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Master's Thesis in Environmental Technology

A NEW DESIGN OF A COST EFFECTIVE MEMBRANE DESALINATION PLANT POWERED BY A WIND TURBINE

Anna Simonova

Abstract

Wind is a plentiful source of energy. Wind turbines used to generate electricity come in a variety of sizes. Large wind turbines, which are usually installed in clusters are called wind farms, and can generate large amounts of electricity. Large wind turbines may even produce several hundreds of megawatts (MW) of electricity – enough to power hundreds of homes. Small wind turbines, which are generally defined as producing no more than 100 kW of electricity, are designed to be installed at homes, farms and in small businesses, either as a source of backup electricity, or to offset use of utility power and reduce electricity bills. Very small wind turbines (20 – 50 Watt units) are used to charge batteries for sailboats and other recreational uses – wind turbines in the range of 1 kW to 7.5 kW are usually used to charge special designed battery power banks – delivering power as needed to for example a membrane water desalination system – and even for treating brackish water or any other polluted water source unfit for consumption.

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Abbreviation list

AC	Alternating Current
ATMA	America's Authority in Membranes Treatment
CA	Cellulose Acetate
DC	Direct Current
DS	Dissolved Solids
ED	Electrodialysis
HPP	High Pressure Pump
HAWT	Horizontal Axis Wind Turbines
LPP	Low Pressure Pump
LWT	Large Wind Turbines
MED	Multiple-effect distillation
MSF	Multi-stage flash distillation
MWCO	Molecular Weight Cut-Off
MWT	Medium Wind Turbines
NF	Nano Filtration
NTU	Nephelometric Turbidity Units
PA	Poly Amide
PACI	Polyaluminum Chloride
PBTCA	Bayhibit
PCVA	Pressure Control Valve
PEEK	Polyether Ether Ketone
PICI	Polyiron Chloride
PMA	Permanent Magnet Alternator
PPM	Parts Per Million
RO	Reverse Osmosis
RPM	Revolutions Per Minute
SDI	Silt Density Index
SHMP	Sodiumhexameta-Phosphate
SOVA	Shut Off Valve
SS	Suspended Solids
SWT	Small Wind Turbines
TD	Thermal Desalination
TDS	Total Dissolved Solids
TFC	Thin-Film Composite
TSS	Total Suspended Solids
UF	Ultra Filtration
UFFV	Ultrafiltration Flush Valve
UV	Ultra Violet
VAWT	Vertical Axis Wind Turbines
VCD	Vapor-compression distillation

Introduction

During the last century the world's population has increased exponentially, and new technology (computers, televisions, refrigerators and other electric consuming articles) are items now looked upon, not only as common, but as necessities that everyone should have rather than being luxury items.

These new developed technologies have undoubtedly increased the demand for more energy. In order to supply the market with sufficient energy, fossil fuels have, up to now, been the number one source of electrical energy production.

Fossil reservoirs are limited and will take millions of year to renew. When fossil fuels are burned, carbon dioxide (CO_2), and other unwanted greenhouse gases, are emitted to the atmosphere, which is one of the reasons for global climate change. The increased atmospheric CO_2 has also affected the Ocean. The diffusion rate of CO_2 (air-water), has lowered the pH of the world's oceans (Royal Society, 2005).

Replacing fossil fuels with renewable energy sources is a necessity. Hydro, wind, and solar power are, at present, the most promising technologies capable of coping with this problem. Recent advances in green technology have proven that renewable energy is more cost effective and environmental friendly as an energy source when compared to fossil fuels (Narasaiah, 2001).

Along with increased energy demand, an increasing population also increases the demand for clean water.

Water is an ideal solvent. Water has a unique chemical property that gives it the ability to dissolve other materials, even organics; there are no other liquids with the same properties. However, the unique properties of water also make it a challenging substance to work with and remove unwanted contaminates. Almost everything water comes in contact with, like fats (plastics), some noble metals and special alloys are hardly or not dissolved at all by clean water.

In Norway, there is an ample supply of water, a situation that is quite the opposite compared to many other places on Earth. In some arid environments, where the infrastructure is poorly developed, water is often either missing or polluted. Along the coast there is more than enough water in the ocean. However, this water needs to be treated (*desalinated*), in order to be drinkable, and this is an energy consuming process.

