An-Najah National University
Faculty of Graduate Studies

Treatment of Surface Water by Autonomous Solar-Powered Membrane Cells

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This thesis was defended successfully on 13/4/2010, and approved by

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3. Dr. Imad Ibrik (Internal Examiner)	…………………

DEDICATION

To my father Spirit ……..

To my mother, who has raised me to be I am today...…….

To my brothers and sister who have support me all the way since the beginning of my studies………..

To my future wife……………

To the memory of my dearest friends ………………..

TO ALL I LOVE

I dedicate this work

ACKNOWLEDGMENT

I would like to take the opportunity to thank all people who spent their time and shared their knowledge for helping me to complete my thesis with the best possible result.

To begin with, my special thanks to Dr. Abdelrahim Abusafa, Professor of chemical engineering, my supervisor, who meticulously and with great care and attention to detail advised and motivated me to produce the final product.

My thanks also go to the staff of Clean Energy and Conservation Strategy Engineering Program in An-Najah National University, especially Dr. Imad Ibrik, the director of Energy Research Center for his help and advice.

Lastly, but not the least, I would like to thank my mother, for their never-ending love and support in all my efforts, my brothers and my sister for their love and support throughout the years, and my friends for there useful help. To all of you, thank you so much for all support you have given me during this research.

الإقـــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

TREATMENT OF SURFACE WATER BY AUTONOMOUS SOLAR-POWERED MEMBRANE CELLS

معالجة المياه السطحية باستخدام الخلايا الغشائية التي تعمل بالطاقة الشمسية

اقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وان هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل أية درجة علمية أو بحث علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's name: **اسم الطالب:**

Signature: **التوقيع:**

Date: **التاريخ:**

Abbreviations

AM	Air Mass
AC	Alternating Current
A.D	Anno Domini
A_{fixed}	Annual Fixed Charges
ACF	Average Concentration Factor
CC	Capital Cost
cfu	Colony Forming Unit
I_{mpp}	Current Maximum Power Point
DC	Direct Current
ED	Electro Dialysis
FC	Fecal Coliform
kWh	Kilowatt Hour
KCL	Kirchoff's Current Law
MF	Microfiltration
MENA	Middle East and North Africa Countries
MCM	Million Cubic Meter
MEB	Multieffect Boiling
MSF	Multistage Flash
NF	Nanofiltration
NTU	Nephelometric Turbidity Units
V_{oc}	Open Circuit Voltage
O&M	Operating and Maintenance
PPM	Parts Per Million
PSH	Peak Sun Hours
PV	Photovoltaic
RO	Reverse Osmosis
I_{sc}	Short Circuit Current
Si	Silicon
STC	Standard Test Conditions
TFC	Thin film Composite
TDS	Total Dissolved Solids
UF	Ultrafiltation
UN	United Nation
VC	Vapor Compression
V_{mppp}	Voltage Maximum Power Point
W_P	Watt Peak
WHO	World Health Organization

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Abstract

In addition to shortage of fresh water resources, Palestine is suffering from shortages in recoverable commercial energy sources such as crude oil and natural gas. The limited energy sources in Palestine makes renewable energy options such as solar power very attractive, especially for remote areas. This will be extremely important for small-scale applications. Due to prevailing tough conditions, such as low water quality and shortage in supplies, there is a large demand for small water treatment units to obtain drinkable water for life support. In this thesis, an experimental study was conducted to investigate the potential to develop a small water treatment unit using photovoltaic powered reverse osmosis system in Palestine. A testing rig was built, where a reverse osmosis (RO) water treatment system driven by photovoltaic power is used. The RO unit consists of a five-micron sediment filter that is made of polypropylene, two active carbon filters with 1–2 micrometer hole diameter, and one polyamide TFC membrane. The system is mechanically powered, One PV arrays panel ($55W_p$) which tilted a 45 to the south directly coupling to a DC motor (Diaphragm), that can give pressure up to 1.2 bar and average flow rate 34.68 L/d by using water from Shraish spring located in Nablus city in West Bank .

The system was operated at variable flow, enabling it to make efficient use of the naturally varying solar resource, with no need of batteries. Different operating conditions of solar radiation, pump pressure, feed water temperature, total dissolved solid, trans-membrane pressure, and flow rates were studied. In order to study the affect on permeate flow rate and water quality.

It was found that increasing the solar radiation, pump pressure, and feed water temperature has enhanced the permeate flux. Increasing the TDS has reduced the permeate flux, and the water quality was within the international standard to be safe drinking water, on the other hand, A pronounced effect on the permeate water quality occurred when the recovery increased, the fecal was observed for the first time when the recovery changed .

Based on the calculations, the estimated cost of water produced by the system is \$17/m^3.The Price of water produced from a solar-powered system for water treatment can not be economically viable, only in remote areas and far from conventional energy sources or during catastrophes where drinkable water is not available.

CHAPTER ONE

INTRODUCTION

Chapter One

Introduction

1.1 Scope

Water resources are essential for satisfying human needs, protecting health, and ensuring food production, energy and the restoration of ecosystems, as well as for social and economic development and for sustainable development [1]. However, according to UN World Water Development Report in 2003, it has been estimated that two billion people are affected by water shortages in over forty countries, and 1.1 billion do not have sufficient drinking water [2]. There is a great and urgent need to supply environmentally sound technology for the provision of drinking water.

This chapter describes the water deficit and scarcity in many areas of the world, such as the Middle East and North Africa countries (MENA) and the need for water treatment, which provides the motivation for this research.

1.2 Water Treatment Systems and Photovoltaic Power

A water treatment system needs a source of power to operate. In general, AC powered system is economic and takes minimum maintenance when AC power is available from the nearby power grid. However, in many rural areas, water sources are spread over many miles of land and power lines are scarce. Installation of a new transmission line and a transformer to the location is often prohibitively expensive.

Today, many stand-alone type water treatment systems use diesel engines. However, they have some major disadvantages, such as: they require frequent site visits for refueling and maintenance, and furthermore diesel fuel is often expensive and not readily available in rural areas of many developing countries.

The consumption of fossil fuels also has an environmental impact, in particular the release of carbon dioxide (CO_2) into the atmosphere. CO_2 emissions can be greatly reduced through the application of renewable energy technologies, which are already cost competitive with fossil fuels in many situations. Good examples include large-scale grid-connected wind turbines, solar water heating, and off-grid stand-alone PV systems [3]. The use of renewable energy for water treatment systems is, therefore, a very attractive proposition.

1.3 Energy Storage Alternatives

Needless to say, photovoltaic are able to produce electricity only when the sunlight is available, therefore stand-alone systems obviously need some sort of backup energy storage which makes them available through the night or bad weather conditions.

Among many possible storage technologies, the lead-acid battery continues to be the workhorse of many PV systems because it is relatively inexpensive and widely available. In addition to energy storage, the battery also has ability to provide surges of current that are much higher than the instantaneous current available from the array, as well as the inherent and automatic property controlling the output voltage of the array so that loads receive voltages within their own range of acceptability [4].

The type of lead-acid battery suitable for PV systems is a deep-cycle battery [5], which is different from one used for automobiles, and it is more expensive and not widely available.

Battery lifetime in PV systems is typically three to eight years, but this reduces to typically two to six years in hot climate since high ambient temperature dramatically increases the rate of internal corrosion. Batteries also require regular maintenance and will degrade very rapidly if the electrolyte is not topped up and the charge is not maintained. They reduce the efficiency of the overall system due to power loss during charge and discharge. Typical battery efficiency is around 85% but could go below 75% in hot climate [3]. From all those reasons, experienced PV system designers avoid batteries whenever possible.

1.4 Water Resources in Palestine – Availability and Consumption

The Israelis and the Palestinians share two interrelated water systems:

1.4.1Groundwater

The Mountain Aquifer traverses the border between the West Bank and Israel, while the surface system - the Jordan Basin - also belongs to Jordan, Syria and Lebanon. The Mountain Aquifer extends for over 130 km, from Mount Carmel in the north to the Negev in the south, and is 35 km wide, from the Jordan Valley in the east to the Mediterranean Sea in the west [6].

It is typically divided into three sub-aquifers. The primary one, due to the high quality of its water, is the Western Aquifer. Most of its recharge area lies in the West Bank, while the entire storage area lies in Israel and 95% of its water is used by Israel.

The second one, the Northern Aquifer, has both its recharge and storage areas essentially located within the West Bank. However, Israel extracts about 70% of the water [6].

Finally, the Eastern Aquifer, which is entirely within the West Bank, has 37% of its water consumed by Israel - mostly by settlers [6].

1.4.2 Springs and Wells

The geographical distribution of springs indicates that 90% of springs are located in north and middle of Palestine. In addition, plenty of rich springs of fresh water are found in the north, lower numbers of weak springs are found in the middle, and rare springs with saline water are found in the south.

The number of measurable springs in the West Bank is 146 and the number of non measurable springs, hardly reached or low discharge is 163.

The average annual flow is around 100 MCM. The amount of fresh water is 55 MCM, used mainly for irrigation. The rest (45MCM) is brackish water [7].

There are 561 wells; 519 Palestinian wells and 42 wells under Israeli control. Out of Palestinian wells, there are 18 new wells and 148 wells out of order. Out of the working wells, 308 wells are used for irrigation (55.4%) and the rest (44.6 %) are used for domestic purposes [10].

Regarding the quality of water, in general, the concentration of chloride ions in water for all wells is acceptable according to the specification proposed by WHO, which should be less than 250 mg/l, while only 70% of wells producing water with acceptable concentration of Nitrate (less than 50 mg/l) according to the specification proposed by WHO [10].

1.5 Water and Energy Crisis in Palestine

Palestine is dry lands; it does not contain a lot of water sources which is not enough with ever increasing population over the years as shown in figure 1.1 and with the presence of the Israeli occupation and drained of water and energy resources over the years of occupation, and as is known the Palestinians do not have control the sources of water, in particular springs, which is considered a key determinant of economic and social development, as it is not available for this country.

The geological factor plays a significant role in natural water pollution. The domestic and industrial wastewater and the use of fertilizers and pesticides in agricultural activities could cause the pollution of water. In regard to the water quality issue, the Palestinians are facing two major problems: the high salinity and the high concentration rate of nitrate [7].

- The major causes for salinization are over-pumping of the wells, seawater intrusion and geological factors.
- The main sources of nitrate pollution are fertilizers, wastewater and cesspits. The high nitrate concentration in drinking water affects infants and causes Blue Baby Syndrome.

Many of the surface water in Palestine suffer from Fecal, K+ and not suitable for drinking.

Palestine suffers from continuous water shortage, whether for drinking or irrigation purposes.

Various alternatives are being considered to alleviate this problem including water treatment.

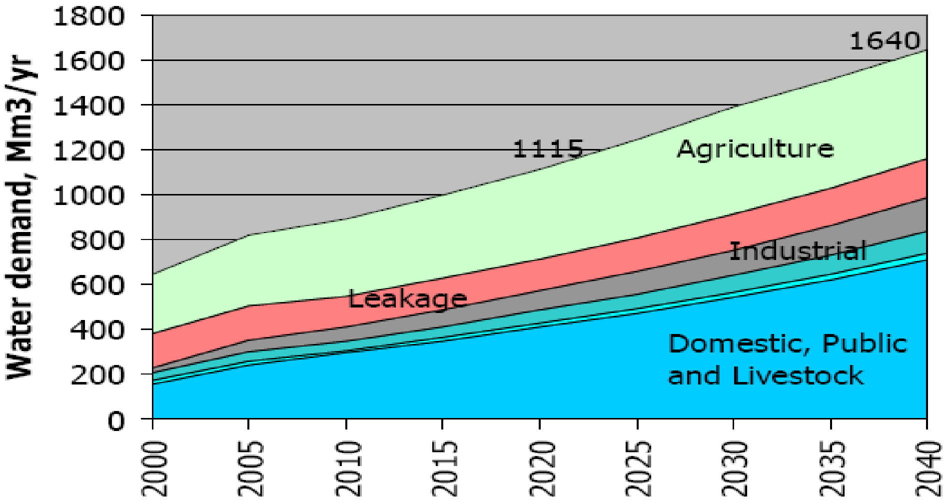


Figure (1.1): Palestine water needs

The use of solar energy for water treatment has been the subject of this research and many experiments on this issue have been conducted.

Because Palestine possesses a high potential for photovoltaic (PV) applications due to the high average annual daily solar radiation, which exceeds 5 kWh/m².day and the Israeli occupations, which has stifled development in all fields related to infrastructure, is another factor that makes PV applications viable.

In addition, Palestine lacks conventional energy resources such as oil and gas, and therefore must import all its energy from Israel at a relatively high cost. Consequently, utilization of PV technologies for treatment of surface water would save hard currency and preserve the environment.

1.6 Water Resources and their Crisis in Nablus, Palestine

a) Water Resources in Nablus

The main sources of water in Nablus district are surface and groundwater:

Surface water

There are 2 sources of surface water in Nablus governorate these are flood water and Jordan River bordering, Bardala, Ein El Bayda, Fasayil and Jiftlik. The source of floods is rainfall on Nablus highlands where runoff occurred through the main streams either to the east or to the west. The amounts of floods were not exactly measured in the area. Before 1967, the farmers of Bardala and Ein El Bayda were using Jordan River to irrigate their farms [8].

Springs

There are 48 springs with a discharge flow exceeding 0.1 Liter/sec, as measured by the West Bank Water Department of which 29 springs are measured and observed on a monthly basis [8].

There are five drinking water springs utilized by the Nablus municipality:

1. Dafna Spring
2. Ra’s Al Ain spring
3. Ayn al Asal spring.
4. Al Qaryon spring.
5. Bayt Al Ma’ Spring.

Wells

There are 79 Palestinian wells in Nablus governorate used for different purposes, (ARIJ Database), including 4 municipal wells used domestic purposes and 75 Palestinian privately wells which are used for irrigation purposes [8].

As for the drinking water artesian wells operated by the municipality they are:

1. Odala well

2. Al Badhan well

3. Al Far’a well

4. Deir Sharaf well

b) Water Crisis in Nablus

The water quality from the wells and springs of the northern Jordan valley of Nablus/Tubas area, are not well suitable for all of the crops planted in the area. Tests of the special wells and springs used for domestic purposes show good water quality with respect to drinking standards. However, the water quality drops from the west to the east of the area.

The Badan and Fara spring systems are of good water quality in the upstream areas, but the downstream at the conjunction between wadi El Fara and wadi El Badan, the water is mixed with the untreated wastewater from the sewerage of Nablus city, thus subjecting the water stream to pollution and the degree of contamination based on fecal coliforms was 64.4% in rain fed cisterns and 56.8% in the springs [8].

Another reason due to population growth following the improvement of health and social conditions and the enlargement of city limits to include the refugee camps of Blata and Asker and the town of Rafidia, the available water resources did not meet the population needs. These realities prompted Nablus City to explore new resources that would satisfy the increasing needs [9].

1.7 Research Aims

This research investigates the following:

1. Quantities and problems of contaminated water and water sources in Palestine.
2. Water treatment methods and the energy consumption.
3. Application of solar energy in springs and underground water treatment.
4. Building an integrated system consisting of suitable membrane that can be powered by solar energy.
5. Determination of the quality of surface water treatment by autonomous solar-powered membrane cells under Palestinian weather and environmental conditions.

CHAPTER TWO

WATER TREATMENT METHODS

Chapter Two

Water Treatment Methods

2. Water Treatment Processes

This chapter introduces treatment of surface water processes starting with the history of treatment and its needs and moving on to the classifications of treatment of surface water processes.

2.1 Needs for Water Treatment

Water is an important resource for use of mankind and it is a resource for Life.It is important for agricultural and industrial growth, as well as for supporting growing populations who require a safe drinking water supply.

Natural resources cannot satisfy the growing demand for water with industrial development, together with the increasing worldwide demand for supplies of safe drinking water.

This has forced mankind to search for another source of water. In addition, the rapid reduction of subterranean aquifers and the increasing salinity of these non-renewable sources will continue to exacerbate the international water shortage problems in many areas of the world.

2.2 History of Water Treatment

Processes of water treatment has been practiced in the form of distillation process for over 2000 years, it is not until the eighteen century

A.D, for people to recognize that the distillation process could be enhanced by cooling the condensing surface.

In the eighteenth century A.D, Jaber Ibn Hayyan an Arabic scientist wrote about the foundations of the treatment process using distillation.

The thermal desalination process for water distillation was the technology employed in the first major treatment plants in the 1950s which were predominantly in the Middle East region.

Membrane technologies were developed in the 1960s and 1970s and by the late 1980s, reverse Osmosis desalination technology made up 40% of desalination plants worldwide. This has now increased to levels approaching 60% [13].

Large improvements in membranes have caused the increased use of reverse osmosis, which have led to greater efficiencies and reduced energy consumption. Such advances have also resulted in electro dialysis now being significantly more expensive than reverse osmosis technology, By contrast, the distillation method uses high energy consumption to heat the water. This major drawback means thermal plants now have higher capital and operating costs than reverse osmosis technology.

2.3 Classification of Water Treatment Processes

Many methods have been proposed for water treatment processes, as can be seen the major processes in figure 2.1,

1. Processes in which treatment taking place involves phase change.

- Multistage flash (MSF).
- Multieffect boiling (MEB).
- Vapor compression (VC).

2. Processes in which treatment takes place without any phase change. These include

The following two main methods:

- Reverse Osmosis (RO).
- Electrodialysis (ED).

