Heat Extraction from the Solar Pond

By

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CERTIFICATE

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DEDICATION

I would like to dedicate my thesis to my beloved parents for their countless support and encouragement for my bright future.

ACKNOWLEDGEMENT

I am extremely grateful to God who through His mercy and grace has given me strength to accomplish this task.

I am grateful to Saltec Energy Solutions for providing the knowledge and data, which was necessary to carry out the current research.

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ABSTRACT

Pakistan energy demand is increasing with the rise of population. Most of the energy demand of the country is being fulfilled by fossil fuels. The demand of energy is also increasing with development and advancement in every field of life; due to which utilization of fossil fuels is increasing. The utilization of fossil fuels has caused severe environmental concerns. The environmental concerns and depleting fossil fuels reserved have forced researchers to get energy from other renewable sources. In renewable, solar energy by utilizing salt gradient solar ponds has obtained the great interest since early nineties. Salt gradient solar pond is an artificially constructed water pond, which has been increasing salt concentration with depth. The solar pond utilizes solar energy to heat water. This stored energy in the saline water can be extracted through the heat exchanger. Heat stored in the pond can be used for various applications; such as water heating, power generation, refrigeration, water desalination, space heating and grain drying. In this study, first effort has been made to evaluate the performance of the solar pond under Pakistan's climate condition. Simulations were carried out in MATLAB. To predict the thermal performance of the solar pond energy balance for the upper convective zone, lower convective zone and gradient zone using first order differential equation by the finite difference explicit method has been used. Weather data for simulation was obtained from Meteonorm, a meteorological database. Simulations were carried out to optimize the zone thickness, so that maximum performance can be achieved. Simulations also evaluate the effect of ground water conductivity and heat extraction on the pond thermal performance. The effect of salt diffusion on pond performance was investigated and suggested that maintenance is necessary for salt gradient profile in the pond. In the further study, solar pond viability for different cities of Pakistan has been analyzed. The study suggested, solar pond will perform well in Quetta and Peshawar.

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PUBLICATIONS

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2. "Modeling and Thermal analysis of salt gradient solar pond for Pakistan Islamabad". Paper presented in International Conference on Energy Systems and Policies (ICESP 2014), 24-26 Nov at Air University Islamabad.**
3. Matlab code for salt gradient solar pond.***

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LIST OF ABBREVIATIONS

$\mathbf{I_o}$	Hourly solar radiations
$\mathbf{I_x}$	Radiations at depth x.
$\mathbf{I_{XR}}$	Radiations reflected from pond bottom.
$\mathbf{T_{amb}}$	Ambient temperature
$\mathbf{T_{sky}}$	Sky temperature
$\mathbf{T_1}$	Upper convective zone temperature
$\mathbf{T_g}$	Ground temperature
t	Time
k	Thermal conductivity
$\mathbf{k_{pi}}$	Thermal conductivity of pipe
$\mathbf{C_p}$	Specific heat capacity
$\mathbf{P_v}$	Partial pressure
$\mathbf{P_a}$	Vapor pressure
$\mathbf{T_p}$	LCZ temperature
$\mathbf{T_{in}}$	Water inlet temperature to heat exchanger
$\mathbf{T_{out}}$	Water outlet temperature to heat exchanger
V	Wind speed
$\mathbf{D_o}$	Diffusion coefficient of saline solution
ν	Kinematic viscosity of water
U	Overall heat transfer coefficient
L	Length of heat exchanger pipe
J	Mass flux
α	Thermal diffusion
B	Coefficient of thermal expansion
Ra	Raleigh number
Re	Reynold number
$\mathbf{N_u}$	Nusselt number
$\mathbf{P_r}$	Prandtl number
$\mathbf{q_g}$	Ground losses
$\mathbf{h_{conv}}$	Convective heat transfer coefficient

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Energy is the basic need for economic development of the country. The most of the Pakistan energy demand is being fulfilled by fossil fuels, in which gas and oil share 49.50 and 30.8 percent respectively as shown in Figure 1.1 [1]. Due to the limited amount of fossil fuel reserves in the country, about 31.46 percent of energy demand is being meet by import [2]. The demand of energy is increasing with the rise in population and technological development. Pakistan is unable to fulfill its energy demand, so there is about 10 to 12 hours load shedding of electricity [3]. The price of energy production is also increasing due to import of fossil fuel. Natural gas is currently being used in domestic sector, fertilizer industries, commercial and in transport sector as shown in Figure 1.2 [1]. Country is also facing about 912 (billion cubic feet) natural-gas shortage [4]. This energy crisis has forced many industries to shut down their operation [3]. Despite that burning of fossil fuels and natural gas also contribute to air pollution and global warming, which cause severe health hazards [5], so there is a need to focus on energy resources, which are secure, readily available, environmentally favorable and cost-effective as well. Renewable energy source can contribute significantly to overcome these problems by decreasing dependency of Pakistan's energy mix from fossil fuels. One of the abundant renewable energy sources is solar energy; about 95 percent sites of Pakistan are blessed with 5-7 $kWh/m^2/day$ global insolation and 7-8 hours daily sunshine [6]. This indicate that Pakistan is blessed with vast solar potential of about 2.9 million MW [7]. This solar potential can be beneficially utilized for solar energy applications such as solar water heating, photovoltaic, desalination, refrigeration, air conditioning and crop drying applications [8]. Utilization of solar energy for water heating can serve as cost effective and environment friendly. Due to high cost of solar water heaters and lack of technical knowledge, this energy source is not being utilized significantly, so there is the need to have detail analysis of solar thermal potential thus maximum benefits can be obtained. In this study, solar thermal potential is analyzed by considering solar pond. The difference between normal pond and solar pond is given below.

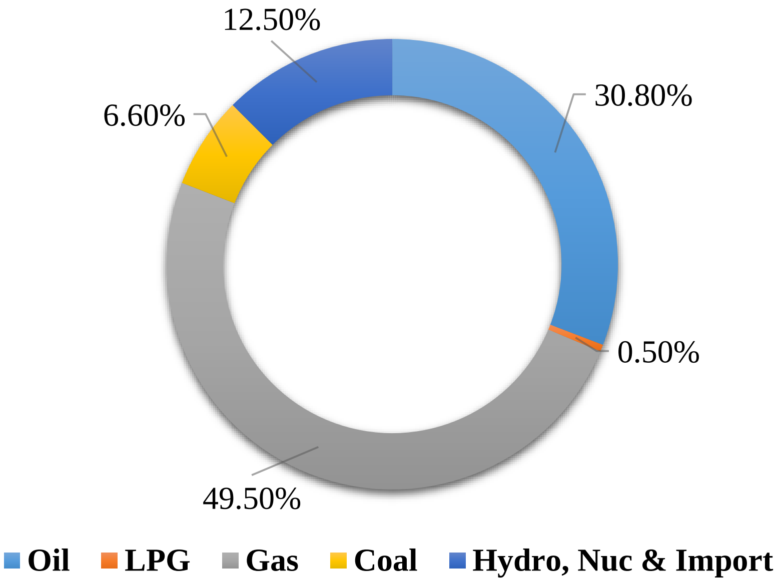


Figure 1.1. The energy supply of Pakistan by source.

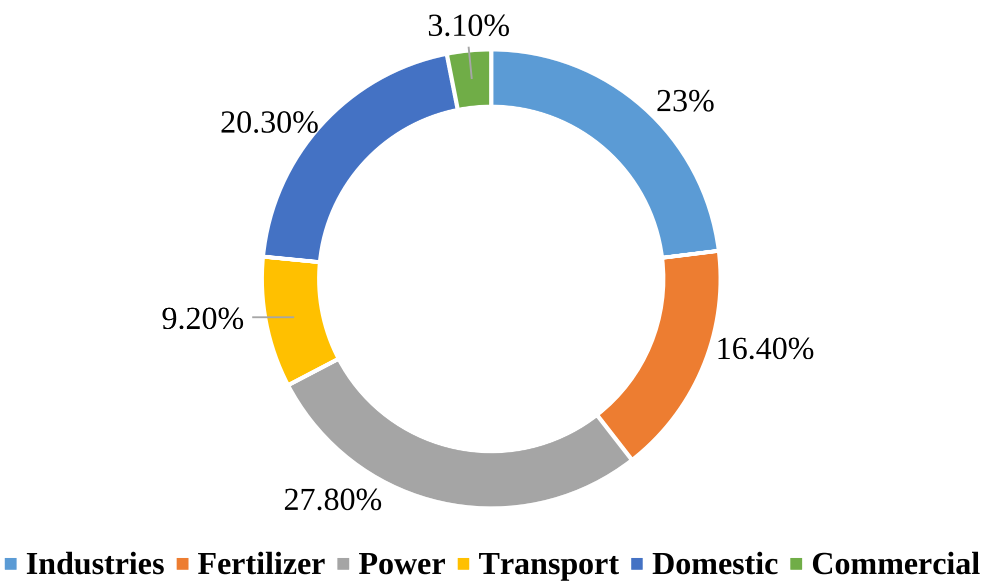


Figure 1.2. Natural gas utilization in different sectors of Pakistan

1.2 Difference Between Natural and Salt Gradient Solar Pond

The difference between natural pond and salt gradient solar pond is that in a natural pond when solar radiations fall on pond surface, water molecules at bottom absorb this energy and become warm. Due to rise in temperature, density of water at the bottom decreases [9]; the warm water upsurge to the pond surface and lose stored energy into atmosphere as shown in Figure 1.3, this phenomenon is called as convection, whereas in salt gradient solar pond, the effect of convection is suppressed by making liquid denser at depth [10]. The water with high density does not rise up, hence convection is suppressed.

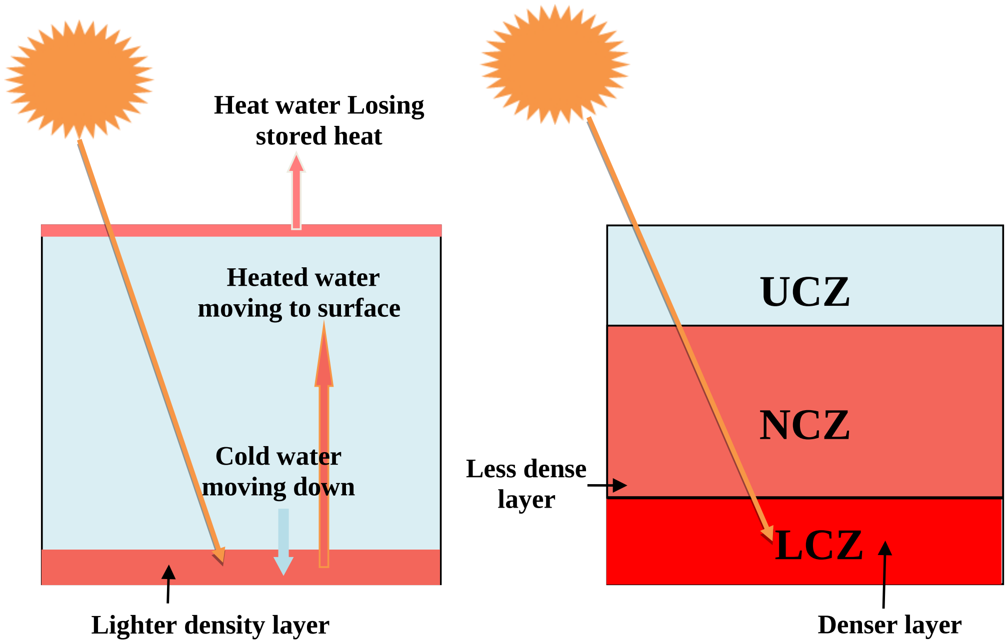


Figure 1.3. Natural pond and solar pond

1.3 Types of Solar Ponds

Solar ponds convert solar irradiations into thermal energy, which has a built-in thermal energy storage unit. All natural lakes and ponds covert solar energy into heat, but most of the stored energy is lost into atmosphere due to convection and evaporation, whereas in the solar pond the vertical convection and evaporation is suppressed [11]. Based on convective behavior solar pond is classified under two categories: convective and non-convective solar ponds [12].

1.3.1 Convective Solar Pond

Convective solar pond contains only one liquid layer. These ponds are shallow and have one type as given below [12].

1.3.1.1 Shallow Solar Pond

The shallow solar pond consists of plastic envelop located inside frame, which is blacken at bottom and top is covered by transparent film [13] as shown in Figure 1.4. The upper clear plastic film is in contact with the water surface, so that no evaporation of water occurs hence the cooling effect due to water evaporation is prevented [14]. Shallow solar pond do not store thermal energy for long time, hence separate storage is required. Before nightfall when water temperature reaches maximum temperature, then pond water is stored in insulated reservoir. So that hot water can be available on next day.

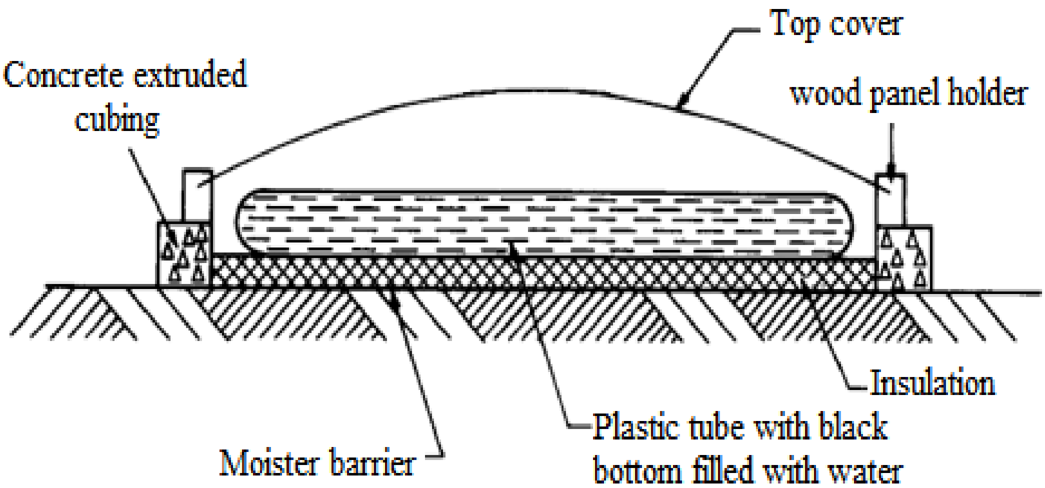


Figure 1.4. Shallow solar pond [13].