By combining green energy, e.g. wind turbine, hydro power or solar plants with the desalination process called Reverse Osmosis two problems can be solved: 1) produce clean drinking water that could then be made readily available, and 2) developing a power source that would provide the energy necessary for this process to occur. Water desalination by reverse osmosis using wind turbines is not an unknown technology. One desalination plant powered by wind turbines was installed on the island of Gran Canaria in the Canarian Archipelago (Carta et al., 2003), which showed the effectiveness of this technology. Similar projects have been developed in Chania, Crete, and Greece, using both wind and solar power as energy sources for water desalination by Reverse Osmosis (García-Rodríguez, 2002).

Chapter one: Wind turbines

1.1 History of Wind Turbines

The weather phenomenon, wind, has existed longer than mankind; however, the knowledge gap has hindered mankind's exploitation of the kinetic energy that wind carries for performing work.

One might ask one's self why the development of windmills to harness energy took millennia. The pioneers of this technology were people who wanted to discover and uncover its unknown potential. The pioneers of windmill technology were challenged by a lack of understanding of wind technology. Since the nature of wind was not truly understood, the first windmills were primitively constructed. As time went by, metallurgists became aware of alloys, which they were able to use to fashion improved turbine blades and make other improvements over time as they revealed themselves.

Before the industrial revolution, people were exploiting windmills to grind grains and for transport of water to irrigation systems. Ancient civilizations (e.g. Persians and Romans Figure 1.1.b) used windmills. In fact, the first known sketch of a windmill was done by the Greek engineer Heron (Drachmann., 1961.) as shown in Figure 1.1.a. Similar ideas about wind energy arose on different continents and even the isolated Chinese Dynasties were operating vertical-axis windmills in draining rice fields (Hau., 2006). Windmills began appearing in other European countries like Denmark, Germany, Scotland, etc… They were largely used in rural regions.

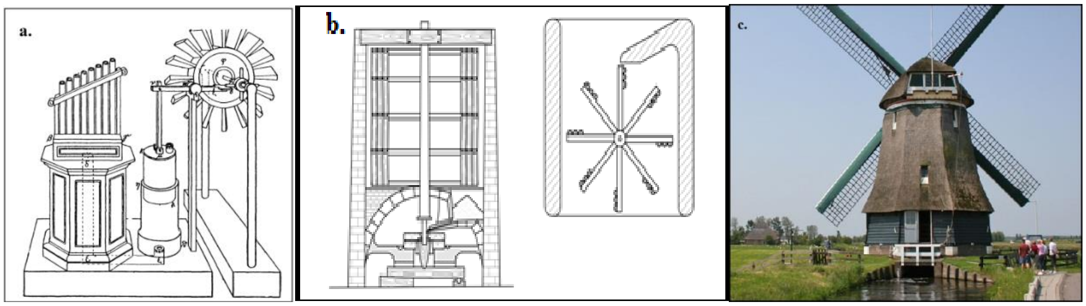


Figure 1.1: Evolution of the windmills: a) Heron's windmill (image_1, 2012); b) Persians vertical axes windmill (image_2, 2012); c) Dutch windmill (image_3, 2012).

The Dutch windmills (Figure 1.1.c) are an iconic symbol of Holland. They were used for milling grain into flour. However, neither electric generating turbines nor batteries were invented at their outset. This meant that windmills were only working *in-situ*, thus the size of older windmills were large. These large windmills consisted of both blades and the specific mechanical equipment required for the task of milling.

The first electricity producing wind turbine was invented in 1887 by Professor James Blyth in Scotland (Alireza Khaligh, 2010). Design of the wind turbines has improved during the last hundred years; wind blades made of wood were replaced by the steel blades, wind shaft production was changed from wood to iron, and so on. Engineers are still working on the improving wind turbine design. The technology has progressed quite a bit and countries like England and Denmark are partly supplied by energy produced from wind turbine farms. Statoil and Statkraft have joined forces to create and develop Hywind (the first full-scale floating wind turbine (Statoil Hywind project, 2012)).

1.2 Wind Turbines

Wind turbines are machines that convert wind energy into rotational energy. The energy gained from the wind turbines can then be utilized in different areas. Wind turbines are essentially windmills used to produce electrical energy.

