (LCZ) and upper convective zone (UCZ). It is also called the non-convective zone (NCZ). It is comprised of salty water whose brine density gradually increases towards the lower convective zone. The NCZ is the key to the working of a solar pond. It allows an extensive amount of solar radiation to penetrate into the storage zone while inhibiting the propagation of long wave solar radiation escaping because water is opaque to infra radiation. Its thickness is considered as a thermal insulation whereas the increase of its thickness decreases the solar radiation penetrating to the storage zone. The thickness therefore should be intermediate. Similarly, the thermal efficiency for this zone is expressed as;

$$\eta = \frac{Q_{net}}{Q_{in}}$$

Where, $Q_{net} = Q_{NCZ,solar} + Q_{down} - Q_{up} - Q_{sides}$ (2.4)

Where $Q_{NCZ,solar}$ is the amount of solar radiation entering the NCZ, which is transmitted from the UCZ after attenuation of incident solar radiation in the UCZ, and Q_{up} is the heat loss from the NCZ to the above UCZ .Thus, the energy efficiency for the NCZ can be expressed as;

$$\eta_{NCZ} = 1 - \frac{\{Q_{sides} + Q_{up}\}}{Q_{NCZ,solar} + Q_{down}} \quad (2.5)$$

The third zone is known as the lower convective zone (LCZ) also called the heat storage zone (HSZ). It is composed of salty water with highest density and salt content. A considerable part of the solar energy is absorbed and stored in this region. The LCZ has the highest temperature; hence the strongest thermal interactions occur between this zone and the adjacent insulated bottom and side walls.

The general energy balance for the HSZ of the solar pond can be written as;

$$Q_{net} = Q_{HSZ,solar} - Q_{bottom} - Q_{up} - Q_{sides} \tag{2.6}$$

Where $Q_{bottom}$the total heat loss to the bottom is wall from heat storage zone and $Q_{HSZ,solar}$ is the amount of solar radiation reaching the zone (Kurt *et al*., 2000; Huanmin *et al*., 2002).

The energy efficiency for HSZ of the solar pond then becomes,

$$\eta_{NCZ} = 1 - \frac{\{Q_{bottom}+Q_{up}+Q_{side}\}}{Q_{HSZ,solar}} \tag{2.7}$$

The thickness of the zones increase from the UCZ to the LCZ where the UCZ has the lowest thickness and the LCZ the highest to make sure that much of the solar radiation is transmitted to the LCZ. The LCZ covers 40%, the NCZ covers 40% and the UCZ 20% (Fadi *et al*., 2007). The range of salt gradient in the UCZ is such that the density is 1000-1045 kgm^{-3} in the UCZ, 1045-1150 kgm^{-3} in the NCZ and 1150-1200 kgm^{-3} in the HSZ. The bottom of the pond is darkened to increase optical absorption and insulated together with the side walls to minimize heat loss through conduction (Karakilcik *et al*., 2006).

2.2.4 Partitioned solar pond

Partitioned Solar Ponds use a physical separation of at least the HSZ to avoid interactions with the NCZ to increase the temperature in the HSZ and thus to increase the performance of the solar pond. This is usually achieved through the use of a membrane. It is important that such a separation has to be of high transmittance to solar radiation; otherwise the advantages from physically separating the HSZ could equal the losses through less irradiation into the HSZ. The big advantage of a physical separation of the HSZ from the rest of the system lies in the increased stability of the several layers when heat is extracted from the HSZ. A membrane does not allow any disruptions and interactions between the HSZ and the upper layer, no matter if it is a NCZ or a UCZ or only one fresh water layer. The disadvantage of adding a physical layer to a system where solar radiation is the only input is obviously the diminished total transmission of sun light to the bottom of the pond. Since this is an optical boundary layer, there will be of course optical effects like reflection, transmission and absorption which counteract the performance of the pond. Another problem which can occur is the stress of the membrane due to thermal expansion of the HSZ or the gravitational pressure of the NCZ. If the HSZ cools down or if heat is taken out of the HSZ a negative thermal expansion will occur. A fracture in the membrane could affect the performance of the pond heavily and cause mixing of the layers (Garg, 1987; Benjamin, 2010).

2.3 Working principle of a solar pond

The solar pond works on a very simple principle.Naturally, solar radiation is absorbed at the bottom of the pond and raises the temperature of the water at the bottom. The hotter water at the bottom becomes lighter and hence rises to the surface. Here it loses heat to the ambient air and, hence, a natural pond does not attain temperatures much above the ambient. The working principle of a solar pond is based on the capture of solar radiation in a salt solution (Duffe and Beckmann, 1991). The bottom layer is a concentrated (saturated) salt solution; the middle layer has a salt concentration gradient with decreasing salt concentration upwards and is the insulating layer with a salt gradient that establishes a density gradient that prevents heat exchange by natural convection. The density of the bottom salt layer compensates for this effect and therefore there will be no upward convection of warm water. The result is that the solar pond will only be hot at the bottom and the heat is trapped in the bottom salt water layer.

Evaluation of thermal performance of a solar pond emphasizes on the LCZ because it is the heat storage zone. An assumption of steady state condition is made and the energy balance of a solar pond can be written as;

Rate of heat input = rate of heat stored in the lower convective zone + rate of heat losses to side and bottom of the pond

The rate of heat input is a function of thermal conductivity of pond water which is dependent on temperature and salinity of the layers and rate of heat stored is a function of specific heat which is dependent on salinity and density of the LCZ. The rate of temperature rise as a function of time is given by;

$$T(t+\Delta t)=\frac{\left\{As[h(z)Io+KwTa/dncz]+[\frac{Tt}{\Delta t}]\right\}}{\left\{\left[\frac{mCp}{\Delta t}\right]+[\frac{AsKw}{dncz}]\right\}} \tag{2.8}$$

Where T is the temperature (^oC), t is the time (s), Δt is the time interval, As is the surface area (m^2), $h(z)$ is the fraction of solar radiation penetrating to the depth z in the pond, Io is the hourly insolation incident upon a horizontal surface (w/m^2), kw is the stored water's thermal conductivity (w/mk) , Ta is the ambient temperature (^0C), $dncz$ is the non-convective zone vertical extent (m), m is the mass of water in storage layer (kg) and Cp is the specific heat capacity of stored water (J/kgK) (Tahat *et al.*, 2000).

In practice the convection in solar ponds is inhibited by raising the viscosity of the pond by adding gelling agents, for example, a polyethene oxide adduct of a hydrophobic residue. Convection is further inhibited by dividing the pond into cells such that the Rayleigh number of the fluid within the cell structure is less than the critical Rayleigh numbers at which convection may occur. The dividers may be translucent or transparent generally horizontal sheets forming matrices which are in horizontal cross-sections. Alternatively, the gelled fluid medium of the solar pond may be bagged in translucent elongated bags which when arranged in the pond have their shortest dimension less than that which will support convection (Karakilcik and Dincer, 2008). Thermal storage has always been the most significant method of energy storage. Solar ponds are a classical application of the thermal energy storage and their performance depends essentially on the storage capacity of the fluid, thermo physical properties of the pond and the surrounding conditions (Dincer and Rosen, 2003).

2.4 Salts used in ponds

Salts are used in solar ponds because of their high heat capacities. Those commonly used are sodium chloride, magnesium chloride and fertilizer salts. Initially natural brine was used but the maximum temperature obtained in the natural brine solar pond is less than sodium chloride used solar ponds (Hassairi *et al.*, 2001). The environmental effects and maintenance problems associated with solar pond dictate what salt to be used. Any possible leak of salt solution to the ground may impede the water table or render the soil highly saline.

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 (Garg, 1987; Rard and Miller, 1979).

- 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 *Ks* should be low.

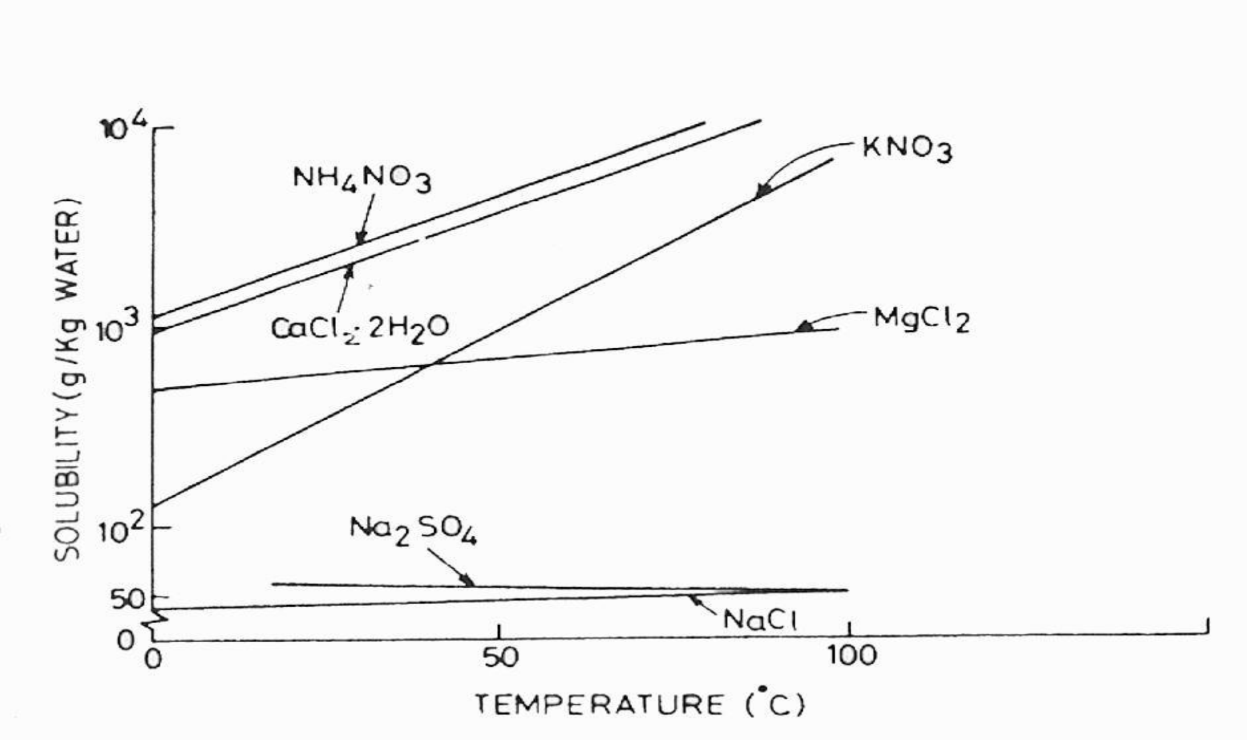


Figure 2.2: Solubility of salts with temperature variation (Garg, 1987)

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 behaviors with temperature change in water, which are summarized in figure 2.2 above. 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_2SO4).

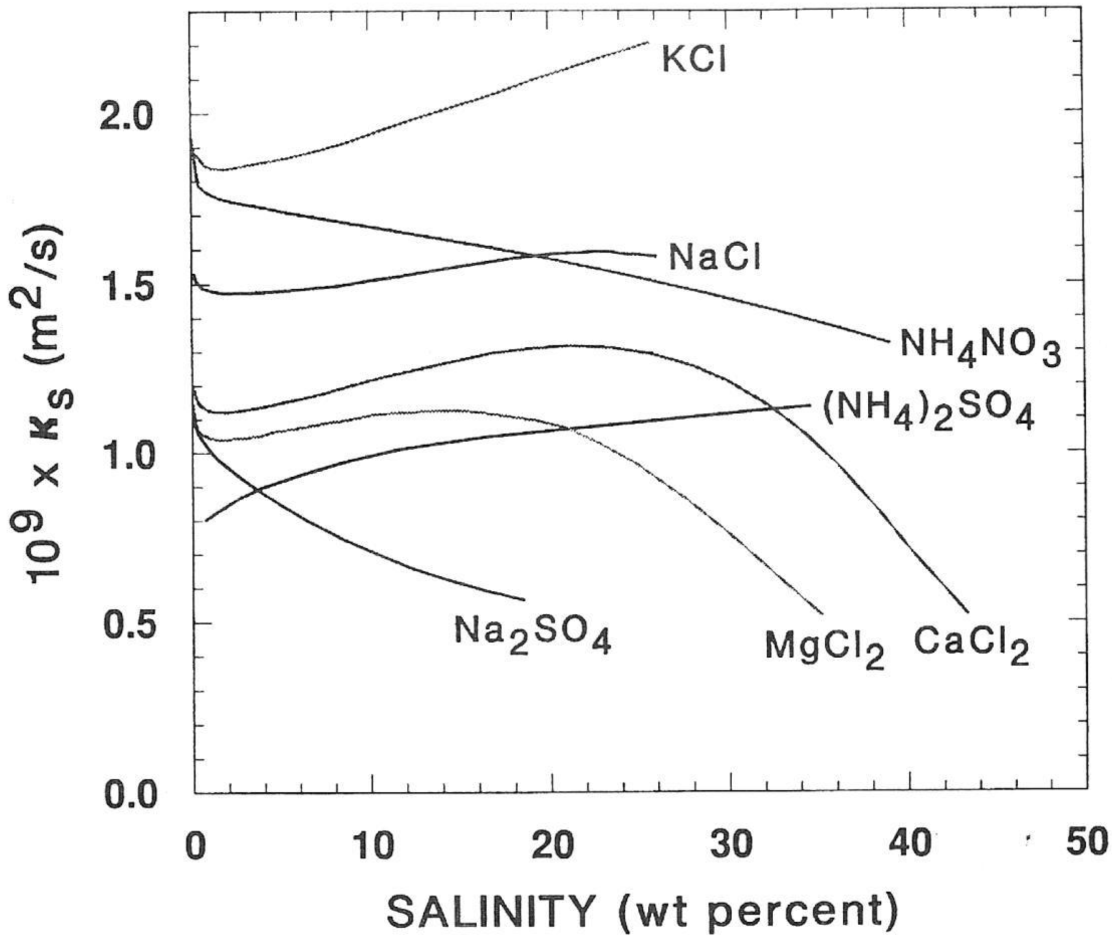


Figure 2.3: Salt molecular diffusivities with salinity variations at 25^{0}C (Hull *et al*, 1989; Rard and Miller, 1979).

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 ^{o}C is 5 times greater that its solubility at 10 ^{o}C (Hull *et al.*, 1989). On the other hand, the molecular diffusivity *Ks* may vary less than 10% with the salinity percentage variation at between 0 and 20 at a certain temperature. The molecular diffusivities of different types of salt at room temperature are given in figure 2.3. Hull *et al.* (1989) reported that the diffusivities at other temperatures have not been investigated but it is understood that the diffusion coefficient usually increases at higher temperatures, which leads to raising the upward salt flux.

According to the above information, it is evident 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 2.3. The vast majority of the US SGSPs have been using sodium chloride (Tabor, 1978; San Francisco Bay Conservation and Development Commission, 2005).

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 salt works 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. This salt has been used in two ponds in Israel and a large pond in the USA (Tabor, 1978; Ochs *et al.*, 1981) 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 densest brine in the world; its average density is about 1230 kg/m^3.