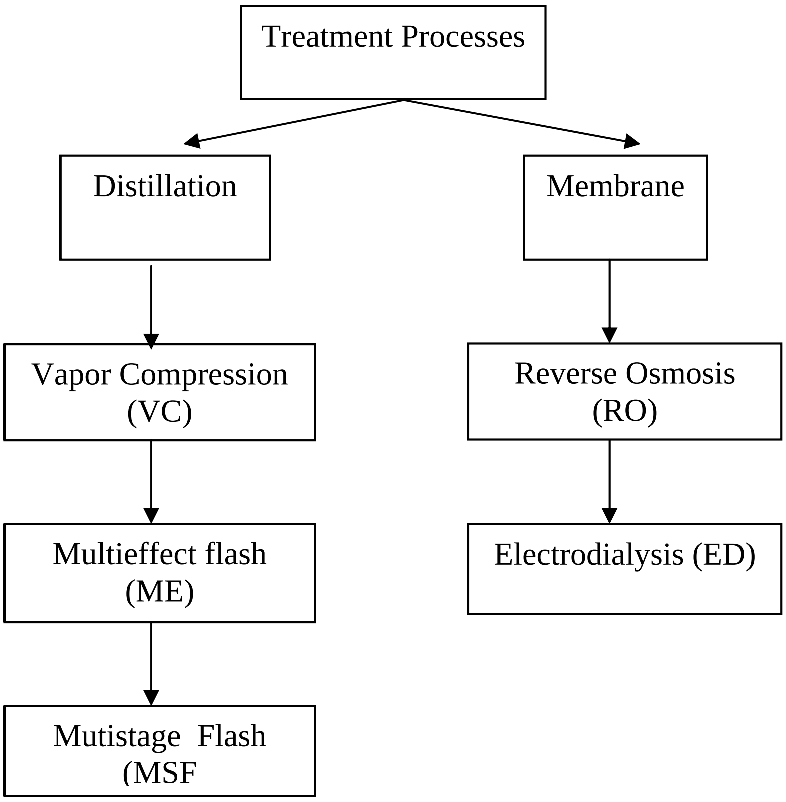


Figure (2.1): Classification of treatment of water processes

2.3.1 Distillation Processes

2.3.1.1Vapor Compression Distillation (VC)

It is a system that treats surface water. The System combines the benefits of distillation with those of vapor compression to greatly lower the cost of distillation for removal of water or concentration of other ingredients. It can be used for a broad range of applications and provides substantial economic and operational benefits to the user. Depending on local energy cost and the volume of liquids being processed. Vapor Compression is a prepackaged closed loop distillation system designed to treat a wide variety of water and process water streams through the use of advanced vapor compression technology.

The Vapor Compression Distillation process as follows:

1. The water entering the system is preheated, and gross solids removed.

2. The water is circulated through a specially designed plate and frame heat exchanger where the water is boiled into vapor. A mixture of water and vapor exit the heat exchanger and enter the separator.

3. The compressor draws the vapor from the separator and compresses it to about 0.35 bar, thereby increasing its temperature. The superheated vapor is then pumped into the condenser side of the heat exchanger where it is used to boil additional water in the evaporator side. As the hot vapor releases its latent heat, it condenses into distilled water, which is then discharged from the system.

4. As additional water is evaporated during the process, the remaining water becomes more concentrated. When the desired level of concentrate is reached, the concentrate is discharged, and more feed stock is added automatically to the system. The system treats industrial process and waste-water streams. It combines the benefits of distillation with those of vapor compression; the system has a wide range of applications and provides substantial economic and operational benefits to the user. Figure 2.2 illustrates the principle of vapor compression distillation.

The vapor-compression process consumes a small amount of energy and has a low operating cost. However, its capacity is limited, and the quality of water produced and maintenance costs do not match those by other distillation processes [11].

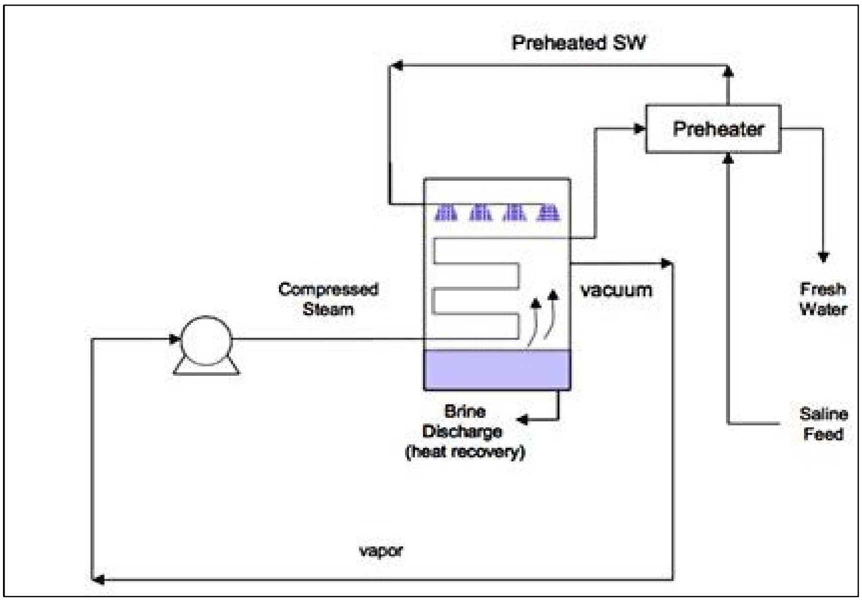


Figure (2.2): Principle of vapor compression distillation

2.3.1.2 Multistage Flash Distillation (MSF)

In Multi –Stage Flash evaporation, the water is heated and evaporated. The pure water is then obtained by condensing the vapour.

The water is heated in a vessel both the temperature and pressure increase, the heated water passes to another chamber at a lower pressure which cause vapour to be formed, the vapour is led off and condensed to pure water using the cold sea water which feeds the first heating stage.

The concentrated brine is then passed to a second chamber at a still lower pressure and more water evaporates and the vapour is condensed as before.

The process is repeated through a series of vessels or chambers until atmospheric pressure is reached. Multistage flash evaporation is considered to be the most reliable, and is probably the most widely used. The principle is illustrated in Fig 2.3 [12].

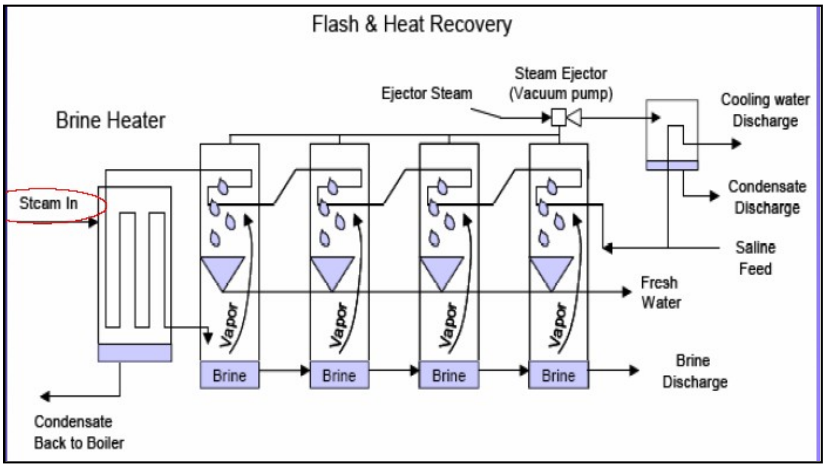


Figure (2.3): Multistage flash process (MSF)

2.3.1.3 Multieffect Boiling Distillation (MEB)

Multieffect distillation (MEB) is in principle similar to multi stage flash evaporation, except that steam is used to heat up the water in the first stage and the resulting vapour is used in subsequent stages to evaporate the water, and the water is used to cool and condense the vapour in each successive stage to that the temperature gradually falls across each stage of the process. The principle is illustrated in figure 2.4[12].

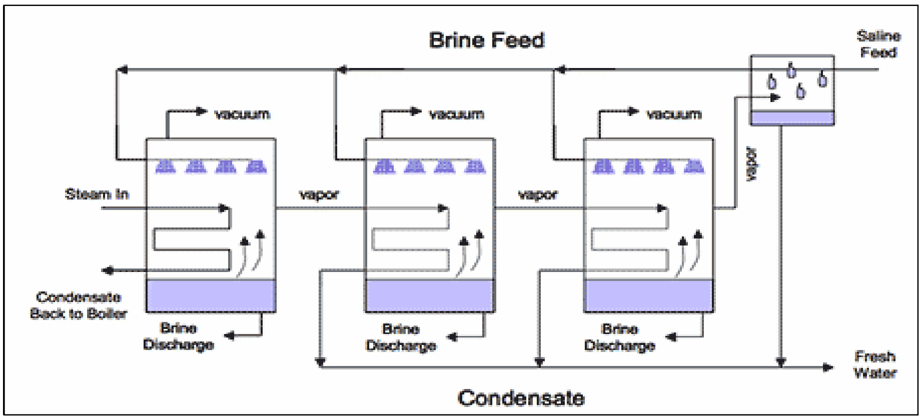


Figure (2.4): Multi effect boiling process (MEB)

2.3.2 Membrane Processes

The membrane performance in terms of the fluxes and selectivity are mainly dependent on the nature of the elements contained in the two phases and the driving forces applied.

This processes use relatively permeable membrane to move either water or salt to induce two zones of differing concentrations to produce fresh water.

The separation takes place at ambient temperature, without phase change, which offers energetic advantages over distillation, and the separation takes place without the accumulation of products inside the membranes. This separation does not require the addition of chemical additives.

Membrane process types

The main membrane processes used in water treatment are:

1. Microfiltration (MF).

2. Ultrafiltration (UF).

3. Nanofiltration (NF).

4. Reverse Osmosis (RO).

5. Electrodialysis (ED).

2.3.2.1 Microfiltration Membrane

Membranes with a pore size of 0.1 – 10 µm perform microfiltration. Microfiltration membranes remove all bacteria. Only part of the viral contamination is caught up in the process, even though viruses are smaller than the pores of a micro filtration membrane. This is because viruses can attach themselves to bacterial biofilm. Microfiltration can be implemented in many different water treatment processes when particles with a diameter greater than 0.1 mm need to be removed from a liquid [13].

2.3.2.2 Ultrafiltration Membrane

The pores of ultrafiltration membranes can remove particles of 0.001 – 0.1 µm from fluids. Ultrafiltration is a selective fractionation process utilizing pressures up to 145 psi (10 bars). It concentrates suspended solids and solutes of molecular weight greater than 1,000. The permeate contains low-molecular-weight organic solutes and salts. UF is widely used in the fractionation of milk and whey, and also finds application in protein fractionation [13].

2.3.2.3 Nanofiltration Membrane

Nanofiltration is a special process selected when RO and UF are not the ideal choice for separation. It is use partially permeable membranes to preferentially separate different fluids or ions, and will remove particles from approximately 0.0005 to 0.005 microns in size. Nanofiltration membrane can perform separation applications that are not otherwise economically feasible, such as demineralization, color removal, and desalination. In concentration of organic solutes, suspended solids, and polyvalent ions, the permeate contains monovalent ions and low-molecular-weight organic solutions like alcohol[14].

2.3.2.4 Reverse Osmosis (RO) Membrane

Osmosis is a physical force. It is the natural tendency of water with a low concentration of dissolved particles to move across a semi-permeable membrane to an area of water with a high concentration of dissolved particles. The water will try to reach equilibrium on both sides, as shown in figure 2.5.

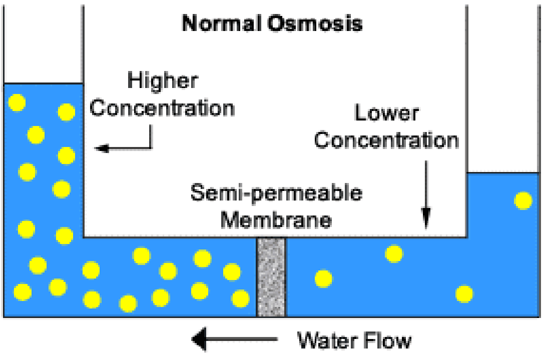


Figure (2.5): Principle of normal osmosis process

The process of reverse osmosis requires that the water be forced through a semi-permeable membrane in the opposite direction of the natural osmotic flow; leaving the dissolved particles in the more highly concentrated solution.

In order for reverse osmosis to occur, the amount of force or pressure applied must exceed the osmotic pressure as in figure 2.6[15].

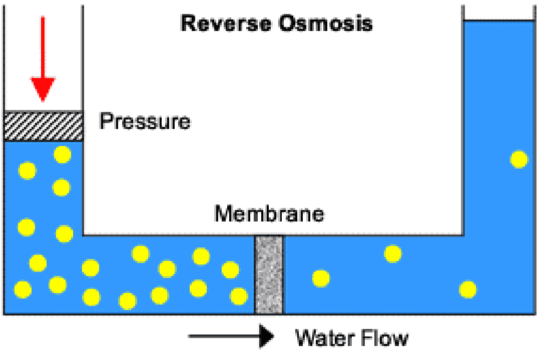


Figure (2.6): Principle of reverse osmosis process

The classification and comparison between these processes is based on many characteristics of each such as, as shown in figure 2.6

1. The driving force [hydrostatic or electrical].
2. The separation mechanism.
3. The nominal size of the separation achieved.

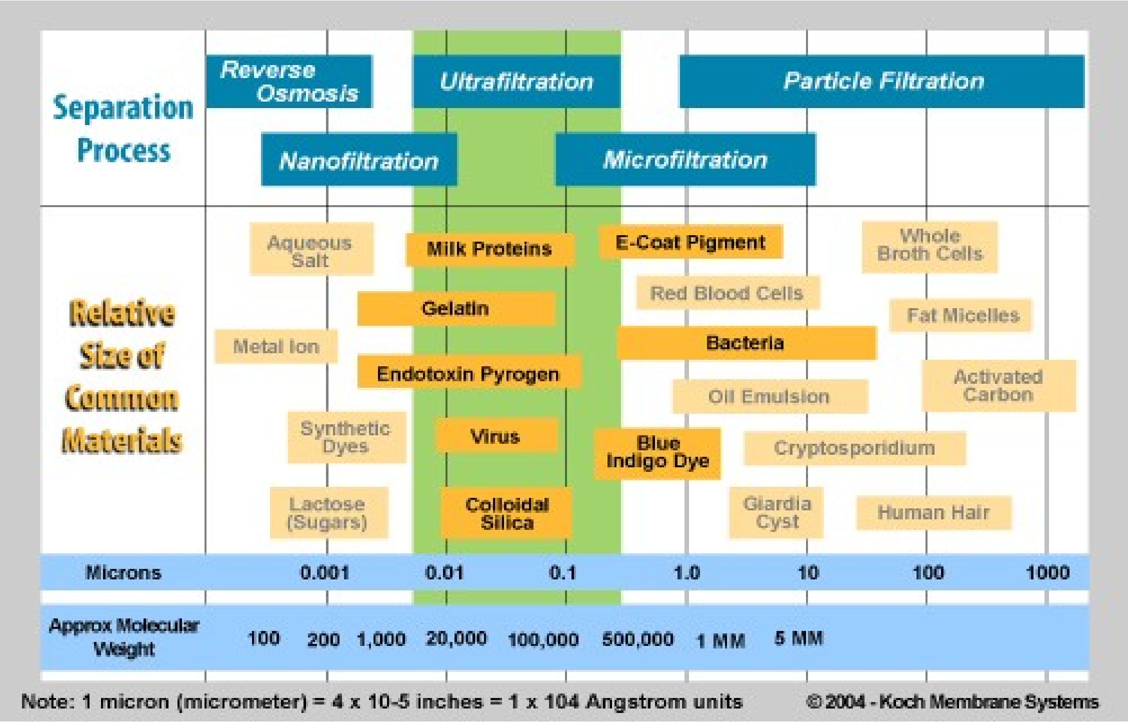


Figure (2.7): Ranges of filtration system

2.3.2.5 Electrodialysis (ED)

It is a voltage driven process and uses an electric potential to move salts selectively through a membrane, leaving fresh water behind.

The salts in seawater are composed of positive ions (called cations) and negative ions (called anions). Electrodialysis uses a stack of ion-exchange membranes which are selective to positive and negative ions. Under the influence of a direct electrical current (DC), the positive sodium ions pass through a cation membrane and the negative chloride ions pass through an anion membrane.

The incoming saline water is thus converted into two streams, one of concentrated brine and one of desalinated (fresh water) [16].

This illustrated in Figure 2.7 Industrial electrodialysis plants consist of stacks of hundreds of membranes.

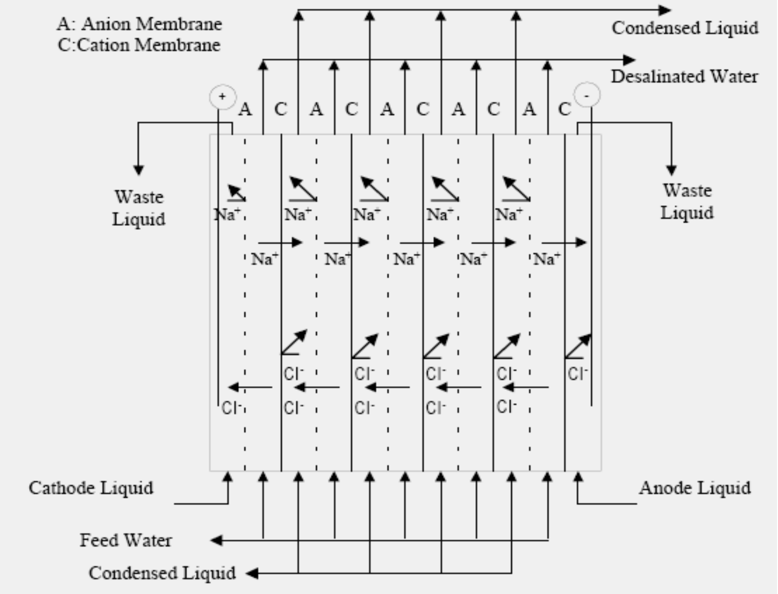


Figure (2.8): Principle of electrodialysis

CHAPTER THREE

REVERSE OSMOSIS PROCESS

Chapter Three

Reverse Osmosis Process

3.1 Introduction

To understand how reverse osmosis purifies water; you must first understand the process of osmosis.

a) **Principles of Osmosis**

Osmosis is the process in which water moves from a higher concentration to a lower concentration. A semi permeable membrane has nothing to do with the definition of osmosis. A membrane is not needed to actually do osmosis but osmosis can occur in the presence of a membrane as shown in figure 3.1.

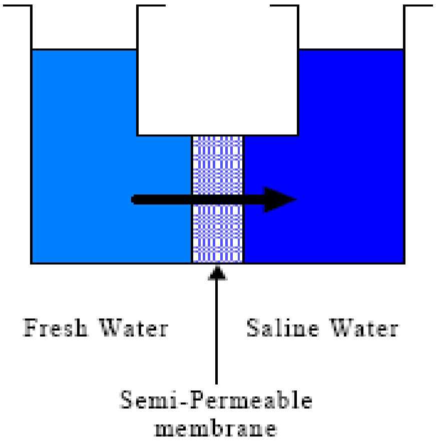


Figure (3.1): Osmosis process

b) **Principle of Reverse Osmosis**

The process of reverse osmosis requires that the water be forced through a semi-permeable membrane in the opposite direction of the natural osmotic flow; leaving the dissolved particles in the more highly concentrated solution. In order for reverse osmosis to occur, the amount of force or pressure applied must exceed the osmotic pressure as shown in figure 3.2.