Many factors have to be considered when improving the working quality of wind turbines. The first wind turbines used direct current (DC) dynamo's, but these have been replaced by the alternating current (AC) generators that have made the wind turbine more efficient. The location of the wind turbine is also very important, especially with respect to placement in the environment. The noise may affect inhabitants in the area surrounding a wind turbine.

In order to achieve good results from the wind turbines, the best locations are chosen using wind maps. Apart from the environmental considerations, two main factors have to be considered in order to find a suitable position for the wind turbine:

1) Wind speed

2) Wind quality (turbulence).

The turbulence of the wind depends heavily on the height above ground level. Closer to ground level the turbulence is high and decreases with increasing height above the ground. Ideally, the wind turbines should be situated 1000 meters above the ground, to ensure an even flow of air. Unfortunately, the technology for hovering wind turbines is not developed; therefore, the wind turbines are situated on the ground or sea where high wind conditions are known to exist. Knowing the wind conditions makes the operation of wind turbines easier and increases the probability of succeeding in producing wind energy.

There are two types of commonly used wind turbines, the horizontal axis wind turbines (HAWT) and the vertical axis wind turbines (VAWT). The HAWT's rotor shaft is installed horizontally with an engine atop (Figure 1.2), whereas the VAWT has its rotor shaft installed vertically with the gearbox and engine situated on the ground (Figure 1.2).

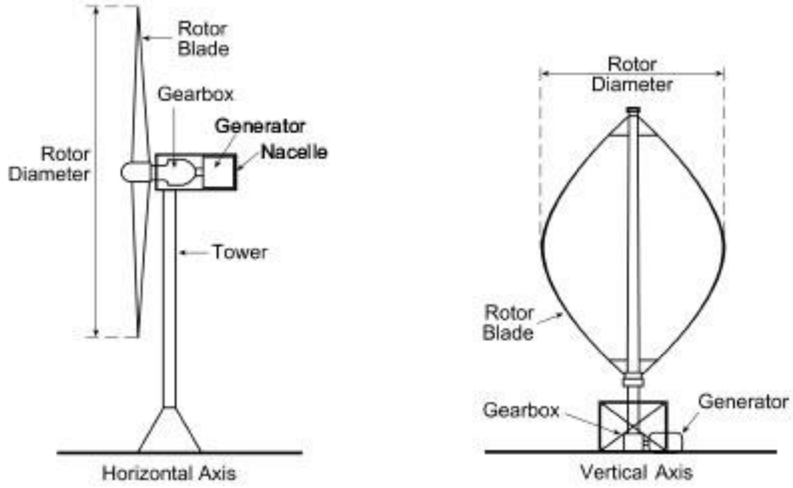


Figure 1.2: Two classes of the wind turbines (image_4, 2012): horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT).

The HAWT is more efficient in converting linear wind energy into rotational energy. The yaw mechanism is not required in VAWTs, but, at the same time, they are standing close to the ground level where wind speed is not constant but rather low and turbulent. The HAWTs make use of the yaw mechanism to make the turbine "face the wind".

Wind turbines can also be subdivided by power capacity into three groups: small, medium, and large. The small wind turbines (SWT) produce less than 20kW and are operate at low wind speeds (3-4 m/s). They are mostly used in supplying house(s) with electricity. The medium wind turbines (MWT) range from 20 kW to 300kW, have 7-20 m blade diameters and can be utilized in supply electricity for commercial buildings. Wind farms producing a large amounts of electricity are built with the largest wind turbines (LWT) (Alireza Khaligh, 2010).

Designing a wind turbine requires a mathematical knowhow to be able to perform calculations appropriately so that a wind turbine can be constructed properly. For example, designing the rotor is a complicated process that requires every component—wind speed, rotor diameter, number of blades, geometric shape, et cetera—to be designed specifically so as to function properly. The construction of turbines is a huge responsibility where mistakes can be costly and destructive.

1.3 Principles behind wind turbine blades

The number of blades installed on the wind turbine is essential; there are usually two or three. The shape of the blade is similar to that of an airplane wing and has the same functionality. Lifting forces are more efficient than the drag forces when describing the motion (rotation) of the wind turbine blades. The wind turbine blade makes use of wind kinetic energy and converts it to the rotational mechanical energy. When the wind hits the blade it gets separated, passing the blade into two separate flows (Figure 1.3).