1.3.2 NON-CONVECTIVE SOLAR PONDS

Non-convective solar ponds usually contain saline water and consist of multiple layers to prevent convection. The concept of saline water is to increase density of water, so that convection can be suppressed at pond surface and water at high temperature can be obtained [15]. Once water becomes hot, the bottom layer can be used as a heat source to provide continuous heat through heat exchanger. Non-convective solar ponds are sub-divided into three main types namely: Salinity gradient solar pond, solar gel pond and membrane stratified solar ponds [12].

1.3.2.1 SALINITY GRADIENT SOLAR PONDS

Salinity gradient solar pond (SGSP) is an artificial large body of the water reservoir that collect energy from sun and utilize it for heating the water. These are also known as the economic and reliable source for collecting and storing solar energy for the long period [16]. In this type of pond convection is suppressed by concentration gradient of salt [17]. Salt concentration gradient is formed by creating three zones in the pond namely; Upper convective zone (UCZ), Non Convective zone (NCZ) and Lower convective zone (LCZ). The schematic view of SGSZ is shown in Figure 1.5.

The UCZ is also known as the surface layer. It is a thin layer, contains fresh water or water with low concentration of salinity, and its temperature is nearly equal to ambient temperature. The cost of building the UCZ is negligible [18], as it uses water with low salinity such as fresh, seawater or brackish water. The function of this layer is to prevent the lower layers from being exposed to evaporation, wind effects and impurities.

NCZ is also known as Gradient Zone (GZ), located between UCZ and LCZ. It is the thick layer with increasing salt concentration from top to bottom. The function of increasing salt concentration is to increase density of water due to which convection is suppressed [12].

LCZ is the layer of high salt concentration. Significant portion of solar energy is stored in this layer due to which significant higher temperature is observed in this layer. This zone is also known as Heat storage zone (HSZ) because significant portion of solar energy is absorbed in this layer [19].

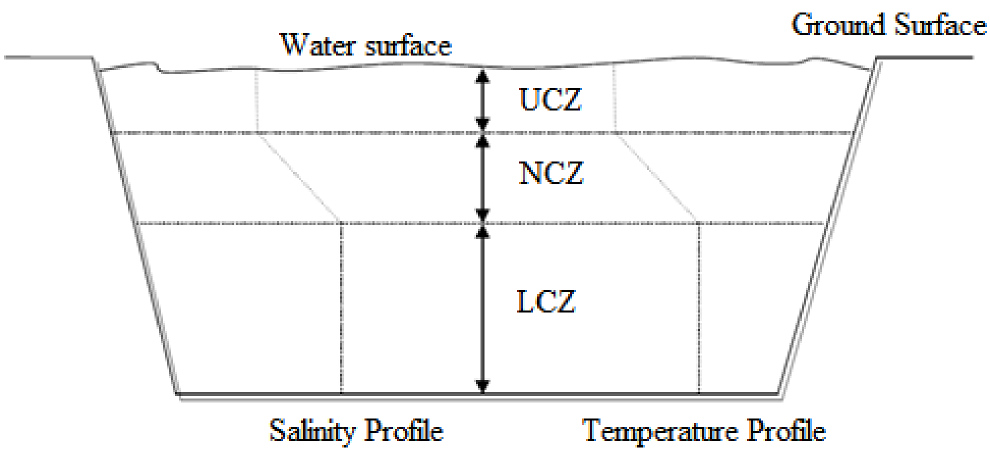


Figure 1.5. Salt gradient solar pond [15].

1.3.2.2 SOLAR GEL POND

The solar gel pond utilizes natural, synthetic or semi synthetic gel. The schematic view of the solar gel pond is shown in Figure 1.6. The LCZ contains water having 2-7% salinity [20], whereas upper surface contains fresh water and NCZ is formed by floating transparent layer of gel on top surface of LCZ; therefore the concentration gradient maintenance is eliminated. The density of polymer gel is intermediate between saline solution and fresh water, which enable it to float on LCZ [20]. This type of pond cuts environmental hazards, losses due to convection and evaporation [21]. Main disadvantage of constructing the solar gel pond is high cost of chemicals required for creating gel.

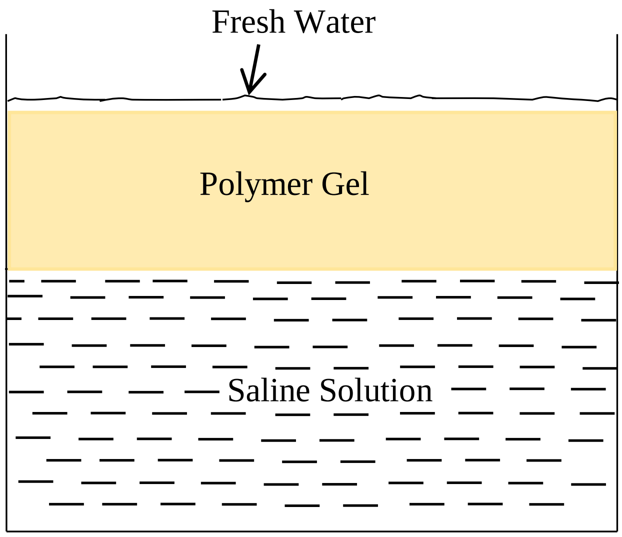


Figure 1.6. Solar gel pond.

1.3.2.3 MEMBRANE STRATIFIED SOLAR POND

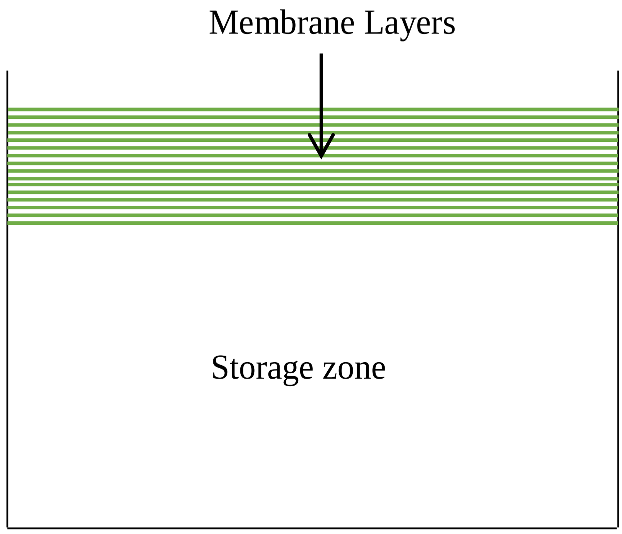


Figure 1.7. Membrane stratified solar pond

Membrane stratified solar pond consists of two zones: NCZ and LCZ. NCZ is composed of fluid layers separated by transparent membrane. The schematic view of membrane stratified solar pond is shown in Figure 1.7. Membrane is the major cost component of the membrane pond [22]. Other major problems include stability, cleaning, membrane life and transparency due to biological growth [23].

1.4 WHY SALT GRADIENT SOLAR POND?

The main aim of utilizing SGSP is that energy can be produced without fossil fuel and pollution factor is also reduced. The cost of construction of SGSP is less than other non-convective solar ponds, and the salt used for solar pond is available at the cheap rate. As this type of pond has built-in storage, so it does not require pumping of hot water in separate storage as a case of the convective solar pond. The heat stored in the pond can be utilized for different applications such as in steam power generation, space heating, water desalination, industrial and chemical processes [24]. Most cost effective solar water heater is the flat plate collector, but cost of the solar pond is even lower than the flat plate collector [25]. Due to these reasons, SGSP is considered throughout this study.

1.5 OBJECTIVES OF THE CURRENT STUDY

The aim of this research was to evaluate the thermal performance of the solar pond under Pakistan's climatic condition.

The objectives of this research are.

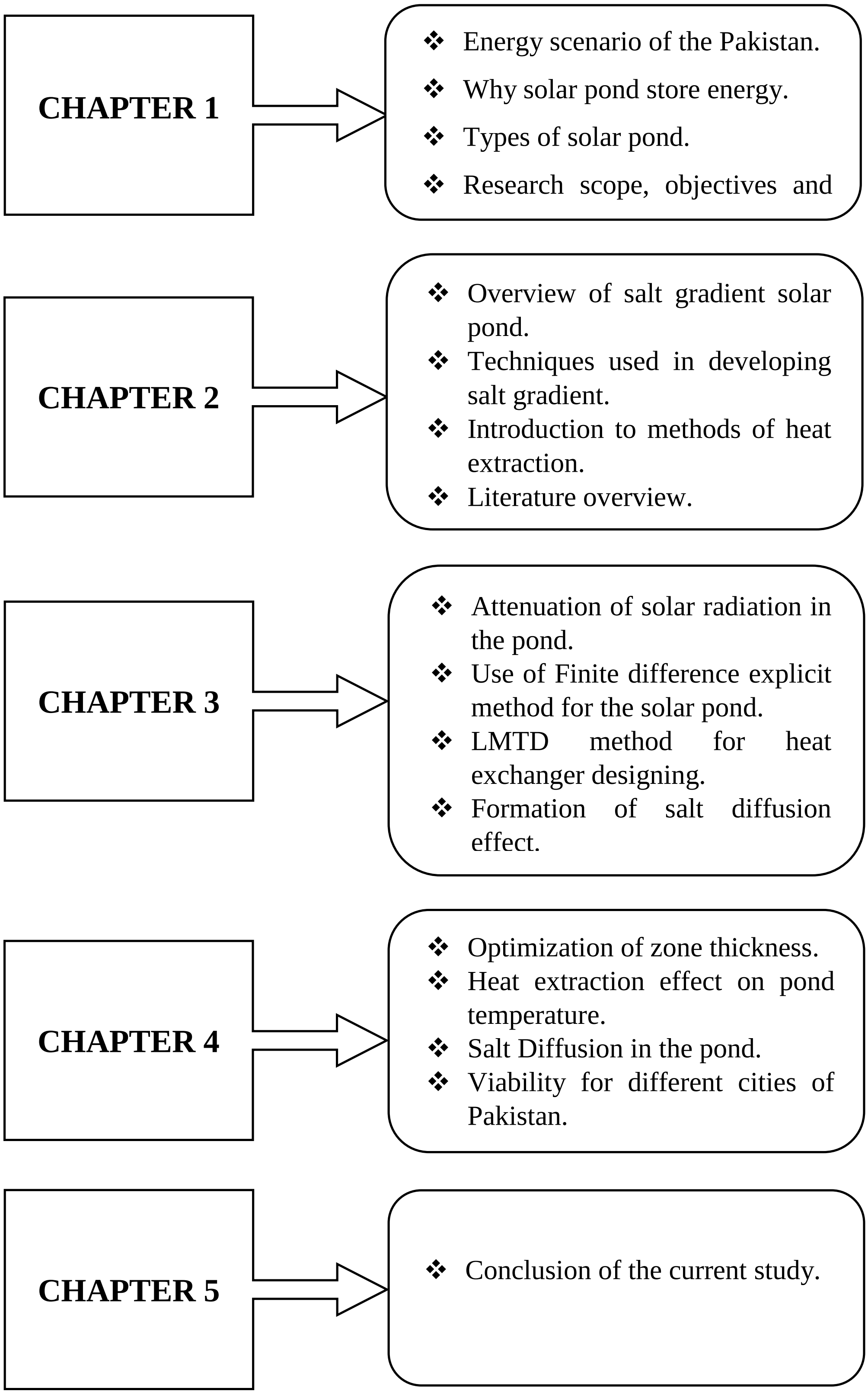
- To predict temperature distribution in the salt gradient solar pond.
- To optimize the thickness of the UCZ, LCZ and NCZ for the maximum temperature gains.
- To predict the effect of heat extraction on pond temperature under varying load conditions.
- To evaluate viability of the salt gradient solar pond for different cities of Pakistan under distinct climatic conditions.

1.6 LIMITATION AND SCOPE OF STUDY

This study is limited to theoretical work only. To develop the suitable mathematical model some assumptions have been taken, such as effect of wind shear, side losses from pond and algae growth are not taken. Further it is considered that heat exchanger performance does not degrade with time. The aim of this study is to evaluate the performance of the solar pond for different cities of Pakistan. As these ponds become operation then dependency on conventional energy sources can be reduced. Solar pond can be used for the water heating, power generation, refrigeration, water desalination and grain drying [20].

1.7 THESIS ORGANIZATION

Thesis consists of the five chapters. The detail of the thesis is shown in the flow chart below.



CHAPTER 1
❖ Energy scenario of the Pakistan.
❖ Why solar pond store energy.
❖ Types of solar pond.
❖ Research scope, objectives and
CHAPTER 2
❖ Overview of salt gradient solar pond.
❖ Techniques used in developing salt gradient.
❖ Introduction to methods of heat extraction.
❖ Literature overview.
CHAPTER 3
❖ Attenuation of solar radiation in the pond.
❖ Use of Finite difference explicit method for the solar pond.
❖ LMTD method for heat exchanger designing.
❖ Formation of salt diffusion effect.
CHAPTER 4
❖ Optimization of zone thickness.
❖ Heat extraction effect on pond temperature.
❖ Salt Diffusion in the pond.
❖ Viability for different cities of Pakistan.
CHAPTER 5
❖ Conclusion of the current study.

