Simultaneous Brine Management and Heat Extraction from Salinity Gradient Solar Pond

By

Kamran Manzoor

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APPROVAL SHEET

Certified that the contents and form of thesis entitled "**Simultaneous Brine Management and Heat Extraction from Salinity Gradient Solar Pond**" submitted by Engr. Kamran Manzoor have been found satisfactory for the requirement of the Master of Science degree in Environmental Engineering.

Supervisor: ____________________

Dr. Sher Jamal Khan

(Associate Professor)

Member: ____________________

Assistant Professor (Dr. Yousuf Jamal)

Member: ____________________

Assistant Professor (Dr. Zeeshan Ali Khan)

DEDICATION

This work is dedicated to my beloved Parents, Brothers, Sister and my Wife, their support and encouragement brought me to this stage today!!

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I am thankful to Allah Almighty for his blessings which made it possible for me to work on this novel project.

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LIST OF ABREVIATIONS

AGMD	Air gap membrane distillation
ºC	Degree Celsius
cm	Centimeter
DCMD	Direct contact membrane distillation
HDPE	High density polyethylene
HCl	Hydro chloric acid
kg/m^3	Kilogram per cubic meter (Density)
LCZ	Lower Convective Zone
$L/m^2.h$	Liter per square meter per hour (Flux)
MBR	Membrane bio reactor
m^3/day	Cubic meter per day
MD	Membrane distillation
$MgCl_2$	Magnesium chloride
mm	Millimeter
mg/L	Milligram per liter
mS/cm	Milli-siemen per centimeter
MGD	Million gallon per day
NaCl	Sodium chloride
NCZ	Non convective zone

PE	polyethylene
PTFE	Poly-tetra-fluoro-ethylene
PVDF	Polyvinyldene fluoride
PP	Polypropylene
PVC	Poly vinyl chloride
P.C.C	Plain cement concrete
RO	Reverse osmosis
R.C.C	Reinforced cement concrete
RMIT	Royal Melbourne Institute of Technology
SGMD	Sweeping gas membrane distillation
SGSP	Salinity gradient solar pond
SMN	Stability Marginal Number
TDS	Total dissolve solids
UCZ	Upper convective zone
VO	Volatile organics
VMD	Vacuum membrane distillation
VFD	Variable frequency drive
WHO	World health organization
µm	Micrometer

Abstract

Pakistan is currently experiencing water shortage as population is growing. The problem associated with the reverse osmosis is its brine disposal. Experimental salinity gradient solar pond (SGSP) with surface area 4.65m^2 was established to pre-heat the reverse osmosis (RO) concentrated brine. Laboratory scale direct contact membrane distillation (DCMD) setup was used to investigate the temperatures gained from (SGSP). In this study, effort has been made to evaluate the performance of the SGSP and DCMD under Pakistan's climatic condition at NUST, Islamabad. The heat extraction was carried out using internal heat exchanger by passing fresh water through it at different flow rates in summer and winter. Maximum of 37°C of heat extracted temperature in summer and 28.5°C in winter was achieved. Least drop in lower convective zone (LCZ) temperature was observed at flow rate of 7.5L/min. In DCMD, four different temperatures (28.5, 37, 50 and 60) ^{o}C at feed side were maintained to observe flux and total dissolve solids (TDS). Flux was increased as temperature difference between feed and permeate increased. As salt concentration was increased in feed side, scaling and decrease in flux was observed. Experiment showed that 28.5°C in terms of SGSP temperature is also feasible for membrane distillation process as flux was increasing with passage of time.

Chapter 1

Introduction

1.1. Background

Sea water covers about 96.5% water of the world. Saline lakes contain brackish and saline water, moreover earth's water consists of 1% ground water which leaves behind 2.5% of fresh water from which consumable water by human is only 1% (Ayoub et al., 2014).

Pakistan is among those nations who are facing shortage of water. Safe drinking water source is not available to more than 780 million people. Pakistan is categorized on 80th number among 120 countries concerning drinking water quality (UNICEF/WHO report, 2011). Pakistan's ground and surface water are polluted with toxic metals, pesticides and coliforms. To increase in fresh water production, there is a need of desalination renewable energy coupled with solar energy. Desalination is a process in which salts remove from water. Reverse osmosis (RO) is commonly and most usable technology in the world and also in Pakistan. But problem with RO is its brine disposal and high energy cost using photovoltaic in the form of desalination coupled with renewable energy (Shannon et al., 2008).

To overcome the problem of brine disposal, brine management and production of fresh water through solar energy coupled with membrane distillation technique is using (Cath et al., 2004). In MD, hydrophobic membrane transports vapor molecules by temperature driven separation process. In solar energy, salinity gradient solar pond (SGSP) is a perfect renewable source for preheating brine used in MD process. The main advantage of solar pond for energy collection and storage are low costs when compared to photovoltaic cell in terms of construction and operation (Qtaishat et al., 2013).

In this study, pilot scale SGSP was used to extract heat from lower convective zone (LCZ) to pre-heat the brine which is used in MD. The simple form of MD on lab scale known as direct contact membrane distillation (DCMD) was used to investigate the performance of different temperatures received from SGSP. In DCMD hot feed solution and cold distillate are in direct contact with membrane on both sides with driving force of vapor pressure gradient.

1.2. Objectives

- ✓ Design and install salinity gradient solar pond (pilot scale) and direct contact membrane distillation (lab scale).
- ✓ Establish gradient layer, heat extraction and analyze physical parameter on salinity gradient solar pond
- ✓ Evaluate the direct contact membrane distillation in terms of
    - Feed temperature
    - Feed concentration

1.3. Scope of study

My research work divided into two phase. Phase 1 consist of construction and observation of salinity gradient solar pond and phase 2 consist of fabrication and observation of lab scale direct contact membrane distillation setup.

1.3.1. Phase1: Salinity gradient solar pond

The study of temperature gradient, certain factors like wind induced convectional currents, heat transfer from walls are not taken into account due to limitation of resources. Moreover, the study is limited to the heat energy balance within the pond based on assumption that no heat transfer takes place from the base and side of the walls. The heat extraction calculations are based on the assumptions that no heat exchange take place from the pipes outside the pond. The salt used for brine production was majorly sodium chloride (NaCl) but was not pure.

1.3.2. Phase2: Direct contact membrane distillation

Laboratory Scale direct contact membrane distillation setup having flat sheet module which use hydrophobic flat sheet membrane. Synthetic made solution of different salts with concentration of 7560mg/L used in this experiment. This concentration was adopted from composition of salts at 40 % recovery of reverse osmosis feed concentration of 4500mg/L which was used in NUST, Islamabad pilot scale reverse osmosis plant.

Chapter 2

Literature Review

Water is the main source of life, the basis of human survival and the economy substantial development of a country. As increasing global population, the gap between supply and demand of water is also increasing. Sea water is round about 96.5% of the world's water. 1% of earth's water is brackish or saline exist in ground water and saline lakes. Fresh water scarcity is growing problem in all over the world because only 1% of earth's water is fresh that is safe for human to drink (Matti et al., 2010).

In initial times, this process was useable to filter sea water into the drinking water. But now several technologies for desalination have been established and executed throughout the world. These technologies are differentiated into three categories. Firstly, sedimentation, screening, coagulation, filtration, centrifugation, separation and flocculation; secondly, aerobic and anaerobic treatments and thirdly, distillation, reverse osmosis(RO), evaporation, ion exchange, crystallization, oxidation, solvent extraction, precipitation, nano-filtration (NF), ultra-filtration (UF), microfiltration (MF) and electro dialysis which are used to attain filtered water and purify inorganic or some organic impurities in it.

However, most of these technologies are simple and modest but unable to desalinate salty water as adsorption methods and some are practically intensive and non-affordable on commercial level. So that, membrane technologies have been introduced as they have natural characteristics.

2.1. Desalination technologies

Table 2.1 The desalination technologies based on their operating principle and application.

Technologies	Operating Principle	Application
Thermal Process		
Multistage flash evaporation	Thermal Evaporation	Desalination of sea Water
Multi effect Distillation with thermal vapor recompression	Thermal Evaporation	Desalination of sea Water
Multiple effect distillation (MED) with mechanical vapor recompression (MVR)	Thermal Evaporation with enhanced energy efficiency	Desalination of sea water
Membrane Process		
Reverse Osmosis	Pressure driven Remove particle down to 0.0001 micrometers	Desalination of both sea and brackish water
Nano filtration	Pressure driven Remove particle down to 0.001 micrometers	Drinking water and industrial water/waste-water treatment

Ultra-Filtration	Pressure driven Sieving up to 0.01 micrometers	Drinking water and industrial water/waste-water treatment
Micro Filtration	Pressure Driven	Drinking water and industrial water/waste-water treatment
Electro dialysis	Charge Driven	Primary brackish water desalting
Membrane Distillation	Vapor Pressure Difference	Desalination of brackish water and sea water

Source (Farmer et al., 1995)

About 90 percent by volume capacity of global desalination, thermal and membrane desalination technologies are using worldwide as shown in table 2.1. Other promising additional technologies are freezing distillation, solar distillation, hybrid etc. In figure 2.1, part (a) shows different technologies of desalination while part (b) shows the global desalination capacity based on technology.

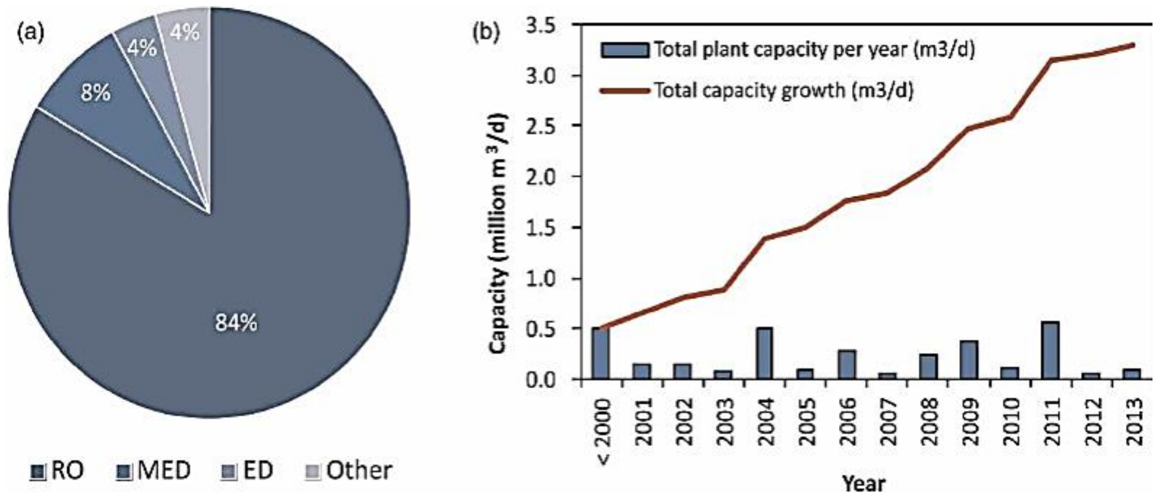


Figure 2.1: The global desalination capacity based on technology (DesalData, 2013)

2.2. Desalination coupled with renewable energy

Around the world communities depend on desalination for potable water supplies. Remote locations in developing countries and small islands frequently lack access to potable water and often to the electric grid. Also, in order to lower its environmental impact, desalination plants require an energy source that has low emissions and at the same time is affordable. Renewable energy sources such as solar photovoltaic and thermal, wind or geothermal energy can be utilized to solve both issues, as using locally available renewable resources is likely to be cost-effective.