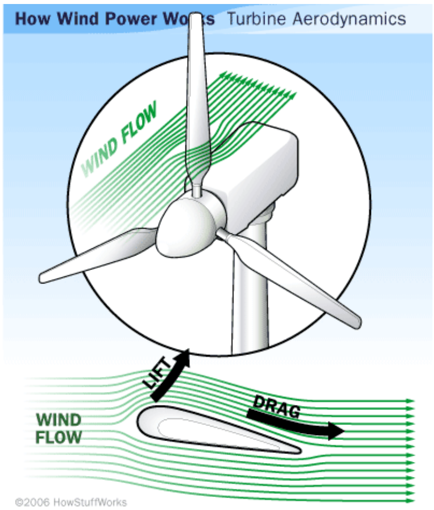


Figure 1.3: Principles behind the wind turbine blade aerodynamics (image_5, 2012).

The superior portion of the blade is longer than that of the inferior. The velocity of the wind passing over the superior part of the blade increases in speed creating a pressure low on the and conversely there is a pressure high on the inferior portion of the blade. The difference in pressure creates a lifting force on the blade. (Hansen, 2008)

Wind velocity, pressure, air density and temperature are all affect the rotor blade, and are the main factors that define the amount of energy that can be exploited from the wind turbine. The forces acting on a blade element do so simultaneously (Figure 1.4).

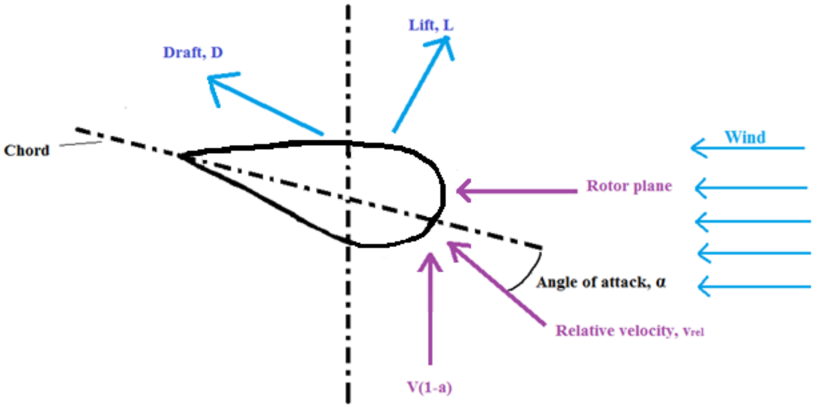


Figure 1.4: The flow of the rotor blade.

Because the relative wind speed varies with increasing distance from the hub, the blade's angle has to be reduced gradually towards the blade's tip. The air density determines the kinetic energy of the wind. A higher blade rotation capacity can be achieved in regions where more dense winds exist. The amount of wind that can be captured by the blades depends on the blade radius. As such, larger blades are able to harvest more wind than smaller blades. The blade radius is used to determine the energy level.

1.4 Power calculations

The theoretical maximum power from the wind can be calculated with help of Betz Law. The wind speed before passing the turbine is higher than the speed after. The reason for this is accounted for in the kinetic energy of the wind, which is extracted by the wind turbine and making it lower. The maximum extracted power can be calculated by using Equation 1.1 (Alireza Khaligh, 2010):

$$\boldsymbol{P_{extract} = \frac{E_k}{t} = \frac{1}{2} \cdot \rho \cdot R^2 \cdot \pi \cdot \frac{d}{t} \cdot \left(v_b^2 - v_a^2\right) = \frac{1}{2} \cdot \rho \cdot R^2 \cdot \pi \cdot \frac{(v_a + v_b)}{2} \cdot \left(v_b^2 - v_a^2\right)} \tag{1.1}$$

Where:

$P_{extract}$ = *maximum extracted power from the wind.*

v_a *and* v_b = *wind speeds after and before passing the turbine.*

$\boldsymbol{\rho}$ = *air density.*

R = *radius of the blades.*

Equation 1.2 (Alireza Khaligh, 2010) shows the total power:

$$\boldsymbol{P}_{\boldsymbol{total}=\frac{1}{2}\cdot\rho\cdot R^2\cdot\pi\cdot v_b^3} \tag{1.2}$$