Hull (1986) explored the possibility of using fertilizer salts like ammonium salts in solar ponds, with particular reference to use in agricultural environment. It was visualized that a solar pond system integrated with the farm, in which the solar pond heat may be used for crop drying, water heating, space heating, or other low temperature applications. The surface runoff containing fertilizer may be applied to farm to supplement the nitrogen to the cropping system (Hull, 1986). Some of the fertilizer salts are nitrogenous fertilizers like ammonium nitrate, ammonium sulphate, ammonium chloride, ammonium phosphate, ammonium super phosphate, ammonium ortho phosphate and ammonium poly phosphate. Among these, the use of complete fertilizers supplying nitrogen and phosphorus, though good for the farm, would aid in growth of algae and other organisms and thus considered unsuitable for solar pond (Saxene *et al.*, 2009). Murthy and Pandey (2002) also considered using fertilizer salts in place of sodium chloride for operating solar ponds. The study was conducted to identify the potentially viable candidate fertilizer salts for Indian conditions. Muriate of potash, a potassic fertilizer, was found to have properties comparable to that of sodium chloride, and can generate energy at cheaper cost than urea.

2.5 Pond stability

A solar pond will be statically stable if its density decreases with height from the bottom. A solar pond is subjected to various disturbances such as the wind blowing at the top surface and heating of the side walls. The criterion for dynamic stability of the pond is somewhat more stringent than that for static stability. This criterion can be obtained by perturbation analysis of the basic laws of conservation of mass, of a steady state solar pond. Rainfall can have beneficial as well as have detrimental effects on the operation of a solar pond. If the rainfall is not heavy, it helps to maintain the density of the surface layer at a low value. During the monsoon, in the Bangalore solar pond, there was no need of flushing the surface layer to maintain its density at a low value. Heavy monsoon rainfall can, however, penetrate to the gradient zone and dilute it. The analysis of heavy rainfall (greater than 40 mm per hour) episodes in the Bangalore solar pond indicated that raindrops can penetrate to about 50 cm from the surface. Hence, it is desirable to maintain higher surface zone thickness during the rainy season (Srinivasan, 1990).

Water turbidity and bottom reflectivity also affects the stability of a solar pond. Turbidity is the suspended matter in solar pond salt water which prevents the penetration of solar radiation. In a study to ascertain the effect of turbidity on the thermal performance of a salt gradient solar pond, it was found that high turbidity levels could prevent ponds from storing energy in the LCZ (Wang and Yagoobi, 1995). In another study, it was proved that reflective bottom and turbidity with certain limits improve the efficiency of a pond and the gravitational stability of a salty layer of a fluid subject to adverse temperature gradient as a result of heat absorption (Giestas *et al.*, 1996, Husain *et al.*, 2004).

2.5.1 Diffusion in a solar pond

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 difference in concentration 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. Suarez *et al*., (2010) investigated numerically the effect of double diffusive convection on the thermal performance and stability of a salt gradient solar pond. They showed that the insulating layer is being eroded by double-diffusive convection which has profound impacts on the overall stability of solar pond.

Salts, such as sodium chloride, dissolve in water producing ions which move around randomly. The rate of diffusion depends upon temperature as it increases the kinetic energy of the particles (Dah *et al.*, 2005). Thus, the speed of these particles increase which in turn increases the rate of diffusion. The stability of a solar pond is affected by both salt and heat diffusion usually referred to as double diffusion. Two mechanisms participate to this transfer: molecular diffusion and thermal diffusion (Celestino *et al*., 2006).

2.5.2Molecular diffusion

Molecular diffusion happens mainly as a result of the differences in concentration gradient in a solution, and this kind of diffusion occurs according to Fick’s law in 1955. A substance diffusing is the primary type of mass transport, which can be represented in the form of salt diffusion inside a solar pond.

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

$$J = Ks\ (\frac{\partial C}{\partial X}) \qquad (2.9)$$

Where J is the diffusive flux of salt (mass/area per time), Ks salt molecular diffusivity (area/time), C the concentration of salt and X is the direction.

According to David (1991) the upward diffusion of salt through the salinity gradient is a destabilizing factor because it affects both the density gradient and the salinity gradient in the salt gradient solar pond and is governed by the diffusion equation:

$$\delta/\delta z\{\mathrm{Ks}\ (\delta s/\delta z)\} = \delta s/\delta t. \qquad (2.10)$$

For steady-state conditions $\left(\frac{\delta s}{\delta t}\right) = 0$, integration across the non-convecting zone gives the salts mass flux $q_{s;}$

$$q_s = \mathrm{Ks}(\frac{\delta s}{\delta z}) \qquad (2.11)$$

This equation is based on the assumption that salt diffusion is dependent only on the salt concentration gradient. However, in the presence of a temperature gradient, this equation is modified to;

$$q_s = -\mathrm{Ks}(\frac{\delta s}{\delta z}) - K_{ST}(\frac{\delta T}{\delta z}) \qquad (2.12)$$

Where, $K_{ST=}$ transport of salt as induced by the temperature gradient, K_S = salt diffusivity, $\frac{\delta T}{\delta z}$ = temperature gradient with depth, $\frac{\delta s}{\delta z}$ = salinity gradient with depth and $\frac{\delta s}{\delta t}$ = salinity gradient with time.

2.5.3 Thermal diffusion

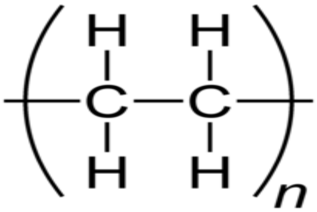
Thermal diffusion was first discovered and reported by Carl Ludwig (Fick’s mentor) in 1856. The observation was based on an experiment in which a tall column of uniformly distributed saline water was cooled from the bottom and heated from the top. At the beginning, the salt concentration was uniform 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 (Cussler, 1984).

2.5.4 Membranes in solar ponds

Membrane solar ponds belong to the group of partitioned solar ponds, where the HSZ is separated physically from the upper layer or layers. The HSZ of a partitioned solar Pond is covered by a transparent membrane, but a salt-gradient zone combined with a fresh water layer is installed on top of it too. This system could be seen as a salt-gradient solar pond with an additional physical separation of the HSZ. The advantage of a physical separation of the HSZ from the rest of the system lies in the increased stability of the several layers when heat is extracted from the HSZ. A membrane does not allow any disruptions and interactions between the HSZ and the upper layer, no matter if it is a NCZ and a UCZ or only one fresh water layer. Furthermore, the heat extraction in a salt-gradient solar pond is a complicated and technically difficult process, where diffusers with intelligent control have to be used for the inlet and outlet to guarantee a stable layer and to avoid eddies and interactions with the NCZ. There have been studies with even two membranes separating each of the three layers from each other but results show that a single membrane salt-gradient pond has a higher efficiency than standard salt gradient ponds (Benjamin, 2010).

The porous media solar pond is an example of a membrane solar pond. A layer of porous media is added at the bottom of the traditional solar pond. Porous media like slag has a small thermal diffusivity with low thermal diffusion coefficient which has good thermal insulation performance. Wence (2010) and Hua (2007) proved that adding porous materials and glass balls at the bottom of solar pond is favorable to raise LCZ temperature. Dark porous media have strong ability to receive thermal radiation and weak ability to reflect heat radiation, which is conducive to the increase of LCZ temperature in addition, glass balls have up to 90% transmittance, and reflect about 8% while absorb about 2%. Therefore a layer of transparent glass balls above dark boiler slag, which can not affect the underlying dark porous media, can have a positive effect on the absorption of solar radiation on the basis of increased thickness of the porous media, to ensure the maximum thickness of the porous media in the solar pond.

Some of the membranes are chemically simple and others are considerably exotic. Polyethylene (below is a partial structure of polyethylene).



For example is water proof and has thermal conductivity of 0.4 W/m per ^{0}C. It has good resistance to dilute and concentrated acids, is flexible and translucent. In a study of the thermal behavior of polymers, it was noted that at a sufficiently low temperature, all polymers are hard rigid solids. As the temperature rises, each polymer eventually obtains an adequate thermal energy to enable its chains to move freely and behave like a viscous liquid (Cowie, 2008).

2.6 Applications of solar pond technology

Solar ponds are used for various thermal applications like greenhouse heating, process heat in dairy plants, desalination, effluent treatment and power production. It was proved that the multi-effect boiling solar pond system is viable for desalination of sea water in an arid environment with performance ratio more than twice the amount of a conventional system (Al Hawaj and Darwish, 1994). SGSP enables the most convenient and least expensive option compared to other solar desalination technologies to store heat for daily and seasonal cycles. For steady and constant water production, this is very important from the view point of operational advantage and economic benefit. The heat storage enables SGSP to power desalination during night time and cloudy days. SGSP used desalination for a 24-hour a day operation needs only half the size to produce same quantity of water compared to other solar desalination options. For desalination SGSP can make the use of reject brine as a basis to build it. This advantage is very important when SGSP is considered for inland desalting for fresh water production or brine concentration to be used in salinity control and environmental clean-up applications. At present the most common and simple technique for large-scale desalination is multistage flash distillation (MSF), which produces fresh water a total amount of about 10 million ton/day globally. The use of solar pond for agricultural application was studied by Murthy and Pandey (2002) where the warm water stored in the solar pond was utilized as a heat source for a gas engine powered heat pump used to heat a greenhouse.

Studies have indicated that there is excellent scope for process heat applications (i.e. water heated to 80 ^{o}C to 90 °C), when a large quantity of hot water is required, such as textile processing and dairy industries, hostels for bathing. Solar ponds can also provide hot air for industrial uses such as drying agricultural produce, timber, fish and space heating are other possible applications. Hot water application for different purposes in agriculture includes paddy soaking in parboiling, sugarcane sett treatment, vegetable blanching, washing of cans in dairy industry and domestic hot water consumption.

Traditionally, parboiling process involves soaking of rough rice in water at ambient temperature in masonry tanks for 3 days and steaming of drained paddy. The method was later improved to soak the paddy in hot water at around 70 °C for few hours depending upon the type of parboiling method. This method could eliminate unwanted odours associated with traditional method and reduce the soaking time from a few days to a few hours (Bhattacharya, 1985).

In other applications, a mini solar pond was used to store the solar thermal energy that was used for sewerage treatment. Experiments were carried out with different salinity in the mini solar pond. It was found that the optimum value of salinity in solar pond water was 80 g/kg. When industrial effluent was used as raw water in the solar stills, it was found that the productivity increases with increase in solar intensity and water-glass temperature difference and decreases with increase in wind velocity (Srithar, 2010).

Some of the major solar pond power plants are listed in Table 1. In these plants, the solution from the lower convective zone is pumped to a heat exchanger that acts as evaporator for an organic Rankine cycle. (Trieb *et al.*, 1997) made a comparative analysis of different solar electricity generation options and found that solar pond produces electricity at a cost of 0.254 German Marks (DM)/kWh as against 1.198 German Marks (DM)/ kWh for photovoltaic cells.

Table 2.1: A comparative analysis of different solar ponds for electricity generation (Trieb *et al.*, 1997).

Name/site	**Power (kW)**	**Pond area (m^2)**	**Operational period**
Ein Boqek, Israel	150	6250	1979 – 1986
Beith Ha'Arava, Israel	5000	250000	1984 – 1989
Alice springs, Australia	15	1600	1985 – 1989
El paso, united states	70 (electricity) 330 (process heat)	3350	1986 to date

2.7 Worldwide experiences of solar ponds

In the 21st century, more than sixty solar ponds have been built around the world. The largest solar pond built so far is the 250,000 m^2 pond in Beith Ha Arava in Israel. In Argentina, solar ponds are being used commercially for production of sodium sulphate using solution-refining techniques. The ore (rich in sodium sulphate) mined in the Andes Mountains is dissolved in a 400 m^2 solar pond constructed adjacent to the mines. The brine is removed and placed in a cooling pond at night where sodium sulphate crystallizes. Solar pond concepts have been used to prevent precipitation of magnesium sulphate in the salt works at the Great Salt Lake in Utah, USA (Lesino *et al.*, 1982).

Four SGSP have been designed, built and operated in Ohio by Ohio State University. Two solar ponds were constructed in Columbus for physical studies, one solar pond was constructed at the Ohio Agriculture Research and Development Center at Wooster and one solar pond was constructed in Miamisburg to heat a community swimming pool and recreational building. Data and recommendations have been developed from these research efforts on site selection, linear selection, salt gradient establishment, heat extraction and environmental protection. Sodium chloride was used as the stabilizing salt for each pond. The costs of building solar ponds varied from \$38 /m^2 to \$60 /m^2. A 3355 m^2 solar pond at E1 Paso, Texas, has demonstrated the use of a solar pond for food processing, power generation and desalination. The feasibility of grain drying using a solar pond has been demonstrated at Montreal (Canada), Ohio (USA) and for heating greenhouses at Lisbon (Portugal). A 20,000 m^2 solar pond in Italy has been used for desalination of sea water and producing 120 tons of fresh water per day (Srinivasan, 1990).

The first solar pond in India was a 1200 m^2 pond built at the Central Salt and Marine Chemicals Research Institute in Bhavnagar, Gujarat, in 1970. This solar pond was based on bittern, which is a waste product during the production of sodium chloride from sea water. The second solar pond was a 100 m^2 circular pond built in Pondicherry in 1980. This pond used sodium chloride and was operational for two years. The LDPE liner used in this pond developed a leak and hence had to be replaced. It was shown that a new liner could be placed in the pond without too much loss of thermal energy (Patel and Gupta, 1981).

A consortium of RMIT University, Geo-Eng Australia Pty Ltd and Pyramid Salt Pty Ltd has completed a project using a 3000 square metre solar pond located at the Pyramid Hill salt works in northern Victoria to capture and store solar energy using pond water which can reach up to 80 °C. Pyramid Salt will use the pond's heat not only in its commercial salt production but also for aquaculture, specifically producing brine shrimps for stock feed. It is planned in a subsequent stage of the project to generate electricity using the heat stored in the solar pond, thus making this local industry more energy self-sufficient (Aliakbar *et al.*, 2005).

İn the subsequent chapters model solar ponds were constructed for experiment purposes. the use of a polyethene membrane to avert salt diffusion in a SGSP was studied. The use of polethene to concentrate solar energy in the LCZ on the principle of greenhouse effect was also studied and the optimum conentration of the layers was also studied.

CHAPTER THREE

Experimental analysis and comparison of salt diffusion in a salt gradient solar pond with a polyethylene and without a polyethylene film.

Abstract

Salt diffusion is one of the impediments affecting solar pond efficiency. Salt diffusion from the LCZ across the NCZ leads to erosion of the gradient zone which eventually leads to occurrence of convectional currents which has negative effect on overall energy stored in the solar pond. Two small-scaled experimental salt gradient solar ponds having surface areas of 0.6 m x 0.4m and depth of 0.2 m were constructed. The aim of the experiment was to quantify and compare salt diffusion in a salt gradient solar pond with a transparent polyethylene film with transmittance above 70% (it allows solar radiation to penetrate and does not allow mass transfer) separating the Lower Convective Zone (LCZ) and Non Convective Zone (NCZ) and that without. Data was collected for a period of 15 continuous days. It was found out that mass transfer indeed exists and is mainly through molecular diffusion. In both ponds, the concentration of the UCZ increases linearly with time while that of the LCZ remains static in a pond with polyethylene film but decreases in a pond without a polyethylene film.

3.1 Introduction

A Salt Gradient Solar Pond (SGSP) is a simple and low cost mean to collect and store solar energy. In practice, a typical solar pond consists of three thermally distinct zones. Two convective zones where the first is at the top usually called Upper Convective Zone (UCZ) relatively thin with less salt concentration or sometimes only pure water. Another convective zone is at the bottom referred to as the Lower Convective Zone (LCZ). This is the layer that has the highest salt content usually near saturation and is this layer that stores the solar energy hence also referred to as the Heat Storage Zone (HSZ). The third layer is the non- convective zone (NCZ) which is the middle layer with intermediate salt content it is also referred to as the gradient zone. The NCZ is the key to the working of a solar pond. It allows an extensive amount of solar radiation to penetrate into the storage zone and suppresses convectional currents in the LCZ from rising to the UCZ.