As desalination worldwide capacity currently surpasses 70 million m^3/day, this solution can result in noteworthy cuts in greenhouse gases. Moreover, as the costs of renewable energy solutions are expected to decline further, these will become more attractive, especially in remote regions with low population density and poor infrastructure for fresh water and electricity transmission and distribution (Hickenbottom et al., 2014). Figure 2.2 tells us about the percentage of indirect solar desalination plants installed worldwide. Figure 2.1 and 2.2 shows that reverse osmosis the commonly use desalination technology in the world and also in Pakistan.

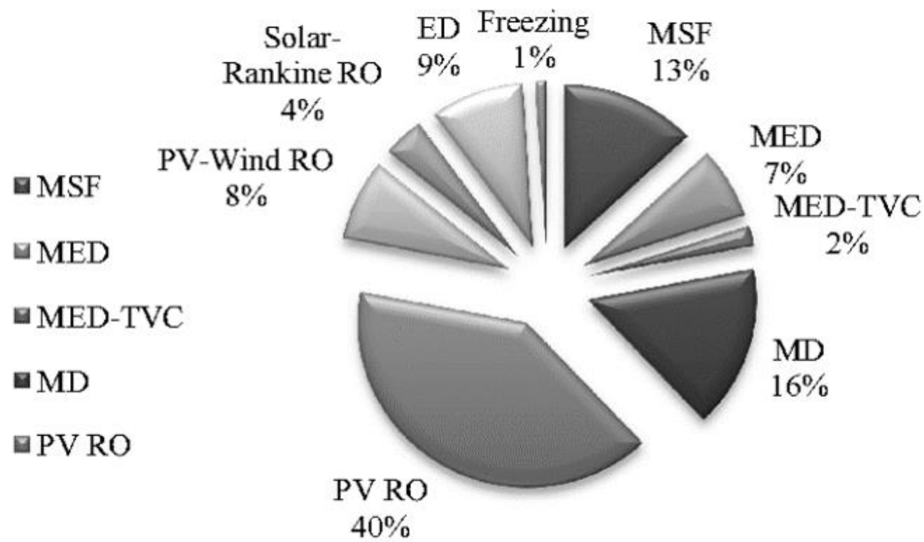


Figure 2.2: Technologies in indirect solar desalination plants installed worldwide (Ali et al., 2011)

2.3. Possible impact from RO desalination technology and solutions:

Minerals concentration is generally 2-10 times higher than that of raw water in brine. This concentration is present in terms of TDS of the raw water (Glater et al., 2003). Now a day, 40-80% of RO plants commercially operate all over the world. The brackish water RO plants normally operate 40-60 % recovery range with TDS range of 1500-25000 mg/L. Brine disposal is the main drawback of RO process and have negative impact on the water environment due to high salinity (Urtiaga et al., 2012).

2.3.1. Options for brine disposal

Though the disposal of brine into an open ocean is a common practice but it is normally not cost effective because of transport the brine from land to ocean for disposal where ocean is not near that area. Ordinary pipelines or tanker can be used for brine disposal to ocean. As brine has high corrosive nature, high quality and special defensive liners must be use in pipes lines and tankers but this will become more expensive brine disposal method in terms of these necessities and transportation cost. Due to corrosive nature, brine may contain substantial amounts of environmentally toxic and harmful constituents. That is why, brine cannot be dispose into surface or inland surface water and onto the soil surface. Deep well injection, land application and evaporation ponds are commonly used disposal options for RO concentrate that are expensive and have negative impact on the water environment due to high salinity (Rosado & Bernaola, 2014). For better brine management and more fresh water production, new innovative methods of temperature driven membranes are needed.

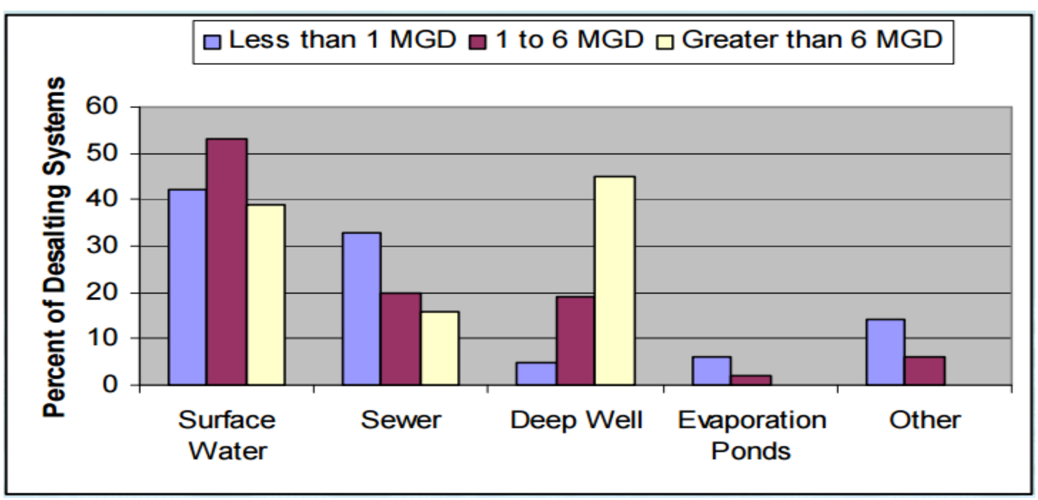


Figure 2.3: How are desalting systems disposing of brine? (Mickley et al., 2001)

2.4. Membrane distillation

Membrane Distillation is thermally driven membrane separation process; micro porous hydrophobic membrane only allows vapor molecules to pass through it. Difference in vapor pressure is act as a driving force that induced by temperature difference. Membrane distillation (MD) is an emerging technology among desalination processes and brine management techniques (Pantoja et al., 2016). In MD, hydrophobic membrane transports vapor molecules by temperature driven separation process. The advantage of MD is it combines both evaporation process and membrane technology and in single unit (El-Bourawi et al., 2006).

2.4.1 Membrane distillation configuration

To separate aqueous solution, four MD configurations have been utilized. These are Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD) and Vacuum Membrane Distillation (VMD).

2.4.2. Direct contact membrane distillation (DCMD)

Both hot (feed) solution and cold (permeate) solution are in direct contact with membrane figure 2.4. At the feed membrane surface evaporation take place, vapor is moved across the membrane due to pressure difference and condensation take place inside the membrane module. At permeate side to cold liquid, partial pressure can be reducing to improve the driving force by using osmosis distillation (OD) water (Lagana et al., 2000). It is simplest and most popular configuration of membrane distillation to perform the experiment (Qtaishat et al., 2008).

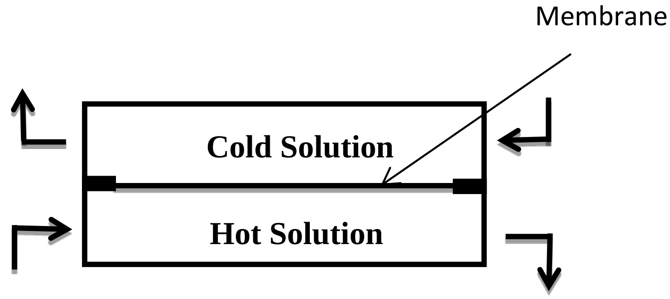


Figure 2.4: Direct contact membrane distillation process

2.4.3. Air gap membrane distillation (AGMD)

In AGMD, feed (hot) solution is in direct contact with membrane surface and on permeate (cold) side air gap exist between membrane surface and condensation surface figure 2.5. Stagnant air is introduced in air gap. One side is rendering with feed heated aqueous solution, the remaining side is separated (Meindersma et al., 2006). Vapor from hot side crosses the membrane and air gap surface, and condense inside the membrane module. Advantage of air gap is to reduce heat loss due to conduction and disadvantage is additional barrier to mass transfer is form due to this air gap. In comparison with other MD configurations, AGMD produced lowest permeate flux (El-Bourawi et al., 2006).

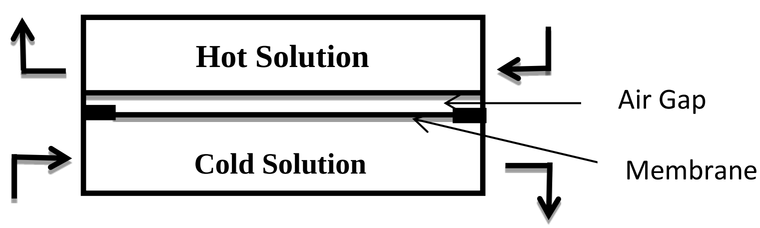


Figure 2.5: Air gap membrane distillation process

2.4.4. Sweeping gas membrane distillation (SGMD)

In SGMD, inert gas is introduced inside the membrane cell, to move the vapor from permeate side to outside of the module where condensation take place figure 2.6. It has alternative name as membrane air stripping (Meindersma et al.,2006). Like AGMD, there is also a gas barrier but this is not stationary and SGMD is typically used to remove volatile compound over water (Khayet & Matsuura, 2011). Main drawback of this configuration is, require a large condenser due to small volume of permeate solution diffuse into a large sweep gas.

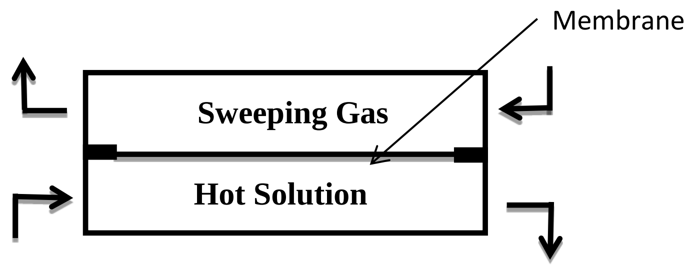


Figure 2.6: Sweeping gas membrane distillation process

2.4.5. Vacuum membrane distillation (VMD)

To sustain the vacuum at downstream side of membrane, vacuum pump is used. Condensation occurs outside the membrane cell. A great advantage of VMD is negligible heat loss by conduction (Sarbatly & Chiam, 2013). It must be noted that saturation pressure of volatile substantial that required to be separated should be higher than vacuum pressure (Khayet & Matsuura, 2011). In VMD, driving force is the pressure difference between each pore or two sides figure 2.7.

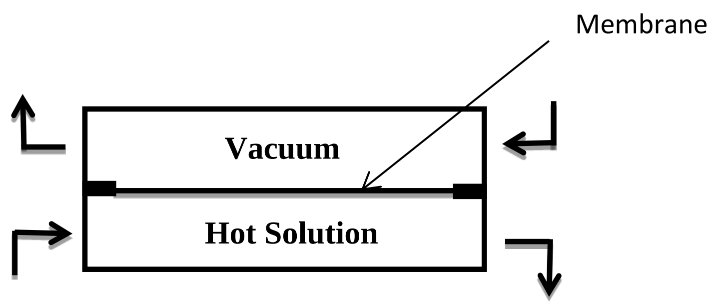


Figure 2.7: Vacuum membrane distillation process

2.5. Fabrication of module and membrane material use for distillation method

MD selection is depending for each characteristic application required. Thermal conductivity, permeate flux, porosity, separation factor and pore size are the combination factor for typical MD process selection (Khayet & Matsuura, 2011).