The maximum theoretical extracted wind power can be calculated by Equation 1.3 (Alireza Khaligh, 2010):

$$\frac{P_{extracted}}{P_{total}} = \frac{\frac{(v_a+v_b)}{2\cdot(v_b^2-v_a^2)}}{v_b^3} = \frac{1}{2}\cdot\left(1-\frac{v_a^2}{v_b^2}\right)\cdot\left(1+\frac{v_a}{v_b}\right) \approx 59.3\% \tag{1.3}$$

Where: $\frac{v_a}{v_b} = \frac{1}{3}$

It must be noted that theoretical calculations do not always reveal the same numbers in practice.

Chapter two: Coleman 600W Wind Turbine

2.1 Coleman Wind Turbine

The intended wind turbine was a 1500W Permanent Magnet Alternator (PMA); however, the price of this wind turbine was too expensive and exceeded this study's budget. The choice was then to select a cheaper solution that produced less power. The Coleman 600W wind generator seemed to be a fairly priced option yielding enough power to charge the batteries. This selected wind turbine is designed to produce either 12V or 24V and was suitable to charge the battery bank. Model specifications are presented below in Table 2.1.

Table 2.1: Colman 600W wind turbine specifications (Coleman, 2010).

Model	600W Turbine
Related speed	12.5 m/s (41 ft/s)
Related power	600W #
Voltage with MPPT	12 or 24 V #
Survival wind speed	157 MPH
Cut-in wind speed	4.5 MPH
Blade length	0.65 m (2.1 ft)
Number of blades	3
Blade material	Fiber glass
Suggested battery capacity	>100 A/Hr

To determine a wind turbine power output, the power curve is used. The power curve shows a relation between electrical power outputs of the wind turbine ant different wind speeds.

Power output performance from Colman 600W wind turbine in relation to the wind speed provided by the supplier (Figure 2.1).

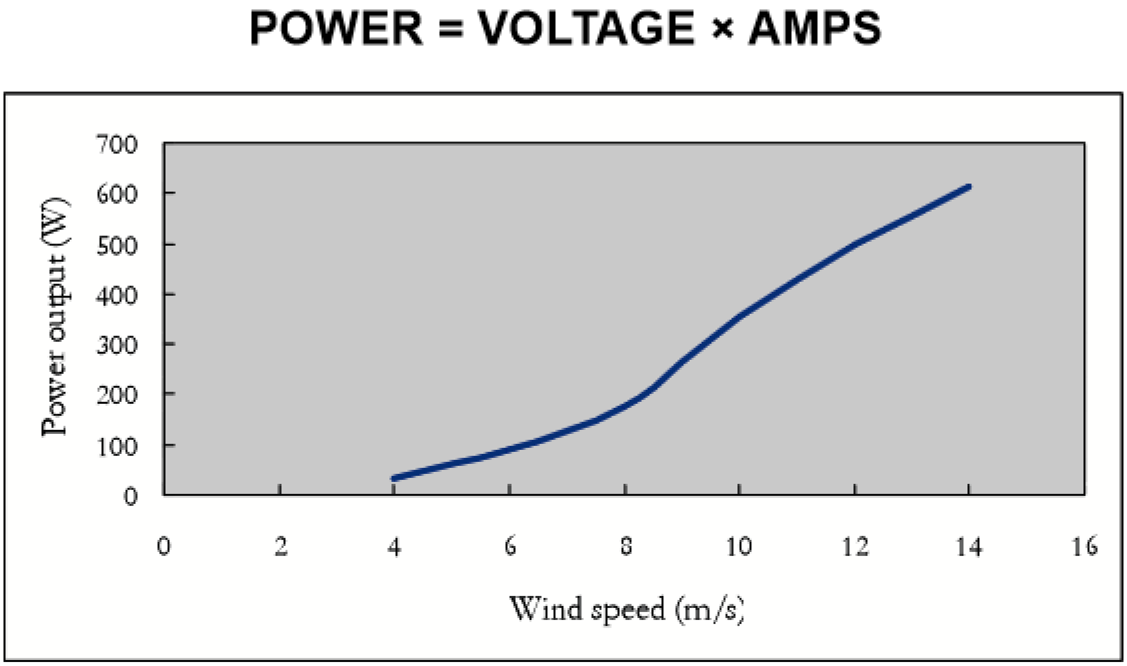


Figure 2.1: Performance specifications (Coleman, 2010).