SUMMARY

Pakistan is currently facing severe energy shortage, which has caused many industries to shut down their operation. Significant portion of the country energy mix is supplied by fossil fuels and natural gas, so to reduce dependency on these fuel alternate energy source is considered. Among alternate energy sources, solar energy is obtaining significant importance. One of the cost-effective ways is to use solar pond for utilization of solar energy. There are two main types of solar ponds namely non-convective solar pond and convective solar pond. Non-convective solar pond contains saline water and consists of multiple layers, in this type of solar pond convection is suppressed in inner layers. Convective solar ponds consist of one liquid layer and in this, convection may take place whereas evaporation is suppressed. Among these two solar ponds, non- convective solar pond has obtained significance importance because of low investment cost. So in current study salt gradient solar pond is considered.

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CHAPTER 2

BACKGROUND OF SOLAR POND

2.1 SALT GRADIENT SOLAR POND

Solar pond collects solar energy and stores it to heat up water at the bottom. Similar concept of heat storage was found in Madve Lagnoon Transylvaria, Hungary by Kalecsinsky in 1902. The temperature observed was about 70 ^{o}C at the depth of 1.32m [1]. Concept of Salt gradient solar pond (SGSP) was given by Dr. Rudolf loch in 1948, and the first practical solar pond was constructed and became operational in 1959 [1]. SGSP is an artificial large body of the water reservoir that collects energy from sun and utilizes it for heating the water. These are about 1-3 meters deep. These ponds can collect store solar energy for the long period of time economically [2]. In this type of pond, convection is suppressed by creating the salt concentration gradient. Salt concentration gradient is formed by creating three zones in the pond namely; Upper convective zone (UCZ), Non Convective zone (NCZ) and Lower convective zone (LCZ). The schematic view of SGSZ is shown in Figure 2.1. The Upper convective zone is also known as the surface layer. It is a thin layer which contains fresh water or water with low concentration of salinity. The cost of building the UCZ is negligible [3], as it uses water of low salinity such as fresh water, seawater or brackish water. The function of this layer is to prevent the lower layers from being exposed to wind [4]. Non Convective Zone (NCZ) is also known as Gradient Zone (GZ), located between UCZ and Lower convective zone (LCZ). It is the thick layer with increasing salt concentration from top to bottom, due to this density also increases; therefore, convection is suppressed [5]. Heat losses can merely take place due to conduction [6]. LCZ also known as Heat Storage Zone (HSZ) is the homogenous layer of high salt concentration. Significant portion of solar energy is stored in this layer, which is transformed into thermal energy [7]. The solar radiation's incidents on the pond surface are firstly absorbed by UCZ, the heat absorbed by this layer is lost to atmosphere due to convection and radiation losses while the remaining radiations are absorbed by NCZ and LCZ [8].

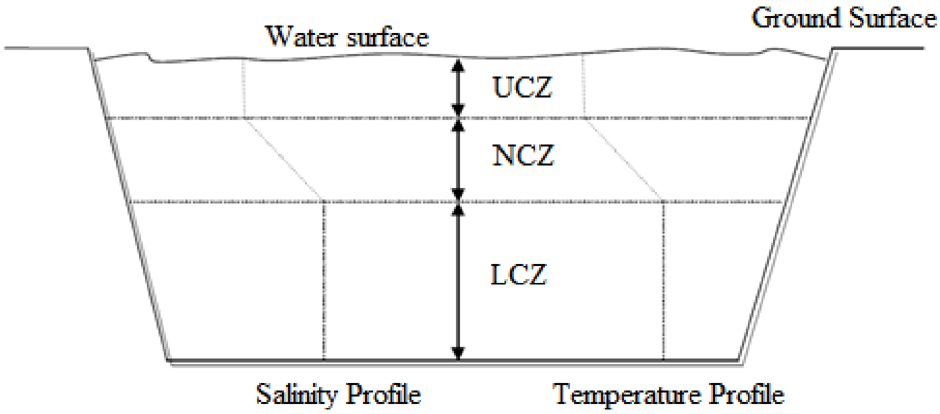

Figure 2.1.Salt gradient solar pond [9].

2.2 SOLAR RADIATIONS ABSORPTION

The absorption of solar radiations in the pond is a complex process because solar radiations are consisting of different wavelengths, and their absorption coefficient varies with depth. Rabl and Neilson divided the solar spectrum in the range of 0.2 to 1.2 µm into four parts, and then determined the fraction of solar radiation [10]. Sodha and Kaushika extended the work of Rabl and Nielson, and divided the spectrum into five parts; however the fifth part is absorbed in first few millimeters of the pond [11]. Hull divided the solar spectrum in 40 parts, and compared the accuracy of a four-part spectrum with 40 parts and concluded that four parts have good accuracy in transmittance [12]. Bryant gave simple equation to estimate solar radiations penetrating into the ponds [13], which has excellent accuracy. Most of the above equations didn't consider the effect of pond bottom reflectivity. The effect of surface reflectivity was first time given by Kooi [13]. He considered that pond bottom is "grey lambert", however the effect of multiple reflection from pond bottom to surface and surface to bottom was first time considered by Hull [14]. The formulation given by Hull has good accuracy but slow computational speed, so Husain gave two formulations to reduce computational time and compared with Hull model. Both formulations showed considerable reduction in computational time, whereas there was error of $\pm$3% and $\pm$7% for formulation 1 and formulation 2 [15]. The net radiations available at depth 'x' is given by

$$I_{xT} = I_x - I_{BR} + I_{SR} \tag{2.1}$$

Where I_x, I_{BR} and I_{SR} represent radiations available at depth 'x, reflected part of radiations reaching at depth x and multiple reflections respectively.

2.3 THE GRADIENT LAYER ESTABLISHMENT

Preparation of salt gradient layer is the time-consuming process. Traditional method of making salt gradient takes about five months. There are following different methods of creating the salt gradient.

i) Earliest method of creating the salt gradient was by natural diffusion, which was given by Tabor in 1963. In this method, first half of the pond is filled with fresh water, then add salt in it. In this method, pump is used for mixing the water and salt. After mixing, the fresh water is added in remaining portion of the pond. After certain period of time, diffusion will occur naturally, which will create the density gradient naturally [16].

ii) One of the methods of gradient establishment is filling the pond by redistribution. In this method, pond is partially filled with high concentration brine, then fresh water is supplied on upper portion of the existing solution through a diffuser. As surface of water rises subsequently, diffuser is also raised with rest to surface of water either in continuous or discrete motion. The movement of diffuser with water surface makes solution diluted in upper portion [17].

iii) Another method of gradient establishment is the salt dissolution used in Bhuj solar pond consists of mixing tank, sedimentation tank and sand bed filter as shown in Figure 2.2. In this method, solar pond is filled with fresh water; then top layer of water is pumped to mixing tank. In mixing tank, salt is added into water and through agitator concentrated brine is obtained. The concentrated brine is pumped to the sedimentary tank, where settling of suspended particles occurs. After settling solution is sent to sand bed filter where filtration occurs and chemicals like copper sulfate and hydrochloric acid are added into the solution to prevent the growth of algae. After sand bed filter, solution is sent to bottom of the pond [18].

iv) In fixed level injection methods, Froude number is the critical parameter. For obtaining complete mixing at diffuser level the value of Froude number needed to be maintained constant approximately 18. If value of Froude number is not maintained at 18, then improper gradient profile will be formed. So to overcome this problem scan injection was introduced. In this method diffuser (scans) moves up and down and scans the fluid. The movement of diffuser in the small range is known as scan range. In order to create the salt gradient in every scan step upper, lower limits of elevation and quantity of fresh (brackish) water are to be determined. The volume of saline water injected depends on desired salt concentration [19].

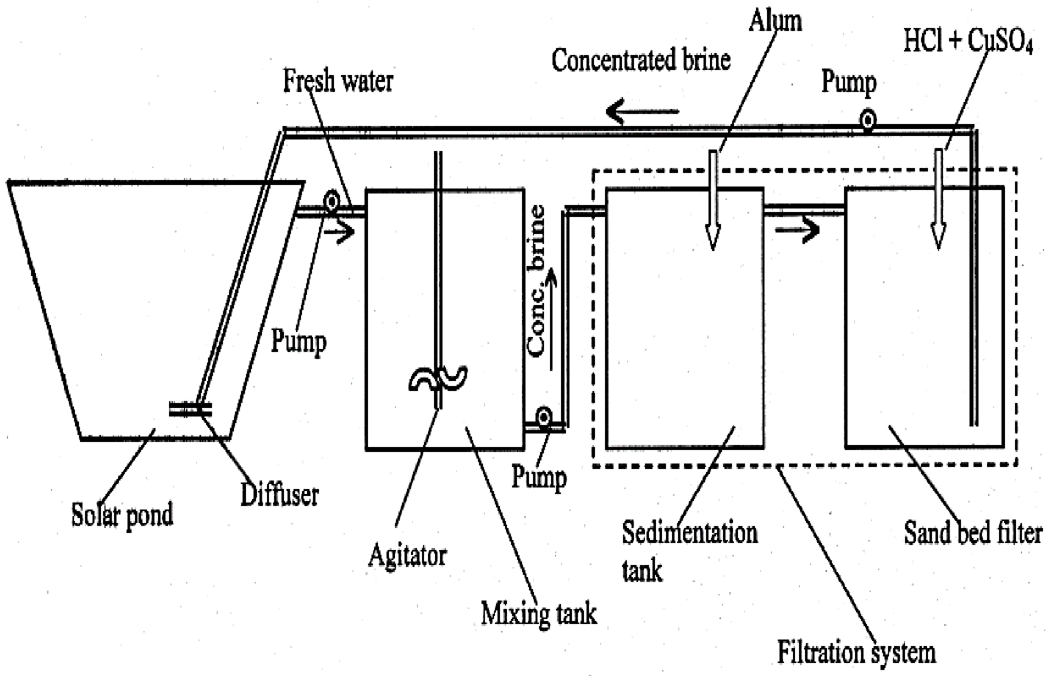

Figure 2.2. Gradient establishment by salt dissolution [19].

2.4 HEAT EXTRACTION TECHNIQUES IN SOLAR POND

Generally, the heat can be extracted by two ways [9]. In one method, heat is extracted by installing heat exchanger in the lower convective zone, while in second method, hot brine is withdrawn from lower convective zone and is sent to external heat exchanger, where it dissipates its heat and then re-circulated to bottom of the pond. The first in-pond heat exchanger was installed in Miamisburg solar pond [20].

2.5 LINERS FOR SOLAR POND

Following different types of liners have been used to reduce ground losses.

2.5.1 XR-5 8130 LINER

XR-5 liner is PVC coated polyester fabric; it was installed in El Paso pond during 1984. The cost of the liner was $ 15 per meter square excluding installation and import duty charges. The cost of the XR-5 liner used in El Paso solar pond was 26% of initial investment. The life of the liner was 20 years; however, liner became failed after 7 years of operation. The high temperature in the HSZ has caused the material to become brittle, due to which strength of material was reduced and about 100 holes were observed [19].

2.5.2 GEOSYNTHETIC CLAY LINER

Geosynthetic clay liner was made of clay/plastic was used in El Paso pond and in Israel's solar pond. The advantage of using geosynthetic liner was that the cost of the liner was low as compared to previous liner and is highly resistance to pierce. However, their characteristics vary from site to site and also depend on installer experience. Geosynthetic clay can be installed HSZ by different ways, but Geosynthetic clay suitable for solar pond is made by gluing 0.2 inch layer of sodium bentonite on the 60-mil polypropylene. The bentonite consists of 92% montmorillonite. The function of montmorillonite is to inhabit the contamination formed due to saline water. Geosynthetic clay is installed by making clay side to the bottom, so that contact between bentonite and saline water can be avoided. This type of liner was installed in El Paso pond from 1997 to 2003. The liner worked satisfactory until decommissioning of the pond [19].

2.5.3 KAOLINITE LINER

Kaolinite liner was used in 6000 m^2 solar pond in Kutch, India. The advantage of using kaolinite is that it was six times cheaper than the bentonite and was less prone to form cracks [21]. However, when Kalonite dries, it also form cracks. To improve this fault clay was mixed with local soil, the optimum ratio of local soil and clay was 1:3. The cost of this type of liner was $ 8 per meter square, including labor and material cost. The complete detail of this type of lining system can be found in elsewhere [21].

2.6 OVERVIEW OF SOLAR POND STUDIES

Various theoretical and experimental studies have been carried out on SGSP throughout the world. The outcomes of studies is shown in Table 2.1.

Table 2.1. Overview of the studies conducted for solar ponds.

Reference	Theoretical	Experimental	Climate Condition	Application	Important Results
[22]/2004	✓	X	Mashad, Iran	X	• The wall shading effect for small ponds plays the significant role in LCZ temperature. • The thickness of NCZ should be more than 0.5 m to obtain higher LCZ temperature.
[23]/2006	X	✓	Mashad, Iran	X	• A small-scale solar pond can fulfill peak load demand for the short period of time.
[24]/2009	✓	X	Jalgaon, India	X	• Water table depth does not affect time required for pond maturation temperature. • After some significant depth of ground water table pond temperature does not rises considerably.
[25]/2010	✓	✓	X	X	• Heat extraction from NCZ enhances the efficiency but reduces the stability of the mini solar pond.
[26]/2011	X	✓	Melbourne, Australia	Electricity generation	• Solar pond can provide electricity by the combination of thermoelectric cell with thermosyphon system. • Thermoelectric modules are suitable for small-scale applications.

Reference	Theoretical	Experimental	Climate Condition	Application	Important Results
[27]/2011	X	✓	Qinghai Tibet plateau China	X	• Qinghai Tibet plateau has the huge potential for solar pond. • LCZ temperature increases by 0.69 ^{o}C per day.
[28]/2011	X	✓	Catalonia Spain	X	• The maximum temperature is observed in NCZ when ground is not insulated. • Ground losses are about 10% of annual solar radiations.
[29]/2012	✓	✓	Chennai India	X	• Increasing salt concentration in LCZ dramatically raises the temperature of LCZ. • For external heat exchanger 50 g/Kg is optimal salinity.
[30]/2013	✓	✓	Bafgh Iran	X	• Energy storage performance of circular solar pond is better than square pond. • Exergy efficiency of solar pond is low due to low quality of stored energy.
[31]/2014	✓	X	Baghdad Iraq	X	• NCZ thickness has the significant effect on LCZ temperature.
[32]/2015	✓	✓	Tirunelveli India	Water distillation	• Solar still productivity depends on solar radiations. • The productivity of solar still increases when fin type solar still is integrated with solar pond.