2.5.1. MD process commercial membranes

Hydrophobic polymer is suitable material for micro porous membrane to avoid the membrane wetting. Different polymer materials can be used as commercial membrane for example: polyethylene (PE), polypropylene (PP), poly-tetra-fluoro-ethylene (PTFE), poly-vinyl-dene-fluoride (PVDF) respectively. These polymer materials can get in several shapes like flat sheet, tubular and capillary. All requirements of MD can be fulfilling by these morphological structures of these synthetic materials (Khayet & Matsuura, 2011).

2.5.2. MD process fabricated membranes

Several hydrophobic porous membranes are manufactured by using various methods based on different materials. MD operating range temperature, aqueous solution, price, thermal conductivity and ease of fabrication are the factors that depend on choice and manufacture (Khayet & Matsuura, 2011).

2.5.2.1. Frame and flat sheet module

Different types of flat sheet membranes having solo hydrophobic layer has been established. Change in the maximum co-efficient of mass transfer of various membranes will occur which depends to each membrane that has different concentration of polymer using different volume of solvent. Normally this module is used in laboratory researches as it is easily cleaned and exchanged. The ratio between areas of membrane to the module volume is very low in the value (Khayet & Matsuura, 2011).

2.5.2.2. Spiral wound module

A flat sheet membrane is rolled and enclosed in a limited space comprised by this type of component. The collection pipe use as a center of the winding. Permeate flux goes into the center tube as well as feed solution movement crossing the membrane surface is into an axial drift. For this module it was confirmed that the consumption of energy was acceptable and had high packing density which was not easy to foul. (Alkhudhiriet al., 2012)

2.5.2.3. Hollow fiber module

Different hollow fiber membranes were manufactured by using various spinning process, polymers and solvents. Few common constituents for hollow fiber are PTFE, PVDF and co-polymers (Khayet & Matsuura, 2011). The main composition of this module was a specific number of hollow fibers bundled and sealed which was included in a shell tube. The main advantages of this module type are consumption of low energy and having limited volume for high membrane area. On the other hand, more chance to get fouling and difficult to clean (Fuji et al., 1992).

Table 2.2: Typical fields of MD application

Application area	MD Configuration			
	DCMD	AGMD	SGMD	VMD
Desalination and pure water production from brackish water	x	x	x	x
Nuclear industry (concentration of radioactive solutions and wastewater treatments; pure water production)	x			
Textile industry (removal of dyes and wastewater treatment)	x			x
Chemical industry (concentration of acids, removal of VOs from water, separation of azeotrophic aqueous mixture such as alcohol/water mixtures and crystallization)	x	x	x	x
Pharmaceytical and biomedical industries (removal of water from blood and protein solutions, wastewater treatment)	x			
Food industry (concentration of juices and milk processing) and in areas where high temperature applications lead to degradation of process fluids	x	x		x

Source: (El-Bourawi et al., 2006)

2.6. Applications, advantages and disadvantages of MD process

Table 2.2 shows the typical fields of MD application

2.6.1. Advantages of MD process

MD has various important advantages such as operate at lower pressure, 99 % ions removal, has less influence of chemicals by solutions procedure on membrane operating process, minimum land requirement, less membrane fouling, minimum external energy source required (Zuo et al., 2011). As in working operation, membrane fouling is not the main problem and module cannot easy to destroy due to low feed temperature and characteristic of membrane material. MD can operate long period of time before cleaning. It also produces high quality distillate and it does not require extensive pretreatment as in pressure driven membrane technology (Qtaishat & Banat, 2013).

2.6.2. Disadvantage of MD process

Though MD technology has many important advantages but it has some disadvantage which limit the application of MD process. The tendency to separate two or more components in a mixture is not possible in MD where both have high vapor pressure. External energy required in MD process to heat the feed solution which may be expensive or not be available on site. Membrane wetting and heat loss by conduction is the main drawback of MD process (Qtaishat et al., 2008).

2.7. Brine management from different techniques of MD

Different studies show that fresh water production and brine management has been examined in various techniques of MD (Rosado et al., 2014). Guillen-Burrieza et al. (2011) studied the AGMD process for brine management. The system has been nourished by using solution of sodium chloride between 1000 and 35000mg/L at temperatures up to 85^{o}C in the feed and up to 75^{o}C in the refrigeration. A fixed solar collector field was provided for that purpose. Vacuum Enhanced Direct Contact Membrane Distillation (VEDCMD) has been investigated by using two RO brines as feed with TDS 7500 mg/L and 17,500 mg/L (Martinetti et al., 2009). It was observed that recovery factor up to 81 % was obtained but this factor was limited by precipitation of inorganic salts on the surface of membrane. To remove the scaling layer from membrane surface and to restore the water permeate flux to almost the initial level, such cleaning techniques were showed by them. Ji et al. (2010) studied the bench scale Membrane Distillation Crystallization (MDC) for sodium chloride crystallization and water recovery. They showed that MDC has capability to distillate RO brines. Industrial scale of MDC process for dealing large volume of brines with no technical difficulty was also examined. Tun and Groth (2011) studied MD along with a crystallizer to concentrate RO brine having 15 mS/cm conductivity from wastewater of industry. They achieved 95% of recovery from complete feed and 3-5 L/m^2.h flux. The method that can be implemented for brine management is DCMD coupled with SGSP which has not been examined to the level where it can be useful for pilot scale or full scale. That is why more understanding of this concept is required.

2.8. Salinity gradient solar pond coupled with direct contact membrane distillation

For energy extraction saline water management, solar pond desalination systems are technically viable and give cost effective solution. Solar ponds desalination is a trustworthy process, brine is rejected in this process which is often considered a waste product is employed to form the solar pond (Gawad et al., 2013). Solar distillation systems are combined with solar ponds is one of the environment friendly and green energy technologies which can be efficiently used to alter saline water to fresh water.

A water body called SGSP contains lower convective zone (LCZ), non-convective zone (NCZ) and upper convective zone (UCZ). Solar radiations are stored in LCZ for long term purpose in the form of thermal energy. These radiations can be consumed for heating applications like thermal desalination by direct contact membrane distillation (DCMD). Heat exchangers extracts heat from Lower Convective Zone (LCZ) (Leblanc et al., 2011). The main benefit of solar pond for storage and collection of energy is, it is less expensive as compared to photovoltaic cell in terms of construction and operation (Qtaishat et al., 2013). DCMD is a simple technique in terms of construction and operation because it requires only a low grade heat source, a membrane module and two low pressure pumps to couple with SGSP for solar powered thermal desalination (Seckler et al., 1999). Solar ponds are used to provide heat for different types of desalination processes by using solar ponds in various studies (Al-Obaidani et al., 2008). In some studies, the performance of DCMD/SGSP coupled system was inspected to attain solar power thermal desalination as shown in figure 2.8 (Suarez et al., 2015).

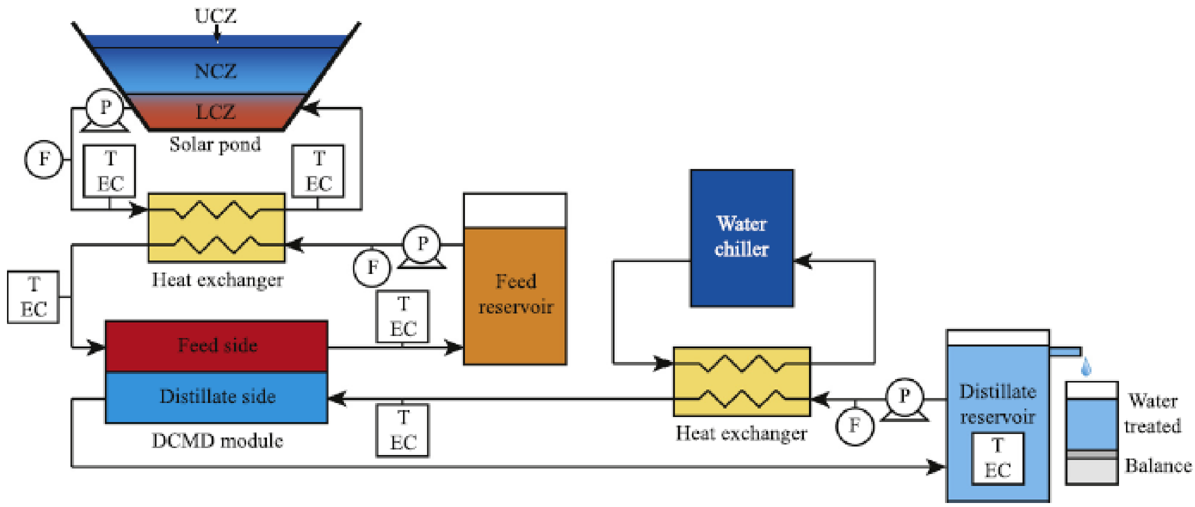


Figure 2.8: DCMD/SGSP coupled system (Suarez et al., 2015)

2.9. Methods of gradient establishment in solar pond

Density gradient in a solar pond can be established using a number of methods mainly depending upon the local requirement. The methods include (Sebai et al., 2011):

- Natural method
- Stacking
- Redistribution
- Falling

2.9.1. Natural method

The natural method is a diffusion method in which concentration at top is maintained by washing the surface regularly and bottom is maintained by adding salt. Due to the diffusion process a salinity gradient is established. This method requires a lot of time and is best suited if the pond is large.

2.9.2. Stacking method

In stacking, the bottom of the pond is filled with high concentration solution and a number of successive layers with decreasing concentration are stacked as the pond is filled. The top layer contains fresh water or water with very low salinity (density less than 1050kg/m^3).

Turbulent mixing is generated during filling the pond and continuous molecular diffusion changes the concentration profile into almost linear concentration profile.

An experimental solar pond in turkey used sodium carbonate salt and established gradient by filing the pond in different layers. LCZ was filled with high concentration brine then NCZ was filled in five layers with the help of floating plastic can. Lesser density solution was poured on the plastic can and then UCZ was filled in the same way with fresh water (Kurt et al., 2006).

2.9.3. Redistribution method

The method of redistribution is best suited for larger ponds. After preparation of homogenous salt solution fresh water is injected at a certain level which dilutes the salt solution to surface from a few centimeters below injection point.

The pond is half filled with high density salt solution (1200 kg/m^3) which is then filled with fresh water with the help of a diffuser. At the beginning diffuser is placed at the bottom and as the level is increased it is moved upward in steps. Timing and height intervals are adjusted so that the diffuser and water surface reach the end level at same time. Successful completion of this process gives a uniform gradient.

An experimental solar pond in Tunisia used this method. Initially the diffuser was placed at a 40cm height (from bottom) and fresh water was injected by moving the diffuser up by increasing 2cm as water level moved 1cm upward. The process was stopped when a height of 88cm was achieved obtaining an 88cm thick NCZ (Sebai et al., 2011).

RMIT solar pond also used the famous Zangrando's method in 1980 for establishment of gradient. Before establishing the gradient, an experimental with $MgCl_2$ solution was used to place the diffuser and observe the patterns of jet flow. The jet had a semi-circle horizontal flow which mounted above the diffuser. Froude number can be used to determine the type of jet flow that springs from the diffuser (Akbarzadeh et al., 2012).

According to Zangrando's work, injection levels of 0.05m worked properly. The first period of injection starts when fresh water is added with the help of diffuser. The diffuser height is increased by 0.1m when the pond surface level increases by 0.05m. This ensures that the salt solution above the diffuser is diluted while the diffuser and pond surface level is increased.

One of the important thing in establishing gradient is selecting the type of flow at which proper mixing occurs above the diffuser. The type of flow can be determined using Froude number which is the ratio of inertia to buoyancy forces of jet. According to Zangrando, the Froude number should be maintained at 18 while establishing the gradient (Zangrando, 1980).