The required wind speed to start charging the batteries, according to the supplier, was 4 mph (~1.78 m/s) and the wind generator is equipped with an over speed protection of 1300 revolutions per minute (RPM). The actual length of each rotor blade is 0.65m, and the wind turbine is manufactured for one or more rechargeable batteries (battery bank) with a suggested capacity greater than 100 Amperes/hour (Coleman, 2010).

The wind turbine arrived as a “do it yourself”-set, and the set contained nine parts plus the required bolts and nuts (Figure 2.2). The nine parts supplied were: three rotor blades, the turbine, charge controller, vertical tail, nose cone, amp meter, and the hub. The procedure of putting the pieces together was described well in the user's manual and was a simple process, which took approximately one hour.

Figure 2.2: Coleman 600W wind turbine set-up (image_6, 2012).

The wind turbine body is built in a weatherproof material (aerodynamic fiber glass) that can withstand harsh weather conditions for several years. The purpose of the included charge controller was to optimize the charging process and the charger efficiency which was stated to be more than 87%. Since the wind will tend to be more laminar at elevated heights, the wind turbine was installed on the roof of the university building (5th floor).

The body of the turbine was installed atop of a six meter long steel pole that was attached to the concrete wall (two points) and secured with two metal wires (Figure 2.3).

Figure 2.3: Installed Coleman 600W wind turbine.

The battery bank was situated in a room approximately 10 meters from the outer wall of the building (with a corridor in between) and the power cable had to be bridged in the ceiling in order to avoid direct contact with anyone passing through the corridor. Several challenges, with respect to drilling the holes through the concrete/brick walls and pulling the power wire, occurred during the process. To ensure the work and permanent installation were carried out in a safe manner, an external specialist was used for this time consuming process.

The wiring between the wind turbines manually operated speed brake and charge controller was done before the wind turbine was put in operation. This process was conducted right before the Christmas holidays and the installation process halted as the university building was closed during this period. During this instillation period, severe weather conditions were experienced. The wind turbine framework along with the wind turbine itself (with the brake activate) stood against 10-15 m/s of wind, without any problems. The wind turbine was designed to handle wind speeds up to 157 MPH (~70m/s).The installation process continued after the holidays and was finished in the beginning of January.

Chapter three: Electricity

Electricity will always contain three different units that can be described as existing: current, voltage and resistance. Current is the movement of electric charge and is measured in amperes. One ampere means $6241 \cdot 10^{18}$ electrons pass a given point in the circuit during one second (John Gabriel Navarra, 1966). The electric current causes a magnetic field around the conductor. Voltage is the potential flow measured in volts. It can be compared with a pressure difference and the main driving force moving between two points. If the points are connected to an electrical circuit an electrical current is produced, which attempts to equalize the potential difference. Resistance is the extent to which a substance prevents electrical current from passing through it. Resistance is measured in ohms and is found in varying degrees in all substances. One ohm is the resistance that results from the difference in the potential of one volt if the current of one ampere passes through (Al Santini, 2003).

The German physicist Georg Ohm derived an equation to describe the electric current in a closed circuit, and called it the Ohm's law (Equation 3.1) (Russell L. Meade, 2003):

$$\boldsymbol{I = \frac{V}{R}} \tag{3.1}$$

Where:

V = *Voltage (Volts)*

R = *Resistance (Ohms)*

I = *Current (Amperes)*

3.1 Magnetism

Magnetism is the term for the phenomena associated with the magnets and the forces they produce. A magnet is understood as a body capable of attracting magnetic materials such as iron, nickel and cobalt from a given distance. Magnetism appears to be concentrated at the magnetic poles. Different magnetic poles attract each other, and the same poles repel each other. The Earth's magnetic North Pole is, therefore, the real south-magnetism and the magnetic South Pole is actually north-magnetism. Magnetic forces work up to a certain distance from the magnet. This distance of effect is called the magnetic field. Ferrous minerals are natural magnets. Some bodies are magnetizable and under the influence of magnets that have magnetic properties and called artificial magnets (Svensen, 1980).