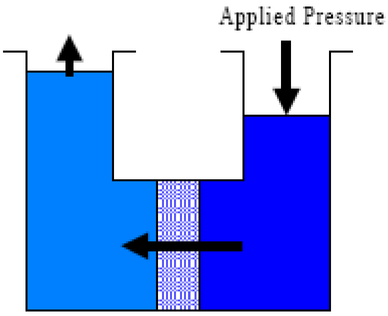


Figure (3.2): Reverse osmosis process

3.2 Process Description and Terminology

In practice, reverse osmosis is applied as a cross flow filtration process. The simplified process is shown in Figure 3.3.

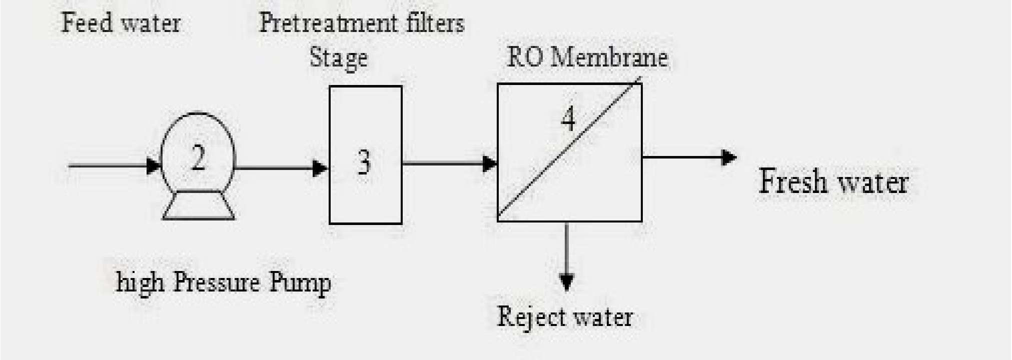


Figure (3.3): Reverse osmosis terminology

3.2.1 Booster (Diaphragm) Pump

The pump supplies the pressure needed to push water through the membrane, even as the membrane rejects the passage of salt through it. The pressure required depends on the concentration and temperature of the feed water. Osmotic pressure increases with increasing concentration, so that the operating pressure must exceed the osmotic pressure corresponding to the concentration of the rejected brine at the membrane outlet.

3.2.2 Pretreatment Filters

The Feed water was treated from replaceable pre filter sediment-carbon cartridges.

- 5 Micron filter, removes sediment, clay, silt and particulate matter to 5 micron range.
- Carbon filter removes chlorine, harmful chemicals, synthetic detergents, as well as other organic contaminants.
- Compacted carbon block, where a combination of mechanical filtration and physical/chemical adsorption takes place to reduce or eliminate a wide range of contaminants.

3.2.3 Membrane Processes Technology

Reverse Osmosis Membrane Modules are commercially available in four configurations:

1. Spiral-Wound Module.
2. Hollow Fine Fiber Module.
3. Tubular Module.
4. Plate-and-Frame Module.

3.2.3.1 Spiral-Wound Module

It consists of two or more leaves (envelopes). Each leaf has two flat sheets of semi permeable membrane separated and supported by a porous backing material as shown in figure 3.4.

It is sealed on three sides and the fourth open side is attached to a perforated pipe.

A flexible feed spacer is added and the flat sheets are rolled into tight circular configuration.

The term spiral is derived from the fact that the flow in the rolled up arrangement of membranes and support sheets follows a spiral flow pattern.

The feed water can be applied to the inside of the fiber (inside out flow), or the outside of the fiber (outside-in flow) [17].

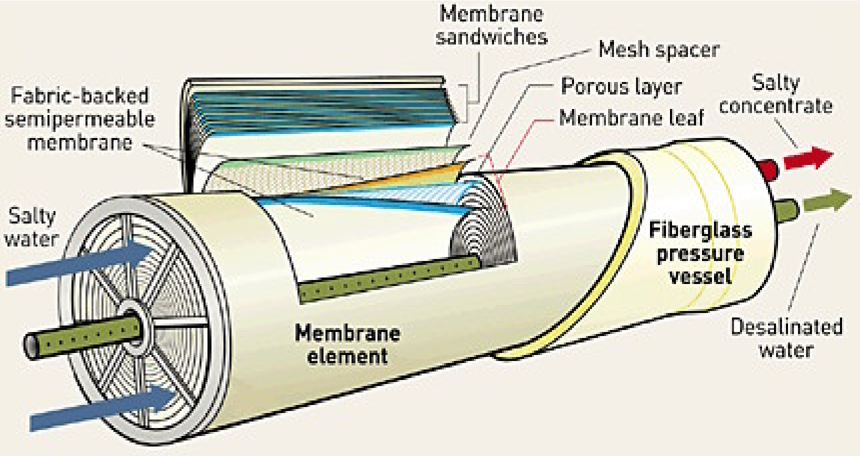


Figure (3.4): Spiral wound module

3.2.3.2 Hollow Fine Fiber Module

In hollow fiber modules hundreds to thousands of hollow fibers are bundled together to form a module. The entire assembly is inserted into a pressure vessel. The feed water can be applied to the inside of the fiber (inside out flow), or the outside of the fiber (outside-in flow) as shown in figure 3.5.

This configuration uses membrane in the form of hollow fibers which have been extruded from cellulosic or non-cellulosic material.

The hollow fiber membrane bundle, 10 cm to 20 cm in diameter, is contained in a cylindrical housing or shell approximately 137 cm long and 15 - 30 cm in diameter. The assembly is called a permeator. The pressurized feed water enters the permeator feed end through the center distributor tube, passes through the tube wall, and flows radially around the fiber bundle toward the outer permeator pressure shell. Water permeates through the outside wall of the fibers into the hollow core or fiber bore, through the bore to the tube sheet or product end of the fiber bundle, and exits through the product connection on the feed end of the permeator [17].

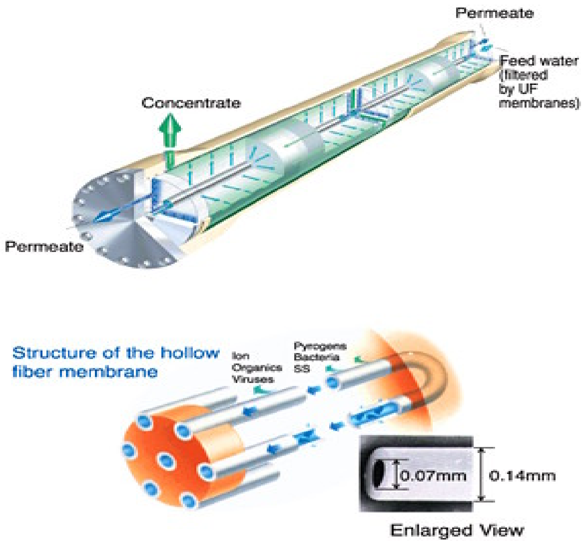


Figure (3.5): Hollow fine fiber module

3.2.3.3 Tubular Module

The description of tubular module with fourteen tubes each of 1.25 meter length and 18 mm internal diameter made up of fiber glass reinforced porous plastic tube and using Cellular Acetate as shown in figure 3.5.

Other membrane material can also be suitably casted in tubular form. The total area of the membrane packed in single module is about 1 m^2.

The typical membrane densities in tubular form are in the range of 60 – 160 m^2/m^3.

The standard velocity range of feed flow is 0.5 ft/sec to 1.5 ft/sec but even higher value up to 5 ft/sec are also acceptable at the cost of higher pressure drops in few specific applications with high turbidity solutions particularly in food and pharmaceutical industries This corresponds to a minimum volumetric feed flow of about 2.3 liter/minute and maximum feed flow of about 23 liter/minute with an optimum range of 5 –10 liter/minute feed flow rate [18].

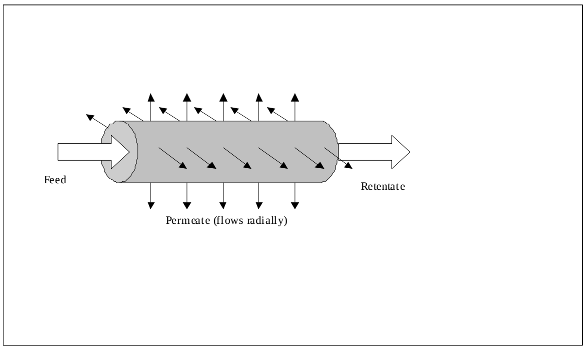


Figure (3.6): Tubular module membrane

3.2.3.4 Plate and Frame Module

As shown in Figure 3.7, Plate-and Frame modules use flat sheet membranes that are layered between spacers and supports. The supports also form a flow channel for the permeate water. The feed water flows across the flat sheets and from one layer to the next. Recent innovations have increased the packing densities for new design of plate-and-frame modules. Maintenance on plate-and frame modules is possible due to the nature of their assembly. They offer high recoveries with their long feed channels and are used to treat feed streams that often cause fouling problems [19].

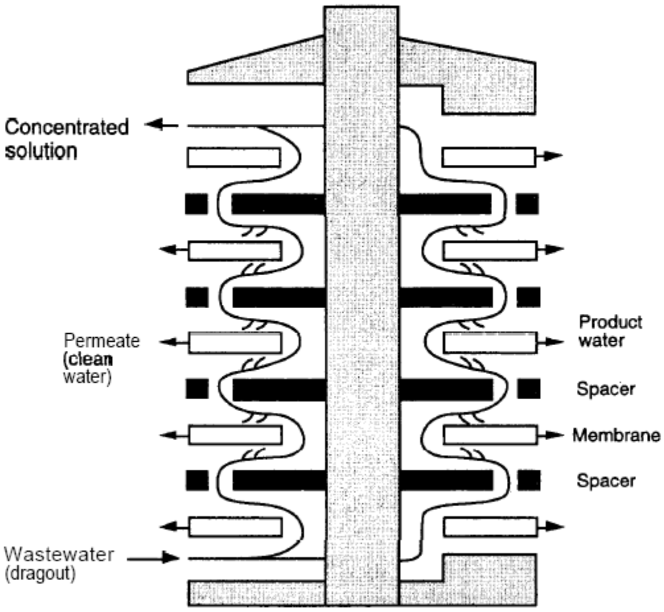


Figure (3.7): Plate-and-frame reverse osmosis module

An ideal Membrane has the following characteristics:-

1. High rate of fresh water
2. High salt rejection.

3. Resistant to high temperature.
4. Resist the presence of excess chlorine less part per million.
5. Resistant to all kind of fouling (inorganic, organic, colloidal, and microbiological Fouling).
6. It is not sensitive to attack bacteria.
7. It is not sensitive to the possibility of collapse with the high temperature and lack of discipline pH.
8. Chemically, physically, and thermally stable in saline water.
9. Long and reliable life.
10. Inexpensive.

There are the factors influencing the membrane performance as shown in figure3.8.

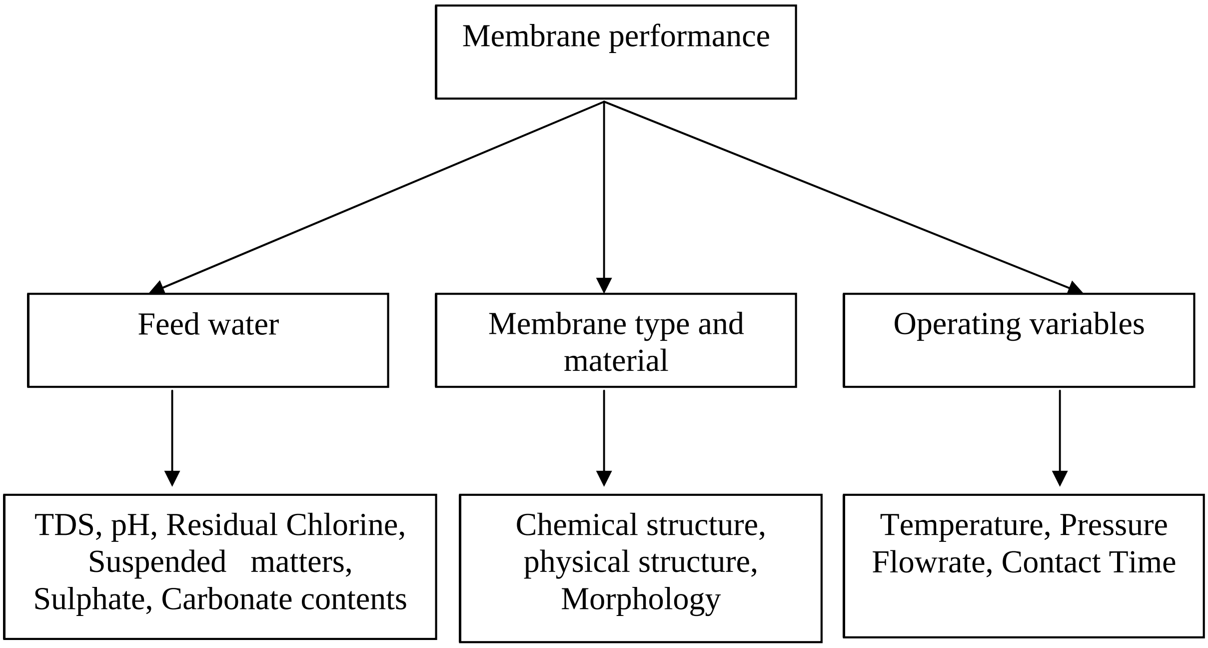


Figure (3.8): Factors influencing the membrane performance

3.3 Basic Transport Equations in Reverse Osmosis

The three streams (and associated variables) of the RO membrane process are shown in Figure 3.9: the feed, the product stream called the permeate, and the concentrated feed stream called the concentrate or retentate.

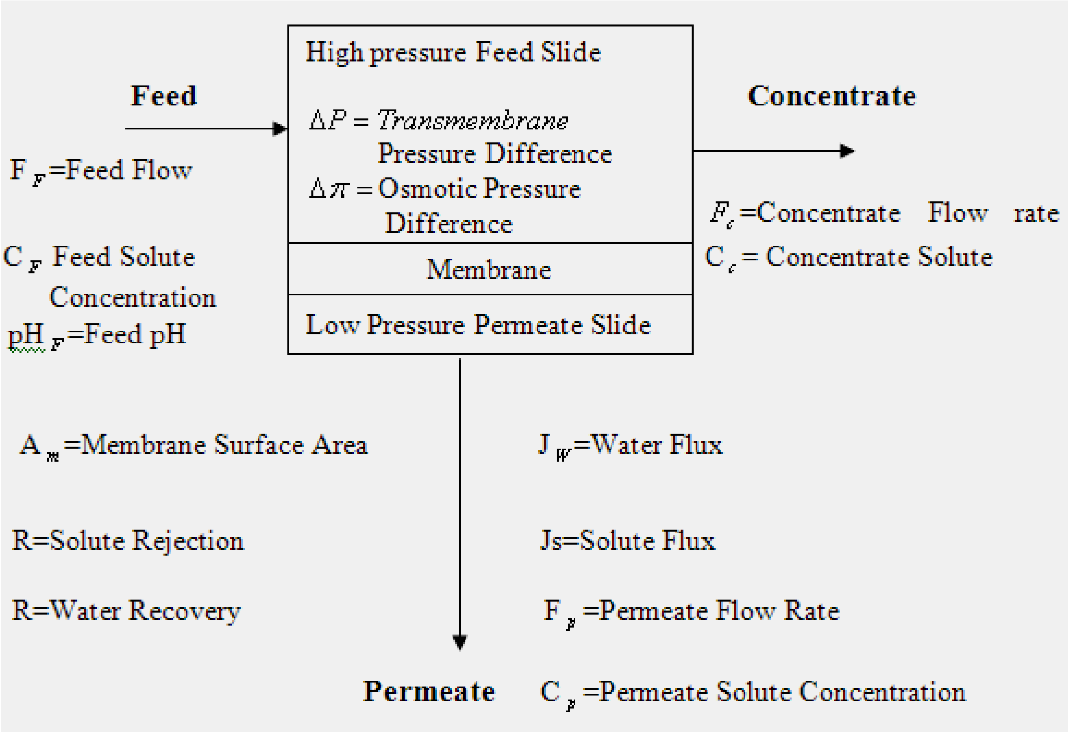


Figure (3.9): Schematic of RO Process Streams [20]

There are a set of terms and equations used to define the parameters governing transport across a membrane.

3.3.1 OSMOTIC PRESSURE

The osmotic pressure, P_{osm} of a solution can be determined experimentally by measuring the concentration of dissolved salts in solution [21]:

$$P_{osm} = 1.19(T+273) \times \sum (m_i) \qquad (3.1)$$

P_{osm} = osmotic pressure (in psi).

T = temperature (in °C).

$\sum(m_i)$ = sum of molal concentration of all constituents in a solution.

3.3.2 Water Flux

The following equation defines the water flux [22]:

$$J_w = K_1(\Delta P - \Delta \pi) \quad (3.2)$$

$$K_1 = K_w\left(\frac{A}{\tau}\right) \quad (3.3)$$

$$\pi = 1.21T\sum M_i \quad (3.4)$$

Where

J_w = Water flux = [m^3/m^2/sec]

ΔP = Hydraulic pressure differential across the membrane = [atm]

π = Osmotic pressure differential across the membrane = [atm]

$K1$ =Pure water transport coefficient, i.e. the flux of water through the membrane per unit driving force = [m3/m2/sec atm]

K_w = Membrane permeability coefficient for water.

A = Membrane area = [m]

τ = Membrane thickness = [m]

T = Feed water temperature =[K]

M_i = Molality of the ith ionic or nonionic materials.

It depends on the membrane properties, temperature of the system and the chemical composition of the salt solution.

3.3.3 Concentration Flux

The salt flux is an indicator for the membrane effectiveness in removing salts from water.

The salt flux is a function of the system temperature and the salt composition [22].

$$F_c = K_2 (C_F - C_c) \qquad (3.5)$$

Where

F_c = Concentrate Flow Rate = [Kg/m2/sec]

K_2 =Salt transport coefficient = [m/sec]

C_F = Feed Solute Concentration= [Kg/m3]

C_c = Product Solute Concentration = [Kg/m3]

As water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration exceeds the salt concentration in the bulk solution. This increase of salt concentration is called concentration polarization.

The effects of concentration polarization are as follows:

1. Greater osmotic pressure at the membrane surface than in the bulk feed solution, ΔP_{osm}, and reduced Net Driving Pressure differential across the membrane ($\Delta P - \Delta P_{osm}$).
2. Reduced water flow across membrane (Q_w).
3. Increased salt flow across membrane (Q_S).
4. Increased probability of exceeding solubility of sparingly soluble salts at the membrane surface, and the distinct possibility of precipitation causing membrane scaling.