2.9.4 Falling method

Falling method includes withdrawal of hot salt solution from the bottom layer without disturbing the layers above. The hot solution is then passed from an evaporator to evaporate some of the water. The solution left contains a higher salt concentration in a lesser volume of water. It is re-injected to the pond bottom is removed water is compensated in the surface layer. Loses from evaporation are also compensated by adding fresh water to the top layer.

2.10. Heat losses

Heat losses accounting for reduction in thermal efficiency of solar ponds occur from sidewalls and bottom surface. Heat losses that occur from the sidewalls are taken negligible when the walls are properly insulated. The heat losses that are considered are losses from the bottom surface which occur due to evaporation, radiation and convection.

To increase absorption of radiation the pond surface can be blackened. This makes possible the complete absorbance of energy that reaches Lower convective zone (Kurt et al., 2006). Conduction of upward heat can be decreased by increasing the non-convective zone thickness.

Different types of insulating materials can be used for side walls and bottom surfaces; the effectiveness depends upon availability, cost and effective insulating behavior. Some of the materials used for insulating purpose are: dry sand, dry cement, mud powder, mica powder, marble dust and lining with appropriate material but lining increases the cost very much though it is required it many locations for performance and environmental purposes.

The insulation can be made more effective by keeping these materials at different interstitial air pressures (though this might be difficult to achieve). The best insulation is achieved at low interstitial air pressure with 0.3-0.5 mm of mercury.

A comparison at normal pressure of heat losses from bottom and sides of the pond for different insulating materials shows marble dust with a thickness of 0.20m is most effective. Dry cement and mica powder give better results than dry sand and mud powder (Beniwal et al., 1985).

The depth of underground water table needs to be considered to minimize heat losses. The underground water table should be at least 5 meters or more below the ground surface. Proper insulation with material like sheets of polystyrene is required if the water table is at a lower depth (Akbarzadeh & Andrews, 2011).

Sussex Solar pond having a diameter of 4.5meters used a 1mm thick rubber liner on the sand directly. Heat losses from sides of the pond were reduced by adding 30cm outer jacket of vermiculite granules between steel walls of the tank and thin hardboard on the outer side.

Bottom losses in this pond were calculated in terms of heat conductivity of ground (Unsworth et al., 1985). One of the important factors in controlling ground heat losses from the perimeter of the pond is the vertical profile of pond. The sloping side walls retain more heat than vertical side walls so the perimeter surface area is not the controlling feature. Results obtained from the 400m^2 solar pond in the Ohio state university show that clay soil surroundings have relatively high ground heat losses (Hull et al., 1984). To avoid heat losses, it is necessary to completely insulate the pond so that the capacity and heat available is not affected from the losses.

Materials and method

3.1 Site selection

The site was selected based on the objective of no building been present in the vicinity of the pond. There is presence of a Membrane Bioreactor Plant (MBR), located about 2- 3 m away from the solar pond. However, due to the solar insulation angle no shading effect of the MBR plant is encountered in the site. The site was selected based on the objective of minimal runoff to the area or else high cost would have been required for building of higher walls. The pond's orientation is considered based on the purpose of the minimizing the shading effect of the freeboard provided to the walls.

3.2 Pond instrumentation

3.2.1 Temperature measurement

For measuring temperature at different heights of the pond, Eight K-type thermocouples were used having the range of 0-1200^{o}C. These thermocouples were placed vertically in the observation glass at the distance of 8cm in between. The measuring tip was placed towards inside of the pond while the wire was placed in the observation and measurement compartment. For reading the temperature values, digital meters (T4WM, Autonics Series, Korea) were used as shown in Figure 3.1. The meter was capable of connecting to five thermocouples at a time. For ten points, two such meters were used. Moreover, three extra thermocouples (TPM-900, SANHNG, China) having accuracy of up to $\pm$ 0.1°C were used to measure the temperature of water entering and exiting the heat exchanger. Their temperature range was -10°C to +110°C.

(a) (b)

Figure 3.1: Temperature indicators (a) Digital meter Autonics Series T4WM with 5 ports & TPM-900 digital temperature indicator (b) Thermocouples fitted in glass

3.2.2. Gravity Measurements

Specific gravity was measured by using three hydrometers having range of

1.000-1.100

1.100-1.200

The accuracy of hydrometers reached up to 0.001.

Figure 3.2: Hydrometers [Ranges (1.000-1.100, 1.100-1.200)]

3.2.3. Sampling points

Six sample points were fitted in sidewall of observation glass at the vertical distance of 10 inches as shown in the figure 3.3. Sample points used ball valve of Stainless Steel Schedule-10 to avoid

Figure 3.3: Fitting of sampling points while construction of walls.

corrosion in the taps. The sampling tubes extended 1.5 feet in the pond for more accurate gravity measurement. Sides of sampling points were sealed with a water sealant SICA BOND HP2.

3.2.4 Diffuser

Diffuser was designed to have two Semicircular disc separated by a constant slit width. The discs were made of metal plates separated by nuts of width 2mm as shown in the Figure 3.3 (a). The hole was punched in the upper disc which was welded to a pipe. Dimensions of the diffuser were

(a) (b)

Figure 3.4 :Diffuser (a) Diffuser design (b) Diffuser in working

calculated. Flow rate required for the density gradient to be established from fixed injection technique was calculated through a Froude Equation. Based on the Flow rate available of up to 40L/min, the slit width was kept at 0.0025 mm as calculated by the Froude equation. The diameter was calculated to be 0.08m. Gradient establishment by diffuser shown in figure 3.3 (b). To adjust the height of the diffuser throughout the NCZ, a particular assembly was constructed. Several pins punched through the pipe to adjust height of the diffuser to different levels.

3.2.5 Heat exchanger

Stainless steel pipe grade 304, Schedule-10S and nominal outer diameter 21.1 mm of 11.6 m length was bent to make an internal heat exchanger. The pipe was prepared as shown in the Figure 3.4(a).

(a) (b)

Figure 3.5: Heat exchanger pipe (a) Bending of pipes for heat exchanger (b) Fitting of Heat exchanger in the walls

3.2.6 Pump

A 1.5 HP pump (PW-600M, Wilo, Korea) was used having flow range up to 70L/min as shown in figure. In order to change or adjust the flow of pump, an especially design Variable Frequency Drive (VFD) (RM5G, RHYMEBUS, Japan) was connected to pump along with the flow meter (PF2A721-03-27M, SMC, USA) range from 3.5 to 30 L/min to measure the flow as shown in figure 3.5(b)(c). Changing the frequency of VFD resulted in changing the frequency of the rotation

(a) (b)

(c)

Figure 3.6: Pump with variable device (a) Centrifugal pump (b) Variable Frequency Drive (c) Flow meter

of the pump. This changed the flow of the pump accordingly and the adjusted flow was measured through the flow meter placed after the pump.

3.3 Pond construction

3.3.1 Pond design and dimensions

The SGSP has the capacity of 300 cubic feet water with the dimensions of 10 by 5 feet with a depth of 6 feet. On one side of the SGSP, a separate compartment is established which is separated by mirror in order to take samples and optically observed the pond's clarity. The thickness of the walls is kept as 10 inches. The Schematic design of the pond is shown in Figure 3.7.

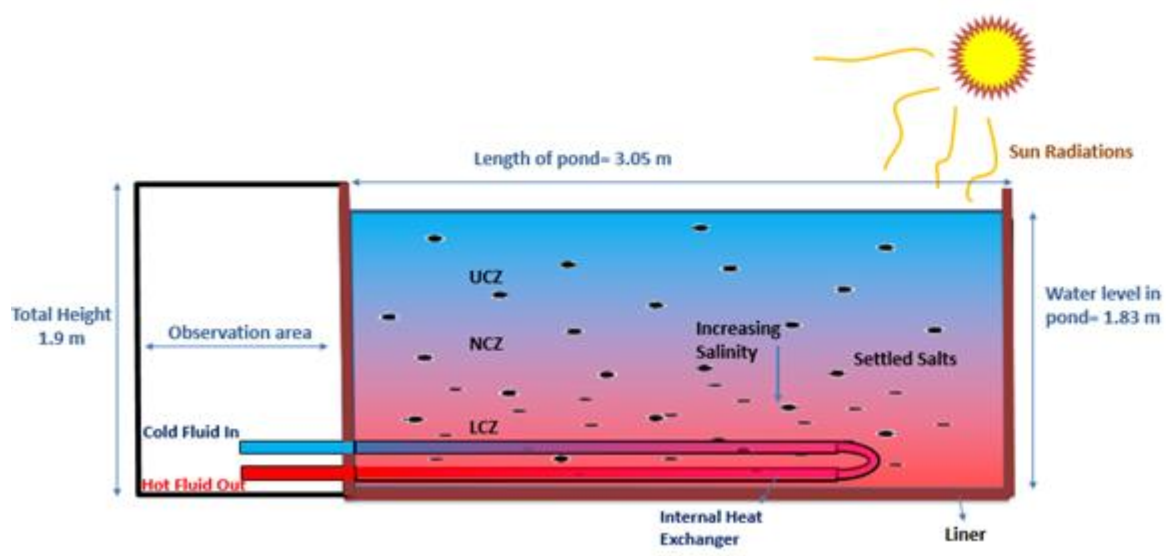


Figure 3.7: Schematic diagram of salinity gradient solar pond

3.3.2 Construction

The foundation of the pond consists of 6" thick P.C.C and 6" thick R.C.C as shown in Figure 3.8 (b). The walls of the pond have been constructed with hollow blocks which are cheaper and locally available as shown in Figure 3.8(c). These blocks were used as walls due to the presence of air pockets which act as a thermal insulator between the pond and the surrounding soil. In order to strengthen the wall in which the glass is attached, bricks have been used. A layer of 1-inch plaster followed by 1-inch layer of chips has been used in order to make the pond water resistant.

.

(a) (b) (c) (d)

Figure 3.8: Pond Construction (a) Excavation (b) Laying of P.C.C and R.C.C
(c) Construction of walls (d) Completed pond

The glass is made from three 12 mm tampered glass sandwiched together and sealed from the sides. In order to ensure prevention of any leakages, a special sealant, Sica HP 2 Bond was lined on both sides of the glass. There were holes punched into the glass in order to insert thermocouples at various heights as shown in Figure 3.8(d). The sampling points were installed at different heights on the brick wall. The phases of construction are shown as in figure 3.8

3.3.3. Liner

The internal walls of SGSP were lined with a High Density Polyethylene (HDPE) line with a thickness of 1mm. It has a black, smooth and stiff surface which allows maximum absorption of the solar radiation in the pond as shown in Figure 3.9. The liner has the capacity of bearing temperature from -100 to 120^{o}C with a melting point of 130^{o}C. The liner has capacity of bearing a pressure of 4550 psi which is suitable to carry the load of the salt water. Furthermore, the liner is used to seal the pond in order to prevent issues of leakage. Due to the straight walls with no slope, the liner could not be held on its own. Hence, it was attached to the walls with the help of Epoxy 2 components comprising of a 1:1 ratio of hardener and a resin. This is a locally available chemical which was helpful in adhering the liner to the cement walls. Great intricacies were

Figure 3.9: Pond lined with thickness of 1 mm High Density Polyethylene Liner

experienced in spreading the liner on a single go due to the already installed pipes of internal and external heat exchanger. Hence, the liner had to be cut down in smaller pieces for proper adherence to the wall. An electric blower was used to attach the pieces of liner with one another, ensuring a leak- proof pond.