SUMMARY

In this chapter, an overview of SGSP is presented, it was observed that concept of the solar pond was obtained from the Madve Lagnoon Transylvaria, Hungary. Various studies related to solar radiation's absorption in the solar pond have been discussed. Different methods of formation of gradient layers have been also presented, in which scan injection techniques is advance method for formation of gradient profile. To insulate ground and reduces losses from pond bottom various types of liners have been discussed.

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CHAPTER 3

METHODOLOGY

3.1 SOLAR RADIATION ABSORPTION

Thermal performance of solar pond depends upon the amount of solar irradiations absorbed in the pond and weather condition [1]. Part of the solar radiations incident on pond surface are reflected back due to suspended particles and transparent organisms [2]. The amount of solar irradiations penetrating in the pond reduces exponentially because of radiations absorbed by upper layers.

3.1.1 SURFACE REFLECTION

Reflection of solar light depends upon the incident angle of the sun as well as the condition of pond surface. A pond with rough surface will fascinate more sunlight as compared to pond with glass like surface. Reflection of light from pond surface having negligible turbulence can be calculated by Fresnel's Equation [3,4]

$$Fr = \frac{1}{2}\left(\frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)} + \frac{\tan^2(\theta_i - \theta_r)}{\tan^2(\theta_i + \theta_r)}\right) \tag{3.1}$$

Where θ_i is angle of incidence and θ_r is angle of refraction in degree. Angle of incidence can be calculated from following equation [5]

$$\cos\theta_i = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \tag{3.2}$$

Refraction angle can be obtained from Snell's law [3,6]

$$\frac{\sin\theta_i}{n_r} = \frac{\sin\theta_r}{n} \tag{3.3}$$

Figure 3.1 shows relation between Fresnel reflection and incident angle. When the angle of incident is less than 50 degrees, about less than 4% incident radiations are reflected back, for incident angle above 65 degree many of radiations are reflected back. The higher incident angle observed at either sunrise or during sunset, at that time solar radiations are also less [7].

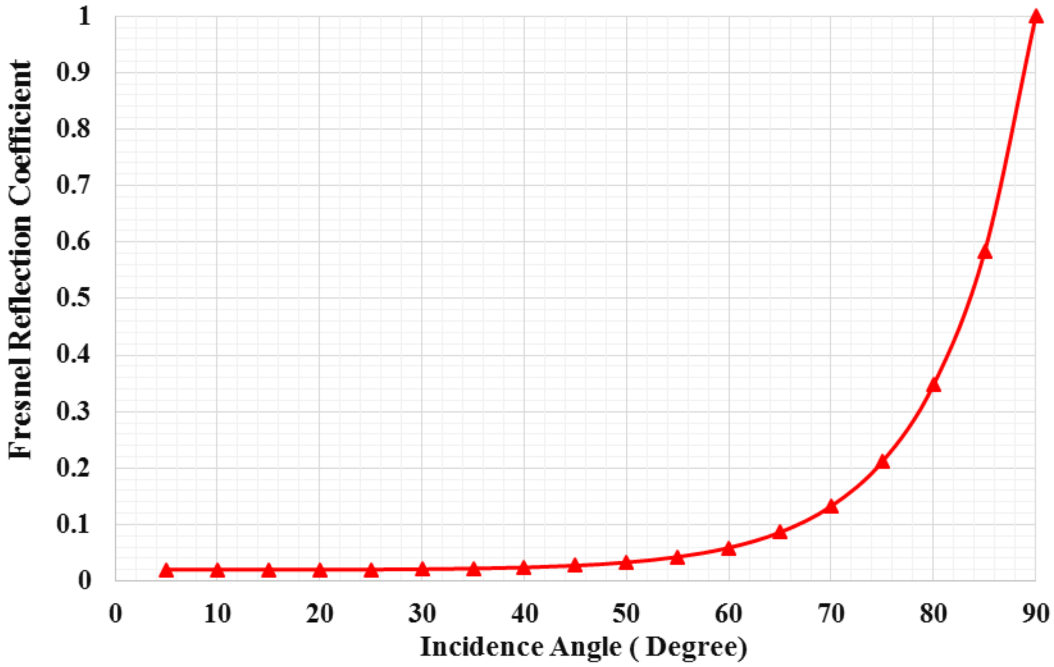

Figure 3.1. Relation between Fresnel reflection and incident angle.

3.1.2 ABSORPTION

Solar radiations available in the pond depend upon the pond's depth, surface, bottom reflectivity and incidence angle. In this study, reflection of radiations from the pond bottom to the surface and vice versa has been considered as shown in Figure 3.2, thus solar radiations are given by [8]

$$I_{xT} = I_x - I_{BR} + I_{SR} \tag{3.4}$$

Where $I_{x,}$ I_{BR} and I_{SR} represent radiations at depth 'x', radiations reflected from the pond bottom to surface and vice versa. The detail of I_x, I_{BR} and I_{SR} can be obtained from the literature [8].

The amount of solar radiations absorbed at a certain depth of the pond is given by.

$$I_R = I(1 - F_r)\theta^{'} I_{xt} \tag{3.5}$$

θ' values depend upon many parameters such as radiation transmission in the pond, salt concentration, bottom reflectivity and water turbidity. Value of θ' is considered as 0.85 as assumed by many other researchers [5,9].

3.2 MODEL FORMATION

A Mathematical model of the solar pond was developed in MATLAB using one-dimensional finite difference explicit method. It was assumed that pond consists of three zones and wall of the pond was vertical and insulated. Therefore, no losses take place from side of the pond. Due to convection, UCZ and HSZ were considered as fully mixed (single layers).

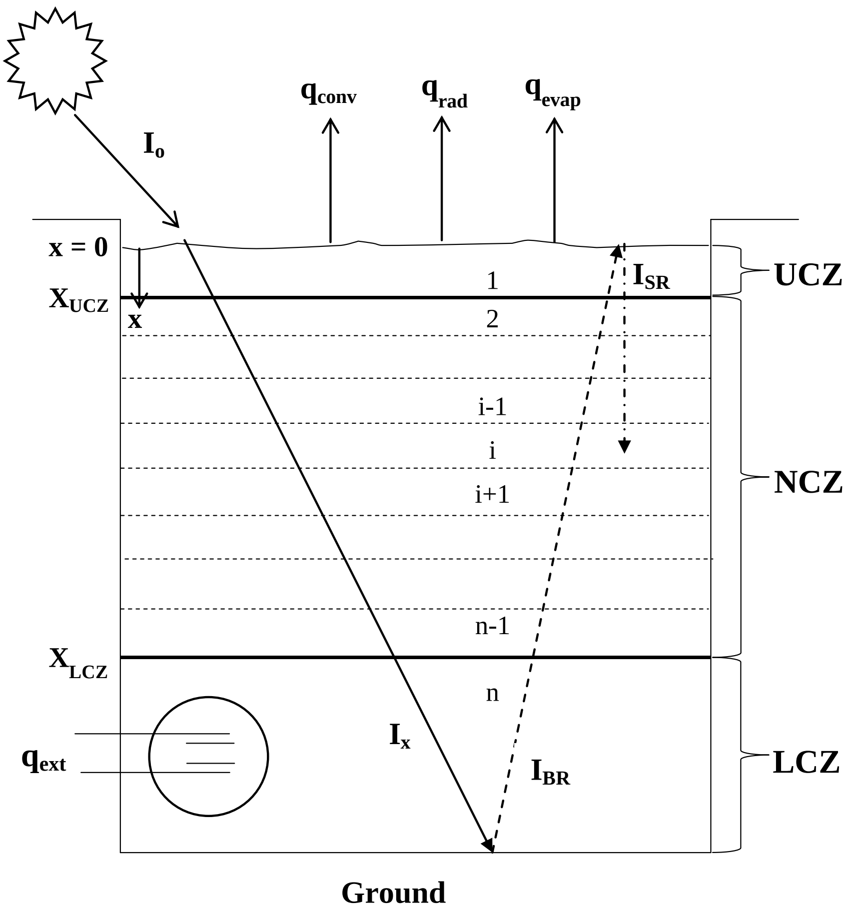

Figure 3.2. Solar pond model.

The value of “x” was taken as zero at the surface, which was increasing downward by using vertical Cartesian coordinate system. It was further considered that at the start of the simulation pond has the uniform temperature thought-out all the layers and is artificially stabilized i-e NCZ has the increasing salt concentration, while UCZ and HSZ has a homogeneous salt concentration same as concentration of fresh water and saturated salty water respectively. In NCZ, convection was suppressed due to varying concentration of salt; therefore, heat loss from NCZ were considered by conduction only [10]. The generalized form of the temperature variation in the solar pond is given by.

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial T}{\partial x}\left(k \frac{\partial T}{\partial x} \right) - \frac{\partial I}{\partial x} \tag{3.6}$$

Hourly air temperature, solar radiations, wind speed and relative humidity data were obtained from “Meteonorm” for different cities of the Pakistan, which are geographically at different locations. Meteonorm is a meteorological database which predicts climatological data [11]. The daily solar radiations incident on the horizontal surface for different cities of Pakistan are shown in Table 3.1.

Table 3.1. Hourly solar radiation's data for different cities of Pakistan.

Daily Solar Radiations on horizontal Surface ($kWh/m^2/day$)					
Month	Lahore	Islamabad	Multan	Peshawar	Quetta
Jan	2.79	2.13	3.33	3.08	3.42
Feb	3.81	3.22	4.16	4.03	4.25
Mar	4.97	3.77	5.14	4.99	4.78
Apr	5.68	4.56	6.03	6.11	6.25
May	6.30	5.26	6.38	7.15	7.03
Jun	6.17	5.67	6.51	7.24	7.75
Jul	5.56	4.79	6.14	6.55	7.00
Aug	5.27	4.63	6.08	5.98	6.64
Sep	5.10	4.36	5.62	5.43	6.42
Oct	4.33	4.33	4.69	4.55	5.42
Nov	3.39	3.13	3.87	3.73	4.11
Dec	2.78	2.32	3.10	3.02	3.33
Annual	4.68	4.02	5.09	5.16	5.54

3.2.1 ENERGY BALANCE OF THE MODEL

Two boundary conditions were considered, at the upper boundary $x=X_{UCZ}$ and the lower boundary $x=X_{LCZ}$. The energy conservation equation was used to find the temperature at Upper boundary and lower boundary, which was represented by T_{UCZ} and T_{HSZ} respectively.

3.2.2 ENERGY BALANCE FOR UCZ

Due to convection UCZ act like a single layer, thus temperature variation in this zone was assumed constant. Three main heat losses take place from this zone were conduction losses, convection losses and radiation losses as shown in Figure 3.3. The temperature variation in this zone is given by.

$$\rho C_p x_{UCZ} \frac{\partial T_{UCZ}}{\partial t} = k \frac{\partial T}{\partial x} + \frac{dI}{dx} - q_{UCZ} \tag{3.7}$$

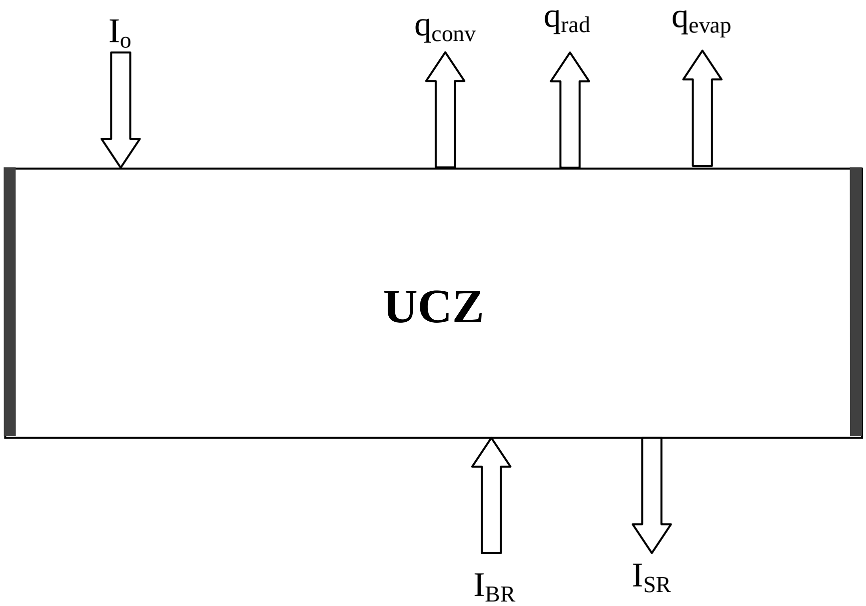

Figure 3.3. Energy balance diagram for UCZ

The solution of equation (3.7) is given by.

$$\rho C_p x_{UCZ} \left(\frac{T_i^{t+1} - T_i^t}{\Delta t} \right) = \left[k \frac{T_{i+1}^t - T_i^t}{\frac{\Delta x}{2}} + I_{x=0} - I_{R_1} - q_{UCZ} \right]$$

$$T_i^{t+1} = T_i^t + \frac{\Delta t}{\rho C_p x_{UCZ}} \left[k \frac{T_{i+1}^t - T_i^t}{\frac{\Delta x}{2}} + I_{x=0} - I_{R_1} - q_{UCZ} \right] \tag{3.8}$$

Where q_{UCZ} is heat loss per unit area from the pond surface.