3.3.4 Salt Rejection

Salt rejection expresses the effectiveness of a membrane to remove salts from the water.

It can be calculated from the following equation [22]:

$$\% \text{ Salt rejection} = \left(1 - \frac{Product Concentration}{Feed Concentration}\right) X100\% \qquad (3.6)$$

$$\% \text{ Salt rejection} = \left(1 - \frac{CP}{CF}\right) X100\%.$$

The salt passage depends on the feedwater temperature and composition, operating pressure, membrane type and material, and pretreatment.

Salt passage and bundle pressure drop are the two indicators of membrane fouling.

3.3.5 Recovery

The recovery rate for an RO system is [22]:

$$\text{Recovery} = \frac{F_P}{F_F} \qquad (3.7)$$

F_P = Permeate Flow Rate [m³/day]

F_F = Feed Flow Rate [m³/day]

The recovery rate affects salt passage and product flow.

As the recovery rate increases, the salt concentration on the feed-brine side of the membrane increases, which causes an increase in salt flow rate across the membrane.

A higher salt concentration in the feed-brine solution increases the osmotic pressure, reducing the net driving pressure and consequently reducing the product water flow rate.

3.4 Description of Variable Effects

Factors affecting RO membrane separations include: feed variables such as solute concentration, temperature, pH, and pretreatment requirements; membrane variables such as polymer type, module geometry, and module arrangement; and process variables such as feed flow rate, operating pressure, operating time, and water recovery.

Water flux is shown to increase linearly with applied pressure.

This behavior is predicted by most of the RO transport models.

Water flux also increases with temperature, as would be expected, since the water diffusivity in the membrane increases and the water viscosity in the membrane decreases with temperature; the increase in water flux can usually be described by an Arrhenius temperature dependence of the water permeability constant or by water viscosity changes [23].

In addition, water flux is greater at higher feed flow rates (high feed velocities over the membrane surface) since this minimizes concentration polarization.

Water flux decreases with increasing feed solute concentration since the higher concentrations result in larger osmotic pressures (and so a smaller driving force across the membrane). This behavior is also predicted by most of the transport models. Water flux can also gradually decrease over operating time (measured in days or months of operation) because of compaction (mechanical compression) or other physical or chemical changes in membrane structure[23].

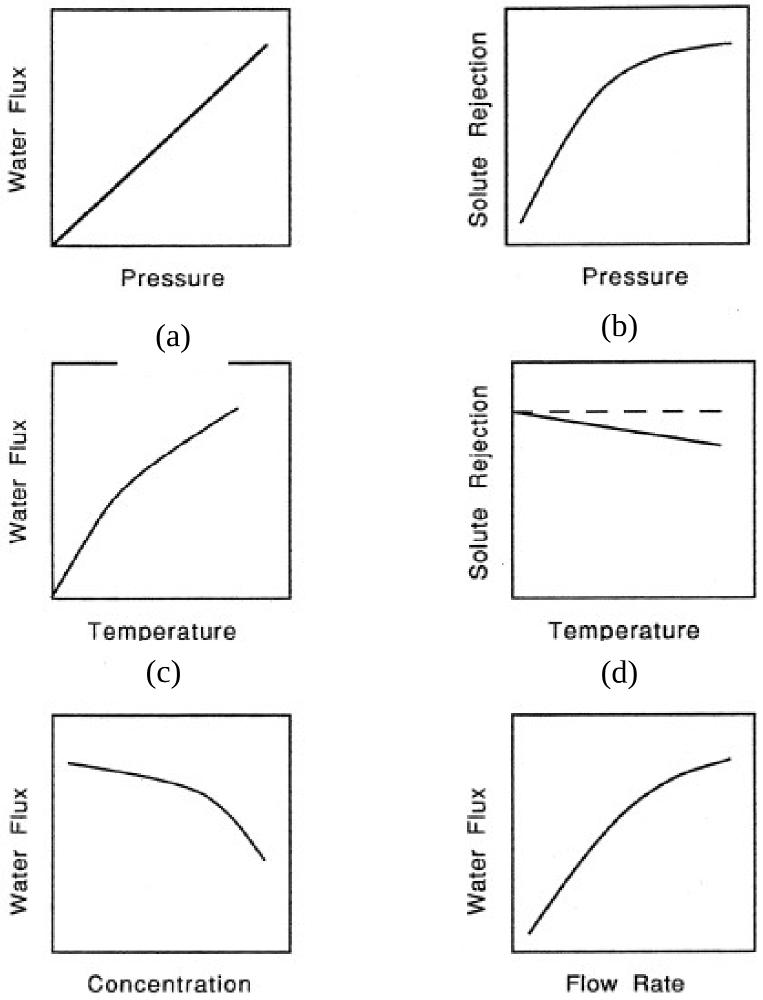
Solute rejection usually increases with pressure since water flux through the membrane increases while solute flux is essentially unchanged when pressure is increased; however, rejection of some organics with strong solute-membrane interactions decreases with pressure.

Rejection of solute remains constant or decreases with increasing temperature depending on the relative increases of water and solute diffusivities in the membrane.

For most simple inorganic systems (such as NaCl, Na2SO4) feed pH does not significantly affect water or solute fluxes. However, for ionizable organics, rejection is a strong function of feed pH: the organic is usually much more highly rejected when it is ionized.

Feed water quality is also important since particulates, colloids, or precipitates present in the feed can cause fouling of a membrane by depositing on its surface, resulting in a substantially reduced water flux. Bacteriological growth can also occur in RO membrane modules, forming bacterial layers that decrease water flux and, in some cases, degrade the membrane polymer.

Selected generalized curves illustrating the effects of some of these variables are shown in Figure 3.10 for non interacting solutes [23].



(a) (b)

(c) (d)

(e) (f)

Figure (3.10): Effects of Variables on RO Separations [23]

- **a- Effect of pressure on water flux.**
- **b- Effect of pressure on solute rejection.**
- **c- Effect of temperature on water flux.**
- **d- Effect of temperature on solute rejection.**
- **e- Effect of concentration on water flux.**
- **f- Effect of flow rate on water flux.**

CHAPTER FOUR

SOLAR ENERGY AND PHOTOVOLTAIC CELL SIZING

Chapter Four

Solar Energy and Photovoltaic Cell Sizing

This chapter describes PV cell operation and the design and the operation of photovoltaic system.

4.1 Solar Radiation

For PV system, solar radiation is the most important data for preliminary design and sizing of a PV power system.

Palestine has one of the highest solar potentials of all the countries of the world.

Palestine enjoys over 2500 sunlight hours every year, with an annual average solar radiation intensity exceeding 5.3 kWh/m^2.day as shown in table 4.1.

Table (4.1): **Monthly average solar radiation in Nablus, Palestine [24].**

Month	kWh/m^2.day
1	2.89
2	3.25
3	5.23
4	6.25
5	7.56
6	8.25
7	8.17
8	8.10
9	6.30
10	4.70
11	3.56
12	2.84

In photovoltaic (solar) module light energy converts into DC electricity. Photovoltaic module is the basic element of each photovoltaic system. Physical phenomenon allowing light-electricity conversion - photovoltaic effect, was discovered in **1839** by the French physicist Alexander Edmond Becquerel. Experimenting with metal electrodes and electrolyte he discovered that conductance rises with illumination. Bell laboratories produced the first solar cell in 1954, the efficiency of this cell was about 5 %, and cost was not a major issue, because the first cells were designed for space applications [25].

In the following years solar cell efficiency increased while the cost has decreased significantly as shown in figure 4.1.

4.2 Photovoltaic Module

A single PV cell produces an output voltage less than 1V, about 0.6V for crystalline silicon (Si) cells, thus a number of PV cells are connected in series to achieve a desired output voltage. When series-connected cells are placed in a frame, it is called as a module.

Most of commercially available PV modules with crystalline-Si cells have either 36 or 72 series-connected cells. A 36-cell module provides a voltage suitable for charging a 12V battery, and similarly a 72-cell module is appropriate for a 24V battery. This is because most of PV systems used to have backup batteries, however today many PV systems do not use batteries; for example, grid-tied systems. Furthermore, the advent of high efficiency DC-DC converters has alleviated the need for modules with specific voltages. When the PV cells are wired together in series, the current output is the same as the single cell, but the voltage output is the sum of each cell voltage, as shown in Figure 4.2.

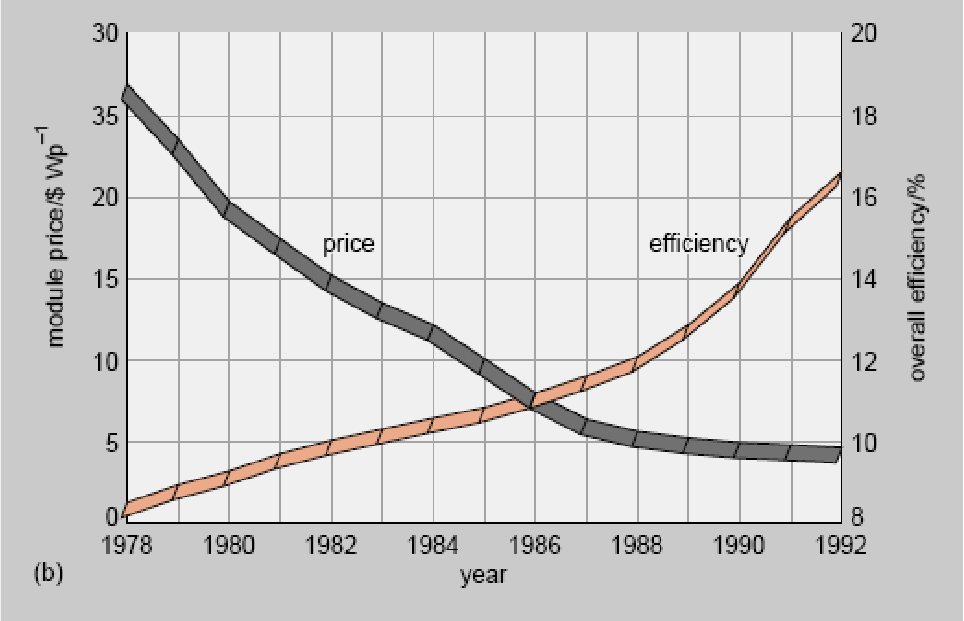


Figure (4.1): Increases in PV module efficiency, and decreases in cost per peak watt, 1978–1992 [26].

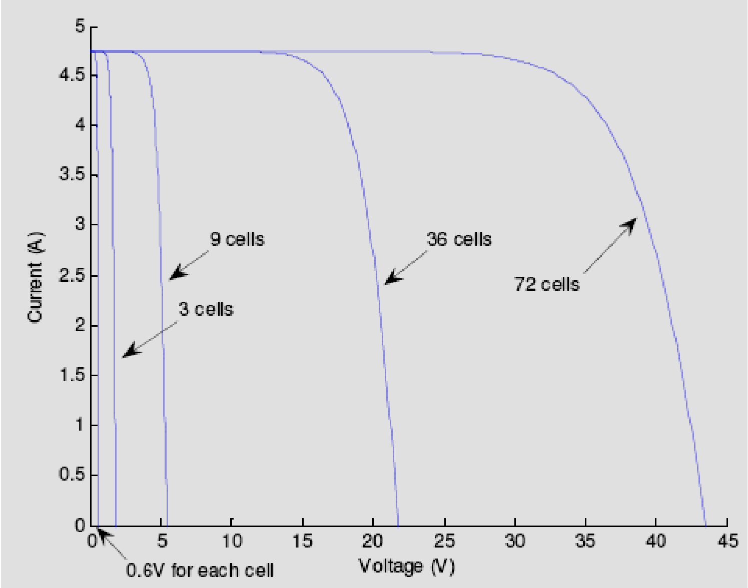


Figure (4.2): PV cells are connected in series to make up a PV module

Also, multiple modules can be wired together in series or parallel to deliver the voltage and current level needed. The group of modules is called an array.

4.2.1 PV Operating Principle

A PV cell is made of at least two layers of semiconductor material. One layer has a positive charge, the other negative.

The photovoltaic effect is the basic physical process through which a PV cell converts sunlight into electricity. Sunlight is composed of photons, or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a PV cell, they may be reflected or absorbed, or they may pass right through. Only the absorbed photons generate electricity. When this happens, the energy of the photon is transferred to an electron in an atom of the cell (which is actually a semiconductor). With its newfound energy, the electron is able to escape from its normal position associated with that atom to become part of the current in an electrical circuit. By leaving this position, the electron causes a "hole" to form. Special electrical properties of the PV cell—a built-in electric field—provide the voltage needed to drive the current through an external load (such as a light bulb) as shown in figure 4.3.

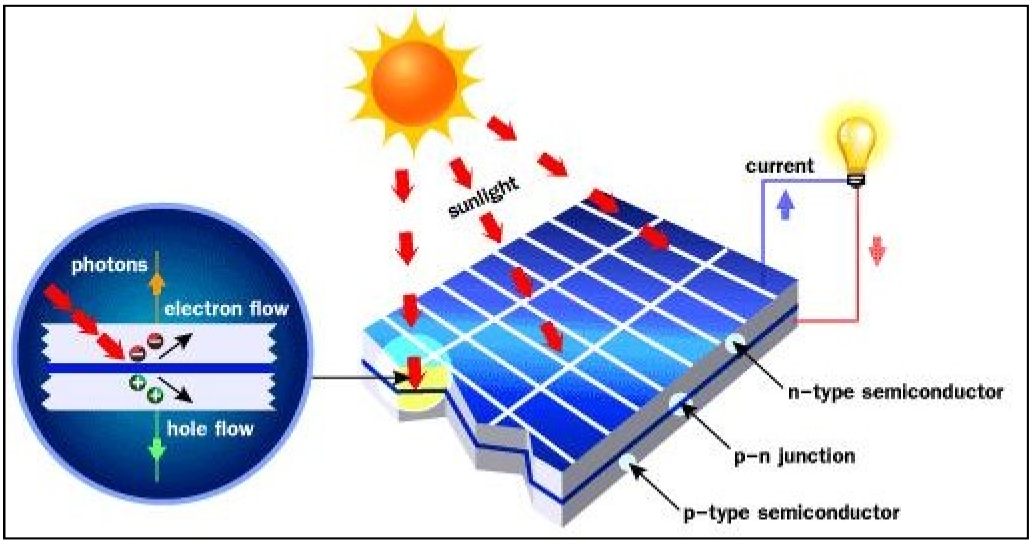


Figure (4.3): Basic solar cell construction

The simplest model of a PV cell is shown as an equivalent circuit below that consists of an ideal current source in parallel with an ideal diode. The current source represents the current generated by photons (often denoted as *Iph* or *IL*), and its output is constant under constant temperature and constant incident radiation of light as shown in figure 4.4.

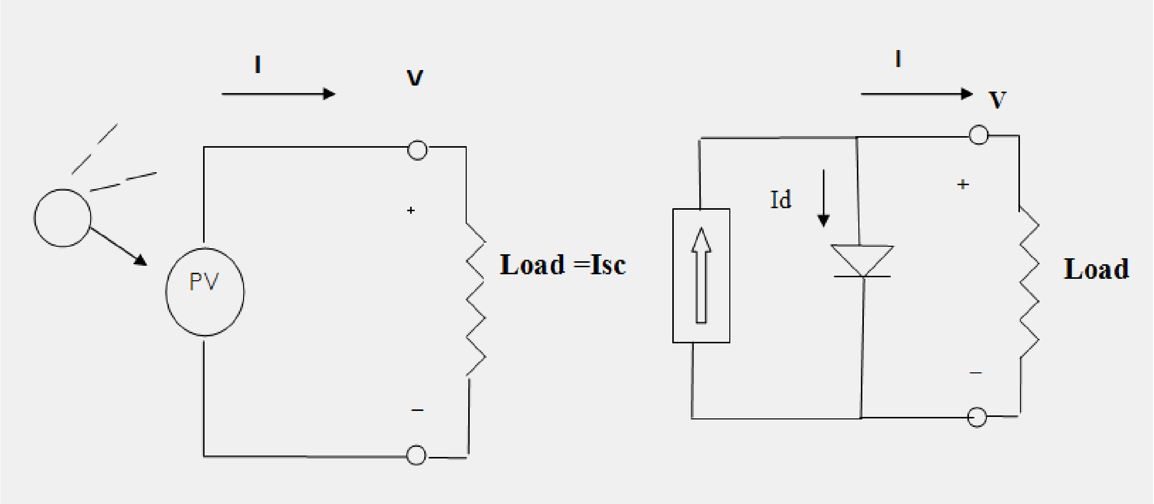
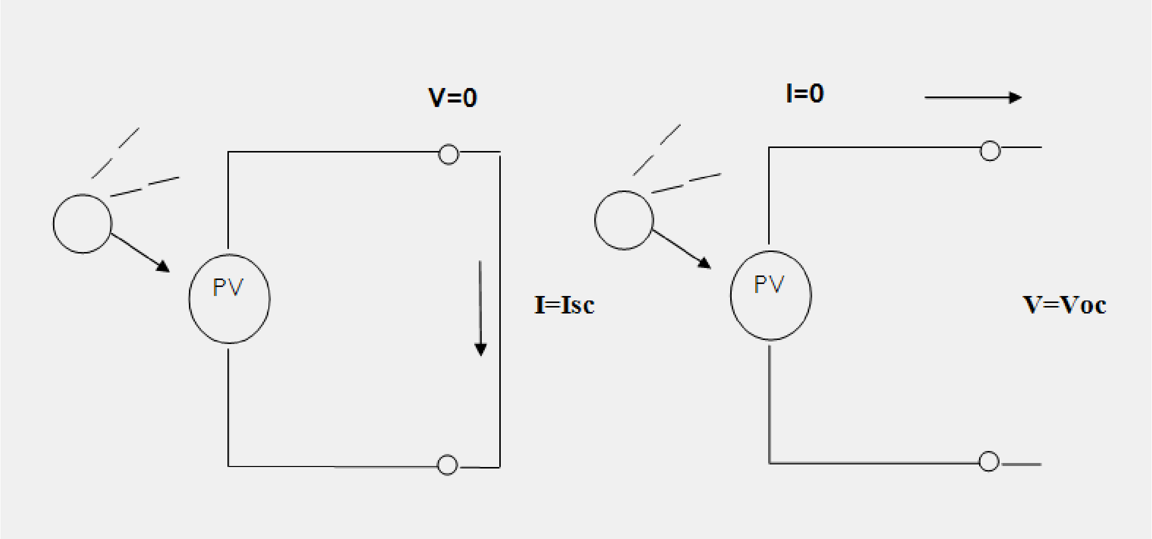


Figure (4.4): PV cell with a load and its simple equivalent circuit [21]

There are two key parameters frequently used to characterize a PV cell. Shorting together the terminals of the cell, as shown in Figure 4-5 (a), the photon generated current will follow out of the cell as a short-circuit current (*Isc*). Thus, *Iph* = *Isc*. As shown in Figure4-5 (b), when there is no connection to the PV cell (open-circuit), the photon generated current is shunted internally by the intrinsic p-n junction diode. This gives the open circuit voltage (*Voc*). The PV module or cell manufacturers usually provide the values of these parameters in their datasheets.