3.3.4. Reflector

Two reflectors were fitted along the length sides of the pond, comprising of an aluminum sheet with a thickness of 1mm placed in metal frame. The reflectors were movable as they were hinged to the side of the solar pond as shown in Figure 3.10. They were movable so that the angle of the reflector was changed according to the optimum angle of solar radiation. The mechanism of the reflector is such so that it could be adjusted according to the required angle. Due to the ability of

Figure 3.10: Fitting of moveable Reflectors/covers and a metal frame

having their positions adjusted, they were also used as cover in case of rainy hours and at night for storing the thermal energy.

3.4 Gradient establishment

3.4.1 Salt requirement and preparation

The salt used for establishment was cheaper and locally available since it was not commercial grade. It was composed of NaCl. Although the salt was not refined, it majorly comprised of NaCl. However, heaps of sand and dust was present in the salt while it was being mixed. The amount of salt used was 1310 kg as compared to the calculated amount, 1260.9 kg from which we were able to acquire a specific gravity of 1.8.

Figure 3.11: Manual mixing of salt in a container

The salt was mixed manually in a 500-gallon water tank as shown in Figure 3.11. For further mixing, the salt solution was transferred into the solar pond with the help of a centrifugal pump. This further dissolves smaller suspended particles through centrifugal force of the pump.

3.4.2 Establishment of gradient

Fixed injection method also known as Re-distribution method was used as proposed by Zangrando in 1980. The entire process of gradient establishment consumed 8 hours. SGSP was filled up to a height of 35 inches, which is half of the solar pond. The diffuser was placed on the interface of LCZ and NCZ. It was positioned along the glass side so that its height could be seen from the scale calibrated on the glass. In summer with the increase in height of 4 inches of the water level, the diffuser was displaced upwards by 2 inches as showing in Table 3.1.

Table 3.1: Flow rates for summer gradient establishment for varying injecting velocity based on the constant slit width

Froude number	Slit width (m)	Ps (kg/m^3)	Q (L/min)
18	0.0025	1175	21.09
18	0.0025	1160	20.17
18	0.0025	1140	18.87
18	0.0025	1120	17.47
18	0.0025	1100	15.95
18	0.0025	1080	14.26
18	0.0025	1060	12.35
18	0.0025	1040	10.09
18	0.0025	1020	7.13
18	0.0025	1000	0

Hence as the diffuser level is raised to the top of NCZ, its level becomes equal to the height of water at that instant. After that fresh water was flushed on the surface. In winter with the increase in height of 4 inches of the water level, the diffuser was displaced upwards by 2 inches as showing in Table 3.2.

Table 3.2: Flow rates for winter gradient establishment for varying injecting velocity based on the constant slit width

Froude number	**Slit width (m)**	**Ps (kg/m^3)**	**Q (L/min)**
18	0.0025	1190	21.98
18	0.0025	1170	20.79
18	0.0025	1150	19.53
18	0.0025	1130	18.18
18	0.0025	1110	16.73
18	0.0025	1090	15.13
18	0.0025	1070	13.34
18	0.0025	1050	11.28
18	0.0025	1025	7.97
18	0.0025	1000	0

Density for summer was 1750kg/m^3 Gradient establishment for winter was establish again due to monsoon rain fall which disturbed the previously established gradient and it was maintained at 1190kg/m^3. Concentration was increased in winter for further observation. The entire process of gradient establishment consumed 8 hours in summer and 10 hours in winter. In summer, height of LCZ, NCZ and UCZ was maintained at 0.508m, 0.762m and 0.56m. While for winter, height of LCZ, NCZ and UCZ was maintained at 0.635m, 0.863m and 0.33m.

In order to enhance horizontal mixing along the interface of LCZ and NCZ, keeping in view that the LCZ layer is not disturbed, the flow rates were changed, as the density of the surrounding liquid decreased with the injection of fresh water. This was achieved by keeping Froude number constant at 18 as stated by Zangrando.

3.5 Pond maintenance and controlling

In order to gain better efficiency, it is very important to keep the effective and regular maintenance of salinity gradient solar pond. This purpose can be achieved by having view on the clarity, pH, temperature and salinity of the pond. The internal strength of the pond is determined by the salinity of the solar pond. This can be showed by the Stability Marginal Number (SMN) which is to be kept above 1. It was considered to lose its stability if the SMN reached below 2.5. This was tested once in a month to confirm that the salinity gradient was maintained. The definite percentage salinity with respect to depth was measured by using the following formula as shown in Eq. (1).

$$\text{Salinity \%} = \frac{\text{Mass of salt after evaporation}}{\text{Mass of salt solution}} \qquad (1)$$

In case the SMN reaches below 2.5, salt water will be inserted into the specific height. 32% concentrated HCl was used to sprinkle on the surface of the pond if we have to maintain the pH below 4.5. Since HCl has high specific gravity it descends the suspended particles in the bottom to maintain clarity as otherwise it can prevent sunlight from penetrating LCZ. Decrease in temperature in the bottom layer is resulted if the sunlight is not reached to the bottom.

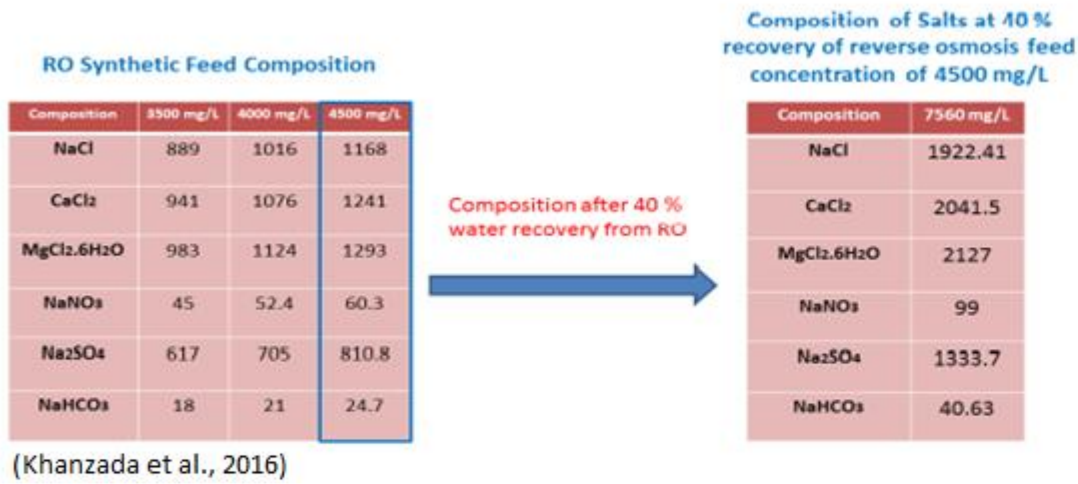
3.6. Lab-scale direct contact membrane distillation setup

3.6.1. Membrane

A flat sheet microporous hydrophobic membrane (Porous Membrane Technology, Ningbo, China) was used in this experimentation. The main features of membrane are polypropylene (PP) supporting layer laminated with 12µm thick poly-tetra-fluoro-ethylene (PTFE) active layer having pore size of 0.2µm and porosity of 70 % respectively.

3.6.2 Synthetic feed characterization

Synthetic brackish water having TDS 3500, 4000 and 4500 mg of TDS/L was used as feed for RO by Khanzada et al., 2016. Based on that, using 4500mg/L at 40 % recovery as an optimum value, synthetic brine of 7560mg/L concentration was prepared. Distilled water was used as permeate and to prepare the synthetic brine solutions as feed. Analytical grade slats were used for synthetic brine solutions preparation with concentrations of sodium chloride (1922.41mg/L), calcium chloride (2041.5mg/L), magnesium chloride hexahydrate (2127mg/L), sodium nitrate (99mg/L), sodium sulfate (1333.7mg/L), sodium bicarbonate (40.63mg/L) as shown in figure 3.12.



RO Synthetic Feed Composition

Composition	3500 mg/L	4000 mg/L	4500 mg/L
NaCl	889	1016	1168
$CaCl_2$	941	1076	1241
$MgCl_2.6H_2O$	983	1124	1293
$NaNO_3$	45	52.4	60.3
Na_2SO_4	617	705	810.8
$NaHCO_3$	18	21	24.7

(Khanzada et al., 2016)

Composition after 40 % water recovery from RO

Composition of Salts at 40 % recovery of reverse osmosis feed concentration of 4500 mg/L

Composition	7560 mg/L
NaCl	1922.41
$CaCl_2$	2041.5
$MgCl_2.6H_2O$	2127
$NaNO_3$	99
Na_2SO_4	1333.7
$NaHCO_3$	40.63

Figure 3.12: Synthetic feed composition used in DCMD process

3.6.3 Experimental set up and procedure

A closed loop laboratory scale direct contact membrane distillation setup used in this study is shown in Figure 3.13.

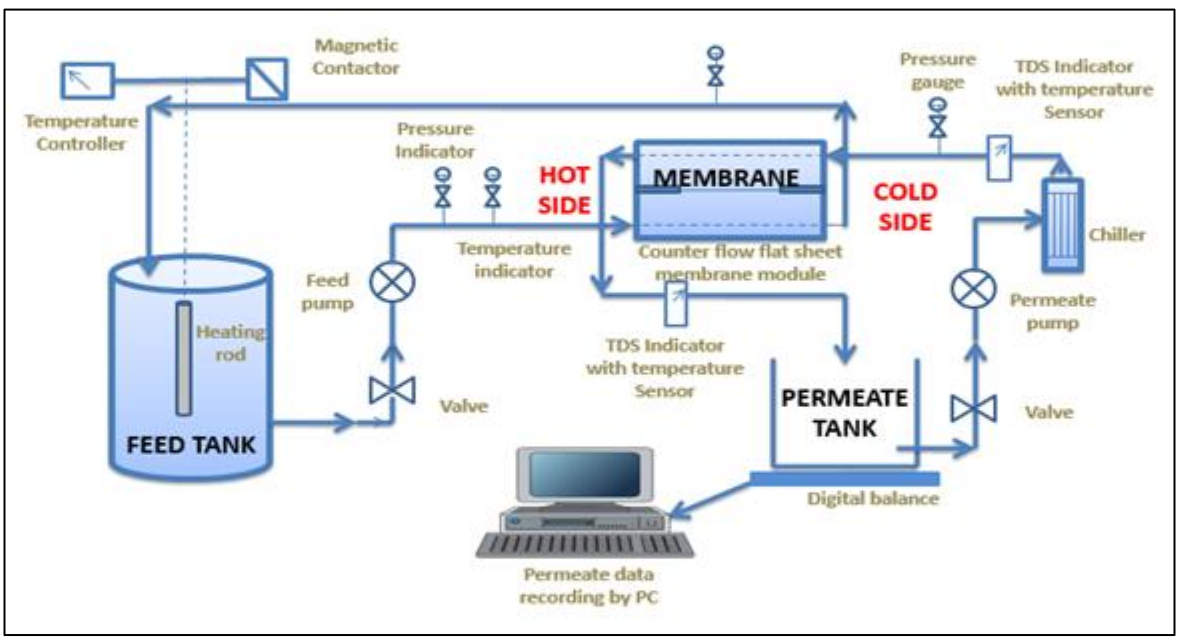


Figure 3.13: Schematic diagram of lab scale direct contact membrane distillation

To overcome the heat losses, the flat sheet membrane module was used which is made of acrylic. Dimensions of module is 14cm length and 6cm width. The effective module dimensions in which membrane operated is 9.5cm long, 4cm wide and 0.1cm deep. The membrane module consists of two sections, the feed side and the permeate side. The module was adjusted horizontally so that feed brine solution(hot) flowed through bottom side of cell and permeate(cold) streamed through upper side of cell. A flat sheet hydrophobic microporous membrane is used to isolate the feed and permeate with membrane effective area of 0.0038m^2. In each experiment, the active layer of membrane encountered the hot stream when the membrane was placed in module. A high quality plastic was used to contain the feed and permeate 10L reservoir and flow at 150 ml/min through membrane module by a peristaltic pump (Model 7524-45, Master flex, USA). A chiller was used to maintain permeate temperature at 20^0C. Two TDS meters (KOMATSU) ranges from (0-5000 mg/L) with temperature sensor were used for permeate in and out. To monitor the feed inlet and outlet temperature, two temperature indicators (TPM-900, SANHNG, China) were used. Stainless steel heating rod, magnetic contactor (GCM-22, LS, Korea) and temperature controller (XMTG-131 China) were used for heating and temperature control in feed reservoir. TDS meter checked the feed TDS after one hour (Sension5, HACH, USA).