3.2 Alternating current and direct current

Alternating current is electrical current that periodically changes directions. This alternating current can easily be transformed into either a high voltage and thus transported over long distances without much loss (Jakob Sandstad, 2012), or into a lower voltage, depending on the transformers design. For small local supplies two conductors are used for energy transport and is called single-phase. For transport of large amounts of energy the losses are smaller when the system is made more complicated, as the use of three- phase where four conductors/wires are used. Unlike single-phase, three-phase creates a rotating magnetic field in the motor. (Svensen, 1980) Three-phase electricity is therefore used in power networks worldwide, and operates most electric motors and appliances.

Direct current, however, is only stable in one direction at a constant voltage. This type of power is used by more delicate low voltage equipment such as telephones, computers and charge batteries. Batteries are low voltage sources and produce direct current. Rectifiers are used to create direct current power from an alternating current source. Figure 3.1 shows alternating current as blue and direct current as red with current / voltage (Y-axis) versus time (X-axis).

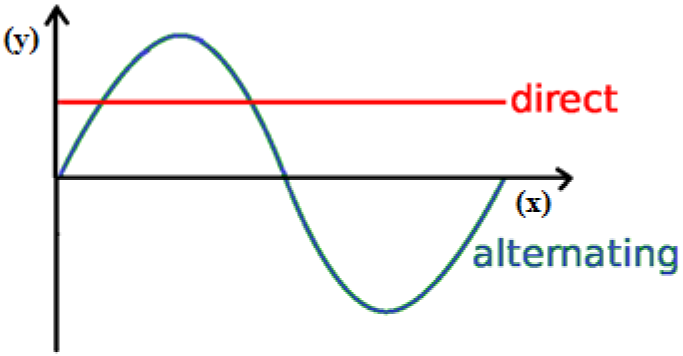


Figure 3.1: Shows Alternating Current and Direct Current.

3.3 Transformer

A transformer is a device that converts electrical alternating current with a certain voltage to alternating current of a different voltage. Single-phase transformers usually consist of two windings on a core of laminated iron sight. The windings on the left side consist of many wraps, whereas winding on the right side have fewer wraps (Figure 3.2).

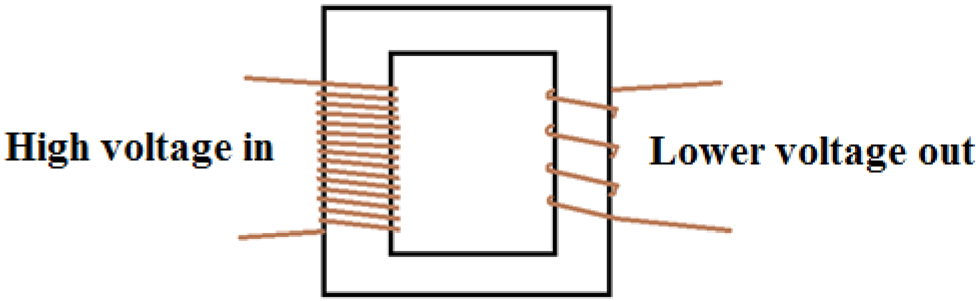


Figure 3.2: Transformer.

If voltage is applied to the left side, the left side is called the primary winding and the right side is the secondary winding. The iron core is magnetized and the induced voltage per winding is approximately equal to the primary and secondary windings, i.e. the voltages are proportional to the windings. Taking the power of the secondary winding, the currents will increase in the primary winding accordingly, so the resulting voltage and current (effect) for both windings is equal.

Chapter four: Desalination

Desalination is the process of removing salts and other dissolved solids from sea or brackish water to make it drinkable. Desalinated water can also be used in households and irrigation. There are many types of desalination such as thermal desalination (distillation), membrane processes, ion exchange, etc… In sea water the salinity level is 34,000 ppm (mg/l), which has to be reduced to 150 ppm in order to make it drinkable and less than 1000 ppm for household purposes (H.T. El-Dessouky, 2002). The process of desalination is an energy intensive process. A lot of research has been done in this field in order to find a cheaper solution for producing fresh water.