(a) Short-circuit current (b) Open-circuit voltage

Figure (4.5): Diagrams showing a short-circuit and an open-circuit condition [21]

The output current (*I*) from the PV cell is found by applying the Kirchoff's current law (KCL) on the equivalent circuit shown in Figure 4.4.

$$I = I_{sc} - I_d \tag{4.1}$$

Where: I_{sc} is the short-circuit current that is equal to the photon generated current, and I_d is the current shunted through the intrinsic diode.

The diode current I_d is given by the Shockley's diode equation:

$$I_d = I_o(e^{qV_d/KT} - 1) \tag{4.2}$$

Where: I_0 =is the reverse saturation current of diode (A).

q = the electron charge ($1.602 X 10^{-19}$ C).

V_d = the voltage across the diode (V).

k = the Boltzmann's constant ($1.381 X 10^{-23}$ J/K).

T =the junction temperature in Kelvin (K).

Replacing Id of the equation (4.1) by the equation (4.2) gives the current-voltage relationship of the PV cell.

$$I = I_{sc} - I_o(e^{qV/KT} - 1) \tag{4.3}$$

Where: *V* is the voltage across the PV cell, and *I* is the output current from the cell.

The reverse saturation current of diode (I_0) is constant under the constant temperature and found by setting the open-circuit condition as shown in Figure 4.5(b). Using the equation (2.3), let *I* = 0 (no output current) and solve for I_0.

$$0 = I_{sc} - I_o(e^{qV/KT} - 1) \tag{4.4}$$

$$I_{sc} = I_0(e^{qV/KT} - 1) \tag{4.5}$$

$$I_0 = \frac{I_{sc}}{(e^{qVoc/KT} - 1)} \tag{4.6}$$

To a very good approximation, the photon generated current, which is equal to *Isc*, is directly proportional to the irradiance, the intensity of illumination, to PV cell, thus, if the value of I_{sc} is known from the datasheet, under the standard test condition, G_0 =1000W/m^2 at the air mass (*AM*) = 1.5, then the photon generated current at any other irradiance, *G* (W/m^2), is given by:

$$I_{sc}I_G = \left(\frac{G}{G_0}\right)I_{sc0}I_{G0} \tag{4.7}$$

4.2.2 Standard Test Conditions and I-V Curve

The rated power of a solar cell or a module is basically reported in "peak watts" $[W_P]$ and measured under internationally specified test conditions, namely Standard Test Conditions (STC), which refers to global radiation 1000 W/m² incident perpendicularly on the cell or the module, cell temperature 25 °C and AM 1.5 (AM: air mass).

Photovoltaic modules have current voltage relationship which is represented in I-V curve as shown in figure 4.6.

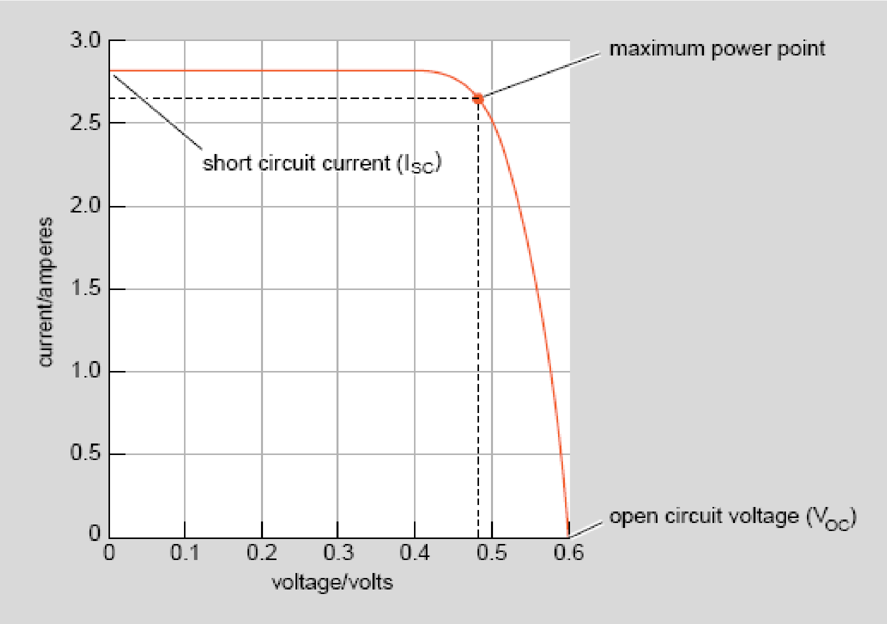


Figure (4.6): (I-V) Characteristics of a typical silicon PV cell under standard test conditions.

4.2.3 Effect of Solar Radiation on PV Performance

For several solar radiation varies between 200 to 1000 W/m² and for a constant temperature equal to 25 °C, we have presented the characteristic I_{pv} = f (V_{pv}) and the P_{pv} =f (V_{pv}) of PV generator, the variations versus the solar radiation of the maximal output PV generator power, and the global efficiency of the PV system as shown in figure 4.7 and figure 4.8.

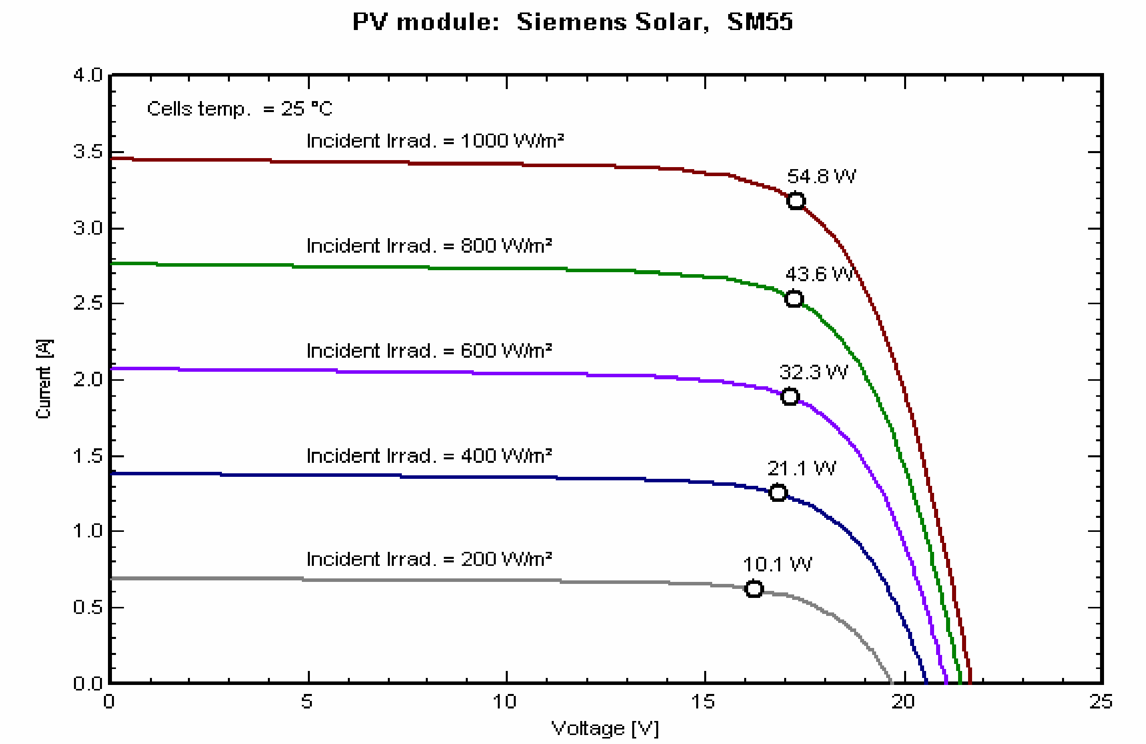


Figure (4.7): PV module (I-V) curve with variation of solar radiation and constant temperature [27].

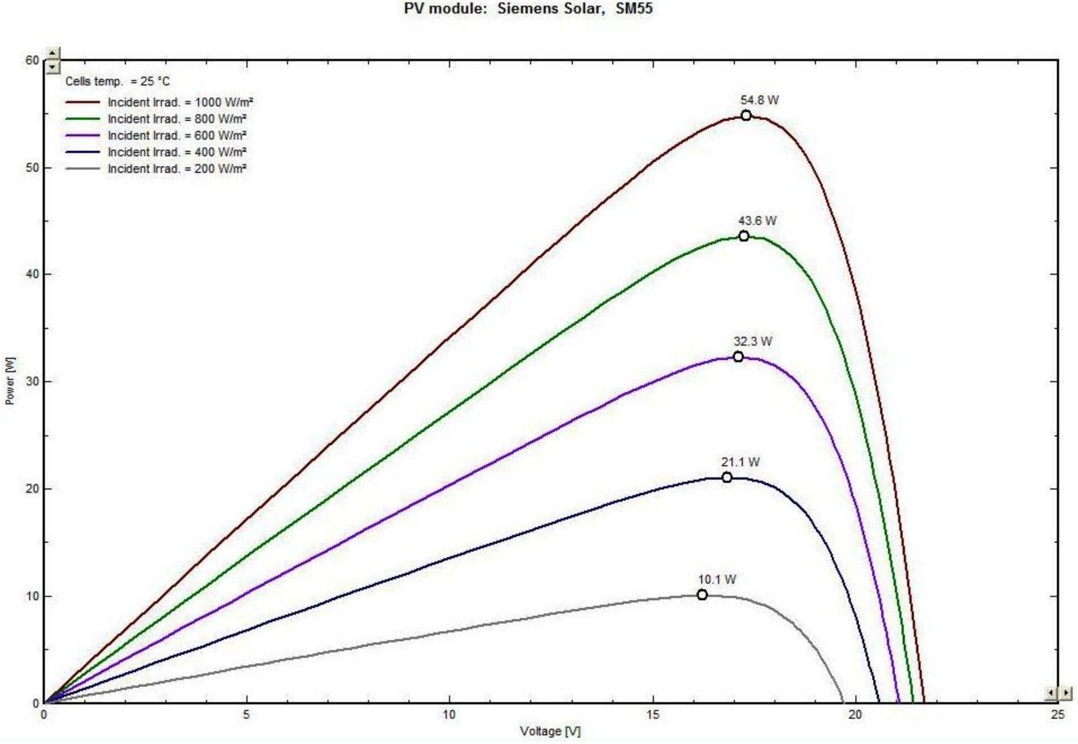


Figure (4.8): PV module (P-V) curve with variation of solar radiation and constant temperature [27].

4.2.4 Effect of Temperature on PV Performance

As known, meteorological parameters, especially the array temperature do not remain constant all day long, but change considerably. It is then worth investigating the influence of the daily average temperature variation on the performances of the optimized system. For several temperature data between 5 and 75 °C and constant solar radiation equal to 1000 W/m².

Figure 4.9 and figure 4.10 display the simulation results as a function of temperature, obtained for a constant solar radiation equal to 1000 W/m². As a result, the global PV system efficiency decreases about 0.03 %/°C. The open circuit voltage decreases as the temperature increases.

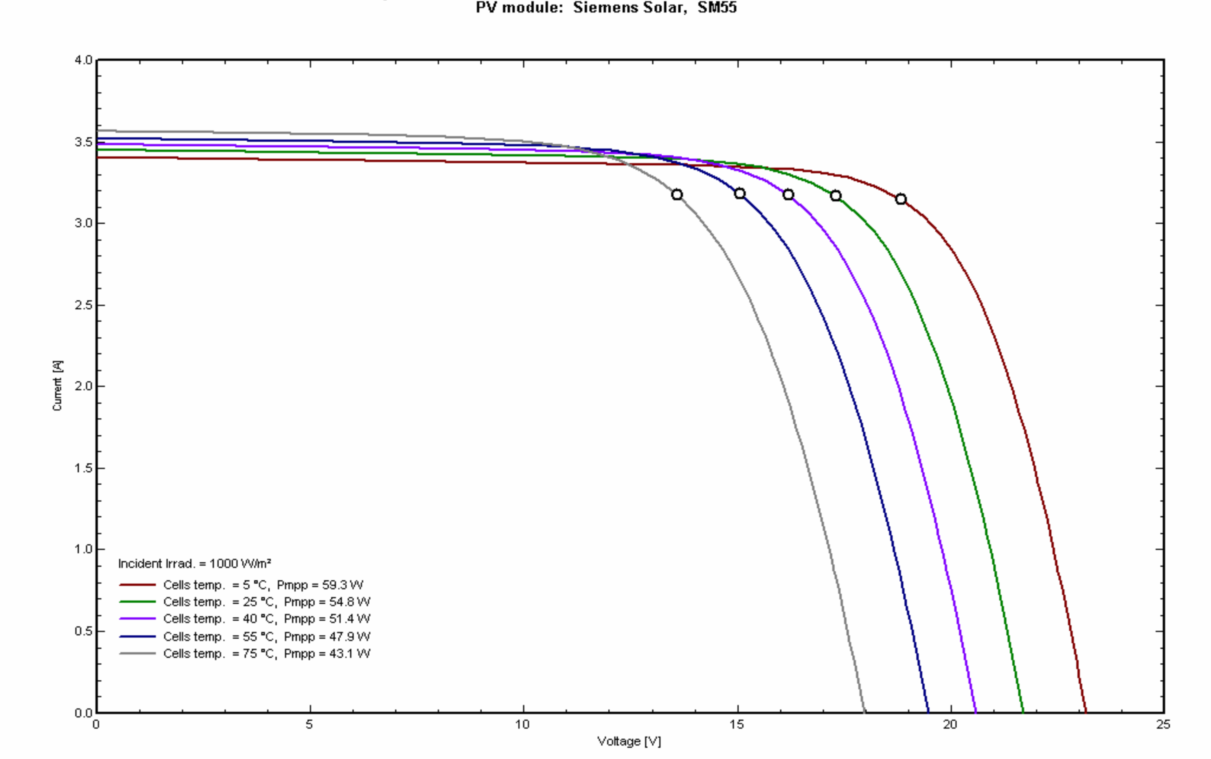


Figure (4.9): PV (I-V) curve with variation of temperature and constant radiation [27].

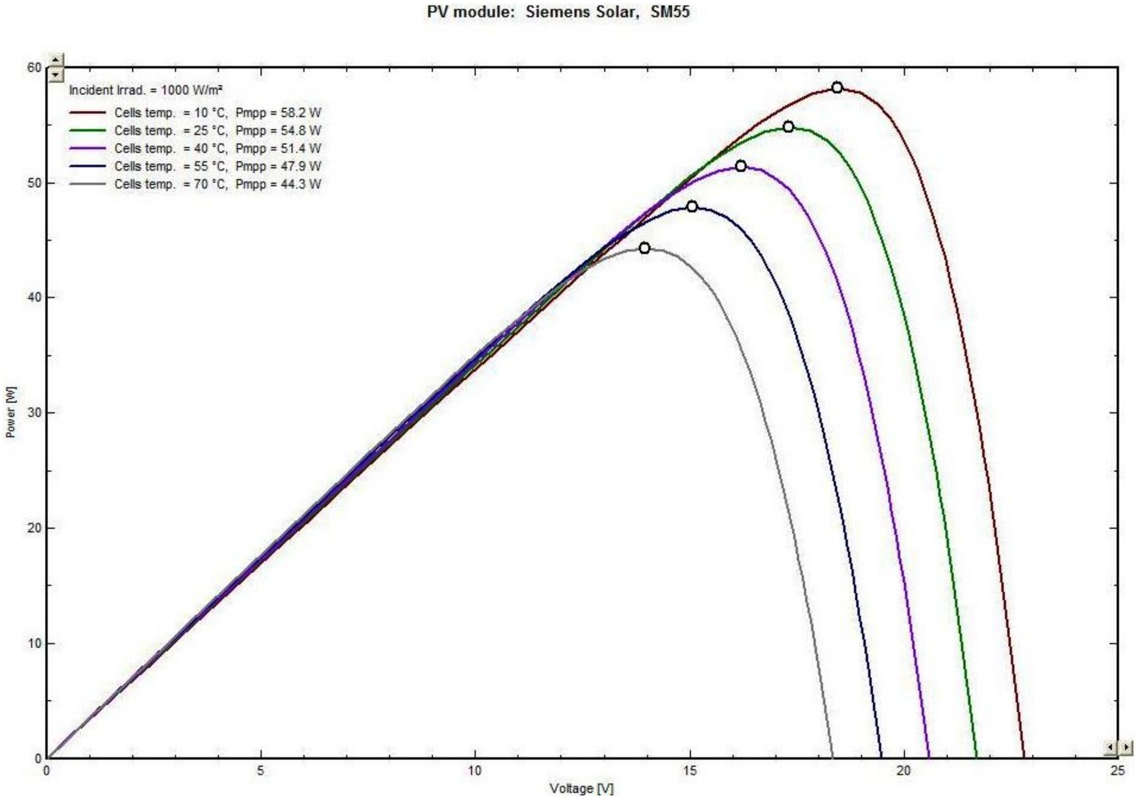


Figure (4.10): PV (P-V) curve with variation of temperature and constant radiation [27].

4.3 Sizing of System Components

1. Identify power consumption demands

The first step in designing a solar PV system is to find out the total power and energy consumption of all loads that need to be supplied by the solar PV system as follows:

- **Calculate total Watt-hours per day for loads.**

Add the Watt-hours needed for all loads together to get the total Watt-hours per day which must be delivered to the loads.

- **Calculate total Watt-hours per day needed from the PV modules.**

Multiply the total loads Watt-hours per day times 1.3 (the energy lost in the system) to get the total Watt-hours per day which must be provided by the panels.