The membrane collected the permeate vapors and returned them back into reservoir where they were measured by digital balance (UX 6200H, SHIMADZU, Japan). Digital balance set for every 5 minute was connected with desktop computer.

Figure 3.13: Instruments used in DCMD process

Chapter 4

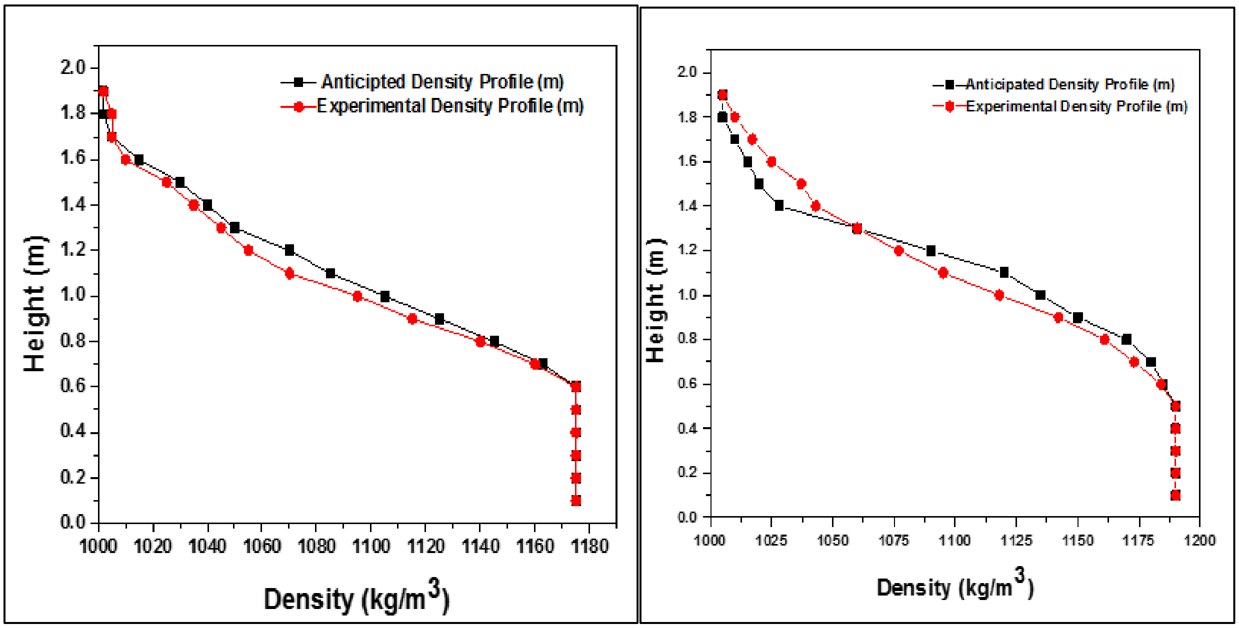
Results and Discussion

4.1. Phase 1: Salinity gradient solar pond

4.1.1. Gradient establishment and density measurement

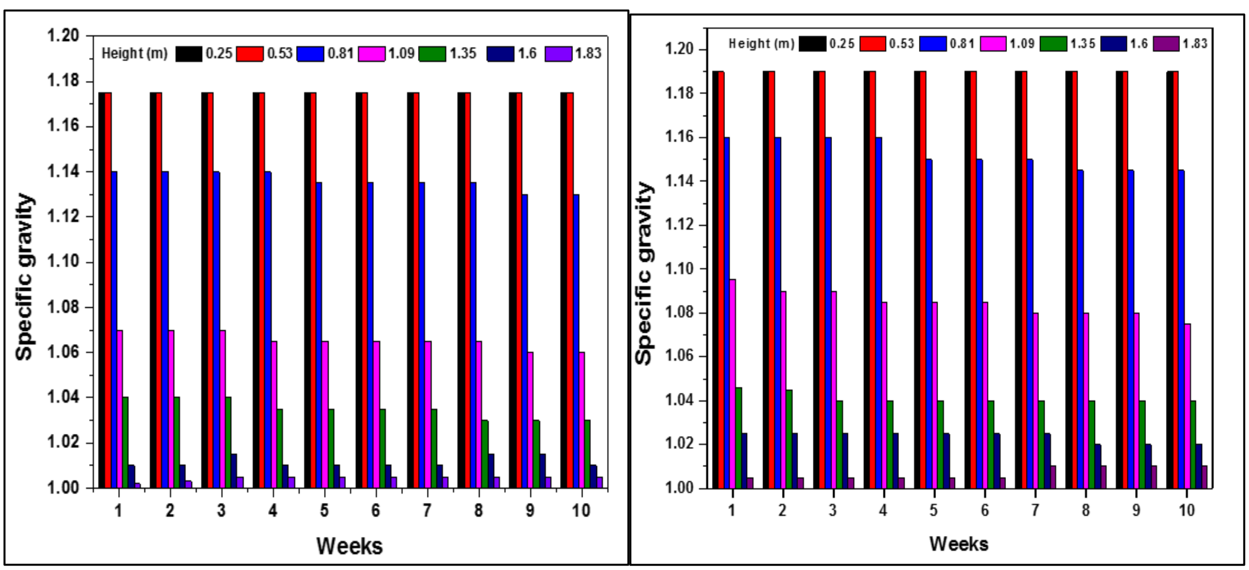
Layers of different densities to establish is very important factor to gain radiations in bottom layer. For both summer and winter seasons, separate gradient layer was established for each process. Density for gradients establishment were different for both processes. Summer process density was kept at 1750 kg/m^3. For winter season, gradient establishment was established again due to monsoon rain fall which distorted the previously established gradient. Its density was maintained at 1190 kg/m^3. Increase in concentration was maintained in winter for further observation and optimization of the result. In summer, the entire process of gradient establishment consumed 8 hours and it took 10 hours in winter. In summer, height of LCZ, NCZ and UCZ was maintained at 0.508, 0.762, and 0.56 m, respectively. While for winter, height of LCZ, NCZ and UCZ was maintained at 0.635, 0.863, and 0.33 m, respectively. As compared to summer, UCZ was kept less in winter as UCZ height should be less and in between 15-25 % of total height of the solar pond (John & Walton, 2001).

SGSP was filled up to a height of 0.89 m in summer season while its height was 1.06 m in winter season. The diffuser was placed at the interface of LCZ and NCZ as suggested by Leblanc et al. for salinity gradient establishment (Leblanc et al., 2011). Diffuser was placed beside the glass side so that its height could be seen from the scale rectified on the glass. Due to Froude number 18 putting in Froude equation, only horizontal mixing was observed during the whole process. Zangrando (1980) and Leblanc et al. (2011) found in their studies that by maintaining Froude number at 18, no vertical mixing was occurred. The diffuser level was raised to the top of NCZ. The diffuser level and the height of water became equal at the top of NCZ. After that, UCZ layer was established by injecting fresh water at the ultimate height of the pond. The same slope was obtained by comparing the experimental density profile and theoretical density profile. However, a little variation from the experimental profile was observed due to a small difference in densities of NCZ and LCZ as shown in Figure 4.1. In this study, density profile slope after gradient establishment complemented the other studies that are using gradient establishment techniques, either on a large scale or small scale setup having different salt concentrations (John & Walton, 2001; Leblanc et al., 2011; Busquets et al., 2012). Weekly density measurements were commenced for both summer and winter as shown in Figure 4.2. No such variations in LCZ due to high salt concentration was observed but there were some variations showed in UCZ and it was due to some evaporation loss and upper level of NCZ. However, these variations did not affect the gradient layer. Long term operation of solar pond should be taken under careful consideration as changes may occur both in LCZ and UCZ with the passage of time (Jaefarzadeh & Akbarzadeh, 2012).



(a) **(b)**

Figure 4.1. (a) Density profile comparisons for summer (b) Density profile comparisons for winter

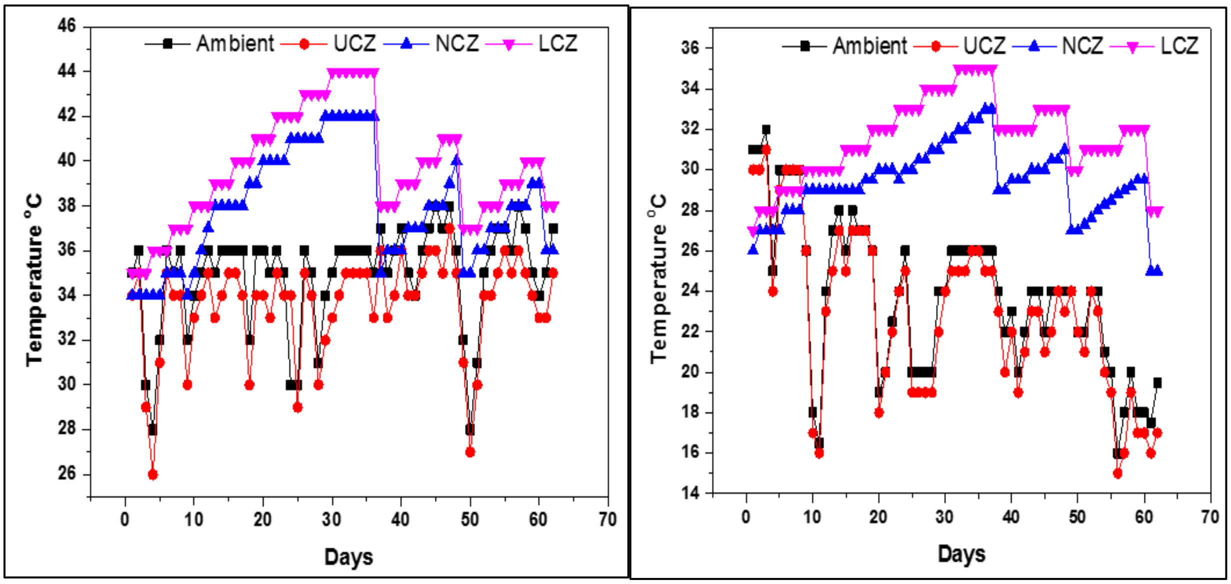


(a) (b)

Figure4.2(a) Weekly specific gravity analysis for summer (b) Weekly specific gravity analysis for winter

4.1.2. Daily average temperatures in LCZ and UCZ during summer and winter

During summer and winter seasons, the temperature differences and heat extraction from lower convective zone (LCZ) in the solar pond were examined. The temperature of LCZ and non-convective zone (NCZ) increased with the increase in time whereas a little variation is shown in upper convective zone (UCZ), depending upon the weather. A maximum temperature of 44^{o}C was observed in LCZ with a ∆T (LCZ-UCZ) of 14^{o}C for summer as shown in Figure 4.3 (a). A maximum temperature 35^{o}C was observed in LCZ with a ∆T (LCZ-UCZ) of 10^{o}C for winter as shown in Figure 4.3 (b). However, other studies considering the effect of ambient temperature in LCZ with time found that the temperature gain was between 38-50^{o}Cthat well matched the temperature attained in LCZ in this study (Jaefarzadeh & Akbarzadeh, 2012; Nakoa et al., 2015). Also it was investigated that the temperature variation in LCZ and UCZ and reported that daily average temperature increase in LCZ was 0.7^{o}C (Leblanc et al., 2011). In this study, it was observed that the average temperature of 0.4-0.8^{o}C increased in LCZ in summer and 0.3-0.5^{o}C increased in winter on daily basis.