Because of its potential applications in thermal and solar energy systems, such as in heating and desalination, the salt Gradient Solar Pond (SGSP), has received much attention from researchers (Shehadi *et al*., 2007). Previous studies on solar ponds include experimental, analytical and numerical investigations carried out to understand the thermal behavior under different operating conditions (Dah *et al*., 2005; Karakilcik *et al*., 2006). However, almost all of the previous studies were performed using a one-dimensional thermal analysis without consideration of the dynamics of fluid layers (Suarez *et al.*, 2010). Kurt *et al*., (2000) modeled the non-convective zone as a series of flat layers, including both heat and mass transfer between layers. The upper and lower convective zone were each modeled as a single, homogenous layer. The thicknesses of each zone were assumed fixed, implying that salt diffusion is negligible or controlled. Mansour *et al.,* (2006) studied the transient heat and mass transfer and stability within a solar pond using a two-dimensional model. Using the density stability ratio, which is used for static stability, it was found that there are two critical zones: one immediately beneath the water surface, and the other near the bottom of the pond. However, the fluid motion caused by buoyancy within the solar pond was neglected. For this reason, the temperature profile did not show the existence of a well-mixed upper or lower convective zone. Thus, even though some of the instabilities were predicted, mixing in these zones and potential erosion of the non-convective zone were not. Akrour *et al.,* (2011) opined that, the thermos-diffusion continues to be the only hydrodynamic transport mechanism that lacks a simple physical explanation, because it strongly varies with the nature of the components of the mixture and with their concentration. He argued that this effect cannot easily be measured experimentally and but can be predicted theoretically.

The crucial aspect of a solar pond operation is the NCZ stability (convective motions are hindered), which is ensured by a strong enough salinity gradient. A solar pond is said to be statically stable if its density increases with height from the top. Wind blowing at the top surface and heating of the side walls, etc. cause disturbance to a solar pond. The criterion of dynamic stability is rather tough and is obtained by perturbation analysis of the basic laws of conservation of mass, momentum and energy the stability criterion is written as;

$$\beta T \frac{\partial T}{\partial Z} < \beta S \, \partial S/\partial Z[(Sc + 1)/\,\mathrm{Pr} + 1] \tag{3.1}$$

Where $\beta T = -\frac{1}{P}\left[\frac{\partial P}{\partial T}\right]$ = Thermal expansion coefficient

$\beta S = \frac{1}{P}\left[\frac{\partial P}{\partial S}\right]$= Salinity expansion coefficient

Pr = Prandt number and Sc = Schmidt number. For typical conditions, the above equations are simplified to;

$\frac{\partial S}{\partial Z} > 1.19 \frac{\partial T}{\partial Z}$ Where S is in kg/m^3 and T in ^{0}C (Srinivan, 1993; Ouni *et al.*, 2001).

The concentration gradient existing in SGSP leads to steady diffusion of salt from higher to lower concentration, that is, from bottom to top through the gradient zone given that diffusion tends to homogenize the salt concentration. Erosion of the gradient zone from below depends upon the density and temperature gradients at the gradient zone – storage zone interface. Nielsen (1983) determined experimentally that the gradient zone – storage zone interface remains stationary if the salinity and temperature gradients satisfy the following relationship.

$$\frac{\partial S}{\partial Z} = A \left[\frac{\partial T}{\partial Z}\right]^{0.63} \text{ where A= 28 (kg/m}^3\text{) (m/k)}^{0.63} \qquad (3.2)$$

The maintenance of the salinity profile within the NCZ can be obtained by addition of salt in the LCZ and flushing with fresh water or low salinity water at the UCZ (this is done in order to take into account both salt diffusion from the NCZ and evaporative water losses at the surface) however, you need to know how much salt diffused so that you know how much to inject. These interventions must be planned by monitoring the modifications of the salinity gradient. Therefore the dynamic of the salt diffusion is a key phenomenon to study and to keep under control (Celestino and Erminia, 2004). Karim *et al.*, (2010) opined that instability of solar ponds could be limited by using porous media placed in the lower layer of the stratification. Experiments on salt diffusion indicates the upward diffusion of salt is slowed down when a porous media is added which helps maintain salt gradient (Yufeng *et al.*, 2011).

The transport of salt through the gradient zone by diffusion is expressed as;

$$Q_m = [(S_L - S_{u)}\ D] / b \qquad (3.3)$$

Where b = Thickness of gradient zone, D = Mass diffusion coefficient and S_l , S_u = Salinity in lower and mixed layers respectively (Srinivasan, 1993; Saifullah *et al.*, 2012). According to Celestino and Erminia (2004), the mathematical model for the principle of mass transfer for the solute results in an equation of the form;

$$\frac{\partial c}{\partial t} = -\nabla . J = \nabla . (vc - D\nabla c \qquad (3.4)$$

Where J is the mass flux, v is velocity, c is the solute concentration, D is the diffusion coefficient and the operator ∇ is $\frac{\partial}{\partial z}$.

This chapter presents an experimental analysis of the amount of salt diffusing through the gradient zone in a day per unit area based on Fick's law refer to equation 2.9.

3.2 Materials and methods

Two experimental salt gradient solar ponds with surface areas of 0.6 m x 0.4 m and depth of 0.2 m were constructed to study experimentally salt diffusion in a solar pond. In one of the ponds a polyethylene film was used to separate the LCZ and NCZ, figures 3.1 and 3.2 shows the experimental set-up. The walls and bottom were made of acrylic glass. The bottom of the pond was painted black to increase optical absorptivity. The thicknesses of the NCZ and the LCZ were 0.0 8 m and 0.08 m, respectively. The LCZ covers 40 %, the NCZ covers 40 % and the UCZ 20% (Fadi *et al.*, 2007). The UCZ thickness was 0.04 m and 0 % salt concentration. Salty layers were formed by pouring the salt solution prepared with a required amount of salt (NaCl) on a floating wood plate on the layer formed before. The bottom and the walls were insulated using saw dust. Temperature variations inside and outside of the solar pond at different points were recorded continuously by means of thermocouples associated with a computer system. The salt diffusion was monitored daily by withdrawing the solution from each layer and their concentrations measured using a refractometer an analytical method called refractometry.

Refractometry is an analysis process used to quickly, reliably, and very accurately identify a sample and determine the concentration and purity levels in a sample. Refractometers measure the refractive index and temperature of liquid and pasty process flows and use mathematical functions/scales to calculate concentration levels. The refractive index of a solution increases with the concentration of the respective solution. The dependency is linear, in a certain range. The relationship is given as;

$$n = kC + n_o \qquad (3.5)$$

(n – Refractive index of the solution, C – Concentration of the solution, n_o– Refractive index of the solvent, k – Empirical constant). The values of parameters k and n_o can be determined by using solutions of known concentration (using their refractive indices).

Knowing k, n_o and refractive indices of unknown solution n_x, the concentration of the unknown can be determined using the variation law:

$$C_x = (n_x - n_o)/k \tag{3.6}$$

Below are the experimental set-ups for the two model solar ponds used in the current work (Plate 3.1 and Plate 3.2).

Plate 3.1: A photograph of solar pond without polyethene film**.**

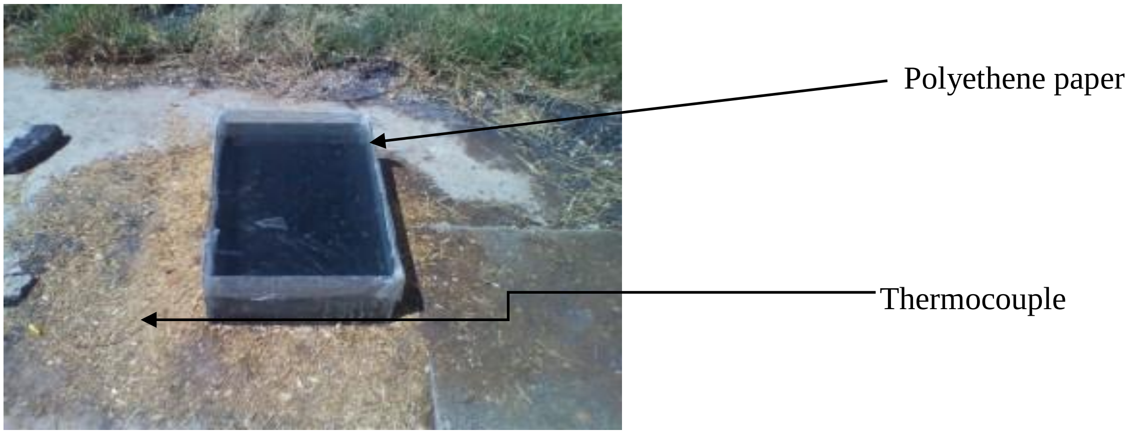


Plate 3.2: A photograph of solar pond with polyethene film.

3.3 Results and discussion

The measurements were taken for a period of 15 continuous days of experimentation. The initial salinities were 0% and 25% for UCZ and LCZ respectively. The salinity profile for NCZ was not monitored because it is expected that the salt concentration increases with increase in depth therefore its concentration is not expected to be uniform (gradient zone). The figures 3.3 and

3.4 show the salinity profiles for the UCZ and the LCZ and a comparison of the salinity profiles for the two ponds (one with the polythylene film separating the LCZ and NCZ).

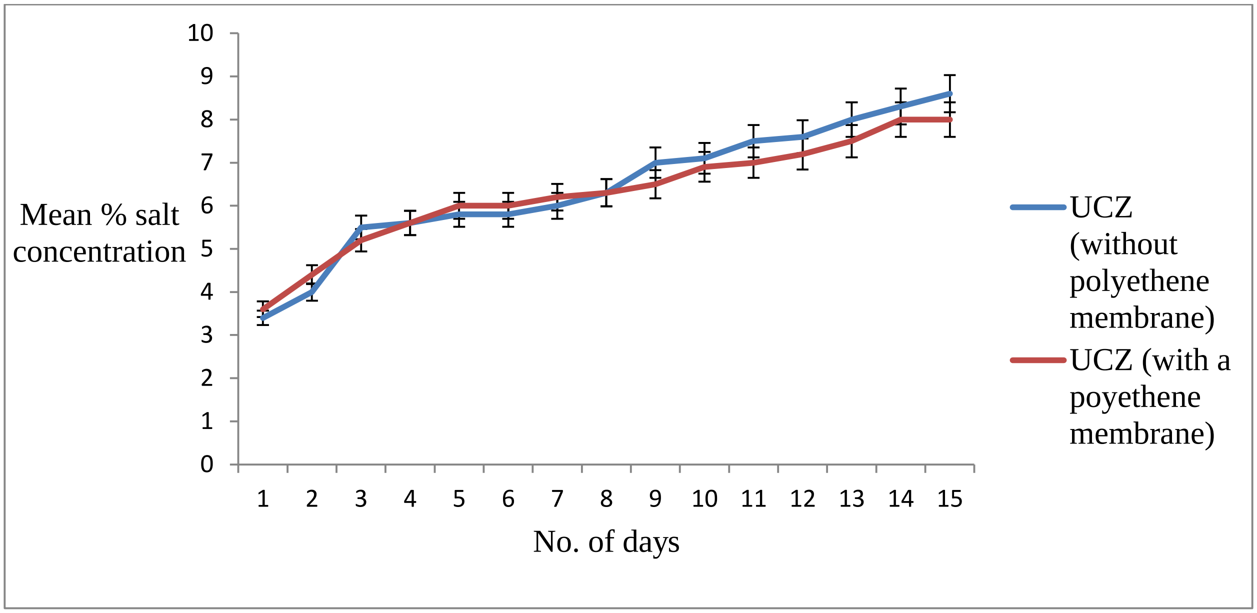


Figure3.1: Salinity profile for UCZ in a solar pond with and without a polyethylene film

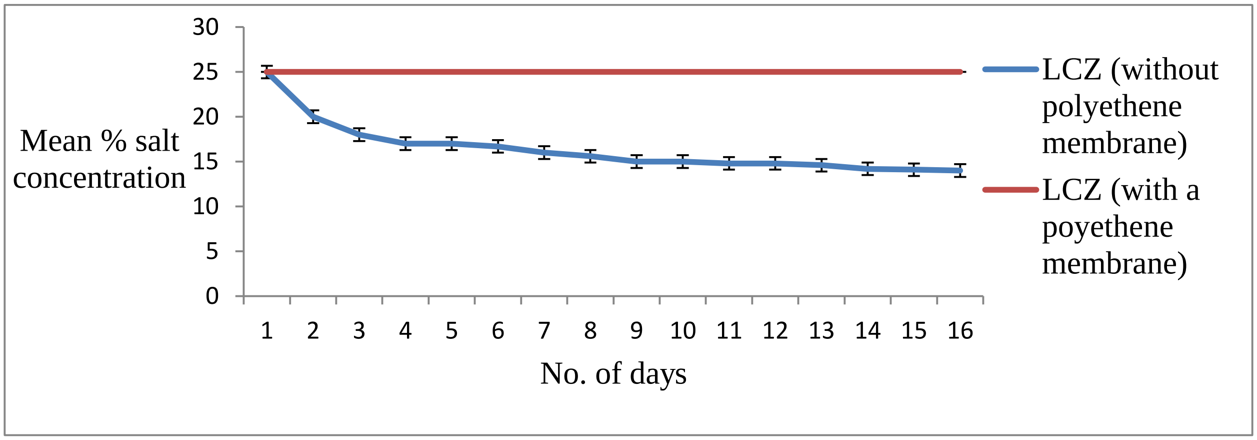


Figure 3.2: Salinity profile for LCZ in a solar pond with and without polyethylene film

From the figures 3.3 and 3.4, it indicates clearly that the salinity at the surface increases. This is due to salt diffusion away from the storage zone and erosion of the gradient zone to the surface layer. The main cause of the non-convective zone erosion seems to be the fast growth in the thickness of the upper zone. This growth is explained by wind effects and penetrative convection as a consequence of the surface cooling at night, which causes rapid changes that occur due to meteorological conditions. This emphasizes how critical is to take into account wind and heat exchange that occur at the surface of the pond. A larger salt-gradient could be one solution to halt the upper zone growth (Suarez *et al.*, 2010). The last few days it is almost constant because there is no more salt to diffuse upwards. This is in agreement with Suarez *et al*. (2010) who opined that without maintenance being carried out, salt diffusion tends to create a uniform salt gradient and thus, the pond overturns and loses its capacity to collect and store heat.

In the pond with a polyethylene film, salinity change in the storage zone was not observed because the polyethylene film could not allow transport of ions from the storage zone to the adjacent layers. The results exhibit a linear variation of concentration with number of days in the x-direction; the gradient itself is the rate of change of the concentration with distance which is the same as the slope of a graph of concentration. These results are in agreement with Ouni *et al*., (2001) who also noticed the existence of salt diffusion from the storage zone to the surface layer. He noted the two mechanisms participate to this transfer: molecular diffusion and the upward movement of the NCZ due to brine injection at the LCZ. The quantity of salt transferred by molecular diffusion is estimated to 20 kg/m^2/year. Nielsen *et al.,* (1977) reported that the salt diffused in the Ohio State SP is estimated to 60-70 kg/m^2/day.