3.2.2.1 HEAT LOSSES FROM POND SURFACE

Convection, evaporation and radiation were main heat losses, which contributed significantly in pond performance. Experimental solar ponds inhibit these losses by immersing floating baffles or rings [12]. Their use can make the system costly, but the overall performance of the system increases [13].

$$q_{UCZ} = q_{conv} + q_{rad} + q_{evp} \tag{3.9}$$

- **Convection heat losses**

Convection heat losses depend on the temperature difference between UCZ and ambient temperature and on wind speed, which were calculated by [14].

$$q_{conv} = h_{conv}(T_1 - T_{amb}) \tag{3.10}$$

Where h_{conv} represents convective heat transfer coefficient and given by.

$$h_{conv} = 5.7 + 3.8V \tag{3.11}$$

Where V represents wind speed, its average monthly values were obtained from Meteonorm software.

- **Radiation heat losses**

Pond surface receives short and long wavelength radiation, which contributes to radiant heat loss and calculated by [15]

$$q_{rad} = \sigma\varepsilon_w \left(T_1^4 - T_{sky}^4\right) \tag{3.12}$$

Where σ and ε_w is Stefan Boltzmann's constant and emissivity of water; their values are 5.67×10^{-8} W/m^2 K^4 and 0.83 respectively. T_1 and T_{sky} are UCZ temperature and sky temperature in Kelvin respectively. Value of sky temperature is given by.

$$T_{sky} = T_{amb} - \left(0.55 + 0.061\sqrt{P_a}\right)^{0.25} \tag{3.13}$$

- **Evaporation heat losses**

Evaporation loss is the function of the weather conditions such as humidity and wind speed. When evaporation occurs, some amount of heat stored in the pond is lost to the environment due to which UCZ remains at the lower temperatures [16]. Thus evaporation losses are calculated by following equation [14].

$$q_{evp} = \frac{h_{fg} h_{conv} \left(P_v - P_a\right)}{1.6 C_p P_{atm}} \tag{3.14}$$

Where P_v is vapor pressure of water in mmHg, and P_a is partial pressure of water vapor in mmHg; given by [17]

$$P_v = \exp\left(18.403 - \frac{3885}{T_1 - 43}\right) \tag{3.15}$$

$$P_a = R_h \exp\left(18.403 - \frac{3885}{T_{amb} - 43}\right) \tag{3.16}$$

3.2.3 ENERGY BALANCE FOR NCZ

The energy equation is formulated by dividing NCZ into different layers. In this zone, losses take place by conduction only. The temperature of first layer of this zone is represented by 2 and last layer by n-1 as shown in Figure 3.4. The energy balance for NCZ is shown in Figure 3.4. The details of I_{SR} and I_{BR} can be obtained from the equation(3.4). The generalized form of the energy balance equation for NCZ is given by.

$$\rho C_p \Delta x\left(\frac{T_i^{t+1} - T_i^t}{\Delta t}\right) = q_{cond_2} - q_{cond_1} + I_{R_{n-1}} - I_{R_n} \tag{3.17}$$

The solution of equation (3.17) is given by

$$\rho C_p \Delta x\left(\frac{T_i^{t+1} - T_i^t}{\Delta t}\right) = k\frac{T_{i+1}^t - T_i^t}{\Delta x} - k\frac{T_i^t - T_{i-1}^t}{\Delta x} + I_{R_{n-1}} - I_{R_n}$$

$$\frac{\rho C_p \Delta x}{\Delta t}\left(T_i^{t+1} - T_i^t\right) = \frac{k}{\Delta x}\left[\left(T_{i+1}^t + T_{i-1}^t\right) + \frac{\Delta x}{k}\left(I_{R_{n-1}} - I_{R_n}\right)\right]$$

$$\left(T_i^{t+1} - T_i^t\right) = \frac{k\Delta t}{\rho C_p \Delta x^2}\left[\left(T_{i+1}^t + T_{i-1}^t\right) + \frac{\Delta x}{k}\left(I_{R_{n-1}} - I_{R_n}\right)\right]$$

$$T_i^{t+1} = \tau\left[\left(T_{i+1}^t + T_{i-1}^t\right) + \frac{\Delta x}{k}\left(I_{R_{n-1}} - I_{R_n}\right)\right] + T_i^t \tag{3.18}$$

$$\tau = \frac{k\Delta t}{\rho C_p \Delta x^2}$$

Where τ represents the stability criteria of the explicit method, its value is taken as less than 0.5 [18]. If it is voided than simulation will not result correctly. When temperature of the nodes i+1, i, i-1 is given at time 't' is known then Equation(3.18) can be used to find the temperature at node 'i' and time t+Δt. Value of 'i' for NCZ ranges from 2 to n-1.

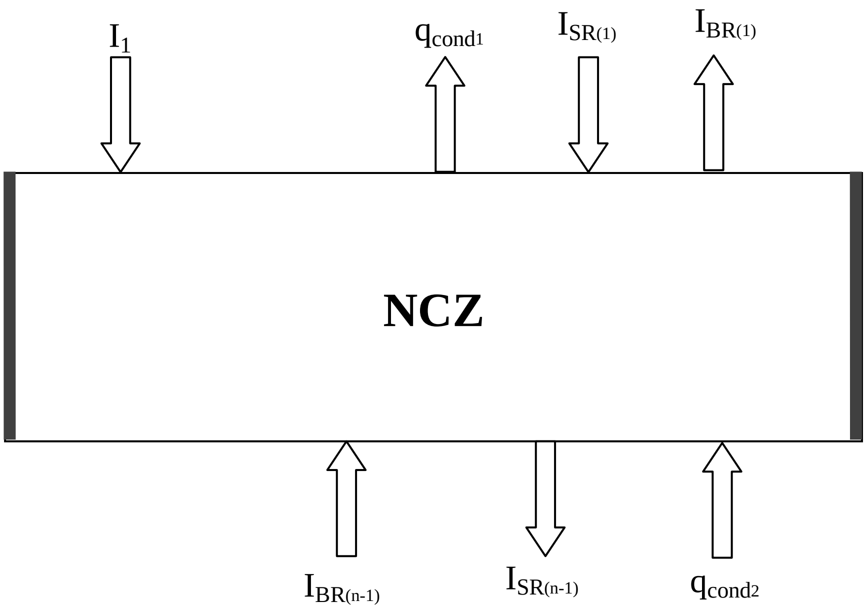

Figure 3.4. Energy balance diagram for NCZ.

3.2.4 ENERGY BALANCE FOR LCZ

LCZ is the main zone in which heat is trapped. Two main losses take place from this zone are ground losses and transfer of heat from LCZ to last layer of NCZ by conduction. The energy balance for LCZ is given in Figure 3.5. The generalized form of the energy balance equation for the LCZ is given by.

$$\rho C_p x_{LCZ} \frac{\partial T_{LCZ}}{\partial t} = I_{R_n} - q_{cond} - q_{ext} - q_g \qquad (3.19)$$

Where q_{cond} is the energy conducted from LCZ to last layer of NCZ, q_g is the ground losses, and q_{ext} is the amount of energy extracted from LCZ. If heat is not being extracted from LCZ, then value of q_{ext} is taken as zero. The ground losses take place owing to pond water contact with soil; these losses depend on thermal conductivity of soil, pond geometry and ground temperature. The equation (3.19) can be rewritten as.

$$\rho C_p x_{LCZ} \left(\frac{T_i^{t+1} - T_i^t}{\Delta t} \right) = \left[I_{R_n} - k \left(\frac{T_i^t - T_{i-1}^t}{\frac{\Delta x}{2}} \right) - k_g \left(\frac{T_i^t + T_g}{d_w} \right) - q_{ext} \right]$$

$$T_i^{t+1} = T_i^t + \frac{\Delta t}{\rho C_p x_{LCZ}} \left[I_{R_n} - k \left(\frac{T_i^t - T_{i-1}^t}{\frac{\Delta x}{2}} \right) - k_g \left(\frac{T_i^t + T_g}{d_w} \right) - q_{ext} \right] \qquad (3.20)$$

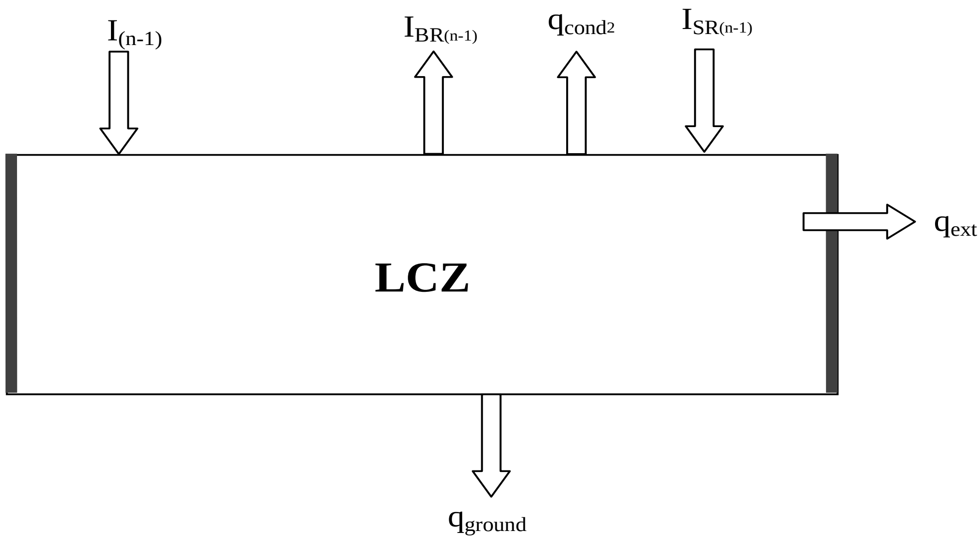

Figure 3.5. Energy balance diagram for LCZ

3.3 HEAT EXTRACTION

In this study, an internal heat exchanger made from polyethylene is designed. The advantage of polyethylene is light weight and can be easily bent into desired shape [19]. It was considered that no fouling occurs and heat was extracted at temperature nearly equal to pond temperature. The schematic view of in pond heat exchanger is shown in Figure 3.6. The rate of heat extraction can be given by [20]

$$Q = UA \frac{\left(T_{out} - T_{in}\right)}{\ln\left[\dfrac{T_p - T_{in}}{T_p - T_{out}}\right]} \tag{3.21}$$

$$Q = U.\pi.d_{out}.L \frac{\left(T_{out} - T_{in}\right)}{\ln\left[\dfrac{T_p - T_{in}}{T_p - T_{out}}\right]} \tag{3.22}$$

Where U represent the overall heat transfer coefficient, A represents external area of pipe and subscript T_{out}, T_{in} and T_p represent outlet, inlet and pond temperature respectively [20].

$$U = \frac{1}{\dfrac{d_{out}}{d_{in}} * \dfrac{1}{h_{in}} + \dfrac{d_{out}}{2k_{pi}} \ln \dfrac{d_{out}}{d_{in}} + \dfrac{1}{h_{out}}} \tag{3.23}$$

Where k_{pi} is the thermal conductivity of pipe, and h_{in} and h_{out} represents the coefficient of heat transfer inside and outside of the pipe.

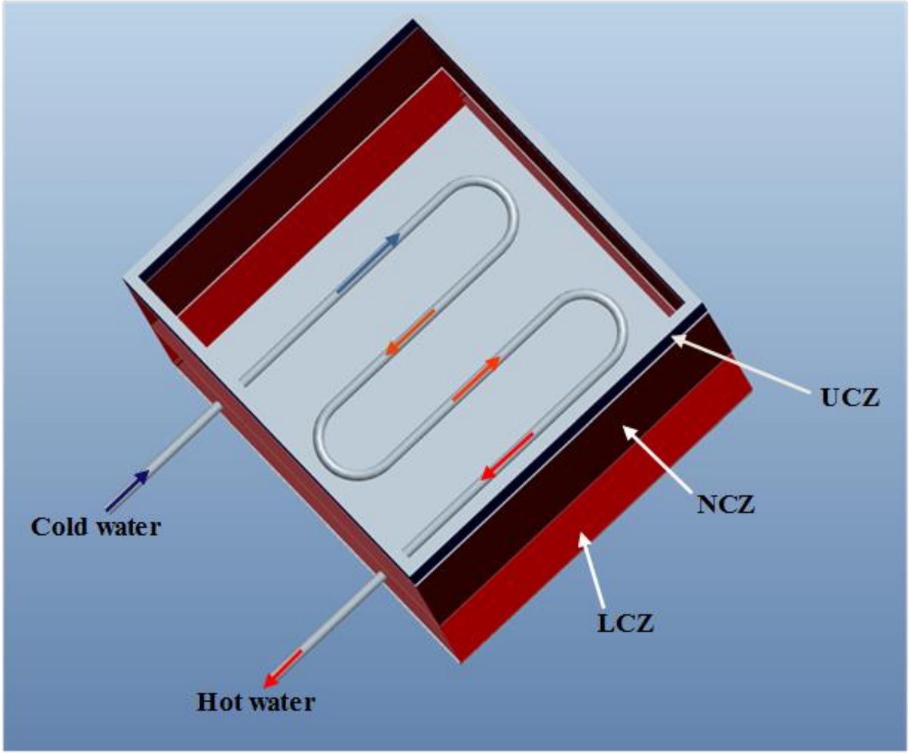

Figure 3.6. Salt gradient pond with heat exchanger

The coefficient of heat transfer within the pipe was determined by using flow through the horizontal pipe [21]. For fully developed laminar flow in the pipe (Re<2000), value of nusselt is taken as 4.36. For turbulent flow Dewitt's equation is used [21]

$$Nu = 0.023 Re^{0.8} Pr^{x} \tag{3.24}$$

The value of the exponent x in the equation (3.24) was taken as 0.4, because fluid entering the heat exchanger is less than pond temperature. The Re and Pr represent Renoyld number and Prandtl number [16]

$$Re = \frac{\rho V_m d_{in}}{\mu} \tag{3.25}$$

$$Pr = \frac{\upsilon}{\alpha} \tag{3.26}$$

α is thermal diffusion coefficient and is calculated using equation

$$\alpha = \frac{k}{\rho . C_p} \tag{3.27}$$

In this study, Reynold's number was usually in the range of laminar flow. Therefore, value of h_{in} for forced convection was obtained from [21]

$$Nu = \frac{h_{in} . d_{in}}{k_{pi}} = 4.36 \tag{3.28}$$

The heat transfer from pond to pipe was through free convection as fluid of the pond was stationary. For free convection Nusselt number is the function of Raleigh's number. Nusselt number, for free convection with uniform temperature is obtained from.

$$Nu = \frac{h_{out}.d_{out}}{k_{pi}} = c.Ra^{n} \tag{3.29}$$

The equation (3.29) is valid for Rayleigh's number in the range of 10^{-10} to 10^{12} , and value of Rayleigh's number (Ra) was obtained from equation (3.30) [18,20]

$$Ra = \frac{gB\Delta Td_e^3}{v\alpha} \tag{3.30}$$

Where g, B and ν represent acceleration due to gravity, coefficient of thermal expansion of air and kinematic viscosity respectively. The value of c and n for different ranges of Rayleigh's number is given in Table 3.2 [20]. The mass flow rate within the heat exchanger was obtained from.

$$\dot{m} = \rho AV_m \tag{3.31}$$

And heat extracted per unit of useful temperature is given by [19]

$$q = \frac{Q}{T_{out} - T_{in}} \tag{3.32}$$

Table 3.2 Values of c and n for Rayleigh number [20].