(a) **(b)**

Figure 4.3 (a) Daily temperatures for summer (b) Daily temperatures for winter

4.1.3. Heat extraction from LCZ in summer

For three different flow rates of 3.5, 5.5 and 7.5 L/min, the process of heat extraction was carried out. Figure 4.4 (a) shows that for 3.5 L/min, drop of 6°C in LCZ was observed and maximum heat extraction of 7451 kJ was achieved. This was due to the increased contact time that allowed greater heat transfer. Figure 4.4 (b) shows that for 5.5 L/min, drop of 4°C in LCZ was observed and maximum heat extraction of 6593 kJ was achieved. Figure 4.4 (c) shows that for 7.5 L/min, drop of 2°C in LCZ was observed and maximum heat extraction of 5651 kJ was achieved. Also, the temperature of LCZ appears to be constant after increase in time. So, there is an inverse ratio between the velocity of water to the contact time of water through heat exchanger as the velocity of water increases, contact time of water through heat exchanger pipe decreased. Figure 4.4 (d) shows the comparison of all three flow rates in summer.

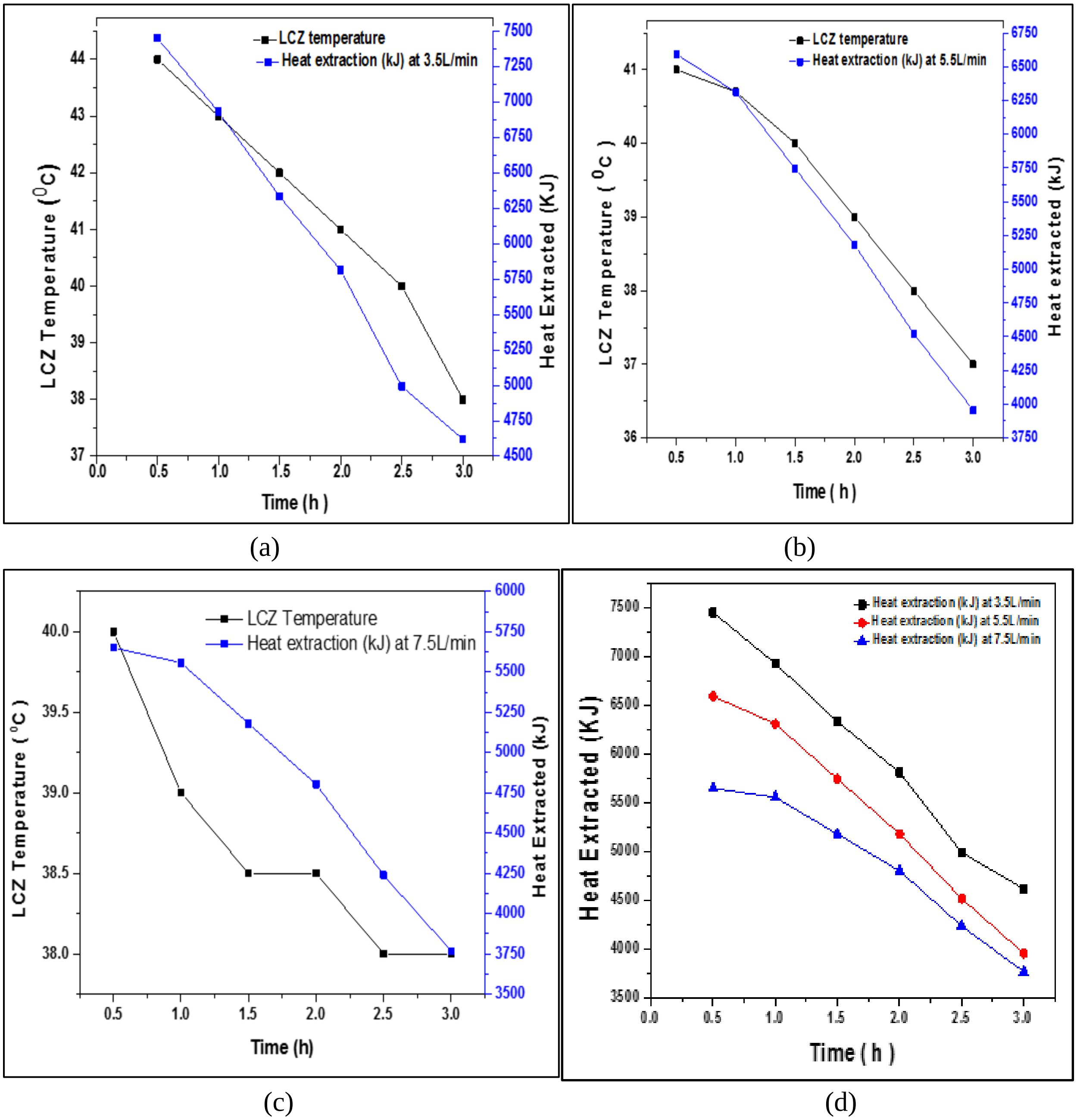


Figure 4.4. (a) Heat extraction at 3.5 L/min (b) Heat extraction at 5.5 L/min (c) Heat extraction at 7.5 L/min (d) Comparison of heat extraction in summer

4.1.4. Heat extraction in winter

Heat extraction was carried out for three different flow rates 7.5, 9.5 and 11.5 L/min. These three flow rates were quite different from those flow rates that were investigated previously for summer in order to optimize the flow rate of heat extraction from LCZ. Figure 4.5 (a) shows that for 7.5 L/min, drop of 2.5^{o}C in LCZ was observed and maximum heat extraction of 5180 kJ was achieved. Figure 4.5 (b) shows that for 9.5 L/min, drop of 2^{o}C in LCZ was observed and maximum heat extraction of 3770 kJ was achieved. Figure 4.5 (c) shows that for 11.5 L/min, drop of 1.5^{o}C in LCZ was observed and maximum heat extraction of 2930 kJ was achieved. Figure 4.5 (d) shows the comparison of all three flow rates in winter. In order to retain the temperature of LCZ, the consequent changes were occurred when the time of the contact hour was fixed to 3 hours. This study shows that the optimum flow rate was found to be 7.5 L/min based upon maximum heat extraction of 5180 kJ and minimum temperature drop of 2^{o}C. Other relevant studies also investigated different flow rates for heat extraction between 3 and 6 L/min (Leblanc et al., 2011; Suarez et al., 2015). In another study theoretical investigation showed the heat extraction using heat exchanger in solar pond for 3 hours. They found that only 1^{o}C loss in LCZ temperature was observed (Tundee et al., 2010). Another experimental study was also conducted to observe heat extraction using internal heat exchanger with 4 m^2 pond area and depth of 1.1 m and found that LCZ temperature drop for first four days was decline from 59 to400^{o}C by using pump discharge of 16.82 cm^3/sec. After increase in LCZ temperature, temperature drop in LCZ for next 2-day decrease from 47 to 38^{o}C and then become stable for three days (Jaefarzadeh, 2006).

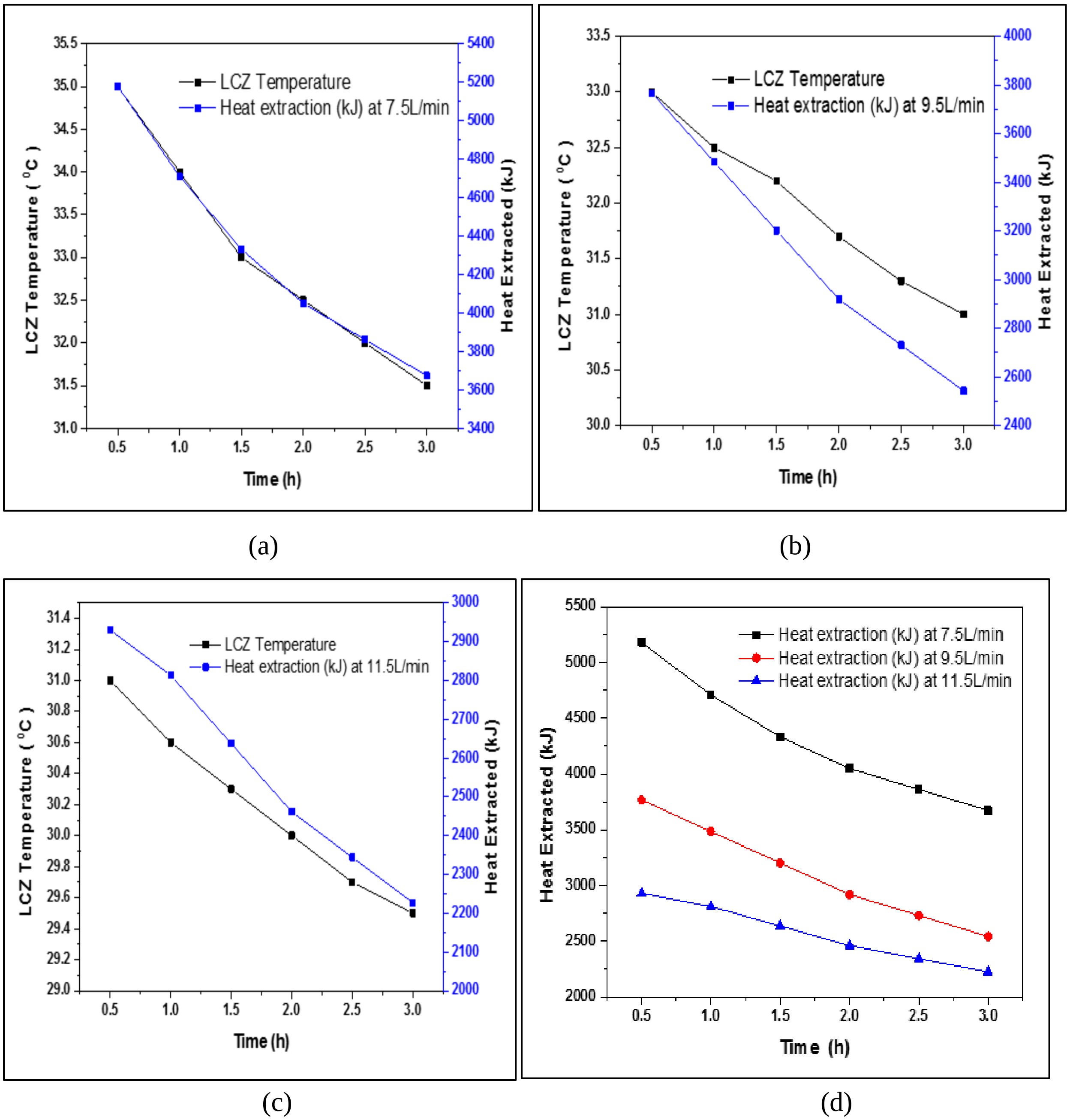
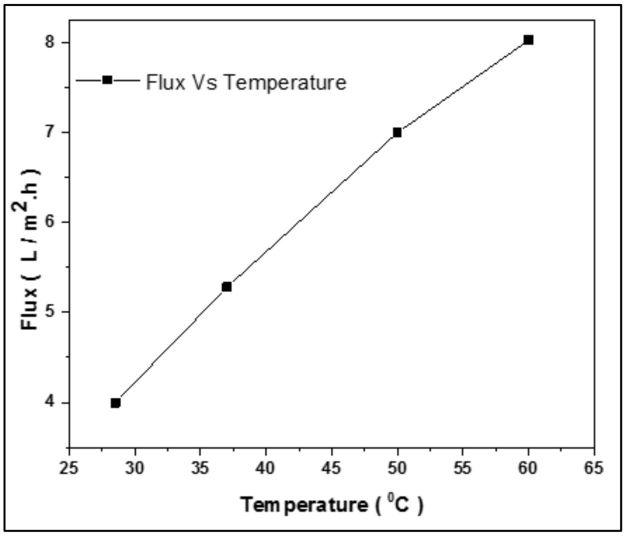
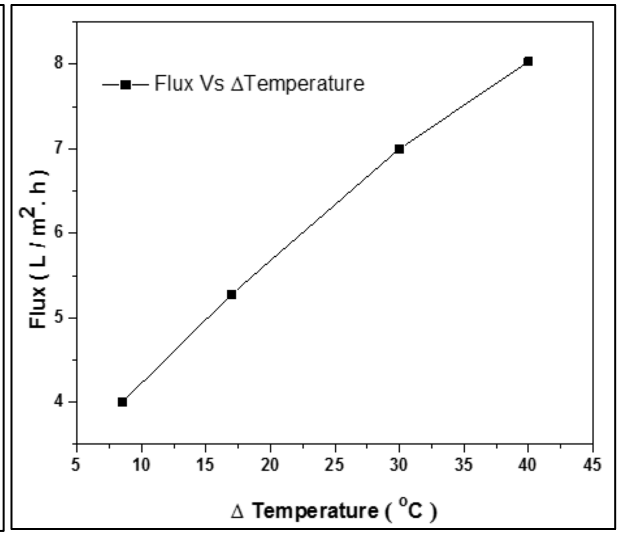