3.4 Conclusion

During the experimentation period, the existence of salt diffusion from the storage zone to the surface is found and it is estimated to be 60-70 kg/m^3/day in a solar pond of surface area of 1 m^2. As a salt gradient solar pond is heated from below, it becomes unstable by an onset of convection currents in the lower layer due to the thermal buoyancy effect. Thereafter the heat and salt is ready to diffuse into the upper layer through the adjacent diffusive interface. To characterize the double-diffusion process in the layers as the destabilizing factor. Although the salt diffusion is a slow process, to make solar ponds operate for many years; one must take into account the variation of salt concentration at the NCZ boundaries. Transparent polyethylene film proves to be better than the conventional solar pond without a membrane as it allows extensive solar radiation to pass through and inhibits transfer or exchange of salt molecules/ ions from the storage zone to the adjacent layers.

CHAPTER FOUR

Study of the thermal storage efficiency of solar pond with and without a polyethylene membrane.

Abstract

This chapter presents the concept of using a polyethylene film to address the shortcomings of the traditional solar pond which are low efficiency, short operation time among others. The thermal behavior of a solar pond with a polyethylene has been analyzed and compared with that without a polyethylene film. The experiments show that: the heat storage layer (LCZ) temperature rising rate was significantly higher than that of single layer porous media solar pond. The polyethylene film of thickness 100 µm was used. The polyethylene film brings about the greenhouse effect where the solar energy that penetrates the film is trapped and improves the efficiency of the storage zone. Results show that the efficiency of a polyethylene stabilized pond rises to about 69 % compared to the traditional solar pond with about 52 %.

4.1 Introduction

Solar radiation constitutes a vast energy source which is abundantly available on all parts of the earth. Solar energy is in many regards one of the best alternatives to non-renewable sources of energy. One way to collect and store solar energy is through the use of solar ponds which can be employed to supply thermal energy for various applications, such as process and space heating, water desalination, refrigeration, drying and power generation. Thermal energy storage has always been the most significant method of energy storage. Solar ponds are a classical application of the thermal energy storage and their performance depends essentially on the storage capacity of the fluid, thermo physical properties of the pond, surroundings conditions, its thermal energy storage capacity, and on its construction and maintenance costs (Dincer and Rosen, 2003; Jaefarzadeh, 2004).Numerous experimental and theoretical studies have been undertaken. Most of the experimental work (Hawlader, 1980; Newell *et al.*, 1990; Alagao *et al.*, 1994) concentrates on design, application, thermal measurements, efficiency and investigations of the thermal performance of various types of solar ponds of different dimensions. Many experimental studies focus on determining the efficiency of inner zones in solar ponds, and determining the zone performance that yields the best solar pond system (Kurt *et al.*, 2000; Li *et al.*, 2000).

The solar ponds which are conventionally referred to as salt gradient solar ponds (SGSP) consists of three distinct zones, the Upper Convective Zone (UCZ) the thinnest and which has a low and nearly uniform salt concentration. Beneath the (UCZ) is the Non-Convective Zone (NCZ) of medium thickness and has a salt concentration increasing with depth, and it is therefore a zone of variable properties. The bottom layer is the Lower Convective Zone (LCZ), also called the storage zone, which has the maximum thickness and has a nearly uniform high salt concentration. The Non convective zone (NCZ) also referred to as salt gradient zone (GZ) is the key to the working of a SGSP. It allows solar radiation to penetrate into the storage zone while prohibiting the propagation of long wave radiation because water is opaque to infrared radiation. The zone suppresses global convection due to the imposed density stratification. It offers an effective conduction barrier because of the low thermal conductivity and the zone thickness. This makes the GZ essentially a double-diffusive layer of salt and temperature. Maintaining the stability of the GZ is, therefore, crucial in its functionality.

Despite numerous studies on solar ponds, there are a number of difficulties and limitations that affect the performance of solar ponds and in some locations limit their use, many of them were recognized and several schemes for solution have been proposed to eliminate or minimize their effect. These problems include, among others, salt diffusion from LCZ to UCZ, wind mixing, evaporation, dust and dirt falling on pond surface. Some of these problems were first investigated by (Tabor and Matz, 1965). Weinberger (1965) and Tabor (1981) addressed the physics of pond’s stability. Later, Hassab *et al.*, (1989) presented a field report on a solar pond constructed in the State of Qatar. They reported the problems encountered in operating SGSPs in the Arabian Gulf region, characterized as a windy and dusty environment. Other problems are excessive erosion of the gradient zone, the formation of sizable localized convective zones, the deterioration of pond water clarity and high rates of surface evaporation. This weather related problems severely impair the pond operation and performance. The salinity in the UCZ increases due to convective mixing (wind, evaporation) with NCZ and salt diffusion from the bottom. In a typical case this diffusion amounts to about 60 tons/km^2/day. Weinberger (1965) estimated the annual rate of this natural diffusion of salts, to be in the range of 20 – 30 kg/m^2, depending on the thickness of NCZ, the temperature profile and the concentration difference between the UCZ and the LCZ. Newell *et al.*, (1990), estimated the salt transported per year from the LCZ to the UCZ for 2000 m^2 solar pond at the University of Illinois, in the range of 25 to 50 tons. In a nutshell therefore, turbidity of water

(Luh and Swift, 2004), the wall design (Liexian, 2001), keeping of salt gradient (Wang *et al.*, 2011), wall insulation as well as environment and climate will have an important impact on the solar pond performance. With these problems, LCZ temperature of the traditional solar pond is difficult to achieve a higher temperature. Since efficiency of the solar pond is measured by how much energy is stored in LCZ, increasing LCZ temperature of the solar pond has important significance.

Many innovations have been devised to improve solar pond efficiency among them is the use of multi layered porous media. The porous media solar pond is a four-layer model and added a layer of porous media at the bottom of the traditional solar pond. Porous media has a smaller thermal diffusivity with low thermal diffusion coefficient which has good thermal insulation performance. Sun Wence (2010) proved that adding porous materials at the bottom of solar pond is favorable to raise LCZ temperature. Porous media is suitable to be selected as the color black and low thermal diffusion coefficient materials, so cheap factory wastes, boiler slag (Hua, 2009) is a good alternative material, however we can reasonably infer that adding too much boiler slag in solar pond leads to the pond not receiving enough solar radiation, resulting in a waste of porous media to a certain extent, and LCZ may not still reach the highest value. For the shortcomings of the traditional solar pond, the concept of MP-SGSP is presented. The bottom of MP-SGSP is added two or more porous media layers, using different porous media properties to achieve the best thermal storage effect. Its advantages are that the darker porous media has strong ability to receive thermal radiation and weak ability to reflect heat radiation, which is conducive to the increase of LCZ temperature while glass balls have up to 90 % transmittance, and reflect about 8 % while absorb about 2 % (Sinha *et al*., 2013), so plus a layer of transparent glass balls above dark boiler slag, which can not affect the underlying dark porous media on the absorption of solar radiation on the basis of increased thickness of the porous media, to ensure the maximum thickness of the porous media in the solar pond, to the greatest extent accepted thermal radiation, a feature that is superior to single-layer porous media.

Another means of improving the thermal performance of conventional SGSP is to increase the bottom surface area by making the surface corrugated (wavy)/V-shaped, which increases the heat transfer capability to the fluid (water) and consequently increases the performance of the solar pond. Rubin *et al*. (1990) performed several numerical and experimental simulation of the solar pond mechanism; they eventually demonstrated that one of the most significant design modifications for increasing the solar pond thermal efficiency was the increased stability of the surface layer. The effect of the various parameters on the thermal behavior with a consideration of the stability criteria in a SGSP are studied results of the steady state indicates that the thickness of the NCZ has a significant effect on the performance of the SGSP.

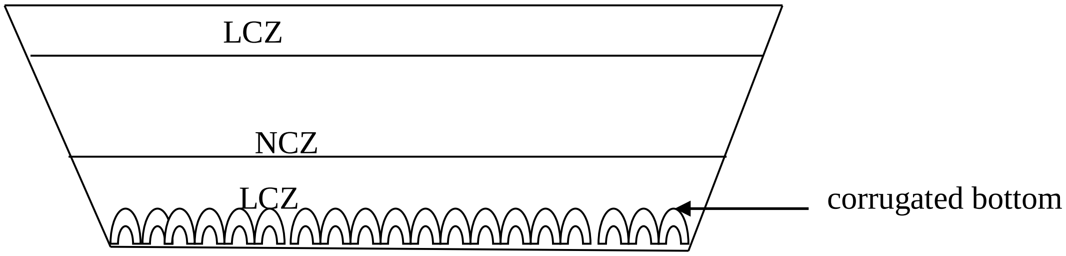


Figure 4.1: Diagram showing a solar pond with corrugated bottom (Sinha *et al.*, 2013).

The results show that there is a significant influence of area enhancement factor on thermal performance of corrugated/V-shaped solar pond. At constant value of heat capacity rate and heat extraction rate the percentage enhancement in temperature efficiency have been found to be 21.16 percent and 22.42 percent, respectively. These results are due to the fact that the increase in heat transfer surface area increases the heat transfer capability to the working fluid (water) and consequently increase the temperature and efficiency of the solar pond (Sinha *et al.*, 2013).

Ebtism and Tac (1987) discussed about the inherent problems encountered with the conventional salt gradient pond leading to the concept of the Solar Gel Pond in which the salt gradient (NCZ) is replaced by the transparent gel layer. They discussed about the relevant properties of the gel. Ebtism (1991) discussed the design, construction and operation of trapezoidal 400 m^2 and 5 m deep gel pond. The pond obtained maximum temperature of 60^{o}Cwith optimal gel thickness of 60 cm. Sherman and Imberger (1991) discussed on the control strategies designed to provide successful high temperature operation of a solar pond year round. The concept of Solar Gel Pond is based on the presence of a Non Convective Zone to trap the solar energy. In a salt gradient pond, the variation in density as a function of salinity and temperature gives raises to this NCZ. By contrast, in the Solar Gel Pond the optical and thermal insulating properties of polymer gels are utilized in forming the NCZ. In a solar gel pond, the gel floats on the storage zone, which acts as the NCZ. At present, 3 to 8 % of salt solution is used in the storage zone to keep the gel layer to float on the top. The gel used in the upper layer comprises of 98 % water and 2 % of the appropriate polymer gel. The advantages of the solar gel pond are the elimination of evaporation and heat loss from the surface. The dirt and debris falling into the pond are retained by the surface and can be cleaned off periodically. There are only two zones, lower zone being the saline water and the gel layer floats above the salt water hence no salt gradient layers need be maintained as in the case of solar pond, leading to low maintenance requirements. If an appropriate gel is developed to float on water, then the environment hazard of salt handling can be eliminated. The salt requirements are less in solar gel pond when compared to salt gradient ponds thereby reducing cost and environmental hazard. The disadvantage is the cost of the chemicals required for making the gel is high. Experimental Collection efficiency for 0.25 m^2 model for the maximum storage temperature of 60 ^oC is 19.73 %. From the above investigations, the Solar Gel Pond is technically feasible and comparable to the performance of the Salt Gradient Solar Pond (Sozhan *et al.*, 2013).

This study aims at improving efficiency of a salt gradient solar pond but with the use of a transparent polyethylene to separate the LCZ and the NCZ. The use of polyethylene proves to be effective because it brings in the greenhouse effect where the trapped solar energy is concentrated in the LCZ and minimizes salt and thermo-diffusion. However, it must satisfy the following conditions;

- Transparent to visible radiation with very little absorption in all ranges of the solar spectrum.
- Chemically and physical stable with respect to a hot saline solution up to 100 ^oC or more
- Inexpensive
- High specific heat and low coefficient of volumetric expansion over the operating temperature range of the pond.
- Inert and nontoxic
- Non-degradable over repeated freezing melting cycles, and by ultraviolet radiation. Apart from that they are
- Mechanically strong and have stable structure.

The thermal performance and efficiency of a SGSP has been shown by Srinivasan (1993) assuming steady state condition as;

$$Q_u = Q_a - Q_e \tag{4.1}$$

Where; Q_u= Useful heat extracted, Q_a = Solar energy absorbed and Q_e = Heat losses.

The thermal efficiency is defined by:

$$\eta = Q_u / I \qquad (4.2)$$

Where I is the solar incident on the pond.

$$\text{Therefore; } \eta = \eta_0 = Q_e / I \qquad (4.3)$$

where $\eta_0 = Q_a / I$ = Optical efficiency of the pond.

$$\text{Again, } Q_e = U_0 (T_s - T_a) \qquad (4.4)$$

Where T_a = Ambient temperature and U_0 = Overall heat loss coefficient

Neglecting heat losses from bottom and sides of the pond and assuming the temperature of the upper mixed layer to be the same as the ambient,

$$U_0 = K_w / b \qquad (4.5)$$

Where K_w = Thermal conductivity of water and b = Thickness of the gradient zone.

4.2 Materials and methods

Model solar ponds rectangular in shape of dimension (0.6 x 0.4 x 0.2) m^3 were made. The walls and base were made up of transparent float glass of 6 mm thick pasted with silicon. Inner surface of the glass plate were painted with matt black to absorb solar radiation. The models were insulated with saw dust of thickness 10 cm.”K‟ type thermocouples made of Chromelalumel were used to measure the temperatures. Thermocouples were fixed at the middle of the three layers and one was used to measure the ambient temperature. A 12 channel temperature indicator (MICROSENSOR) was used to measure the temperature of the thermocouples with an accuracy of ±0.1 ^oC however a thermometer was used to confirm the values indicated by the digital thermometer. Known concentration of sodium chloride salt was used for the three zones. Mixing was carried out in order to ensure that the salt had completely dissolved in the water to obtain a homogeneous mixture. Polyethylene was used in one of the ponds to separate the NCZ and the LCZ. The polyethylene had to be suitable as it satisfied the requirement of the following properties like uniformity, specific gravity, transmissivity, cost, and resistance to corrosion and anti-bacterial nature. In order to study the effect of climate and operational parameters on the performance of solar pond, experiment had to be carried on a daily basis varying the concentrations of the zones.

4.3 Results and Discussions

In this section emphasis was put on thermal efficiency of the storage zone in both ponds; with a polyethylene film and without a polyethylene film.