Ra	c	n
10^{-10}-10^{-2}	0.675	0.058
10^{-2}-10^{2}	1.02	0.148
10^{2}-10^{4}	0.85	0.188
10^{4}-10^{7}	0.48	0.250
10^{7}-10^{12}	0.125	0.333

The required length of pipe is computed by solving equations (3.22) and (3.32),

$$L = \frac{q}{\pi.d_{out}.U} \ln\left[\frac{T_p - T_{in}}{T_p - T_{out}}\right] \tag{3.33}$$

3.4 SALT DIFFUSION

Diffusion of salt plays the significant role in the performance of the solar pond. The convective mass transfer occurs in UCZ and LCZ and diffusive mass transfer in LCZ. In this study, it was considered that diffusion occurs in vertical direction, was independent of the thermal process; mass of saline was kept constant and convective motion was suppressed, upon these assumptions one dimensional mass diffusion equation given by.

$$\frac{\partial C(x,t)}{\partial t} = -\frac{\partial J}{\partial x} \tag{3.34}$$

Where J is mass flux and given by [14]

$$J = -D\frac{\partial C(x,t)}{\partial x} \tag{3.35}$$

Combining equations (3.34) and (3.35)

$$\frac{\partial C(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C(x,t)}{\partial x}\right) \tag{3.36}$$

The above equation was also solved by two boundary conditions as mentioned above. The salt concentration equation for NCZ is given by.

$$C_i^{t+1} = \frac{D\Delta t}{\Delta x^2}\left[C_{i-1}^t - 2*C_i^t + C_{i+1}^t\right] + C_i^t \tag{3.37}$$

For Upper boundary condition

$$D\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t}x_{UCZ}$$

$$C_i^{j+1} = D_o * \frac{dt}{x_{UCZ}}\left[\frac{C_i^j - C_{i+1}^j}{dx}\right] + C_i^j \tag{3.38}$$

And for lower boundary condition

$$D\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t}x_{LCZ}$$

$$C_i^{j+1} = D_o * \frac{dt}{x_{LCZ}}\left[\frac{C_i^j - C_{i-1}^j}{dx}\right] + C_i^j \tag{3.39}$$

Where D_o is the saline water diffusion coefficient and its value is taken as $3*10^{-9}$ m^2/s [22].

SUMMARY

The mathematical model for salt gradient solar pond has been discussed in detailed. The model is formulated by the finite difference explicit method. For this two boundary conditions have been considered to evaluate temperature at different nodes of the pond. Current model also gives the information related to solar radiation's absorption in the pond. Further an in pond heat exchanger has been designed using log mean temperature difference method.

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CHAPTER 4

RESULTS AND DISCUSSIONS

A mathematical model has been developed in MATLAB using the finite difference explicit method as discussed in chapter 3. Weather data for different cities of Pakistan was obtained from Meteonorm [1]. Model analyses the amount of solar radiations absorbed in the pond, temperature profile of the solar pond, effect of different zone's thickness and heat extraction on the HSZ temperature.

4.1 SOLAR RADIATION ABSORPTION

The amount of solar radiation penetrating into the pond are shown in Figure 4.1. It is observed that only 71% of radiation are available at the pond surface, while the remaining 29% are reflected back due to surface reflectivity of water. The results also reveal that radiation penetrating into the pond reduce sharply in the first few centimeters due to convection occurring in UCZ. As in NCZ and LCZ, convection is inhabited, so with depth, there is a lesser decrement in radiations penetrating into the pond after 0.3 m. Only 30% of radiation are available at a depth of 2 m, which contributes to increasing pond temperature. These results have been validated with the literature.

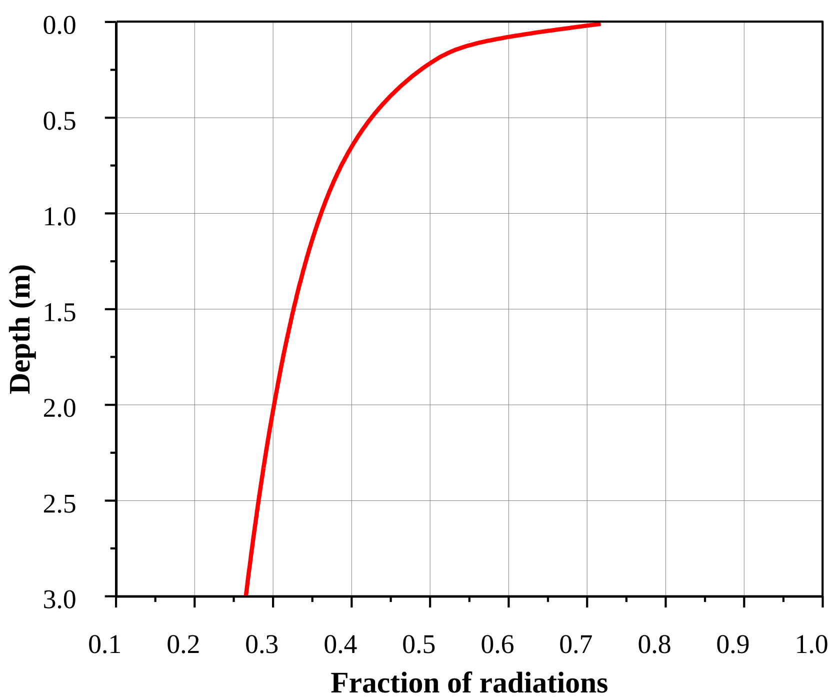

Figure 4.1. Fraction of solar radiations absorbed with depth of solar pond

4.2 SOLAR POND TEMPERATURE PROFILE

First of all simulations were carried out for the solar pond having the depth of 2.2 m; thickness of UCZ is considered as 0.2 m, whereas NCZ and HSZ both are considered as 1.0 m. The monthly average weather data for Islamabad is given in Table 4.1, which was obtained from Meteonorm software. It was assumed that all layers of the pond are at 25 ^{o}C initially before the start of the simulation. Figure 4.2 depicts temperature variation in the solar pond for different days. It is analyzed that, in NCZ temperature increases throughout the depth; this rise in NCZ temperature is caused by density gradient of water throughout the depth. Temperature of UCZ depends on ambient temperature. The dependency of UCZ temperature on the ambient temperature is shown in Table 4.2, which shows that temperature of UCZ will remain approximately equal to the ambient temperature. It is also observed that HSZ temperature rises with time. The HSZ temperature rises only 6 ^{o}C after ten days of operation. The HSZ after eighty days of operation reaches to 45 ^{o}C, which means SGSP requires enough time to store heat in the HSZ.

Table 4.1.Monthly average weather data for Islamabad.

Month	Ambient temperature (^{o}C)	Daily solar radiation (kWh/m^{2}/day)	Wind speed (m/sec)	Relative humidity (%)
January	10.0	2.13	1.6	69.7
February	13.1	3.22	2.1	64.0
March	17.9	3.77	2.7	59.4
April	23.4	4.56	3.2	50.1
May	28.8	5.26	3.4	42.0
June	31.3	5.67	3.8	47.2
July	29.6	4.79	3.1	69.3
August	28.6	4.63	2.5	75.3
September	26.8	4.36	1.9	69.6
October	22.1	4.33	1.6	62.4
November	15.9	3.13	1.2	64.8
December	11.3	2.32	1.3	69.6
Annual	21.6	4.02	2.4	62.0

Table 4.2. UCZ and Ambient temperature.

Time (hour)	Ambient Temp (ºC)	UCZ Temp (ºC)	Time (hour)	Ambient Temp (ºC)	UCZ Temp (ºC)
1:00	14.0	15.0	13:00	22.3	15.3
2:00	13.3	14.7	14:00	23.0	16.3
3:00	12.6	14.4	15:00	23.2	17.2
4:00	11.9	14.0	16:00	22.5	17.8
5:00	11.2	13.6	17:00	21.2	18.0
6:00	10.4	13.3	18:00	19.4	17.8
7:00	9.7	12.9	19:00	18.8	17.3
8:00	13.2	12.5	20:00	18.2	16.8
9:00	15.5	12.4	21:00	17.6	16.4
10:00	17.6	12.7	22:00	17.1	16.0
11:00	19.6	13.3	23:00	16.5	15.7
12:00	21.2	14.2	24:00	15.9	15.5

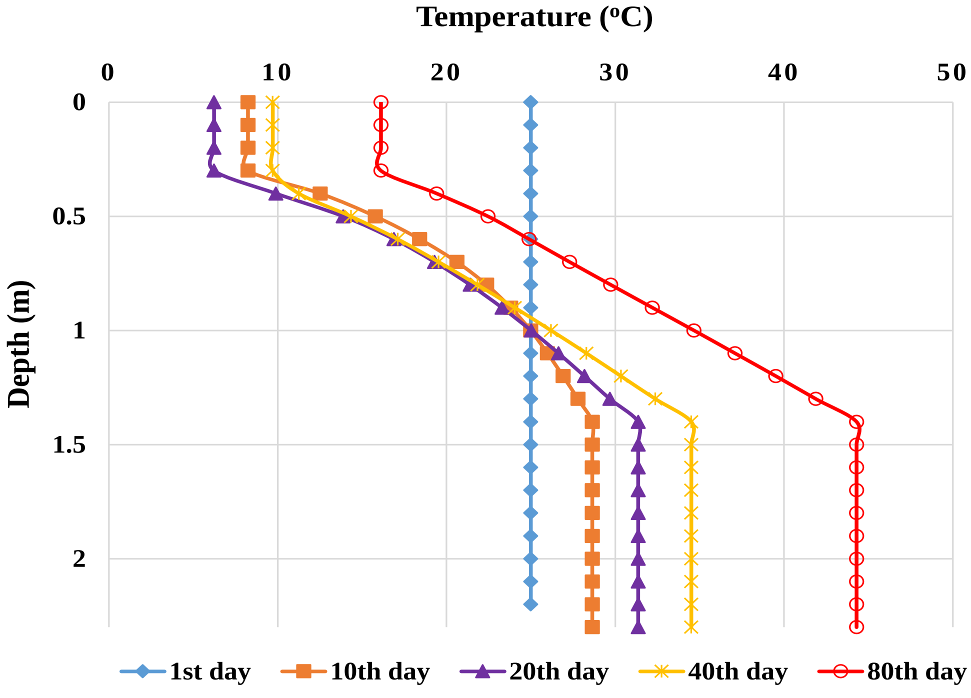

Figure 4.2. Temperature development profile in solar pond.

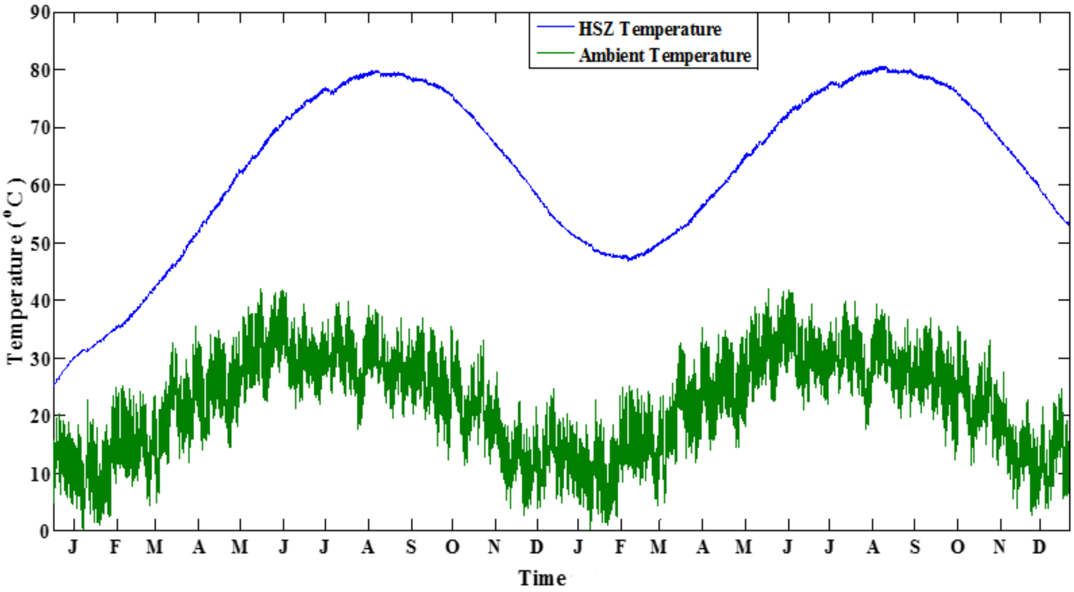

Figure 4.3. HSZ temperature and ambient temperature for two years.