2. Size the PV modules

Different size of PV modules will produce different amount of power. To find out the sizing of PV module, the total peak watt produced needs. The peak watt (W_P) produced depends on size of the PV module and climate of site location. We have to consider "panel generation factor" which is different in each site location. To determine the sizing of PV modules, calculate as follows:

- **Calculate the total Watt-peak rating needed for PV modules**
  Divide the total Watt-hours per day needed from the PV modules by panel generation factor to get the total Watt-peak rating needed for the PV panels needed to operate the loads.

- **Calculate the number of PV panels for the system**

Divide **total watt-peak rating needed** by the rated output Watt-peak of the PV modules available to you. Increase any fractional part of result to the next highest full number and that will be the number of PV modules required.

Result of the calculation is the minimum number of PV panels. If more PV modules are installed, the system will perform better.

If fewer PV modules are used, the system may not work at all during cloudy periods [28].

Another method to calculate the sizing of PV Panel, by using the peak power of the PV generator to cover the total load demand is obtained as in equation (4.8).

$$P_{pv} = \frac{E_l}{\eta_v X \eta_R XPSH} XS_F \qquad (4.8)$$

Where E_l is the daily energy consumption in kWh, PSH is the peak sun hours (PSH= 5.4); η_R, η_v are the efficiencies of charge regulator and inverter respectively (η_R= 0.92, η_v=0.9) and S_f is the safety factor for compensation of resistive losses and PV-cell temperature losses S_f =1.15 [29].

CHAPTER FIVE

EXPERIMENTAL WORKS

Chapter Five

Experimental Work

The water treatment by membrane separation is widely used all over the world.

The reverse osmosis is the most used in membrane technology.

The working principle of a reverse osmosis method setup used in this work is described in figure 5.1.

On a sunny day, the photovoltaic Panel Siemens (SM55), which converts solar radiation energy to electricity, was connected parallel into Booster DC Pump to operate it, without the need of using any inverter or converter; it is used to increase the feed water pressure. The feed water is mechanically pre-filtered to remove particulates and sediments or chemical that may clog the RO membranes.

The pressurized feed water enters the reverse osmosis membrane at a certain pressure to allow water molecules to pass through the membrane but prevent passage of salts and other contaminants.

Many experiments were carried out to examine the effect of solar radiation, pressure, permeate flow rate, retentate flow rate, TDS, pH, and feed water temperature on the performance of the system.

A high pressure pump is used to drive water to the RO unit, the power and pressure of such pumps should be selected according to the treated water salinity and other characteristics.

In this work the water salinity used is 397 mg/L which can be considered to be low but it contains many contaminants such as fecal coliform and high potassium concentration.

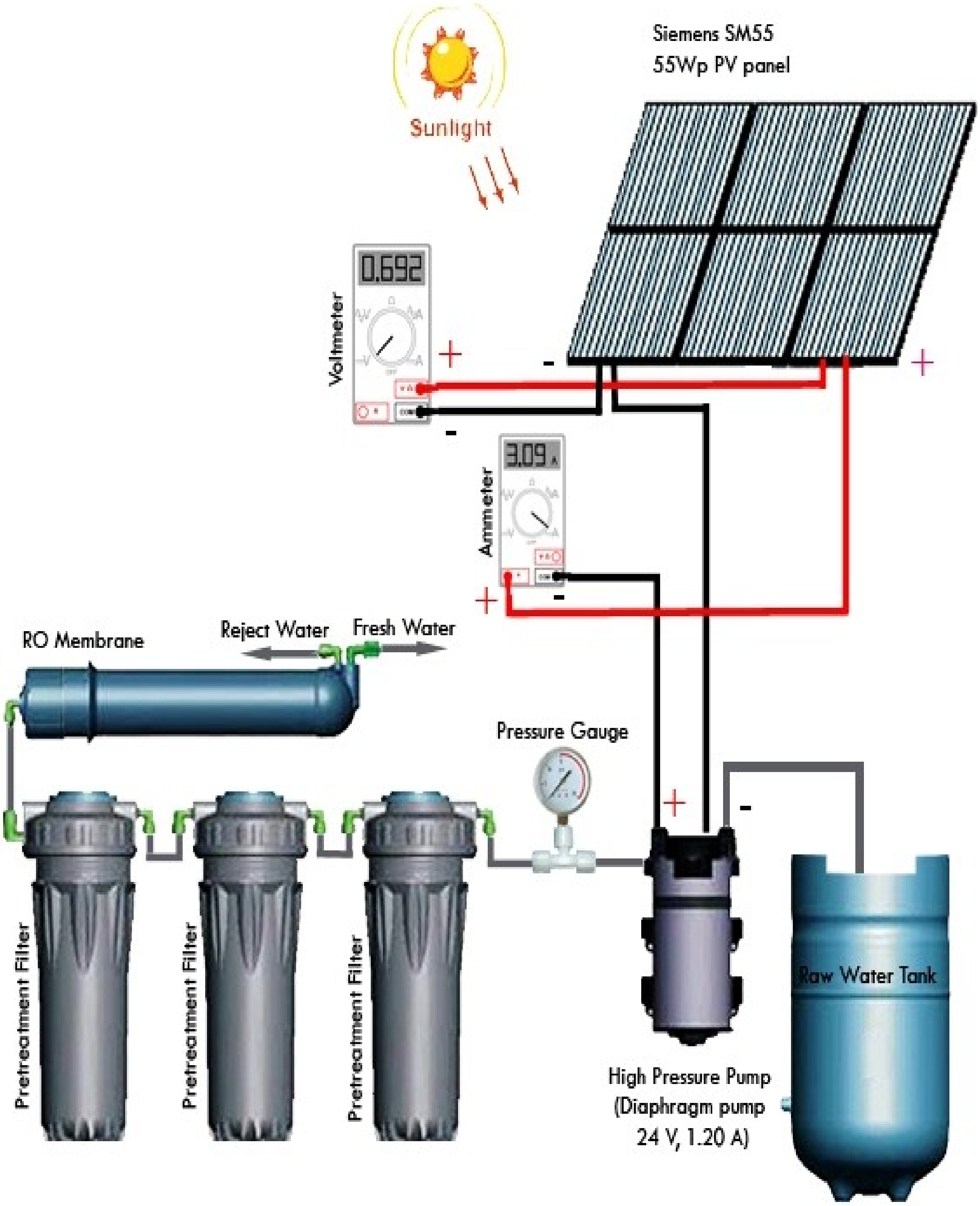


Figure (5.1): Assembly diagram of the PV-RO system

The main characteristics of this water are given in table 5.1, the main source of this water is shraish spring located in Nablus city in West Bank.

Table (5.1): Characteristics of shraish spring

pH	TDS (mg/L)	Fecal (cfu/100ml)	Turbidity (NTU)	K^+ (mg/L)
7.62	397	600	0.26	30

The used Pump is Booster (Diaphragm) Pump that can give 378 liter/day flow rate, the specification of the Pump is listed in table 5.2.

Table (5.2): Specification of the DC pump

Power	11 Watt
Input Voltage:	DC 24 V
Pressure	Up to 4 Bar
Prime	Self-Priming up to 2~3 meter
Capacity	378 L/day

The selected pump can be driven easily by small PV panel, a single photovoltaic module was used because it is enough to operate the 11 watt DC Pump.

The specification of the photovoltaic is listed below in table 5.3.

Table (5.3): Specification of the photovoltaic cell

Solar module SM55(Siemens)	
Electrical parameters	
Maximum power rating Pmax [Wp]	55
Rated current I_{mpp} [A]	3.15
Rated voltage V_{mpp} [V]	17.4
Short circuit current I_{sc} [A]	3.45
Open circuit voltage V_{oc} [V]	21.7
Thermal parameters	
NOCT [°C]	45±2
Temp. coefficient: short-circuit current	1.2mA / °C
Temp. coefficient: open-circuit voltage	077V / °C

The Feed water was treated from replaceable prefilter sediment-carbon cartridges.

The water first passes through the first filter; 5 micron filter, removes sediment, clay, silt and particulate matter to 5 micron range.

The second carbon filter removes chlorine, harmful chemicals, synthetic detergents, as well as other organic contaminants.

The third filter compacted carbon block, where a combination of mechanical filtration and physical/chemical adsorption takes place to reduce or eliminate a wide range of contaminants.

The reverse osmosis membrane was made with a polyamide thin film composite membrane in spiral wound configuration with flow rate of 150 liter per day, which is not chlorine tolerant, it is separates up to +99% of most remaining unwanted impurities from water, including bacteria, chlorine, virus, hardness trihalomethanes, E.coli, giardia, cryptosporidium, nitrates, fluoride, heavy metals, inorganic minerals, and makes water safe for drinking.

Many experiments were conducted to study the affect of operating parameters on the membrane performance; of these parameters the following were investigated.

1. **Effect of Solar Radiation**

The solar radiation is an important parameters that affects the system performance.

The power generated in the solar panels is directly affected by the solar radiation.

The power input to the pump is significantly affected the pressure and this affect the flow rate of water and the separation process.

To study the effect of solar radiation, the system was operated under different solar radiation values on different day times.

All other parameter such as input water quality were kept constant.

2. Effect of Retentate Flow Rate

In order to see the effect of recovery (flow rate of permeate to input flow rate ratio).

The system was modified by fixing an adjustable valve. The value was set to different opening ratios while keeping other factors constant.

3. Effect of Feed Water Temperature

The system was modified by adding a water heat exchanger to heat water before entering the reverse osmosis membrane, the experiments were carried out at different input temperatures of 33, 25, 38, 40, and 44C$^{\circ}$.

All other parameters were kept constant during these experiments.

4. Effect of Feed Water Salinity

The input water salinity is one of the most important parameters that may affect the water treatment processes, as known the higher the water salinity, the higher the osmotic pressure..

The working pressure should be adjusted to a suitable value to overcome the osmotic pressure, since the working pressure is dependent on the solar radiation, it is expected that either the flow rate or permeate water quality could be affected.

The input water salinity was adjusted by adding NaCl to produce solution concentrations of 500, 650 and 800 ppm. All other parameter were kept constant.

CHAPTER SIX

RESULTS AND DISCUSSION

Chapter SIX

Results and Discussion

The experimental results were measured by using many appropriate devices such as: ammeter and voltmeter to measure the current and voltage through the pump that helps to calculate the photovoltaic panels output power, pressure gauge to measure the pressure output from the DC pump. The water quality was analyzed using conductivity meter (Dist 1, HANNA H198301), pH meter (pH 211, microprocessor based, Bench pH/mV/C meters), Turbidity meter (Cole Palmer, model 8391-45) and each sample is tested for Fecal Coliform (FC) as follows:

1. Filter 250 ml of bottled water or 100 ml of Water using membrane filteration technique.
2. Place filter on m-FC broth (1-7 ml) for FC at 44-50 °C.
3. Incubate FC for 18-24 hours.
4. Count the number of colony forming units and report per 100 ml.

6.1 Effect of Solar Radiation

In order to study the effect of solar radiation on the system performance, the system was operated under different solar radiation, this was performed by selecting different times during the day, as known, the maximum solar radiation can be obtained around 13:00 PM, the initial salinity of inlet water was fixed at 397mg/L as can seen in table 6.1.

As can be seen in figure 6.1 there is almost a direct proportional relationship between the power input to the pump and the solar radiation.

The system was operated in a sunny day in June 2009 at 9:00 AM when the solar radiation was (478.75) W/m^2. At this value of radiance the PV panel provides electrical current directly to the high pressure pump, whose speed increases as the power from the PV panel increases.

The permeate flow followed the behavior of the feed flow and reached to 7.5 L/h. The total amount of permeate produced was around 44 L with 8 h of operation as shown in figure 6.2.

Table (6.1): Effect of operating conditions on produced water quality

Date	Time	Solar radiation W/m^2 [30]	Power (W)	Flow rate of permeate (L/h)	Pressure (Bar)	pH	TDS (mg/L)	Fecal (cfu/100ml)	Turbidity (NTU)	K^+ mg/L
2/6/2009	09:00	478.75	3.6	4.1	0.63	7.8	71	0	NA	5
2/6/2009	10:00	636.75	4.9	4.3	0.71	7.6	58	0	NA	5.3
2/6/2009	10:30	748.75	7.4	4.8	0.84	6.5	28	0	0.22	6
03/06/2009	12:00	790.25	8.1	5.4	0.92	7.2	33	0	NA	8.8
03/06/2009	13:00	815.25	10.7	7.5	1.20	7.5	54	0	0.16	9.3
03/06/2009	14:00	805.75	10.2	7.1	0.95	6.9	32	0	0.19	NA
03/06/2009	15:00	790.25	8.2	5.6	0.88	7.2	33	0	NA	NA

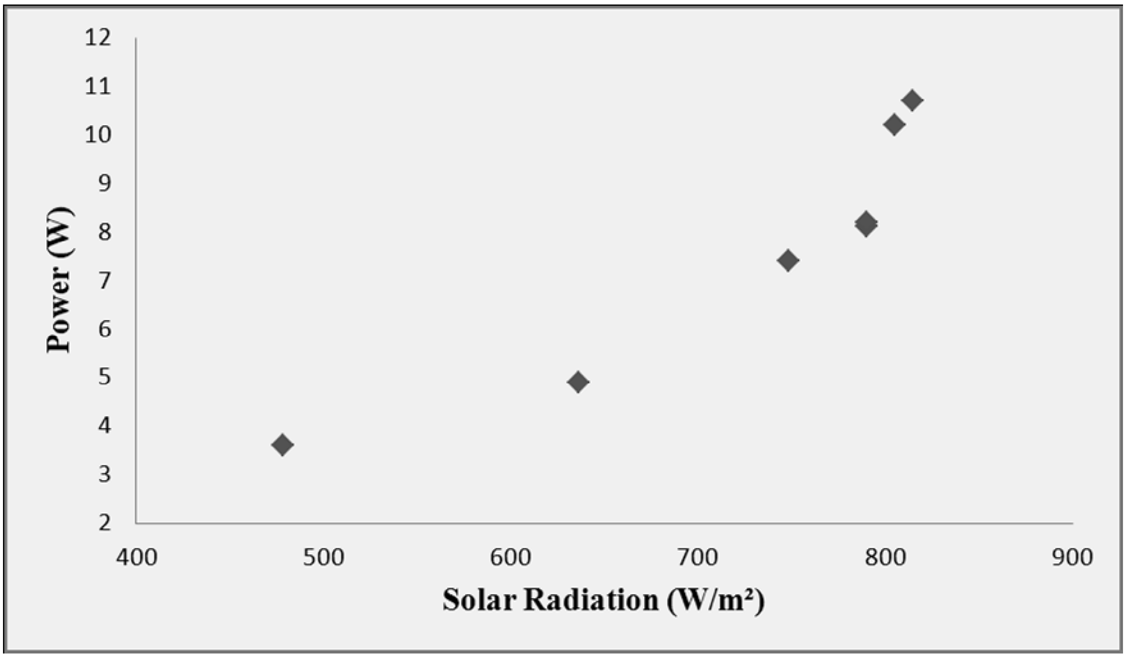


Figure (6.1): Effect of solar radiation on power input to the pump

The pressure output of the pump exit is directly proportional to the power input to the pump (as shown in figure 6.3) and as indicated earlier the power received from the solar panel is also directly proportional to the solar irradiation.

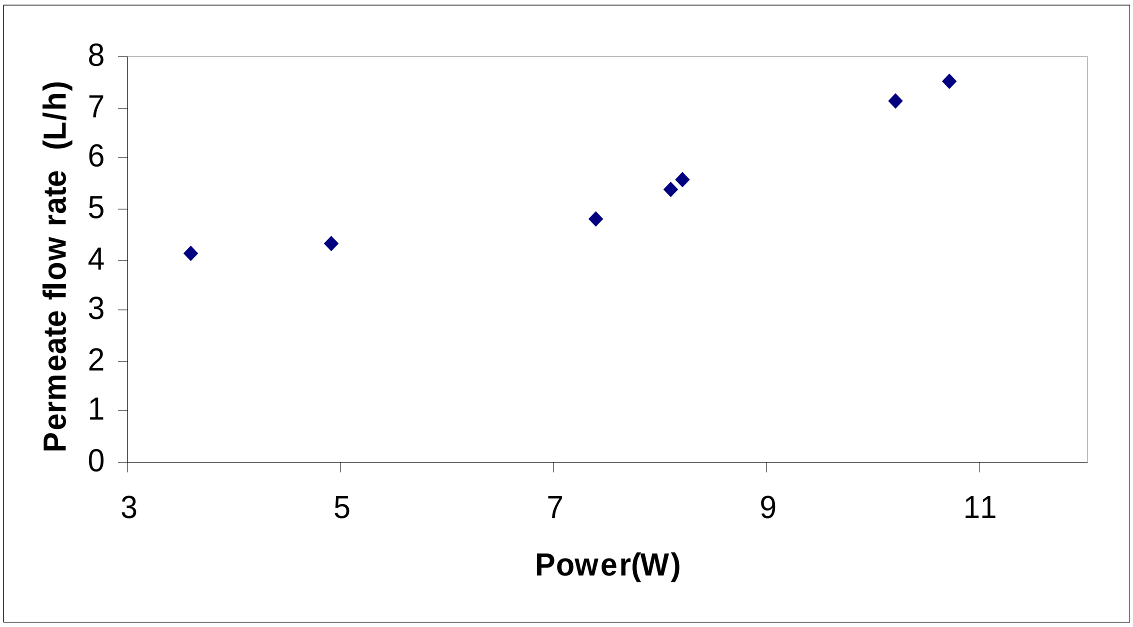


Figure (6.2): Effect of power input to the pump on permeate flowrate

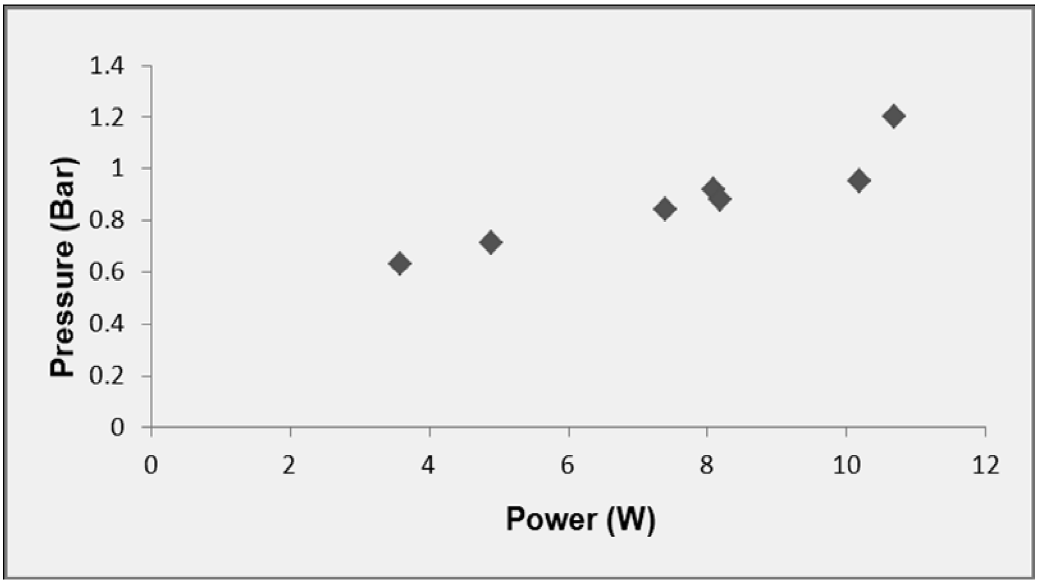


Figure (6.3): Relationship between the power input to the pump and pump pressure

As a result, one can conclude that The PV panel provides electrical current directly to the high pressure pump whose speed increases as the power from the PV panel increases.