Figure 4.5. (a) Heat extraction at 7.5 L/min (b) Heat extraction at 9.5 L/min (c) Heat extraction at 11.5 L/min (d) Comparison of heat extraction in winter

4.2. Phase 2: Direct contact membrane distillation (DCMD) process

To determine permeate flux, DCMD experiment was carried out at four different feed water temperatures. Four different temperatures (28.5, 37, 50, 60^{o}C) at feed side were maintained in this phase to observe permeate flux and TDS concentration. Constant temperature of 20^{o}C was maintained at permeate side and 24-hour operation time was maintained under each feed side temperature condition. Figure 4.6 (a) shows the behavior between fluxes versus time at different temperatures. It shows that as temperature of feed increased, flux also increased linearly. At the higher feed water temperature, the permeate flux was also higher. At temperature of 60^{o}C, the temperature influence was more significant on permeation flux as compared to 28.5^{o}C depicting that vapor pressure and temperature has an exponential relation. Same trend was shown in Figure 4.6 (b) between flux vs. ΔT (8.5, 17, 30, and 40^{o}C). It shows the effect of change in temperature between feed and permeate water on the performance of DCMD. With increase in temperature and vapor pressure difference across the membrane, increased the conductive heat flux and driving force across the membrane surface. It was investigated that the DCMD performance at different temperatures coupled with solar pond. They maintained the permeate temperature at 20^{o}C and feed temperatures varied between 29 and 45^{o}C. They reported that at higher feed temperature, permeate flux was higher (Nakoa et al., 2015). It was also investigated that the DCMD coupled with solar pond and observed steady state condition in first 2.5 hour at feed temperature of about 36^{o}C. 3.3 L water was produce during the first 34 hours of operation (Suarez et al., 2015).





(a) (b)

Figure 4.6(a) Flux (L/m^2.h) at (28.5, 37, 50 and 60) ^{0}C (b) Flux (L/m^2.h) at temperature difference (8.5, 17, 30 and 40) ^{0}C

4.2.1. Effect of temperature on permeate flux propensity

Permeate flux and permeate conductivity behaviors with respect to time by using PTEF membrane are discussed in this section. Figure 4.7 shows that flux increased as temperature difference between feed and permeate increased. The permeate flux as a function of time declined significantly during the first 8 hours for 60^{o}C, 10 hours for 50°C and 12.5 hour for 37°C. Membrane washing at these times can be applied for sustainable membrane performance.

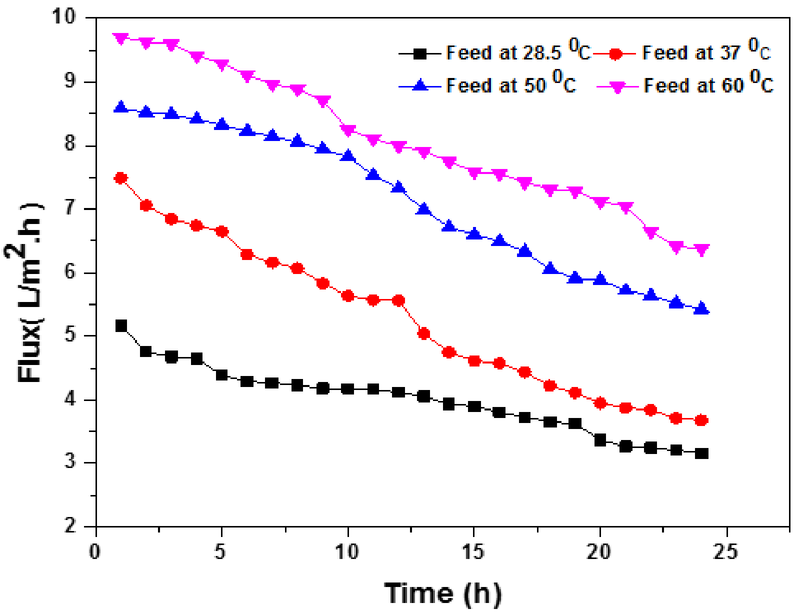


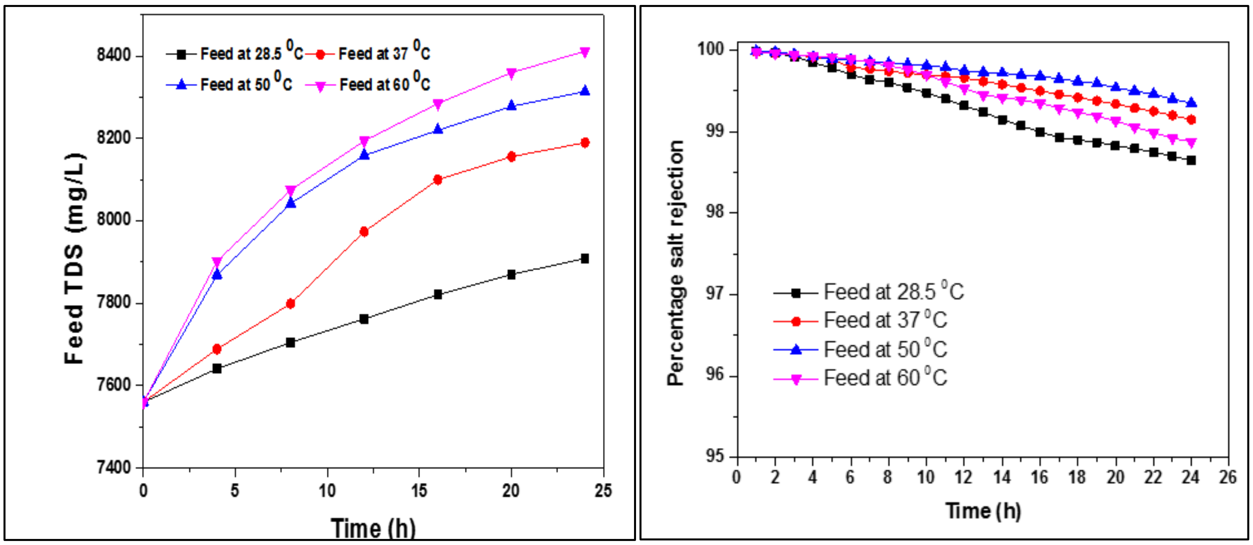
Figure 4.7 Flux (L/m^2.h) at temperature (28.5, 37 50 and 60)^{0}C for 24-hour duration

28.5°C is also feasible for DCMD process as flux was stable with passage of time. Figure 4.8(a) shows that feed TDS increasing with respect to time as temperature of feed increased. Figure 4.8 (b) shows that after 24 hours, the percentage of salt rejection is acceptable for all temperatures even at 28.5°C which is about 98.7 %. Percentage of salt rejection was calculated by using Eq. (2).

$$\text{Percentage of salt rejection} = \frac{C_f - C_p}{C_f \times 100} \tag{2}$$

Where C_f is the concentration in feed and C_p is the concentration in permeate. It was studied that the performance of DCMD for sodium chloride and synthetic feed salt solution at 40°C. They found that salt rejection was greater than 99.9% and the salt concentration in the feed had only minor effect on the water flux (Cath et al., 2004).

However, even after 24 hour of continuous operation, the TDS concentration was well below the permissible limit of 1000 mg/L as per WHO Guidelines for Drinking Water Quality (WHO, 2011). These results showed that even low SGSP extracted temperature of 28.5°C was also feasible for MD process as flux was stable with time and TDS concentration increased with reduction of feed side volume.



(a) (b)

Figure 4.8 (a) Feed TDS vs. Time (b) Percentage salt rejection vs. Time

Conclusions and Recommendations

5.1 Conclusions

0.4-0.8ºC increase in LCZ was observed in summer and 0.3-0.5°C in winter on daily basis. 0.2-0.3°C heat loss in LCZ for summer and 0.3-0.5ºC heat loss in winter during absence of solar radiation (Rain and clouds) was observed. Maximum of 37°C of heat extracted temperature in summer and 28.5°C in winter was achieved. Optimized flow rate of 7.5 L/min should be used to least drop in LCZ temperature.

Lowering feed temperature (28.5°C and 37°C) reduces the thermal efficiency, reduces the flux but increases the operation duration required for a specific initial feed volume. Gradual decrease in MD performance with respect to water flux and increase in salt concentration in permeate was observed. The permeate flux increased with increasing temperature difference through membrane side. Permeate flux as a function of time had sensitive decline during the first 8 hours for 60°C, 10 hours for 50°C and 12.5 hour for 37 °C. 28.5°C is also feasible for DCMD process as flux decrease not significant with passage of time.

5.2. Recommendation

1. Membrane in series can be used for further concentrate the solution if temperature is above 50^{o}C.
2. For zero discharge, vacuum evaporator can be used for hot feed after passing through membrane and energy for vacuum pump can attain from solar ponds.

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