4.3.1 Temperature profile for LCZ (25% salt) in solar ponds with polyethylene and without polyethylene

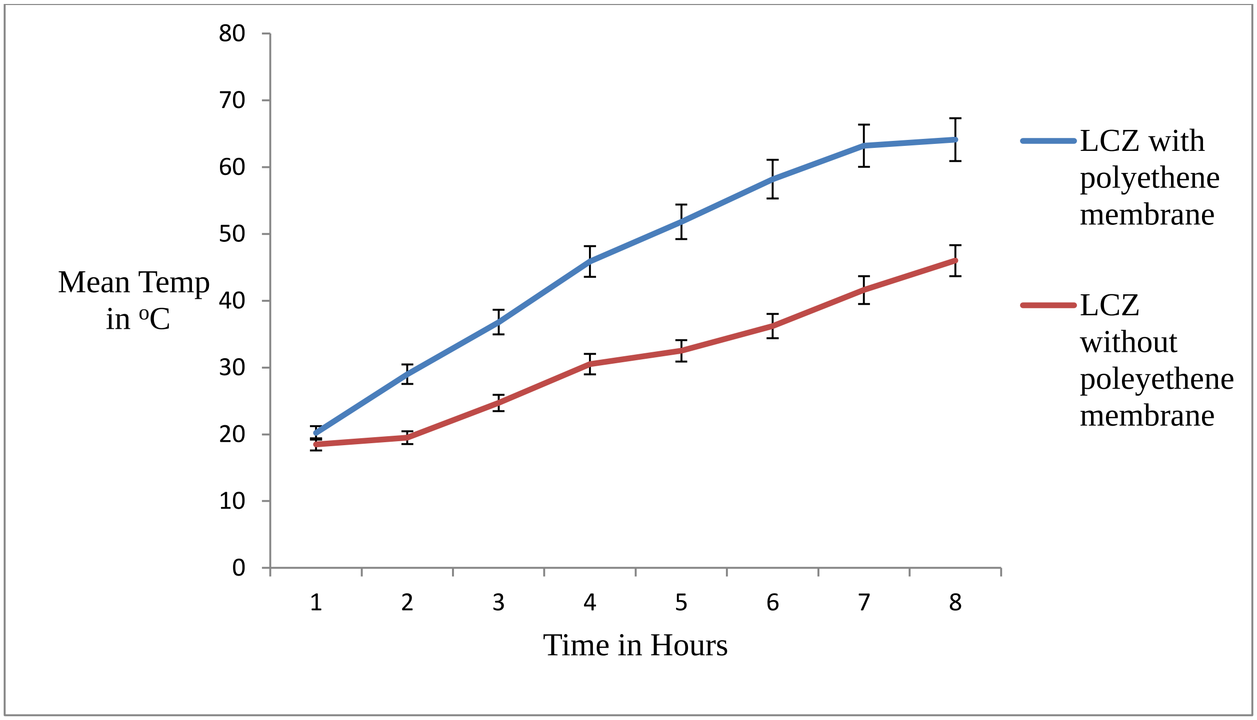


Figure 4.2: The temperature profile for LCZ at 25 % salt concentration.

From figures 4.1 and 4.2 above, it is evident that a solar pond with a polyethene film as a membrane separating the LCZ and NCZ has a capacity to hold or accumulate more thermal energy as compared to a solar pond without a polyethylene film because it inhibits convection. At 25% salt concentration of the LCZ, after just 7 hours, the solar pond with a polyethylene film had rose to 64.1°C which represents 69 % efficiency as compared to that without with only 44.1^{0}C which is about 52% efficiency.

4.3.2 Temperature profile for LCZ (20% salt) in solar ponds with polyethylene and without polyethylene

Figure 4.3 gives a summary of the variation of temperature against time at 20% salt concentration. Though the thermal storage efficiency for the two is low, it is clear that a solar pond with a polyethylene film has a higher efficiency as compared to that without a polyethylene film.

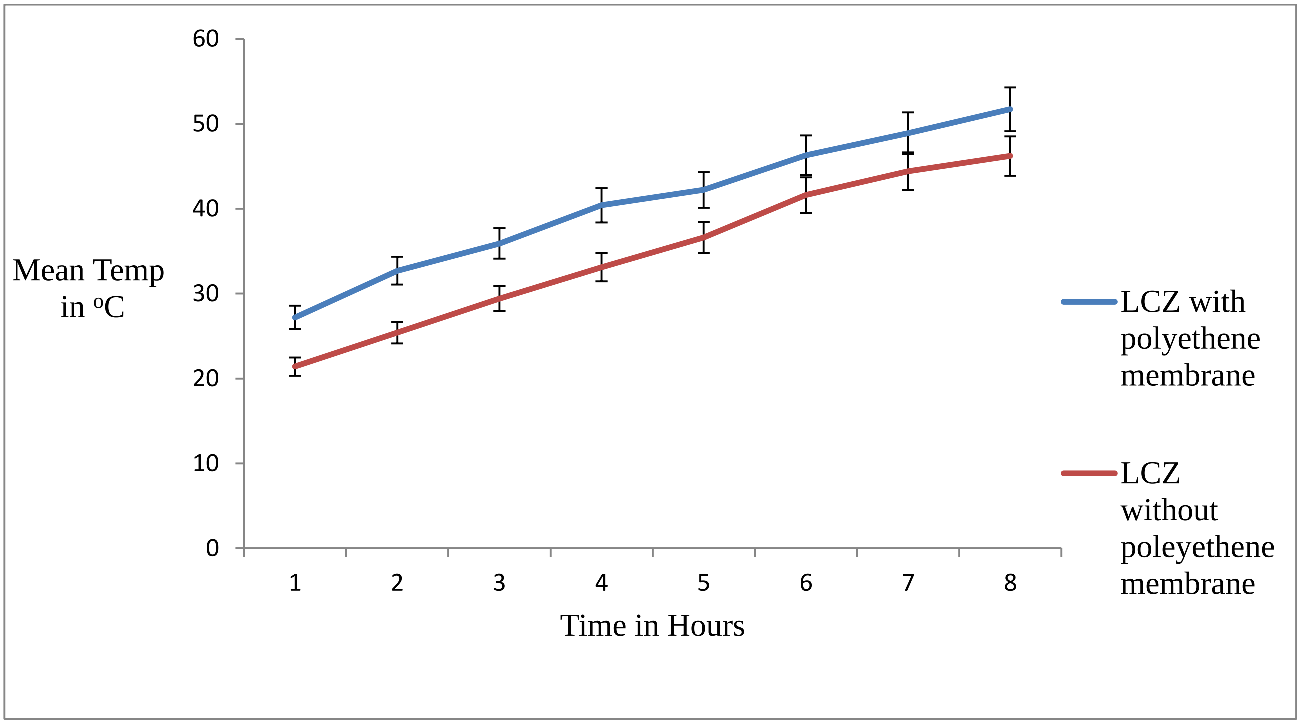


Figure 4.3: The temperature profile of LCZ at 20% salt concentration.

4.3.3 Temperature profile for LCZ (22% salt) in solar ponds with polyethene and without polyethene

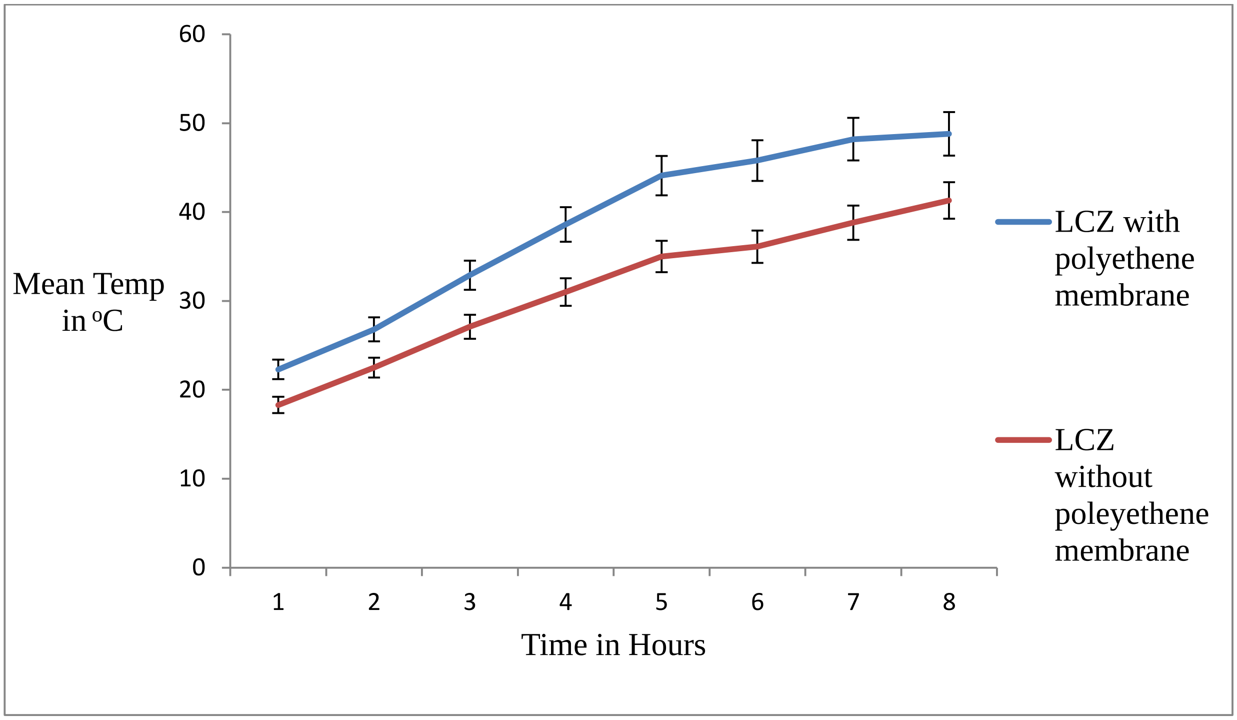


Figure 4.4: Temperature profile for LCZ at 22% salt concentration

Figure 4.4 shows the variation of temperature with time. In both cases, the variation is linear. Comparatively the solar pond with a polyethylene film gains more thermal energy and thus the temperature rise is higher than that without a polyethylene film. The temperatures of the zones generally increase with incident solar energy per unit area of surface. There are heat losses from each zone and this is the largest in the storage zone which affects the storage performance directly and drastically. In order to improve the performance and increase the efficiency, we should minimize the losses appropriately. As consistent with Karakilcik and Dincer (2007) the convection in solar ponds is inhibited by raising the viscosity of the pond by adding gelling agents, for example, a polyethyleneoxide adduct of a hydrophobic residue. Convection is further inhibited by dividing the pond into cells such that the Rayleigh number of the fluid within the cell structure is less than the critical Rayleigh number at which convection may occur. The dividers may be translucent or transparent generally horizontal sheets or generally vertical sheets, forming matrices which are rectangular, hexagonal or triangular in horizontal cross-sections. Alternatively, the gelled fluid medium of the solar pond may be bagged in translucent elongated bags which when arranged in the pond have their shortest dimension less than that which will support convection.

4.4 Conclusion

From the experimental study on the solar pond with and without a polyethene, the following conclusions have been arrived at. Polyethylene transmits solar energy and the energy is trapped in the storage zone thus heats up the zone besides, it also inhibits convection. With respect to the concentration of the LCZ these results were obtained. It was found that, as the salinity of the LCZ increases, the temperature of the LCZ and efficiency of the pond increases. The maximum storage temperature was observed after 7 hours which was found to increase from 21 ^{o}C to 64 ^{o}C in a layer with saturated salt concentration (25%) in a pond with a polyethylene film as compared to that without polyethene at 46 ^{o}C. The average temperature difference between storage zone and the ambient temperature was about 30^{o}C. Experimental collection efficiency for the maximum storage temperature of 64 ^{o}C is 69 % in solar pond with the membrane and 52 % in that without a membrane. From the above investigations, the solar pond with a polyethene is technically feasible compared to the conventional solar pond.

CHAPTER FIVE

Study of the optimal combination of salt concentration of the layers for optimum thermal storage efficiency.

Abstract

Solar pond technology has made substantial progress in the recent years. Despite the progress, there are some areas which have not been sufficiently addressed. One such area is the optimal salt concentration of a solar pond. Only simulation studies have been done .This paper presents an experimental analysis of modeling a solar pond. Emphasis is not only put on the bottom layer of the solar pond, which is also known as lower convective zone (LCZ), where heat is stored but also the non-convective zone and the upper convective zone. A solar pond of height 0.2m and area 0.6 m x 0.4 m was used for this study. LCZ was varied at the salinity of 20 %- 25 %, NCZ was varied at salinity of 5 %- 18 % and the UCZ was maintained at 0 % salinity for the experiment work. Nine k-type thermocouples were used for measuring the temperature of pond at various zones. The results show that efficiency of the storage zone increases with increasing salinity and the optimal LCZ concentration was found to be 25 % salinity, 10 % for NCZ and 0 % for UCZ.

5.1 Introduction

Solar energy is radiant energy that is produced by the sun and every day sun radiates, or sends out an enormous amount of energy. The sun radiates more energy in one second than people have used since beginning of time (Islam *et al.*, 2010). To be put to work solar energy must be converted into more useful forms of energy. Solar technology is expanding rapidly into areas other than traditional applications (solar water heating, space heating and to cook and dry food); therefore, Solar energy can be used in many different ways. One way to harness solar energy is the use of a solar pond. The working principle of solar ponds is based on the capture of solar radiation in a salt solution. A solar pond is a pond filled with water that consists of three distinct layers of salt concentration solution. The bottom water layer is a concentrated (saturated) salt solution commonly referred to as the Lower convective Zone (LCZ) or thermal layer; the middle layer has a salt concentration gradient with decreasing salt concentration upwards referred to as Non convective Zone or the gradient zone. The top layer which is sometimes mainly fresh water is referred to as Upper convective Zone (UCZ). The solar radiation arriving at the bottom of the

Solar Pond is completely absorbed by the pond bottom, provided that it is completely black. If the pond bottom is insulated the energy absorbed in the bottom leads to heat flux which enters the thermal layer.

Thermal performance of solar ponds critically depends on a high transparency of the pond brine to solar radiation. Impairment of transparency may arise from dissolved colored substances, suspended particles or populations of algae and bacteria (Hull, 1980) the simulated results of solar-pond are for surface area $1.2m^2$, and $d_{ncz} = 0.32m$. Salt concentrations of 40g/kg, 50 g/kg, 60 g/kg, and 70 g/kg were considered for the simulation. As the salinity increases the temperature of the LCZ increases. But 50 g/kg salt concentration was found to be most optimal for the above pond. (Irfan *et al.*, 2012). For the experimental work, a solar pond with surface area dimensions of 2 m x 2 m, and a depth of 1.5 m, was built at Cukurova University in Adana, Turkey. The salt-water solution is prepared by dissolving the NaCl reagent into fresh water. The thicknesses of the UCZ, NCZ and HSZ are 0.1, 0.6 and 0.8 m, respectively. The range of salt gradient in the inner zones is such that the density is 1000–1045 kg/m^3 in the UCZ, and 1045–1170 kg/m^3 in the NCZ, 1170–1200 kg/m^3 in HSZ. Temperature variations are measured at the inner and outer zones of the pond (Karakilicik and Dincer, 2006).

Pioneer researchers on solar pond like Al-Jamal and Khasan (1995) argued that the optimum concentration and thickness of the layers depends on application of the SGSP. For long term energy storage, the LCZ must be greater than 0.5 m with saturated salinity. Mohammed (2008) argued that the optimum value of this thickness is found to vary with the rate of the heat to be extracted from the system.

According to Irfan *et al*., (2012) who experimented on solar still integrated to a solar pond, the still is maintained at 0.01m water depth which is the optimum value found from the previous experiments. The base of the still is coated with granular activated carbon to enhance its evaporative efficiency. The solar-pond is made of mild-steel, 0.95 m height and 1.25 m in diameter resulting in the surface area of 1.23 m^2 exposed to solar radiations. Based on the above mathematical model of solar pond, 50 g/kg salinity concentration was found optimal for the LCZ from the simulation done in Matlab, for the given dimensions of the solar-pond. However the efficiency of the pond was found to increase as the salinity of the LCZ increases.

5.2 Materials and methods

Two experimental salt gradient solar ponds with surface areas of 0.6m x 0.4m and depth of 0.2 m were constructed to study the optimum salt concentration of the layers in a solar pond. In the pond a polyethylene film was used to separate the LCZ and NCZ. The walls and bottom were made of acrylic glass. The bottom of the pond was painted black to increase optical absorptivity. The thicknesses of the NCZ and the LCZ were 0.08 m and 0.08 m, respectively. The UCZ thickness was 0.04 m and 0 % salt concentration but the concentration of the NCZ was varied from 5 % salt content to 18 % salt content. The LCZ salt concentration was varied from 20 % to 25 %. Salty layers were formed by pouring the salt solution prepared with a required amount of salt (NaCl) on a floating wood plate on the layer formed before. The bottom and the walls were insulated using saw dust. Temperature variations inside and outside of the solar pond at different points were recorded continuously by means of thermocouples associated with a computer system.