6.2 Effect of Pump Pressure on the Permeate Water Flow rate

The membrane tube was used to study the effect of Pump Pressure on the permeate flow rate. The results are shown in Figures 6.4.

The permeate flow rate of water through the membrane is directly proportional to the pressure drop across the membrane input and output. Since the pressure at the product side is constant, and then the water flux is directly related to the feed pressure which in line with the theoretical case as shown in figure (3.10) a.

When the feed pressure increased from 0.63 bar to 1.2 bar, the permeate production increased by 83%. The permeate flow was around 7.5

L/h. The total amount of permeate collected in that day was around 60 L. The permeate salinity and salt rejection were 54 mg/L and 86.4%, respectively.

At low operating pressure, less water permeates the membrane. At higher operating pressures more water permeates from the membrane which affects water quality such that: pH, TDS decrease and K^+,turbidity increases when the flow rate of permeate water increased as can seen in figure 6.5, figure 6.6, figure 6.7 and figure 6.8 respectively. In most cases, the water pH was within the international standard which is between 6.5 and 8. [31]. These changes could be a result of water content variation.

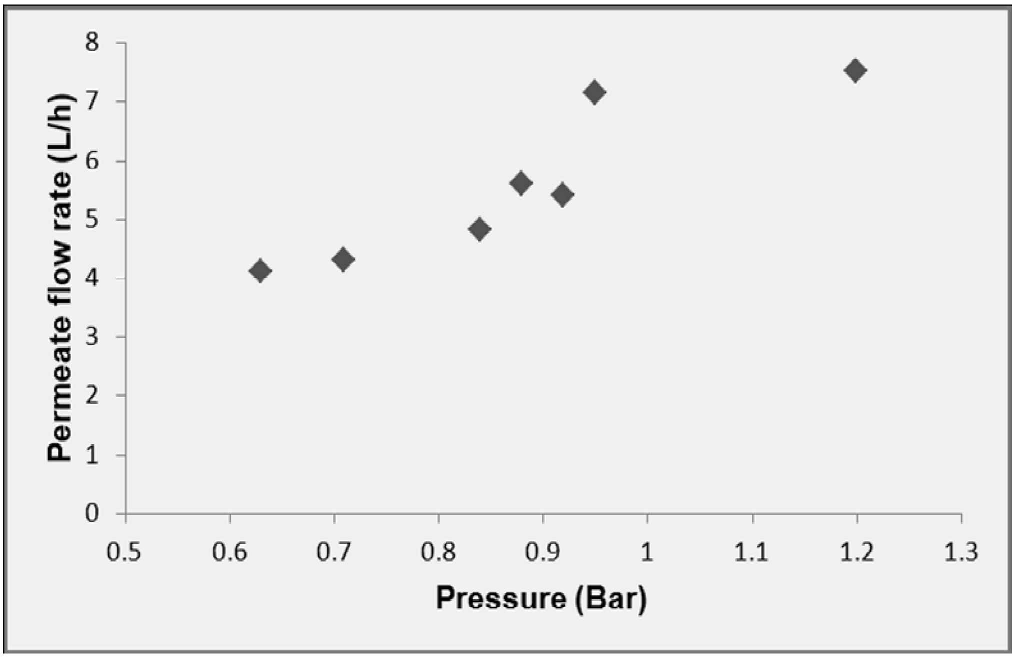


Figure (6.4): Effect of membrane Pressure on permeate flowrate

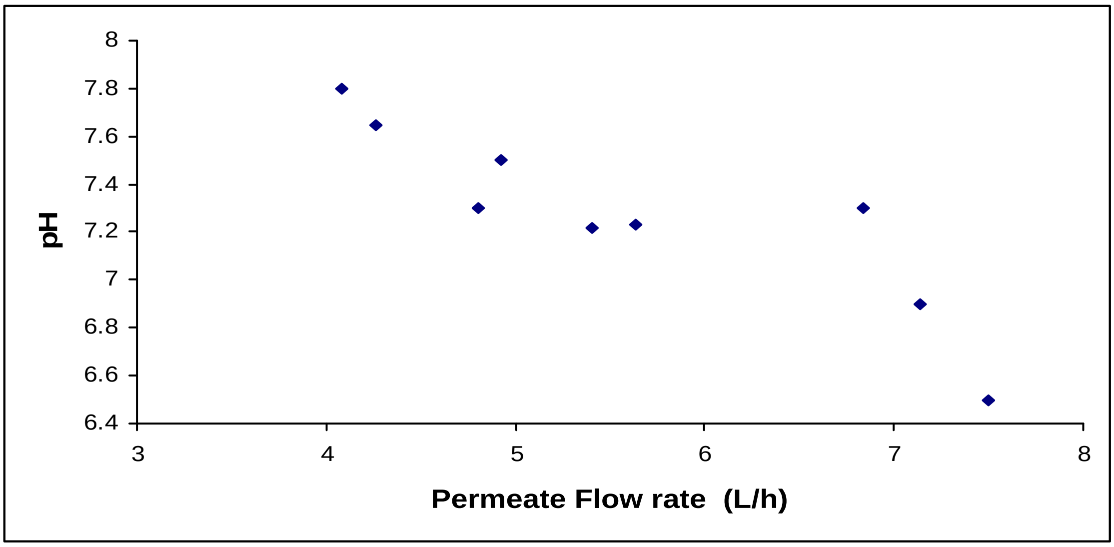


Figure (6.5): Effect of permeate flow rate on permeate pH

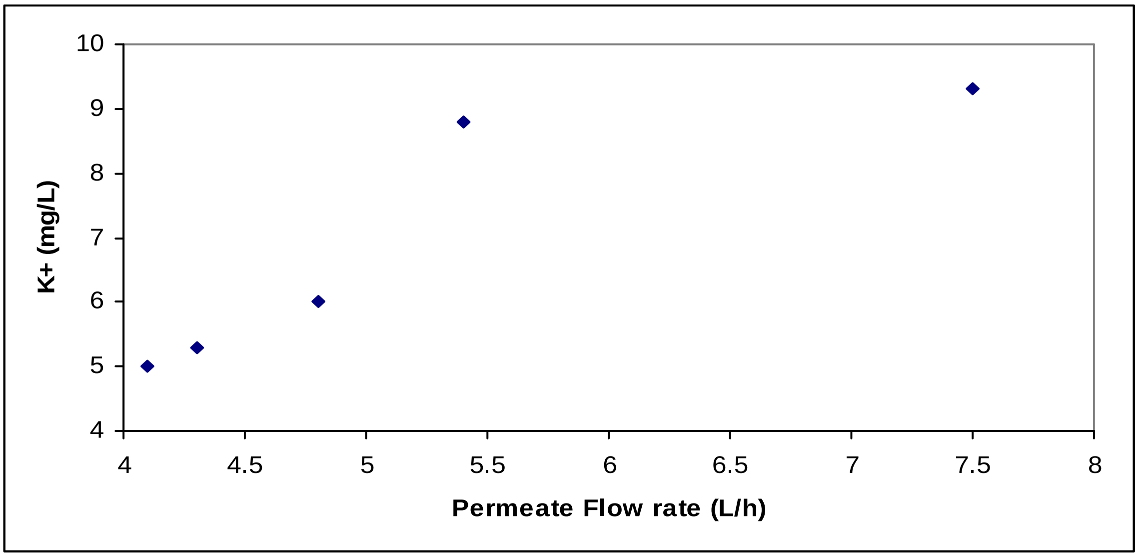


Figure (6.6): Effect of flow rate of permeate water on K^+ concentration

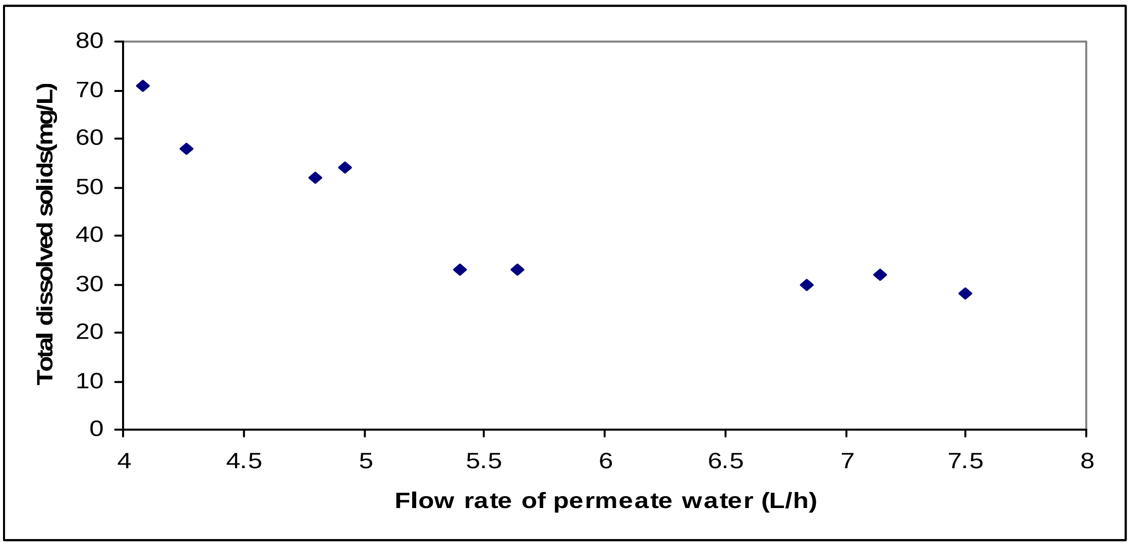


Figure (6.7): Effect of flow rate of permeate water on total dissolved solids

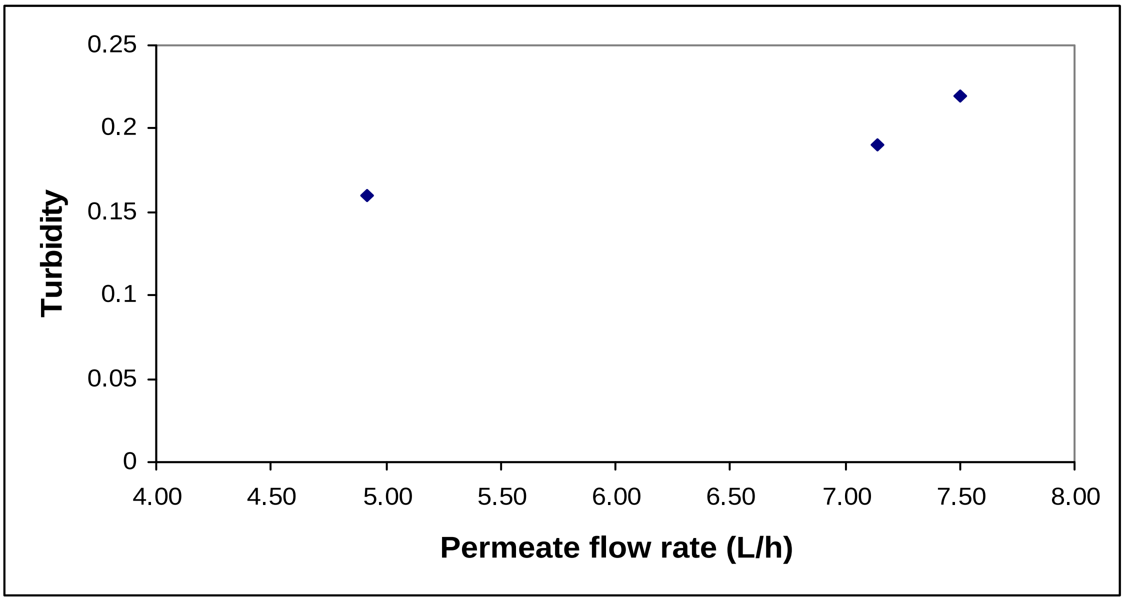


Figure (6.8): Effect of flow rate of permeate water on turbidity

6.3 Effect of Feed Water Temperature on Permeate Flow rate

Membrane productivity is very sensitive to changes in feed water temperature. As water temperature increases, water flux increases almost linearly primarily due to the higher diffusion rate of water through the membrane as elucidated in Figure 6.9 which in line with theoretical case as shown in figure (3.10) c.

The main reason for this trend is the reduction in viscosity with temperature increase. As viscosity decrease the mass transfer through the membrane surface is enhanced. Moreover the diffusion coefficient also increases with temperature [23].

Increased feed water temperature also results in lower salt rejection or higher salt passage. This is due to a higher diffusion rate for salt (salt flux) through the membrane. The opposite happens when the feed water temperature decreases; it can be calculated from the following equation:

$$\% \text{ Salt rejection} = \left(1- \frac{ProductTDS}{FeedTDS}\right) X100\% \qquad (6.1)$$

The percentage salt rejection decreased from 87.9% to 87.1% when the feed temperature increased from 33°C to 44°C.

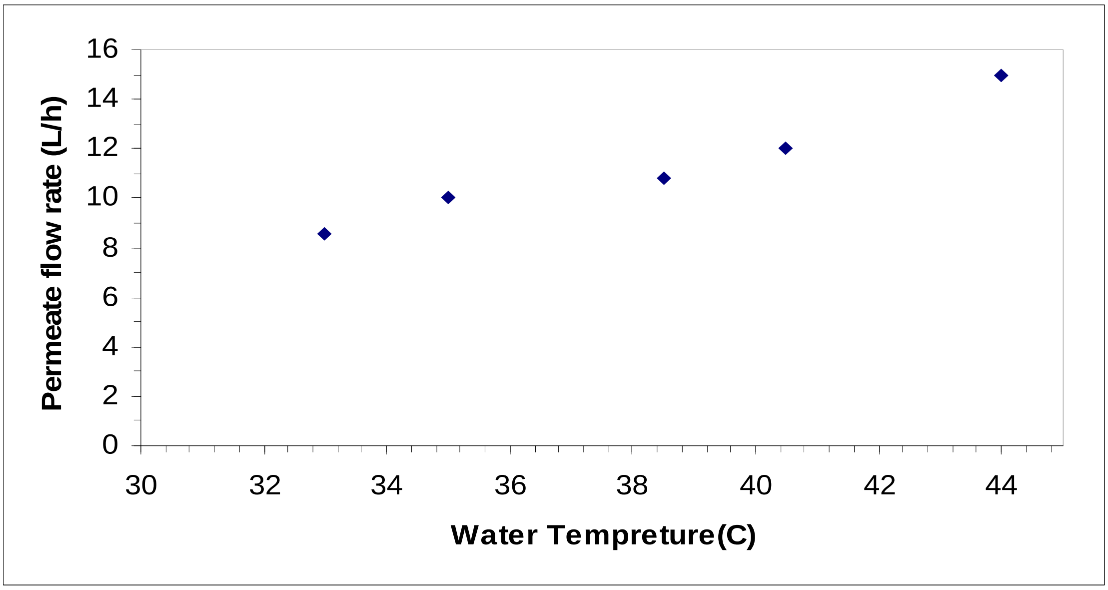


Figure (6.9): Effect of temperature on water permeate flow rate

In addition, the effect of feed water temperature on product quality is generally very small. For instance, the TDS increased from 48 to 51mg/L when the feed water temperature increased from 33 to 44 C, respectively. On the other hand, the permeate flow rate increased from 8.6 to 15 L/h for the same operating temperature. Higher temperature may not give similar results since the membrane operating temperature is recommended to be less than 50 C.

The used temperature range was found to have no effect on fecal permeability as can see in table 6.2. As expected and as can be seen in table 6.3, the retentate water quality changes consistently with the permeate water quality.

Table (6.2): Effect of water temperature on permeate water quality

Feed Water Temp (C) **Permeate Quality**	**33**	**35**	**38**	**40**	**44**
Flow rate (L/h)	8.6	10.0	10.8	12.0	15.0
pH	6.1	7.3	6.3	5.9	6.7
TDS (mg/L)	48	50	49	50	51
Fecal (cfu/100ml)	0	0	0	0	0
Turbidity (NTU)	0.15	0.14	-	-	-
K^+ (mg/L)	7.1	7.5	8.4	8.4	8.3

Table (6.3): Effect of feed water temperature on retentate properties

Feed Water Temp (C) **Retentate Quality**	**33**	**35**	**38**	**40**	**44**
Flow rate (L/h)	27	28.56	27.6	27.6	30
pH	7.28	8.01	7.32	7.13	7.3
TDS (mg/L)	474	477	470	491	493
Fecal (cfu/100ml)	80	70	-	-	-
Turbidity (NTU)	0.146	0.144	-	-	-
K^+ (mg/L)	39.5	38	44	44.5	45

6.4. Effect of Feed water Salinity on Flowrate Salinity of Permeate Water

Reverse osmosis membrane is highly effective in removing low total dissolved solids (TDS) from water at low pressures. Higher salinity requires very high pressure since the osmotic pressure of water increase almost linearly with increasing salt content. The osmotic pressure π, is given by van't Hoff formula, which is identical to the pressure formula of an ideal gas: $\pi = cRT$, where c is the molar concentration of the solute, R = 0.082 (liter.bar) / (deg.mol), is the gas constant, and T is the temperature on the absolute temperature scale (Kelvin). The osmotic pressure does not depend on the solute type, or its molecular size, but only on its molar concentration. As a result, higher operating pressures are needed to overcome the osmotic pressure. If low pressure pump is used, generally very low recovery can be achieved. Figure 6.10 shows the rapid decrease in permeate flowrate when the feed water contains high salt concentration. As a result, the obtained permeate concentration also increase which in line with theoretical case as shown ij figure (2.10) e. As shown in table 6.4, the permeate water salinity increased from 72 to 127 mg/L when the feed salinity increased from 495 to 811mg/L, respectively.