The HSZ temperature in the pond of size 2.2 m is shown in Figure 4.3. Results reveal that until the month of March, pond charge up and become stabilized. Maximum temperature achieved by the pond is observed from June to September because both solar radiations and ambient temperature were high during these months shown in Table 4.1. The results also reveal that temperature from September to January is dropping because both solar radiation and ambient temperature were lower in these months, showing that the temperature of HSZ depends on ambient temperature and solar radiations.

4.3 Selection of Zone Thickness

In order to optimize the pond performance, simulations were carried out to study the effect of zone thickness on the HSZ temperature. The effect of different zone thickness on pond performance is given below:

4.3.1 Optimization of UCZ Thickness

The model showing the effect of UCZ thickness on pond temperature has been developed and validated with the literature by keeping similar parameters [2]. In order to evaluate the influence of UCZ thickness on HSZ temperature, four different thicknesses of UCZ 0.0 m, 0.2 m, 0.4 and 0.6 m were taken, whereas thickness of NCZ and LCZ was kept 1.0 m. Figure 4.4 depicts that, when there is no UCZ; SGSP can achieve maximum temperature up to 85 °C and when UCZ thickness reaches to 0.6 m, maximum temperature of SGSP decelerates to 74 °C; showing that growing thickness of UCZ reduces the SGSP temperature. This decrement in temperature of LCZ is observed because the solar radiation reaching the pond depth have reduced, and losses from the pond surface have increased. Therefore, UCZ thickness should be minimum to obtain the maximum temperature of SGSP. However, thickness of 0.2 m for UCZ is practically unavoidable [2]. Therefore, in next case thickness of UCZ is taken as 0.2 m.

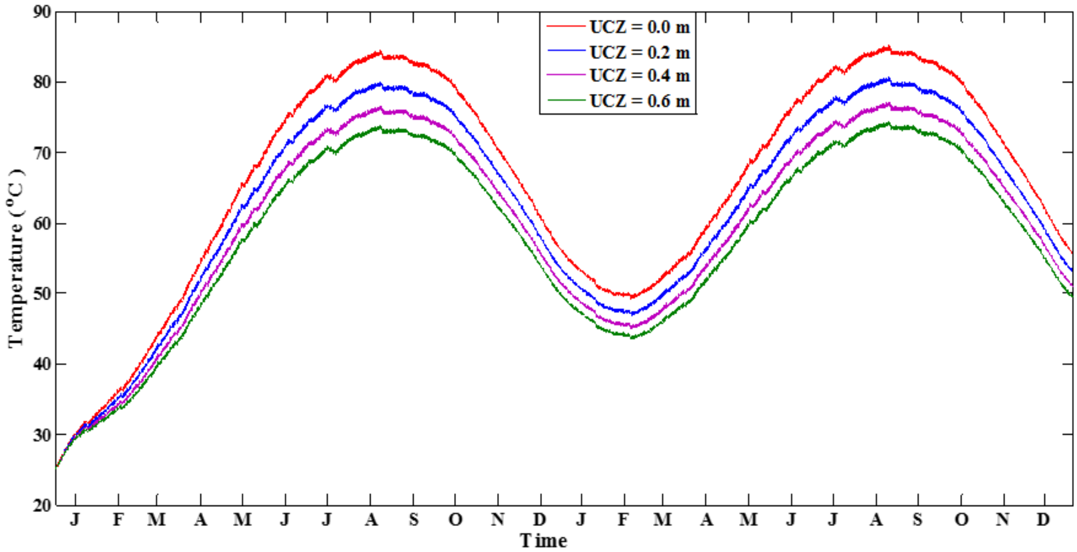

Figure 4.4. Effect of UCZ thickness on pond HSZ temperature.

4.3.2 OPTIMIZATION OF NCZ THICKNESS

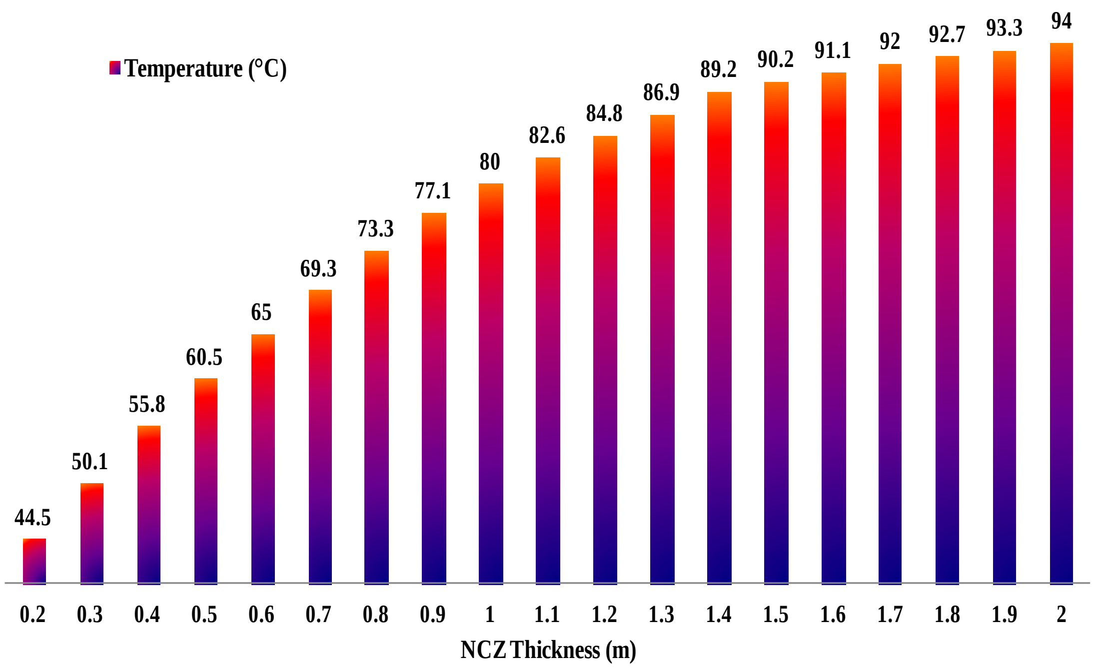

Figure 4.5. Effect of NCZ thickness on maximum temperature achieved by HSZ.

The model has been developed for effect of NCZ thickness on pond temperature and validated with the literature by keeping same parameters [2, 3]. The variation in maximum temperature achieved by HSZ is shown in Figure 4.5. It is observed that, rise in thickness of NCZ raises the temperature of the HSZ/LCZ. This is because NCZ is providing insulation and preventing heat losses taking place from HSZ to UCZ. Heat losses are only taking place in the NCZ by conduction only. As the heat capacity of water is high, meaning that water can absorb more heat and consequently take more time to lose heat to the outer surface by conduction only. The results also reveal that the maximum temperature achieved by HSZ is not linearly proportional to the thickness growth of the NCZ. This is due to the amount of solar radiations reducing with depth, that's why when the thickness of NCZ is increased from 0.2 m to 1.4 m, an increase of 38.8 ^{o}C in HSZ temperature is observed. A further rise in thickness does not raise the temperature of HSZ significantly as the intensity of solar radiation is reducing and quantity of water is increasing, which may also disturb the stability of the pond.

4.3.3 OPTIMIZATION OF LCZ THICKNESS

The variation in LCZ temperature for 2 years is shown in Figure 4.6, whereas thickness of UCZ and NCZ were kept constant 0.2 m and 1.4 m respectively. Results depict that thickness of LCZ is inversely proportional to HSZ temperature. When thickness of LCZ is 0.6 m, then pond can store more heat from March to September and when winter starts, losses more heat to the environment because of the great temperature gradient between ambient and HSZ temperature; Thus layers having higher temperature losses more heat to environment during winter months. It is also noted rise in the thickness of LCZ decreases temperature fluctuation throughout the year; this is due to the increasing water quantity in HSZ. The selection of LCZ thickness depends on the operating temperature requirement and on the type of application. When high temperature is required, then thickness of LCZ should be the less, but fluctuations in temperature from winter to summer season will be more. If less fluctuation in HSZ temperature is required, then the thickness of HSZ should be 1.4 m or even more.

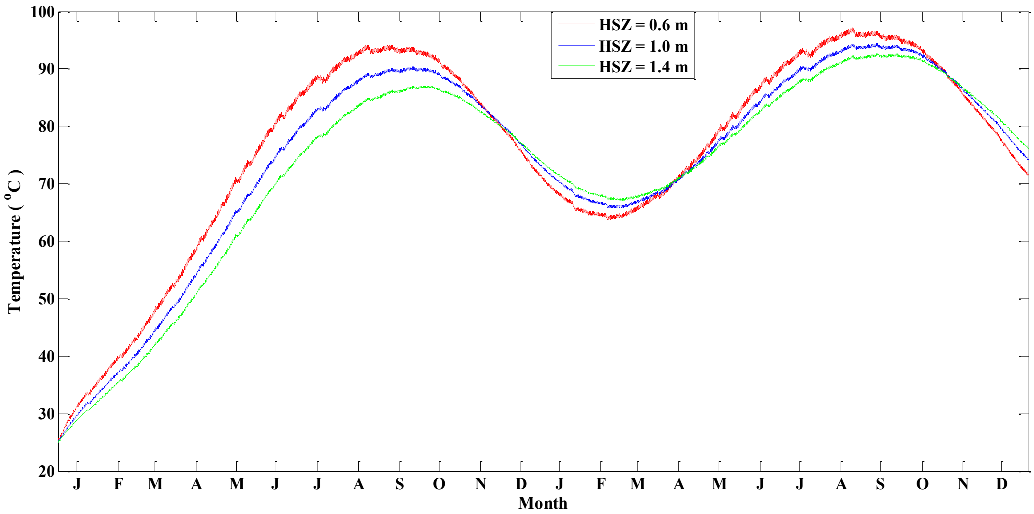

Figure 4.6. Effect of LCZ thickness on HSZ temperature.

4.4 EFFECT OF GROUND CONDUCTIVITY ON POND TEMPERATURE

Three different ground water conductivities were considered; such as insulated ground, the grounds with conventional conductivity and ground with relatively high conductivity as shown in Figure 4.7. It is observed that when the ground is insulated then pond can achieve highest temperature up to 96 °C during the first year of operation. The increasing ground conductivity results in the decrement in the pond maximum temperature, which suggest that ground conductivity plays significant role in the performance of the pond.

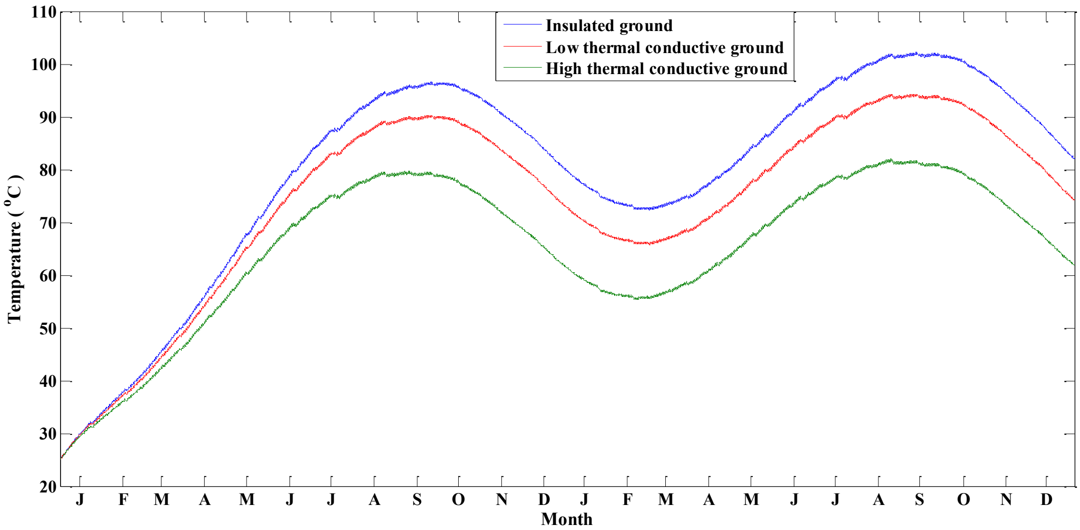

Figure 4.7. Ground conductivity effect on HSZ temperature.

4.5 HEAT EXTRACTION FROM SOLAR POND

Heat can be extracted from HSZ by keeping either mass flow rate or energy output constant. So in order to get same water quantity daily, first case is considered. The temperature variation in HSZ under the heat extraction mode is shown in Figure 4.8 for the period of two years. In this study. effect of boiling is ignored, so that the simplified temperature development model can be obtained; however; in practical solar pond temperature does not go above the local boiling point of saline solution otherwise salinity gradient will disturb [4]. To extract heat from the salt gradient solar pond at least, 5 ^{o}C temperature difference is requisite between heat transfer fluid and LCZ fluid. For end use application at least further 5 ^{o}C more temperature difference is requisite [5]. Hence for end use applications, it is considered that water at 45 ^{o}C temperature must be present. Figure 4.8 shows the effect of heat extraction on the pond LCZ temperature for various mass flow rates. Results reveal that heat extraction was started after four months of operation. It is pragmatic that, heat extraction has the significant effect on pond temperature, rise in mass flow rate causing decrement in pond temperature, which means quality of energy available for end use application is reducing. Results also depict that, when the mass flow rate is 26 kg/m^2/day, then pond temperature drop below 45 ^{o}C during winter months, which is not suitable. Therefore, it is suggested that if the constant flow rate is required than 17.3 kg/m^2/day is selected as optimum mass flow rate. Further, it is suggested that heat should be extracted at a rate of 17.3 kg/m^2/day during winter months and 26 kg/m^2/day during summer months so that maximum energy can be supplied to the load.