5.3 Results and discussion

5.3.1Effect of varying salt concentration of layers in the solar pond

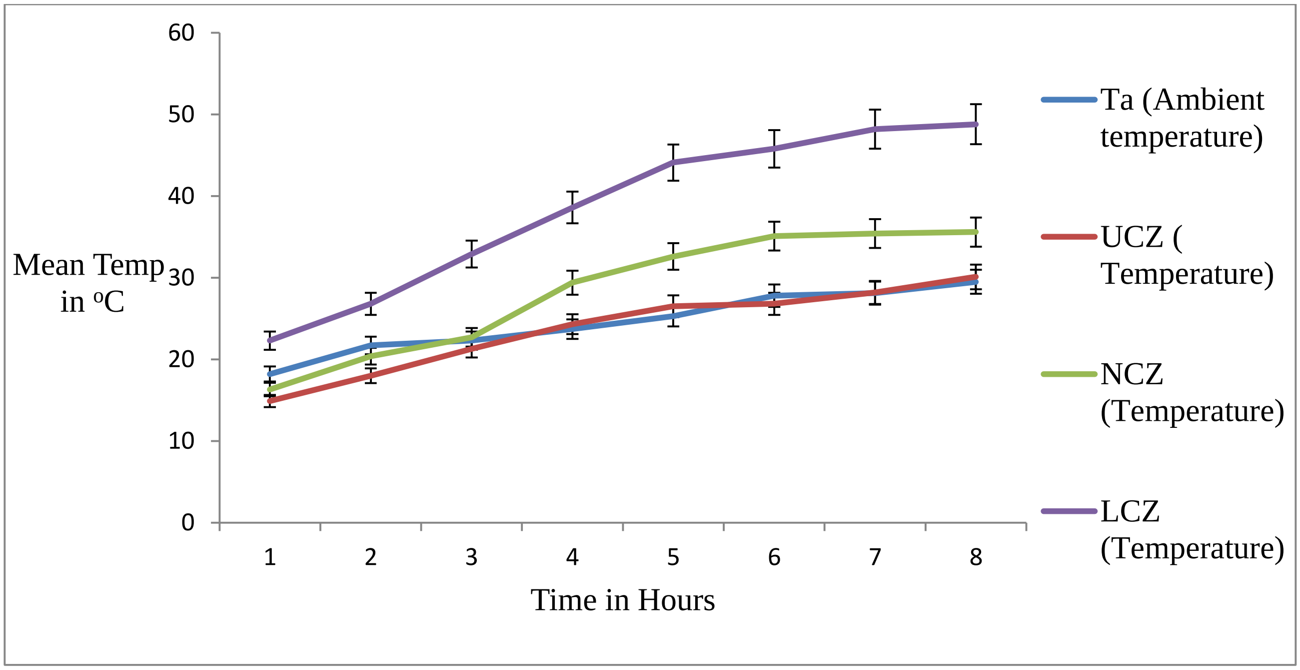


Figure 5.1: Variation of temperature for LCZ (22%), NCZ (14%), UCZ (0%) and Ta (ambient)

From the results in figure 5.1 it has been found that the temperature of the solar pond remains almost constant in upper convective zone and ambient, whereas in the non-convective zone the temperature of the solar pond exponentially increases with increasing depth and again rises constantly in lower convective zone or storage zone. The maximum value attained in storage zone was 48 °C. The NCZ and UCZ temperature values did not rise above 35 °C. The value of temperature in NCZ and UCZ and comparative statistical analysis (ANOVA) shows that there is no significant difference between the two zones and ambient temperature.

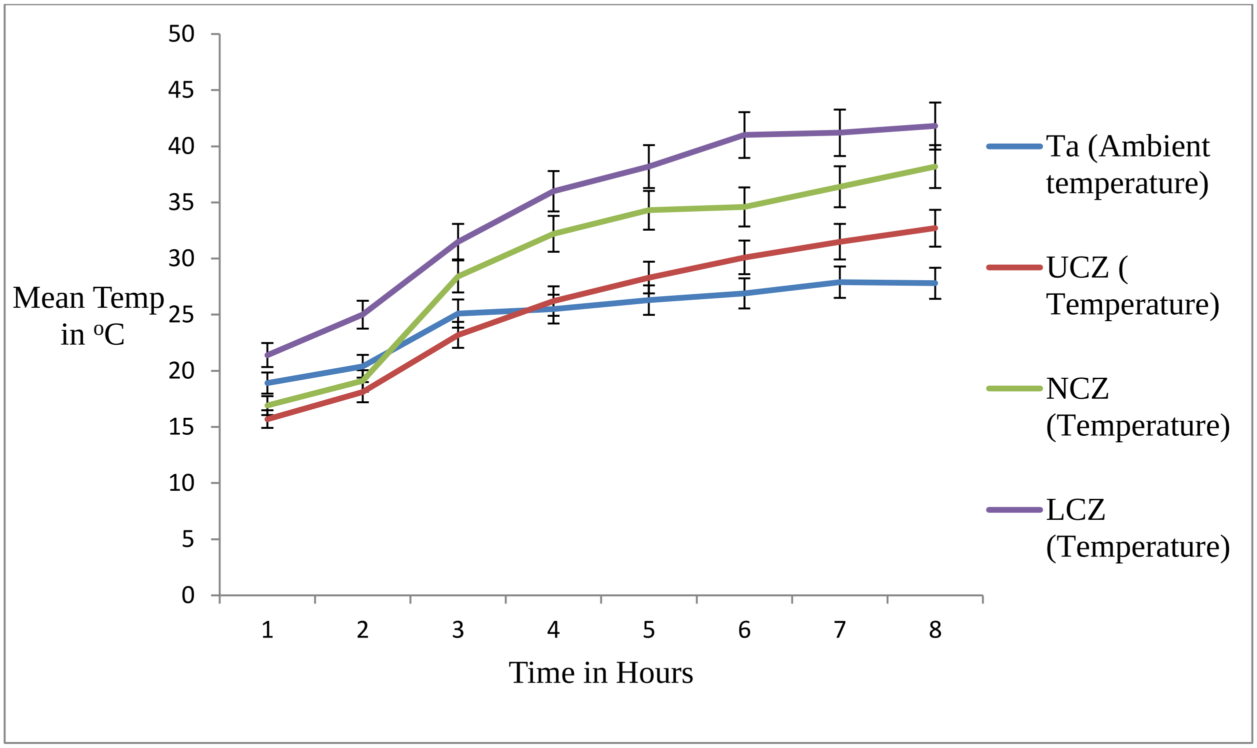


Figure 5.2: Variation of temperature for LCZ (22%), NCZ (10%), UCZ (0%) and Ta (ambient)

Fig. 5.2 shows the temperature of the lower convective storage zone, non-convective zone, upper convective zone and ambient air temperature. It is observed that the maximum temperature of 44 °C is obtained after 7 hours and the total temperature increase was found to be 28 °C. Based on statistical analysis (ANOVA) there was no significant difference between the upper convective zone and the ambient temperature.

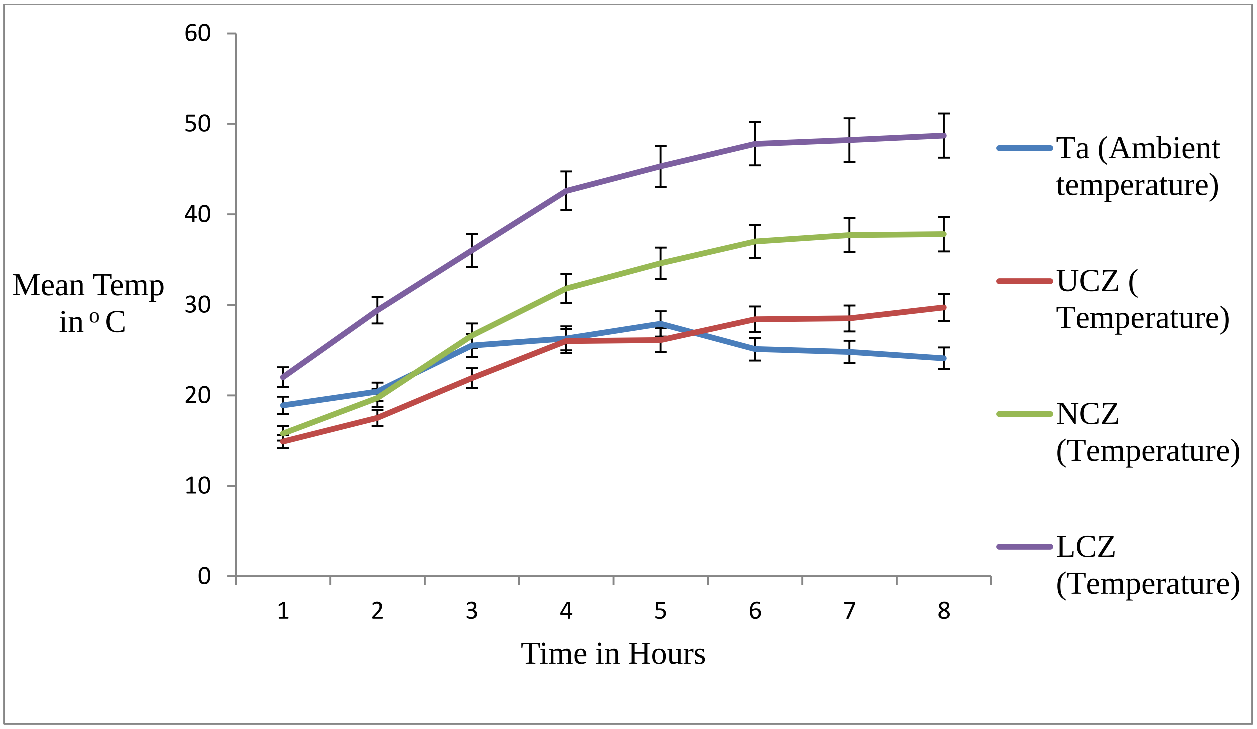


Figure 5.3: Variation of temperature for LCZ (25%), NCZ (14%), UCZ (0%) and Ta (ambient)

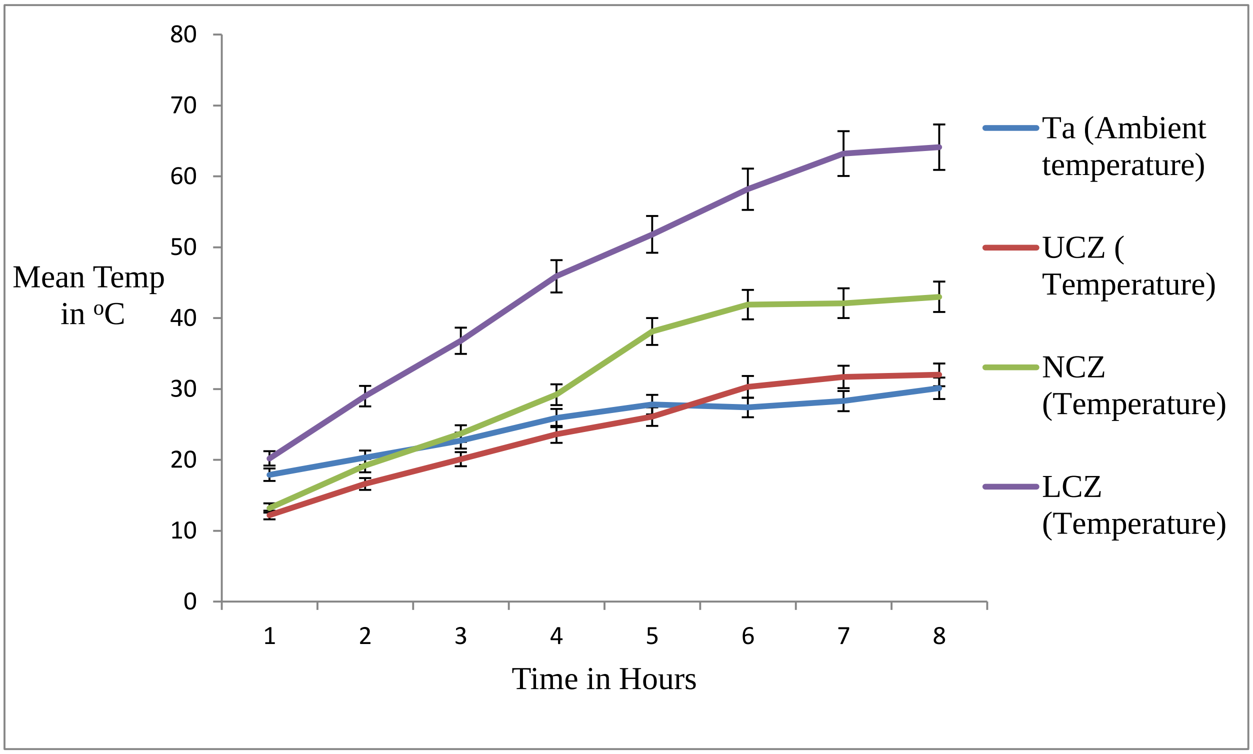


Figure 5.4: Variation of temperature for LCZ (25%), NCZ (10%), UCZ (0%) and Ta (ambient)

Fig. 5.3 and 5.4 shows the temperature profile for the layers at 25% salt content in LCZ but varied salt content for NCZ at 10% and 14%. The lower convective storage zone at it is observed, rose to a maximum temperature of 64°C which was obtained in 7 hours and the total temperature increase (Δt) was found to be 43 °C. It can be deduced that as the concentration of NCZ increases towards the concentration of the LCZ, efficiency of the solar pond is lowered. The solar pond gives optimal efficiency when the concentration of the NCZ is at about 10% salt concentration. This can be attributed to formation of a clear gradient zone between the UCZ and the LCZ. At 14% concentration of the NCZ, it is assumed that the convectional currents may lead to thermos-diffusion where heat from the LCZ is lost to the NCZ due to close concentration of the two and can be seen in figure 5.3 where initially the temperature of the NCZ, UCZ and the ambient are no different but rises as the temperature of the LCZ rises. These results are better than Abhishek and Varun (2013) who investigated the thermal performance of double glazed salt gradient solar pond. Efficiencies are expressed by using energy balance equations, for UCZ, NCZ and LCZ. It was observed to get a maximum temperature 34.51 °C (UCZ), 40.62 °C (NCZ), and 51.53 °C (LCZ), while the minimum temperature was observed to be 27.76 °C (UCZ), 35.54 °C (NCZ), and 42.39 °C (LCZ).