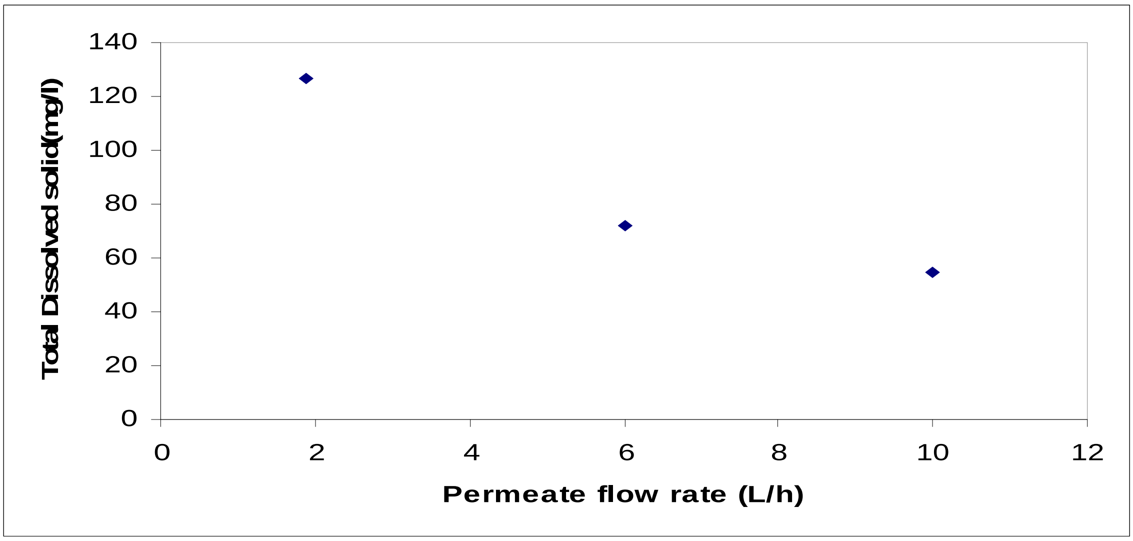


Figure (6.10): Effect of total dissolved solids (TDS) of feed water on flowrate of permeate water at constant power and feed pressure.

Table (6.4): Effect of TDS on flow rate of permeate water

Feed Water TDS(mg/l) **Permeate Quality**	**495**	**652**	**811**
Permeate flow rate (L/h)	10	6	1.87
TDS (mg/L)	55	72	127

6.5 Effect of Recovery on Permeate Water Quality

The recovery is defined as the ratio of permeate flowrate to the feed flowrate. This ratio is recommended to be more than 90% to have efficient desalination process. But if the water to be treated is biologically contaminated, the obtained recovery became a key factor in the operating conditions. Generally, one can change the recovery by forcing the retentate water to change. For this purpose a special type of valve is fixed at the retentate exit. A pronounced effect on the permeate water quality occurred when the recovery increased. As shown in table 6.5, the fecal was observed for the first time when the recovery changed (all previous experiments were performed keeping free retentate flowrate). Also higher TDS values were noticed while no remarkable changes in pH and potassium values were observed.

Table (6.5): Effect of recovery on permeate water quality

Power (W)	Permeate flowrate (L/h)	Retentate flowrate (L/h)	Permeate water properties				Recovery
			pH	TDS (mg/L)	Fecal (cfu / 100ml)	K^+ (mg/L)	
8.73	5.88	22.73	5.97	35	10	6.1	20%
7.98	13.04	13.95	6.1	43	17	6.6	48%
8.17	14.15	6.98	6.2	63	45	6.8	67%

CHAPTER SEVEN

ECONOMIC EVALUATION OF SMALL RO UNIT POWERED BY PV SYSTEM

CHAPTER SEVEN

ECONOMIC EVALUATION OF SMALL RO UNIT POWERED BY PV SYSTEM

7.1 Cost Analysis

It is one of the most important steps in solar-powered water treatment system planning. The photovoltaic energy system differ from conventional energy systems in that they have high initial cost and low operating costs.

The product cost is strongly correlated with unit capacity, quality of feed water, pretreatment, types of water treatment technology, site condition, costs of land and additional costs.

So the average daily water flow rate can be calculated as the following:

During June, the average flow rate 44.32 L/day, (day= 8hours) and the monthly average solar radiation was 8.25 kWh/m^2.day.

According to other months, the average water flow rates were calculated corresponding to the monthly average solar radiation as shown in table 7.1.

Table (7.1): Average daily water flow rates

Month	Monthly averge solar radiation KW.hr/m².day [19]	Water Flow rate (L/day)
1	2.89	0
2	3.25	0
3	5.23	28.09
4	6.25	33.57
5	7.56	40.61
6	8.25	44.32
7	8.17	43.89
8	8.10	43.51
9	6.30	33.84
10	4.7	25.24
11	3.56	19.12
12	2.84	0
Total		312.19

The average water flow rate = $\frac{312.19(L/d)}{9}$ =34.68 L/day

The major cost elements for water treatment plants are capital cost and annual operating costs.

To determine the average annual cost of the water treatment system, it depends on common economic parameter such that interest rate, expected lifetime and total initial investment. These parameters are listed below:

- Plant life time is 25 years.
- Operating days per year are 270 days.
- Feed water TDS is 400 mg/L (normal case).
- Operating and maintenance (O&M) costs are 20% of the system annual payment.

- Annual rate of membrane replacement is 20%.
- Interest rate is 10%.
- Plant availability (f) is 74%.
- Capacity(M)=35 L/day
- Salvage value of the units will be zero.

7.1.1 Capital Cost

The total capital cost of PV module = 55Watt X 7.27 $/Watt.

=400$

A detailed cost analysis of the system has been completed and is summarized below in table 7.1.

Table (7.2): Capital cost summary

Item	Cost
PV module (Siemens SM55, 55Wp)	400$
Reverse Osmosis Membrane	100$
Booster Pump (12VDC)	150$
3 stages pretreatment filters, accessories	100$
Total	750$

7.1.2 Annual Operating Costs

Annual operating cost covers all expenses after commissioning and during the actual operation

7.1.2.1 Fixed Charges

To determine the fixed charge value of the capital costs, these costs are multiplied by an amortization factor (*a*)

The fixed charges factor is a function of the interest rate(i) which is value 10% of the capital and the numbers of years over which the investment is recovered which is value 25 years. The fixed charges factor can be calculated using the following relationship [32].

$$\boxed{a = \frac{i(1+i)^n}{(1+i)^n - 1}} \qquad (7.1)$$

Where *i* is the interest rate of the amortized investment (%) and *n* is the period of repayment of capital expenditures (life time).

$$a = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$a = \frac{0.1(1+0.1)^{25}}{(1+0.1)^{25} - 1}$$

$$a = 0.11y^{-1}$$

- **Annual fixed charges (A_{fixed}):**

$$\boxed{A_{fixed} = (a) \text{ X } (CC)} \qquad (7.2)$$

A_{fixed} = 0.11 y^{-1}X750$ =82.5$/year

7.1.2.2 Operating and Maintenance (O&M) Costs

This includes the operation and maintenance staff cost, cost of spares, etc. This cost shall be expressed on a yearly basis for each item for all the commercial operation period. The annual O&M costs are estimated at 20% of the plant annual payment [33].

- **Annual operating and maintenance costs (*AO&M*)**

$$\boxed{A_{o\&m} = \mathbf{(20\%)\ X\ (} A_{fixed} \mathbf{)}} \qquad (7.3)$$

$A_{o\&m}$ = (20%) X (82.5) \$/year=16.5\$/year

7.1.2.3. Membrane Replacement

The success of an RO system depends upon membrane life and performance Membranes lose performance and are replaced due to raw water quality, the deposition of unwanted materials on the surface. In addition, a decrease in membrane performance may be due to other factors, i.e., degradation by chemical (oxidation, hydrolysis).

Replacement rate may vary between 5%–20% per year [32].

- **Annual membrane replacement costs ($A_{replacement}$):**

$$\boxed{A_{replacement} = (20\%)\ \text{X}\ (\text{Membrane Cost})} \qquad (7.4)$$

$A_{replacement}$ = (20%) X100\$=20\$/Year

- **Total annual cost (A_{total})**

$$\boxed{A_{total} = A_{fixed} + A_{replacement} + A_{o\&m}} \tag{7.5}$$

A_{total} =82.5$/year+20$/Year+16.5$/year=119$/year

- **Unit production cost (A_{unit})**

$$\boxed{A_{unit} = \frac{(A_{total})}{(f)(M)(300)}} \tag{7.6}$$

$$A_{unit} = \frac{119\$ / year}{(74\% \times 0.035 m^3 / day)(270 day / year)}$$

A_{unit} =17$/m^3

7.2 Life Cycle Cost

For the present system, the life cycle cost will be estimated as follows:

1. The life cycle of the system components will be considered as 25 years.
2. The interest rate is about 10%.

The initial cost of the system =PV module + reverse osmosis membrane cost+ pump cost+ pretreatment filters cost.

The initial cost of the system = 400$+100$+150$+100$

=750$

The annual maintenance and operation cost is about 20% of initial cost which is equal 150$/year, salvage value of the system will be zero.

The life cycle cost of unit is obtained by drawing cash flow as in figure (7.1)

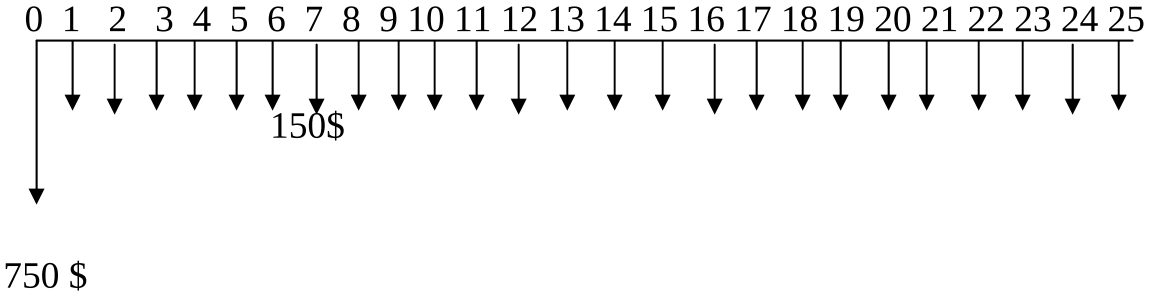


Figure (7.1): Cash flow of units

To calculate the equivalent uniform annual series A of cash flow in figure(7.1) which include randomly placed single amounts and uniform series amounts, the most important fact to remember is to first convert everything to a present worth or future worth. Then the equivalent uniform series is obtained with appropriate A/P or A/F factors [34].

The life cycle cost of the system = initial cost of the system + present worth of maintenance and operation – present worth of salvage value.

The life cycle cost of the system = 750$ + 150 (P/A$_{i,n}$) - 0

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad i \neq 0 \qquad (7.7)$$

P = A (9.077)

(P/A$_{i,n}$)=9.077

PW= 750$ + 150 X 9.077

= 2111.55 $.

Then the equivalent annual worth AW is obtained with appropriate A/P, as follow:

AW = PW $(A/P_{i,n})$ =2111.55$ $(A/P_{10\%,25})$.

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \qquad i \neq 0 \qquad (7.8)$$

A=P (0.11017)

$(A/P_{10\%,25})$ =0.11017

AW= PW $(A/P_{i,n})$ =2111.55$ X0.11017=232.6$

The Cost of 1KWh producing from PV was calculated corresponding to the average Power consumption and the average flow rate at June month.

During June, the average flow rate 44.32 L/day, (day= 8hours) and the average power consumption was 7.59 W.

According to other months, the average power consumption was calculated corresponding to the monthly average water flow rate as shown in table 7.3.

Table (7.3): Monthly average power consumption

Month	**Power (W)**	**Water Flow rate (L/day)**
1	0	0
2	0	0
3	4.81	28.09
4	5.75	33.57
5	6.95	40.61
6	7.59	44.32
7	7.52	43.89
8	7.45	43.51
9	5.80	33.84
10	4.32	25.24
11	3.27	19.12
12	0	0
Total	53.38	312.19

- The average water flow rate = $\frac{312.19(L/d)}{9}$ =34.68 L/day.
- The average power consumption = $\frac{53.38W}{9}$ =5.93W

Energy consumption/year= average yearly power consumption/day X operating hours.

=5.93W X 8 h X270 days=12.8KWh/year

The cost of 1 KWh from the PV generator = 232.6$/12.8KWh

= 18.17$/KWh.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

Chapter Eight

Conclusions and Recommendations

8.1. Conclusions

- The looming water crises in Palestine can be significantly reduced by the exploitation of the abundant brackish and surface water resources such as Wadi Fara'a Stream which is a natural catchment of a great value due to its abundant water resources represented by four groups of springs that irrigate large areas of agricultural lands.

Palestine has very rich solar radiation intensity. The average annual daily solar radiation ranges 5 kWh/m^2.day which provides the optimal option to generate the energy demand for small water treatment units in remote areas.

The combination between renewable energies specially (photovoltaic cells) and RO Water Treatment Processes very suitable in Palestine for remote sites lacking of electric grids where water scarcity is a big problem and, at the same time, the solar energy potential is high.

- The pressure output of the pump exit is directly proportional to the power input to the pump and the power received from the solar panel is also directly proportional to the solar irradiation.

- The rate of production of fresh water by using a photovoltaic-powered household RO unit without storage batteries under different operating conditions, varied throughout the day according to the available solar power.

- The effect of operating parameters on the reverse osmosis membrane performance was investigated. It was found that increasing the solar radiation, pump pressure, and feed water temperature has enhanced the permeate flux. Increasing the TDS, on the other hand, has reduced the permeate flux, and the water quality was within the international standard to be safe drinking water.

- The effect on product quality is generally a very small change compared to the Change observed in productivity when the feed temperature increased from 33°C to 44°C.

- Reverse osmosis membrane is highly effective in removing low total dissolved solids (TDS) from water at low pressures.

- Economically, it was found that although the energy is free, the water production cost from the PV–RO unit is \$17/m^3 which is still expensive and can not be economically viable, only in remote areas and far from conventional energy sources compared to water produced from plants that run on grid electricity.

- It is not economical or practical to provide all energy with PV modules because the solar radiation in the main three winter months is low. Large number of PV modules would be in this case required to meet load requirements for 24h/day. This issue will increase the initial investment cost and will increase the waste or dumped energy in summer where the solar radiation is high.

- One source of renewable energy was not economically viable and could be used as another source assistant as hybrid system which is economical and available for 24h/day along the year.

8.2. Recommendations

- It is recommended that future work be focused on another Power source as a wind turbine and can be utilized in such sites where the annual average wind speed exceeds 5 m/s.

- Other sources of water with different characteristics can be also tested. The effect of fecal concentration can be investigated by changing the source of water.

- Different membrane arrangement such series and parallel configurations can be also tested to see the effect of recovery.

- Design of solar heaters that can heat the feed water prior to membrane treatment is highly recommended.

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جامعة النجاح الوطنية

كلية الدراسات العليا

معالجة المياه السطحية باستخدام الخلايا الغشائية التي تعمل بالطاقة الشمسية

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قدمت هذه الأطروحة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد الإستهلاك بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.

2010م

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الملخص

بالإضافة إلى نقص موارد المياه العذبة، فلسطين تعاني من نقص موارد الطاقة التقليدية مثل النفط الخام والغاز الطبيعي ومصادر الطاقة المحدودة في فلسطين يجعل خيارات الطاقة المتجددة مثل الطاقة الشمسية جذابة للغاية وخاصة في المناطق النائية وبالتالي سيكون أمرا بالغ الأهمية للتطبيقات صغيرة الحجم بسبب الظروف الصعبة السائدة مثل تدني نوعية المياه ونقص في الإمدادات حيث أن هناك طلب كبير على وحدات صغيرة لمعالجة المياه للحصول على مياه صالحه للشرب.

في هذه الأطروحة، أجريت دراسة للتحقق من إمكانية تطوير وحدة معالجة مياه صغيرة تعمل بالخلايا الشمسية باستخدام نظام التناضح العكسي في فلسطين. وقد تم بناء نموذج اختبار يشمل على نظام معالجة المياه بالتناضح العكسي تعمل بطاقة الخلايا الشمسية ويتكون النظام من فلتر الرواسب الترابية (5 ميكرون) وهي مصنوعة من مادة البولي بروبيلين واثنين من فلتر الكربون النشط 1-2 مايكروميتر، ومركب غشاء التناضح العكسي وخلية شمسية واحدة بقدره مقدارها 55 واط مائلة بزاوية 45 درجة جنوبا وهي موصولة مباشره بمضخة ذات تيار كهربائي مستمر التي يمكن أن تعطي ضغط يصل إلى 1.2 بار ومعدل تدفق مياه يصل إلى 34.68 لتر/ يوم باستخدام مياه عين شريش تقع في مدينة نابلس في فلسطين.

إن النظام يعمل بتدفق المياه بشكل متغير مما مكّن من تحقيق الاستخدام الأمثل لمصدر الطاقة الشمسية الطبيعي والمتغير دون الحاجة إلى بطاريات.

تمت دراسة ظروف التشغيل المختلفة من الإشعاع الشمسي وضغط المضخة ودرجة حرارة المياه المغذية للنظام، والمواد الصلبة الذائبة بالمياه والضغط عبر الغشاء من أجل معرفة مدى تأثيرها على معدل تدفق وجودة المياه .

وجد أن زيادة الإشعاع الشمسي وضغط المضخة ودرجة حرارة المياه يعزز تدفق المياه الناتجة، وإن زيادة المواد الصلبة الذائبة يقلل من تدفق المياه الناتجة مع بقاء جودة المياه ضمن المعايير الدولية لمياه الشرب المأمونة، من ناحية أخرى، هناك تأثير واضح على جودة المياه الناتجة عند زيادة الاسترداد، حيث أنه للمرة الأولى التي يلاحظ فيها وجود بكتيريا في المياه الناتجة.

استنادا إلى الحسابات، تُقَدر تكلفة المياه الناتجة من قبل النظام ب $ 17/ متر مكعب. وثمن المياه الناتجة من نظام يعمل بالطاقة الشمسية لمعالجة المياه لا يمكن أن تكون مجديه اقتصاديا إلا في المناطق النائية والبعيدة عن مصادر الطاقة التقليدية أو أثناء الكوارث التي لا تتوافر فيها المياه الصالحة للشرب.