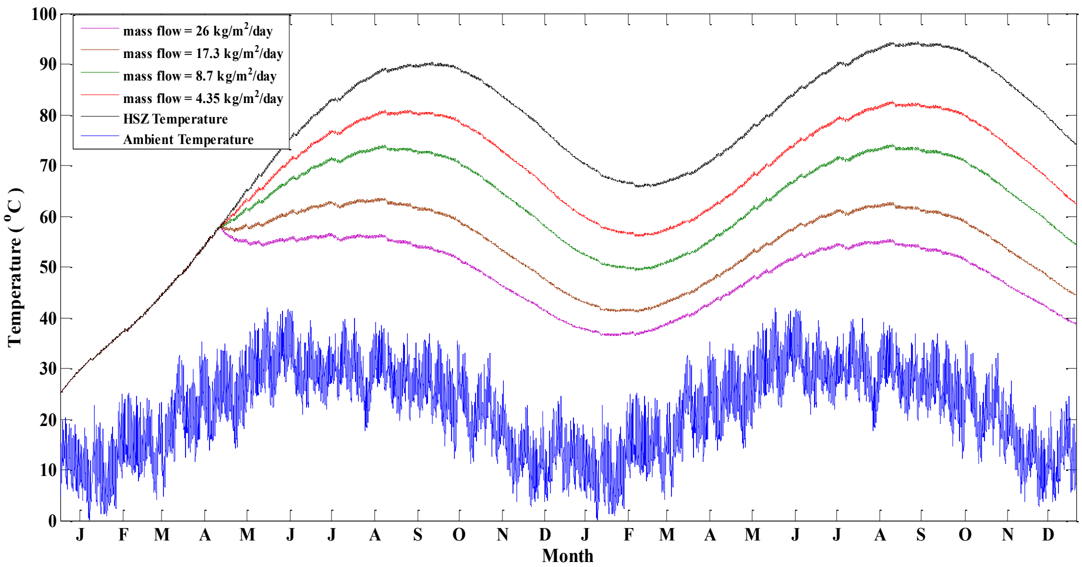

Figure 4.8. Effect of the heat extraction on LCZ temperature.

Figure 4.9 shows incident and absorbed solar radiations in the pond. Results reveal that, when bottom reflectivity of 0.3 is considered, then small portions of radiations is absorbed in the pond approximately 24%. These results were verified from the literature [6]. The effect of energy extraction on the pond temperature during the second year of operation is shown Table 4.3. Results reveal that during summer season (April to August) about 45 to 70 % absorbed energy is extracted; subsequently remaining amount of absorbed energy is compensating with losses and causing rise in LCZ temperature. In winter season more portion of energy is being extracted in comparison to absorbed energy, because more energy was trapped during summer season. Further, it is noted that during the winter season (September to February) temperature of the pond is reducing due to both ambient temperature and incident solar radiations.

Table 4.3. Incident energy and output from the solar pond.

Month	Absorbed W/m^2	Extracted W/m^2	Energy extracted vs absorbed %	Ambient Temperature °C	HSZ Temperature °C
Jan	16443	11950	72.68	1	4.2
Feb	19470	10103	51.89	13.1	43
Mar	27422	12437	45.35	17.9	45
Apr	31785	14599	45.93	23.4	49.25
May	36565	18426	50.39	28.8	54.62
Jun	36914	20695	56.06	31.3	59.4
Jul	35984	23149	64.33	29.6	62.2
Aug	33719	23921	70.94	28.6	63.46
Sep	28970	22570	77.91	26.8	62.5
Oct	23621	21582	91.37	22.1	59.7
Nov	17741	17171	96.79	15.9	54.35
Dec	15644	14794	94.57	11.3	48.75

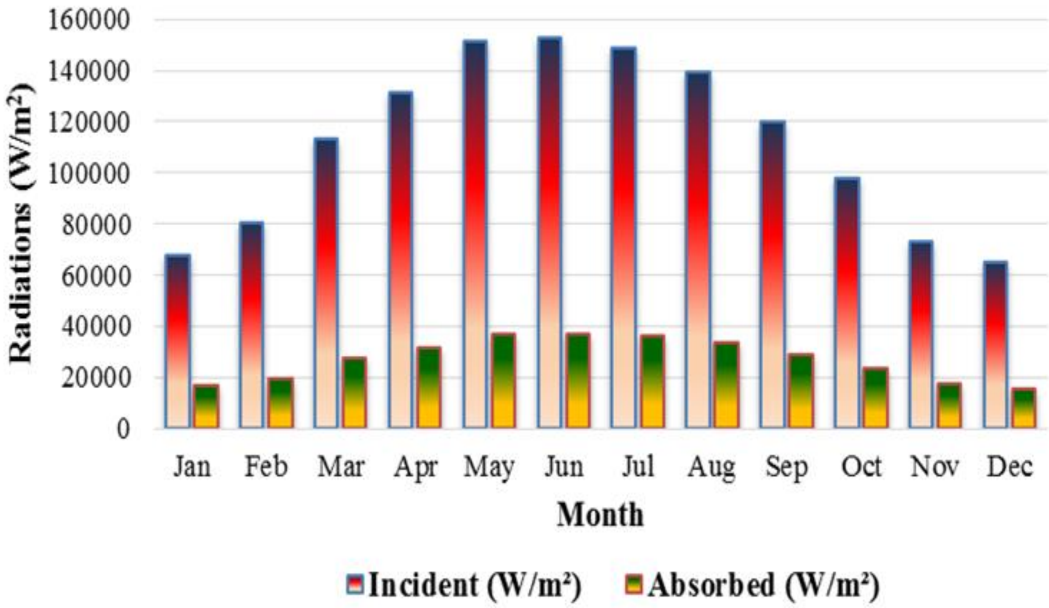

Figure 4.9. Incident solar radiations vs absorbed solar radiations for Islamabad.

4.6 SALT DIFFUSION IN THE POND

Before start of simulation it was considered that UCZ and LCZ had homogeneous salt concentration; UCZ had a low concentration of salt 35 kg/m^3 and LCZ had higher concentration of salt 180 kg/m^3 whereas NCZ had linearly been increasing salt concentration. Figure 4.10 shows the salt diffusion profile in the pond. It is observed that until 1200 hours, there is a negligible change in salt concentration profile, which means the pond is stable and does not require any maintenance during this period. The figure also depicts that due to salt diffusion from LCZ to UCZ, after 7200 hours concentration of salt is increasing significantly in UCZ and consequently declining in LCZ, which mean pond is not stable. This change in salt concentration is observed due to diffusion of salt and mass transfer from high concentration to low concentration. If this phenomenon continuously happens, then there will be no stratified region and pond will not store energy. Therefore, it is necessary to carry out maintenance for long term operation of the solar pond by flushing fresh water on UCZ and adding saturated saline water in LCZ [7, 8]. These results were verified with the literature [9].

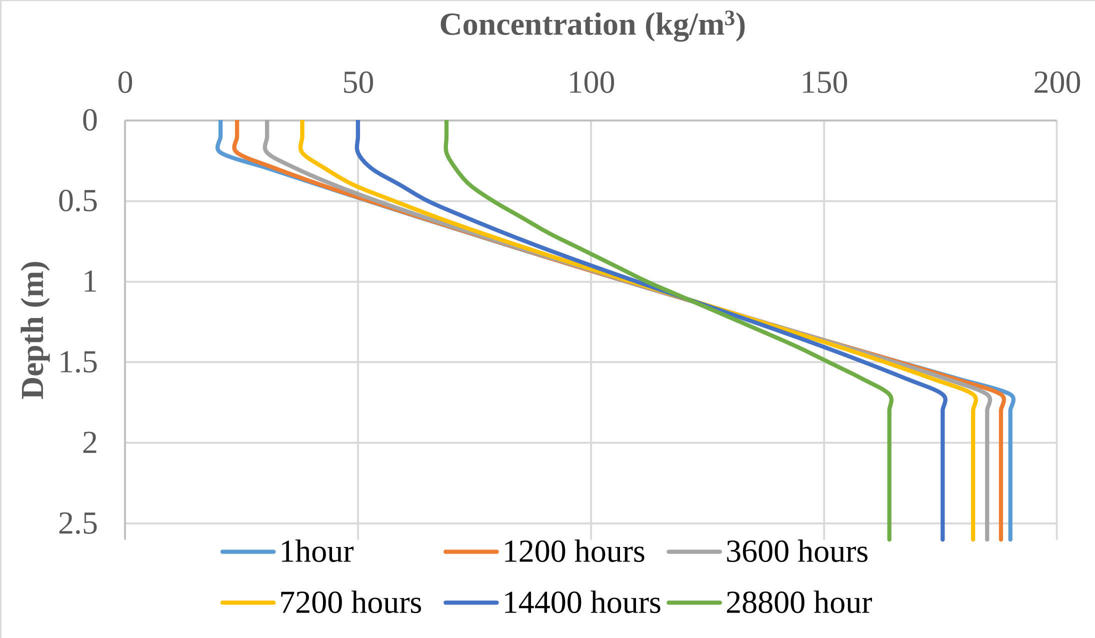

Figure 4.10. Effect of salt diffusion in the solar pond.

4.7 Selection of Suitable Site

The model has been developed for five different cities of Pakistan, which are geographically at different location as shown in Figure 4.11. The maximum temperature achieved by HSZ, monthly average radiation and ambient temperature for Islamabad, Lahore, Multan Quetta and Peshawar is shown in Figure 4.12. Results depict that the maximum temperature achieved by HSZ for Islamabad, Lahore, Multan Quetta and Peshawar is 94.5 °C, 115 °C, 118.5 °C, 119.7 °C and 122 °C respectively. In practice, HSZ temperature should not exceed 90 °C because saline water may boil, which may exterminate pond density structure. To avoid rising of temperature usually a heat exchanger is operated [4]. Results reveal that solar radiation are maximum in Quetta, but HSZ temperature is maximum in Peshawar because the ambient temperature is lower than in Quetta. Due to low ambient temperature, losses from the pond surface to environment are more. It is also observed that the maximum temperature difference between ambient temperature and LCZ temperature of 104 °C is observed in Quetta, whereas for Islamabad, Lahore, Multan and Peshawar is 73 °C, 90 °C, 93 °C and 99 °C respectively. As the temperature of hot water is more in Peshawar and Quetta, so for solar pond Peshawar and Quetta are suggested as most suitable sites of Pakistan.

Figure 4.11. Position of selected cities of Pakistan in Map [10].

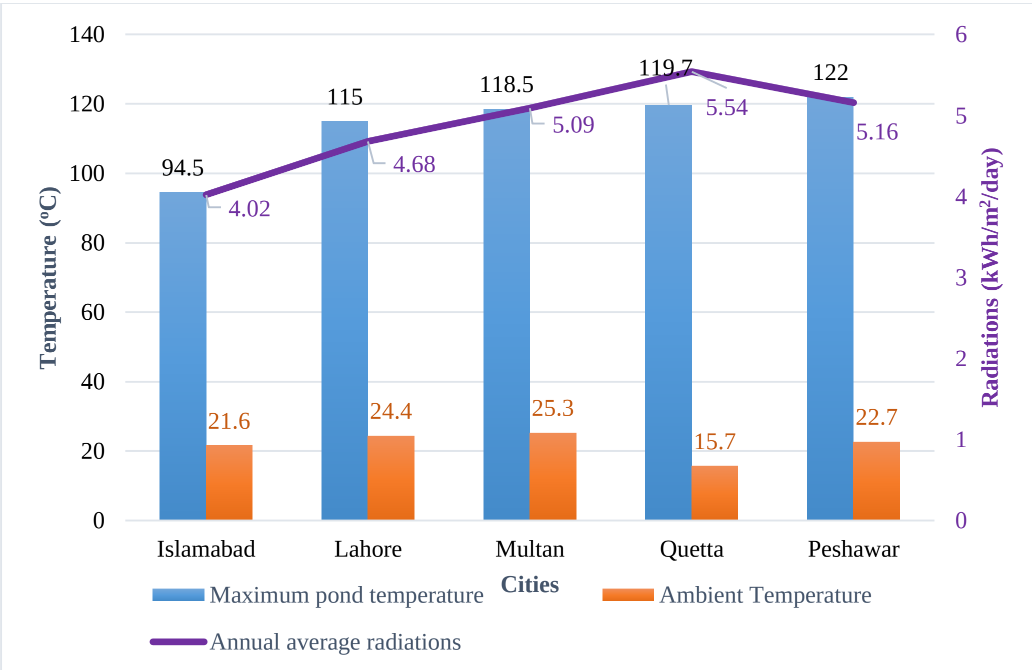

Figure 4.12. Viability of solar pond for different cities of Pakistan.

SUMMARY

The model has been developed to evaluate pond performance. The model evaluates the development of the temperature profile in the solar pond. In order to get maximum performance optimization of UCZ, NCZ and HSZ has been carried out. To reduce the ground loss effect of ground conductivity on HSZ has been carried out. In order to get energy output from the pond, the effect of different mass flow rate on pond performance has also been investigated. In the further study amount of energy available and viability of the solar pond for different cities was also calculated.

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CHAPTER 5

CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS

- Solar pond can provide more heat in summer, so it can be used for many applications.
- For maximum performance of the solar pond, UCZ thickness should be about 0.2 m, whereas thickness of NCZ should be from 1.2 to 1.4 m.
- LCZ thickness depends on the type of application. If the high temperature is required for less time than thickness of LCZ should be about 0.5 m.
- Ground insulation is necessary if the solar pond is installed at a location having higher thermal conductivity.
- Effect of heat extraction from LCZ has great influence on pond temperature. If the higher temperature is required, then the mass flow rate of water should be low.
- Solar ponds provide low quality heat. Solar pond is suitable for industries where the large area is available.
- Diffusion of salts plays a significant role. Maintenance of the solar pond is necessary for long term operation.
- The site with higher ambient temperature and higher solar radiations is most suitable for open solar ponds.
- Peshawar and Quetta are suggested as the most suitable site for solar pond operations.
- Very little amounts of solar radiations are available at the depth of 2.5 m. In future, the effect of the mirror on pond performance needed to be tested.
- Effect of heat extraction from NCZ and LCZ on performance and stability of the pond through external heat exchanger is to be tested.