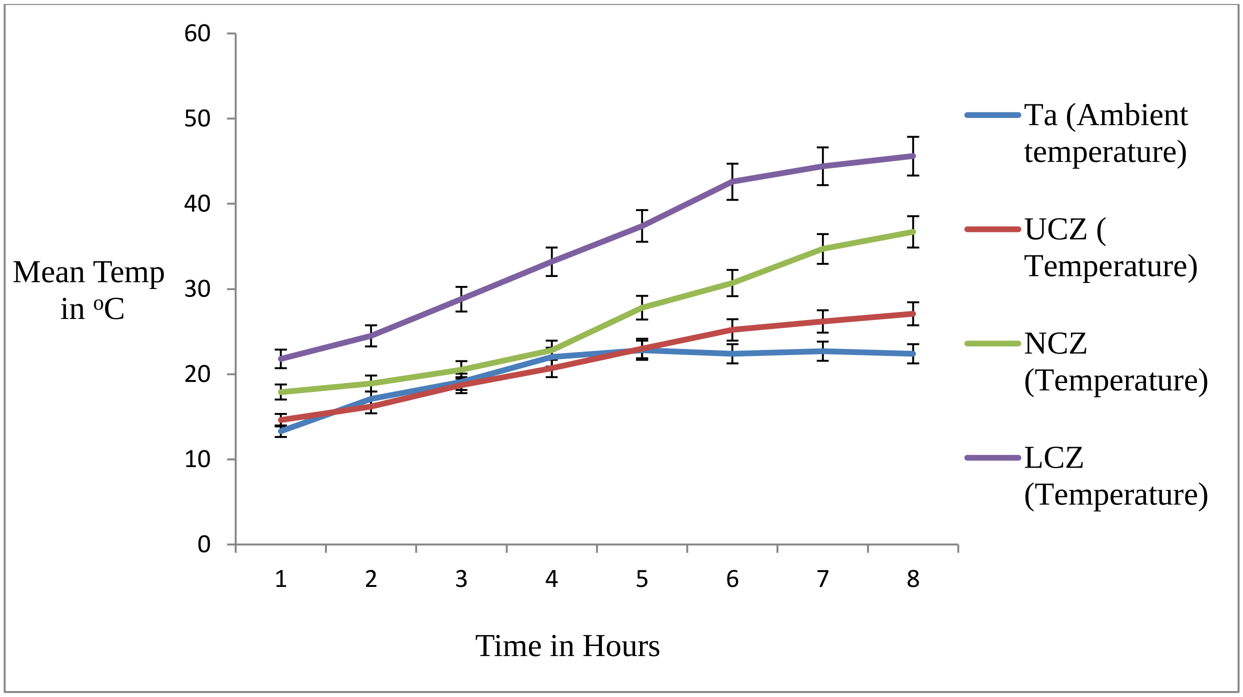


Figure 5.5: Variation of temperature for LCZ (20%), NCZ (14%), UCZ (0%) and Ta (ambient)

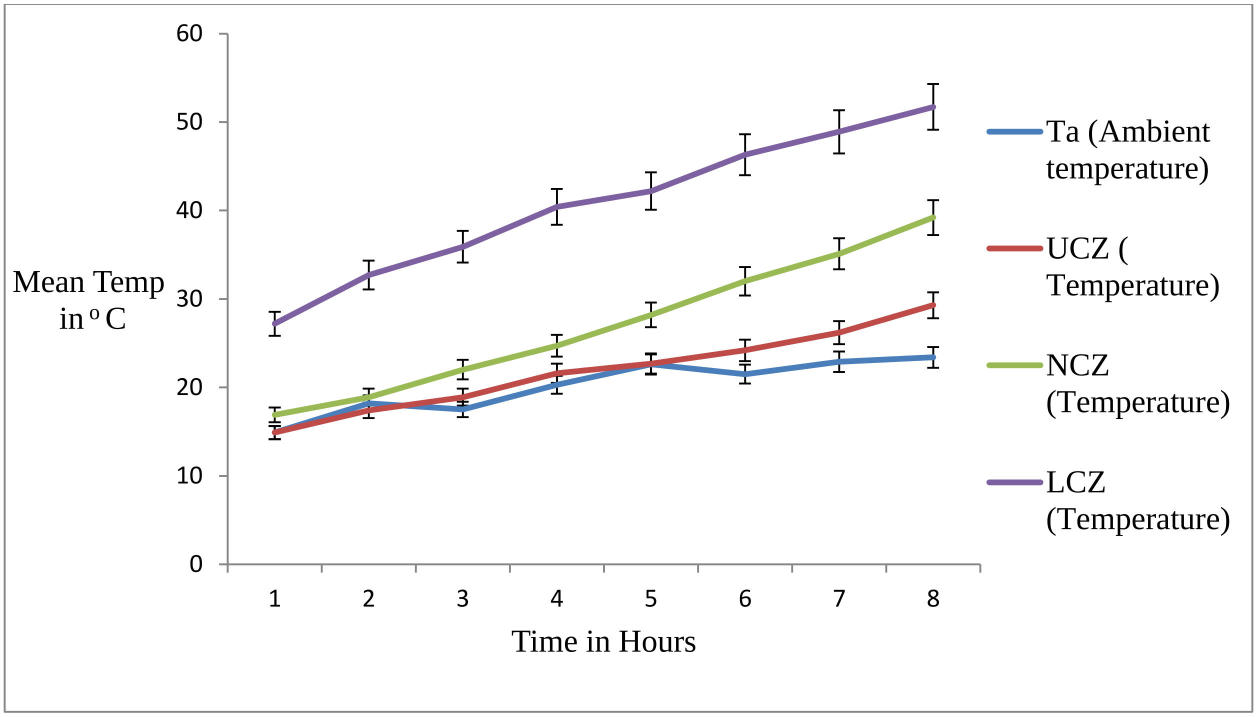


Figure 5.6: Variation of temperature for LCZ (20%), NCZ (10%), UCZ (0%) and Ta (ambient)

From these results, the concentration of 20% salt for LCZ does not give expected results. Fig. 5.5 gives the variation of temperature for the layers and looking at the relationship between NCZ (14 %) and LCZ (20 %), there is statistically no significant difference in the mean temperatures obtained between the two. This can be attributed to lack of formation of a clear gradient zone between the UCZ and the LCZ. At 14 % concentration of the NCZ, it is expected that the convectional currents may lead to thermos-diffusion where heat from the LCZ is lost to the NCZ due to close concentration of the two layers. Though NCZ at 10 % and 20 % for LCZ values are not close, the results are not significantly different at 95 % confidence level. It follows that as the concentration increases so does the thermal storage efficiency of a solar pond the results agree with Irfan *et al.*, (2012) who found that, as the salinity of the LCZ increases, the temperature of the LCZ and efficiency of the pond increases and that 50 g/kg is the optimal salinity for the LCZ for solar pond.

The above results where the temperature of the UCZ is almost the same as ambient are in agreement with Karakilcik *et al.*, (2006) who opined that although the greatest amount of solar radiation is incident on the upper convective zone, the lowest efficiencies are found for this zone. This is because of the zone's small thickness and the fact that it is responsible for the largest heat losses to air from upper surface. This is why the temperature increases a little during daytime, but decreases more significantly during night. The heat loss due to the evaporation usually represents an average of 50 % of the total heat loss. The temperature difference between the UCZ and LCZ is an important parameter that affects the pond performance. If the temperature gradient increases, flux of thermal energy out of the LCZ would increase and cause decreased ability to store energy (Saleh *et al*., 2011). In the case under consideration, where the annual average ambient temperature is low the temperature difference will be reduced and the pond is expected to have a high thermal efficiency.

5.4 Conclusion

By increasing the density of the storage layer by increasing the salt concentration will increase the temperature as more and more heat will be trapped. It can be concluded that, as the salinity of the LCZ increases, the temperature of the LCZ and efficiency of the pond increases. The optimal concentration is when the LCZ is saturated approximately at 25 % salt concentration, this is the saturation point. Results have shown that for the NCZ, 10 % gives desirable results and with this concentration a clear gradient zone is established where density increases with increase in depth. Desirable results were obtained from the thermal modeling of pond. The heat storing capacity of the solar pond can be increased by increasing the salt concentration in the Lower Convective Zone.

CHAPTER SIX

Conclusions and Recommendations

6.1 Conclusions

The results of the experiment show the possibilities of a membrane stratified solar pond and solar ponds in general. In a pond with a polyethene film, salinity change in the storage zone was not observed because the polyethene film could not allow transport of ions from the storage zone to the adjacent layers. In a solar pond without a membrane, there was erosion of the gradient zone therefore reasonable temperature rise could not be realized. The results exhibit a linear variation of concentration with number of days in the x-direction. It is evident that a solar pond with a polyethene film as a membrane separating the LCZ and NCZ has a capacity to hold or accumulate more thermal energy as compared to a solar pond without a polyethene film. At 25 % salt concentration of the LCZ, after just 7 hours, the solar pond with a polyethene film had rose to 64.1 ^{0}C which represents 69 % efficiency as compared to that without with only 44.1^{o}C which is about 52 % efficiency. The results show that as the salt content increases so do the efficiency and the solar pond gives optimal efficiency when the concentration of the NCZ is at about 10 % salt concentration and LCZ is 25 %. This can be attributed to formation of a clear gradient zone between the UCZ and the LCZ. At 14 % concentration of the NCZ, it is assumed that the convectional currents may lead to thermos-diffusion where heat from the LCZ is lost to the NCZ due to close concentration.

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 cover about 20 %, the non-convecting gradient zone around 40 % and the lower convecting storage zone also 40 %.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. It has also been proved that storage efficiency of the storage zone increases with increasing salinity and the optimum concentration is when the storage zone has a saturated concentration of the salt. 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. This work has shown that the use of a polyethene membrane between the storage zone and gradient zone does minimize completely upward salt diffusion thus showing that injecting salt back into the pond may not be necessary. 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. This is ideally suited to areas within the tropics owing to the abundance of solar radiation, the thermal energy from which can then be employed to generate power for various purposes.

6.3 Recommendations

Solar ponds have been shown to have good heat storage potential due to their big thermal storage ability. Even drastic changes in weather such as irradiation or wind speed hardly affect the pond's thermal performance, which makes them more interesting for thermal generation as well as thermal uses. The only disadvantage is the low energy density capacity which makes them more interesting for thermal uses as for power generation.

Further work should be done in the following areas:

- Improving the insulation, especially at the ground and wind-shielding,
- More work should be done to ascertain which shape between a circular and rectangular pond yields better results when a polyethylene is used as a membrane
- Applications of solar ponds in heating fish ponds at night when temperatures drop.

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APPENDICES

APPENDIX A- RESULTS

MEAN TEMPERATURES FOR THE Ta, UCZ, NCZ AND LCZ IN SOLAR PONDS WITH AND WITHOUT POLYETHENE FILM AT VARIOUS CONCENTRATIONS.

	WITH POLYETHENE			T_a (ºC)	WITHOUT POLYETHENE		
HRS	UCZ (0 %)	NCZ (18%)	LCZ (25%)		UCZ (0%)	NCZ (18%)	LCZ (25%)
0	15.1	15.1	15.6	18.7	14.7	14.8	15.0
1	18.4	18.9	21.8	20.4	18.7	18.8	20.1
2	21.8	22.3	26.1	22.6	19.9	20.1	24.3
3	24.7	25.1	30.8	25.3	22.9	23.4	27.8
4	27.2	27.6	33.1	26.9	25.3	25.7	30.3
5	29.5	30.1	36.3	27.7	26.8	27.1	32.4
6	31.5	31.8	38.0	27.5	29.3	29.5	33.8
7	32.8	33.1	39.1	28.3	32.3	32.5	35.1

	WITH POLYETHENE			T_a (ºC)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (16%)	LCZ (25%)		UCZ (0%)	NCZ (16%)	LCZ (25%)
0	14.0	14.7	15.1	18.2	14.2	14.5	15.0
1	18.0	20.4	23.9	21.7	18.1	18.5	20.2
2	24.2	26.7	27.6	25.3	22.1	22.7	23.2
3	28.2	30.3	30.7	27.9	25.0	25.9	26.9
4	30.1	32.4	32.8	27.8	27.0	27.9	28.3
5	32.3	35.2	36.7	28.3	32.1	33.4	34.5
6	34.0	37.2	38.1	30.7	34.0	34.7	35.8
7	34.8	38.3	39.8	29.5	34.3	35.1	37.0

	WITH POLYETHENE			T_a (ºC)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (14%)	LCZ (25%)		UCZ (0%)	NCZ (14%)	LCZ (25%)
0	14.9	15.8	22.0	18.9	15.0	15.5	22.3
1	17.5	19.7	29.4	20.4	19.5	19.7	25.3
2	21.9	26.6	36.0	25.5	25.7	25.9	29.0
3	26.0	31.8	42.6	26.3	29.8	30.8	33.3
4	26.1	34.6	45.3	27.9	32.2	32.7	34.3
5	28.4	37.0	47.8	25.1	32.7	33.0	34.5
6	28.5	37.7	48.2	24.8	33.2	33.4	35.9
7	29.7	37.8	48.7	24.1	34.0	34.7	36.1

	WITH POLYETHENE			T_a (^oC)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (12%)	LCZ (25%)		UCZ (0%)	NCZ (12%)	LCZ (25%)
0	16.4	16.6	17.8	18.6	16.1	16.4	16.9
1	20.1	22.3	25.7	21.7	21.0	21.5	22.5
2	24.9	25.1	30.6	26.9	26.1	27.0	27.3
3	26.9	27.1	36.1	27.3	29.2	29.4	30.7
4	29.6	30.3	39.0	26.3	30.2	31.7	32.1
5	30.1	31.9	42.6	27.8	30.8	32.6	33.6
6	30.8	34.3	46.5	25.7	31.4	33.1	34.7
7	31.1	35.7	48.9	25.3	32.6	34.6	35.8

	WITH POLYETHENE			T_a (^oC)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (10%)	LCZ (25%)		UCZ (0%)	NCZ (10%)	LCZ (25%)
0	12.2	13.2	20.2	17.9	11.2	12.0	18.5
1	16.6	19.2	29.0	20.3	15.8	15.4	19.5
2	20.1	23.7	36.8	22.7	20.9	20.3	24.7
3	23.6	29.2	45.9	25.9	24.5	24.7	30.5
4	26.1	38.1	51.8	27.8	28.9	29.2	32.5
5	30.3	41.9	58.2	27.4	31.3	33.6	36.2
6	31.7	42.1	63.2	28.3	32.0	35.7	41.6
7	32.0	43.0	64.1	30.1	33.2	37.9	46.0

	WITH POLYETHENE			T_a (^oC)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (8%)	LCZ (25%)		UCZ (0%)	NCZ (8%)	LCZ (25%)
0	16.1	16.9	22.1	18.6	16.0	17.2	19.4
1	17.5	19.4	25.9	21.7	19.1	20.8	24.3
2	20.0	24.2	32.1	25.3	23.5	25.2	27.5
3	25.6	30.1	37.3	25.7	26.3	29.3	32.4
4	29.0	33.6	43.0	26.9	29.7	32.5	36.5
5	32.7	34.7	44.4	26.3	30.4	33.4	38.9
6	33.6	35.2	46.2	27.8	31.3	34.2	40.8
7	34.5	35.6	46.8	27.3	32.1	35.8	41.3

	WITH POLYETHENE			T_a (^{o}C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (5%)	LCZ (25%)		UCZ (0%)	NCZ (5%)	LCZ (25%)
0	16.1	18.0	22.5	21.2	16.3	17.5	19.8
1	19.4	21.3	28.7	24.9	19.6	20.9	22.9
2	23.2	27.6	33.1	26.0	24.1	26.1	28.8
3	26.6	30.1	37.7	26.7	28.1	28.6	32.9
4	29.3	34.3	40.2	28.5	31.2	33.3	36.3
5	31.0	36.1	41.7	29.5	33.5	35.3	37.2
6	33.2	37.9	42.6	31.4	34.3	35.7	38.3
7	35.1	38.2	43.1	30.1	35.2	36.1	39.0

	WITH POLYETHENE			T_a (^{o}C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (14%)	LCZ (22%)		UCZ (0%)	NCZ (14%)	LCZ (22%)
0	15.7	16.9	21.4	18.9	16.0	18.1	19.5
1	18.1	19.1	25.0	20.4	18.7	20.8	21.9
2	23.2	28.4	31.5	25.1	23.5	25.1	26.9
3	26.2	32.2	36.0	25.5	26.3	29.3	30.3
4	28.3	34.3	38.2	26.3	28.1	30.6	32.7
5	30.1	34.6	41.0	26.9	30.5	32.6	35.8
6	31.5	36.4	41.2	27.9	31.3	33.6	36.0
7	32.7	38.2	41.8	27.8	31.9	34.8	37.8

	WITH POLYETHENE			T_a (^{o}C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (10%)	LCZ (22%)		UCZ (0%)	NCZ (10%)	LCZ (22%)
0	14.9	16.3	22.3	18.2	15.9	17.8	18.3
1	18.0	20.4	26.8	21.7	18.2	20.6	22.5
2	21.3	22.7	32.9	22.3	23.1	25.8	27.1
3	24.3	29.4	38.6	23.7	25.0	29.9	31.0
4	26.5	32.6	44.1	25.3	28.0	33.3	35.0
5	26.8	35.1	45.8	27.8	28.1	34.5	36.1
6	28.2	35.4	48.2	28.1	30.1	35.0	38.8
7	30.1	35.6	48.8	29.5	31.4	37.4	41.3

	WITH POLYETHENE			T_a (°C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (8%)	LCZ (22%)		UCZ (0%)	NCZ (8%)	LCZ (22%)
0	15.9	17.8	23.4	18.3	15.7	18.0	19.9
1	18.4	19.7	32.1	23.6	18.9	21.6	23.6
2	22.3	26.7	36.6	26.5	23.3	27.3	30.0
3	24.4	27.6	40.8	28.8	27.0	30.9	33.0
4	27.2	34.2	43.1	28.5	30.5	34.4	36.8
5	29.5	35.5	44.6	28.9	33.3	35.9	38.6
6	31.1	38.8	45.6	30.0	34.5	36.2	39.2
7	32.5	39.2	45.8	29.7	35.8	37.3	40.1

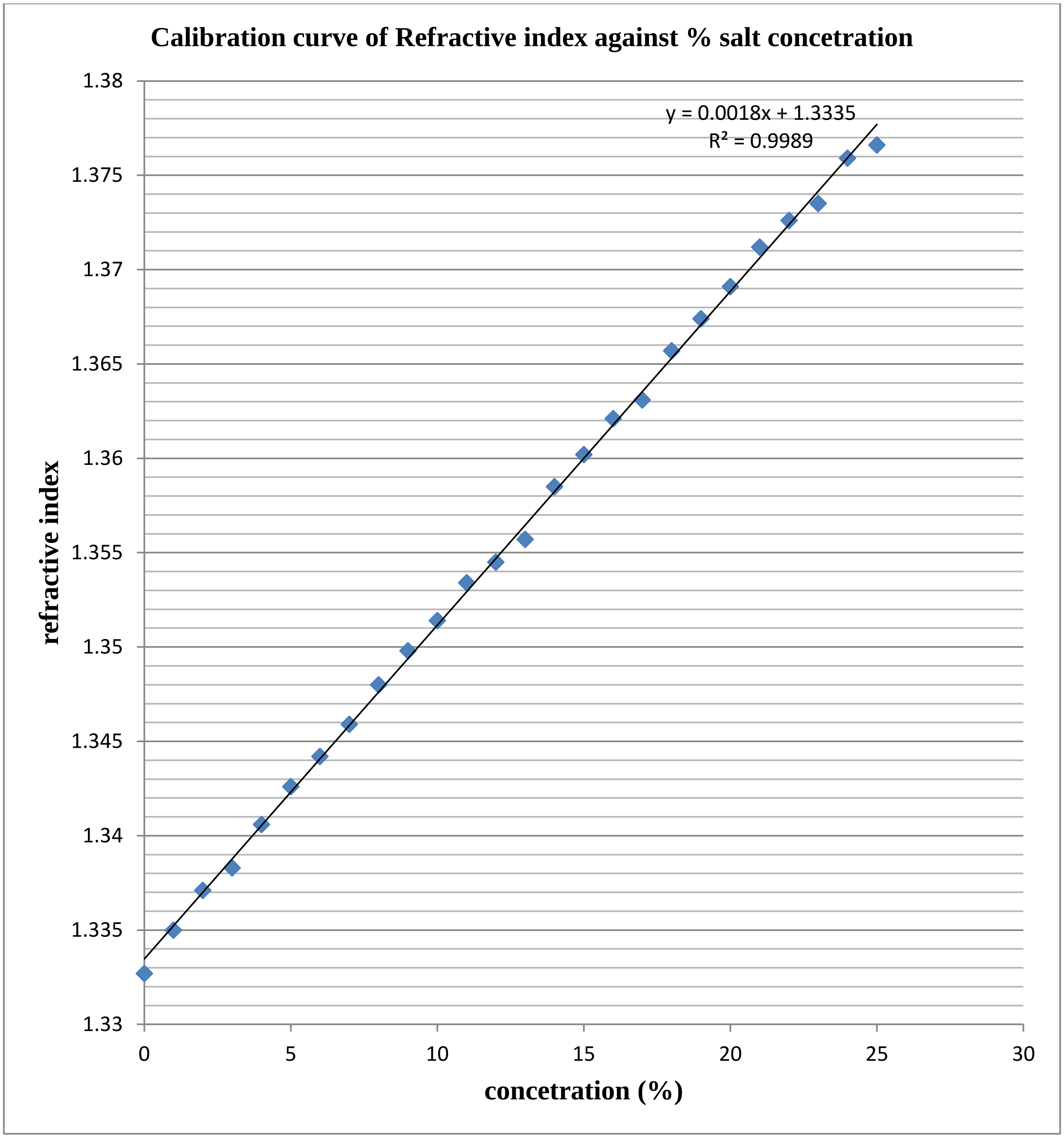
	WITH POLYETHENE			T_a (°C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (5%)	LCZ (22%)		UCZ (0%)	NCZ (5%)	LCZ (22%)
0	16.3	18.3	21.7	18.7	16.9	17.1	19.7
1	20.4	23.0	25.3	24.6	20.3	20.3	22.6
2	24.1	28.6	29.7	25.5	24.8	24.8	27.2
3	28.8	32.5	34.8	26.9	29.2	30.2	32.4
4	31.3	34.5	37.2	28.0	31.9	32.3	35.7
5	32.5	36.8	37.7	30.1	32.6	34.3	38.1
6	34.0	37.2	39.0	29.7	33.8	36.3	38.8
7	36.7	38.1	41.7	29.3	36.0	37.8	39.2

	WITH POLYETHENE			T_a (°C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (14%)	LCZ (20%)		UCZ (0%)	NCZ (14%)	LCZ (20%)
0	14.6	17.9	21.8	13.3	14.9	17.0	20.4
1	16.2	18.9	24.5	17.1	16.5	18.7	22.8
2	18.7	20.5	28.8	19.1	18.5	20.7	26.6
3	20.7	22.8	33.2	22.0	21.1	23.1	30.6
4	23.0	27.8	37.4	22.8	23.2	27.7	34.7
5	25.2	30.7	42.6	22.4	25.3	29.7	40.1
6	26.2	34.7	44.4	22.7	25.7	31.1	41.8
7	27.1	36.7	45.6	22.4	26.0	34.3	42.3

	WITH POLYETHENE			T_a (^{o}C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (12%)	LCZ (20%)		UCZ (0%)	NCZ (12%)	LCZ (20%)
0	15.3	17.6	24.0	15.5	15.4	18.7	21.7
1	17.9	19.2	28.4	18.5	18.1	19.5	26.3
2	19.9	22.5	33.5	18.3	20.0	22.7	31.2
3	21.9	25.0	38.3	19.7	22.2	26.3	34.8
4	23.2	28.1	40.0	20.0	23.0	28.8	36.4
5	25.1	31.9	43.9	22.2	25.4	30.3	41.6
6	25.3	32.6	44.7	20.5	26.5	31.7	41.8
7	27.8	35.0	46.9	21.0	28.0	33.3	42.4

	WITH POLYETHENE			T_a (^{o}C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (10%)	LCZ (20%)		UCZ (0%)	NCZ (10%)	LCZ (20%)
0	14.9	16.9	27.2	14.9	14.8	19.1	21.4
1	17.4	18.9	32.7	18.2	17.4	19.9	25.4
2	18.9	22.0	35.9	17.5	19.0	24.1	29.4
3	21.6	24.7	40.4	20.3	21.5	27.5	33.1
4	22.7	28.2	42.2	22.6	23.3	29.0	36.6
5	24.2	32.0	46.3	21.5	25.9	34.7	41.6
6	26.2	35.1	48.9	22.9	26.9	36.9	44.4
7	29.3	39.2	51.7	23.4	30.1	38.7	46.2

	WITH POLYETHENE			T_a (^{o}C)	WITHOUT POLYETHENE		
HRS	UCZ (0%)	NCZ (5%)	LCZ (20%)		UCZ (0%)	NCZ (5%)	LCZ (20%)
0	14.1	15.2	21.7	15.0	14.1	15.7	21.8
1	17.1	18.8	27.7	18.1	17.3	18.7	25.8
2	20.0	22.8	32.9	20.2	20.0	22.6	29.6
3	22.7	25.2	38.2	22.1	22.8	25.8	33.6
4	25.6	29.3	42.3	23.2	25.1	27.9	36.9
5	27.8	31.5	44.4	23.3	26.1	30.7	39.4
6	28.7	32.4	47.1	24.0	26.5	32.5	41.3
7	30.1	34.0	50.1	24.3	29.1	35.1	43.1


Calibration curve of Refractive index against % salt concetration
y = 0.0018x + 1.3335
R² = 0.9989
refractive index
1.38
1.375
1.37
1.365
1.36
1.355
1.35
1.345
1.34
1.335
1.33
0
5
10
15
20
25
30
concetration (%)

SALINITY PROFILES FOR THE UCZ AND LCZ

UCZ (INITIALLY (0%)   without polyethene UCZ (INITIALLY 0%) with polyethene

Day	Refractive Index	% Salt Concentration	Day	Refractive Index	% Salt Concentration
1	1.3334	3.4	1	1.3366	3.6
2	1.334	4	2	1.3374	4.4
3	1.3385	5.5	3	1.3382	5.2
4	1.3386	5.6	4	1.3386	5.6
5	1.3388	5.8	5	1.339	6
6	1.3388	5.8	6	1.339	6
7	1.339	6	7	1.3392	6.2
8	1.3393	6.3	8	1.3393	6.3
9	1.34	7	9	1.3395	6.5
10	1.3403	7.1	10	1.3399	6.9
11	1.3405	7.5	11	1.34	7
12	1.3406	7.6	12	1.3402	7.2
13	1.341	8	13	1.3405	7.5
14	1.3413	8.3	14	1.341	8
15	1.3416	8.6	15	1.341	8

LCZ (INITIALLY 25%) without polyethene   LCZ (INITALLY 25 %) with polyethene

Day	Refractive Index	% Salt Concentration	Day	Refractive Index	% Salt Concentration
1	1.3691	20	1	1.3766	25
2	1.3657	18	2	1.3765	25
3	1.3631	17	3	1.3766	25
4	1.3631	17	4	1.3764	25
5	1.3627	16.7	5	1.3765	25
6	1.3621	16	6	1.3766	25
7	1.3614	15.6	7	1.3766	25
8	1.3602	15	8	1.3765	25
9	1.3602	15	9	1.3764	25
10	1.3598	14.8	10	1.3765	25
11	1.3598	14.8	11	1.3766	25
12	1.3594	14.6	12	1.3766	25
13	1.3590	14.2	13	1.3764	25
14	1.3585	14.1	14	1.3766	25
15	1.358	14.0	15	1.3767	25

APPENDIX B- DATA ANALYSIS

T-Test

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	with	15.787	15	1.6831	.4346
	without	25.000	15	.0000	.0000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	with - without	-9.213	1.6831	.4346	-10.145	-8.281	-21.201	14	.000

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	with	6.433	15	1.5022	.3879
	without	6.293	15	1.2453	.3215

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	with & without	15	.989	.000

25% and 10%

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LCZ Temperature	Between Groups	1845.040	7	263.577	.	.
	Within Groups	.000	0	.		
	Total	1845.040	7			
LCZ temp	Between Groups	813.555	7	116.222	.	.
	Within Groups	.000	0	.		
	Total	813.555	7			

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	LCZ Temperature	46.150	8	16.2351	5.7400
	LCZ temp	30.675	8	10.7806	3.8115

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	LCZ Temperature & LCZ temp	8	.986	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	LCZ Temperature - LCZ temp	15.475	5.8836	2.0802	10.556	20.394	7.439	7	.000

25% and 14%

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LCZ Temperature	Between Groups	690.980	7	98.711	.	.
	Within Groups	.000	0	.		
	Total	690.980	7			
LCZ temp	Between Groups	189.719	7	27.103	.	.
	Within Groups	.000	0	.		
	Total	189.719	7			

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	LCZ Temperature	40.000	8	9.9354	3.5127
	LCZ temp	31.338	8	5.2060	1.8406

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	LCZ Temperature & LCZ temp	8	.995	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	LCZ Temperature - LCZ temp	8.663	4.7812	1.6904	4.665	12.660	5.125	7	.001

22% and 10%

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LCZ Temperature	Between Groups	715.499	7	102.214	.	.
	Within Groups	.000	0	.		
	Total	715.499	7			
LCZ temp	Between Groups	457.139	7	65.306	.	.
	Within Groups	.000	0	.		
	Total	457.139	7			

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	LCZ Temperature	38.438	8	10.1101	3.5745
	LCZ temp	31.263	8	8.0812	2.8571

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	LCZ Temperature & LCZ temp	8	.994	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	LCZ Temperature - LCZ temp	7.175	2.2537	.7968	5.291	9.059	9.005	7	.000

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	LCZ Temperature	34.513	8	7.8123	2.7621
	LCZ temp	30.113	8	6.7953	2.4025

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	LCZ Temperature & LCZ temp	8	.993	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	LCZ Temperature - LCZ temp	4.400	1.3266	.4690	3.291	5.509	9.381	7	.000

20% and 10%

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LCZ Temperature	Between Groups	491.219	7	70.174	.	.
	Within Groups	.000	0	.		
	Total	491.219	7			
LCZ temp	Between Groups	571.559	7	81.651	.	.
	Within Groups	.000	0	.		
	Total	571.559	7			

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	LCZ Temperature	40.663	8	8.3770	2.9617
	LCZ temp	34.762	8	9.0361	3.1947

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	LCZ Temperature & LCZ temp	8	.995	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	LCZ Temperature - LCZ temp	5.900	1.0650	.3765	5.010	6.790	15.669	7	.000

20% and 14%

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
LCZ Temperature	Between Groups	590.049	7	84.293	.	.
	Within Groups	.000	0	.		
	Total	590.049	7			
LCZ temp	Between Groups	523.989	7	74.856	.	.
	Within Groups	.000	0	.		
	Total	523.989	7			

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	LCZ Temperature	34.788	8	9.1811	3.2460
	LCZ temp	32.413	8	8.6519	3.0589

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	LCZ Temperature & LCZ temp	8	1.000	.000

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	LCZ Temperature - LCZ temp	2.375	.5994	.2119	1.874	2.876	11.207	7	.000