Desalination using processes such as reverse osmosis or nanofiltration are technologies which have undergone extensive development during the last 20-30 years.

Traditionally, desalination of seawater has been done by distillation, which is a very power intensive process. Thermal desalination includes Multi-stage flash distillation (MSF), Multiple-effect distillation (MED), and Vapor-compression distillation (VCD). A disadvantage of using thermal desalination methods is its high cost due to its large energy requirements (8.0-25 kWh/m^3 (Lucio Rizzuti, 2007)). Membrane based desalination is accomplished by reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and electrodialysis (ED). Reverse osmosis and multiple-effect distillation are the two most used techniques in water desalination, but reverse osmosis is more widely used due to its low cost (0.5-9.0 kWh/m^3 (Lucio Rizzuti,

2007)). However, multiple-effect distillation is still number one in Middle East because of the low cost of fossil fuels and its capacity to desalinate high saline water (Fritzmann et al., 2007).

Traditionally, RO uses electric power from a country’s power grid. In Norway much of the electrical energy is from renewable energy sources (hydropower and windmills); however, this is a different story in many other countries where much of the electrical power comes from atomic reactors, gas power plants, or coal plants. The purpose of this paper and master’s thesis study is to make use of renewable energy (wind energy in this case), in order to reduce the high operational costs. This idea will also make the water treatment plant independent from other energy sources.

The reason for writing about this topic was to find a cost effective solution capable of ensuring a clean water supply for the people who live in areas where fresh water is no longer drinkable or in coastal areas where there is ample sea water resources but little fresh water.

This is a compact and mobile unit which can be used for both emergencies and as an extensive solution in areas with little access to water, where it is capable of delivering 3000l of water a day for sustaining up to 1000 people drinking water needs.

Several developing countries lack the necessary infrastructure to cope with the increasing demand for freshwater. Not only do they lack the necessary treatment plants, but they also lack pipelines for delivering the water to their population. Thus, by proving this solution works, there are possibilities for improving public health and standard of living for the people who have limited or low quality water sources.

4.1 Thermal desalination

Thermal desalination is generally called distillation. Distillation is one of the oldest methods of producing fresh water from salt water. The process consists of boiling salt water to produce vapor or steam that cools and condenses to form fresh water, therein removing the salts which remain in the tank (Mujtaba, 2004). Distillation is a process consisting of two steps, where the first step is evaporation and the second step is condensation (Figure 4.1).

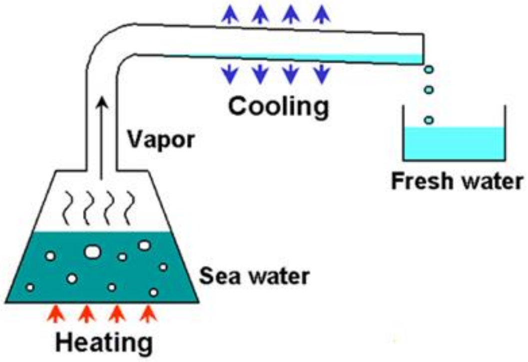


Figure 4.1: Thermal desalination (image_7, 2013).

Heat is added to create evaporation and during condensation the heat is released. The distillation process is an energy intensive process, because getting water to its boiling point is not enough to produce vapor, more heat is required. There are three major forms of thermal desalination: multi-stage flash distillation, multiple-effect distillation and vapor-compression distillation.

4.1.1 Multi-stage flash distillation

The process of multi-stage flash distillation takes place in several stages (chambers) (Figure 4.2), usually containing 19-28 stages in a treatment plant. Each stage has a heat exchanger and a condensate collector. Saline water is preheated by the latent heat of condensation, and then it is heated by the low pressure steam before entering boiling chamber. When the heated saline water enters the boiling chamber pressure is low and results in evaporation. The brine, under lower temperatures, is sent further to the next evaporator flash chamber where a similar process takes place. The product of the MSF is distilled water which is collected in a condensate collector in every stage.

MSF distillation plants have an operation temperature range of 90-120^{o}C. There is an inherent of risk of scale formation and corrosion if the temperature exceeds 120^{o}C. (Saidur et al., 2011)

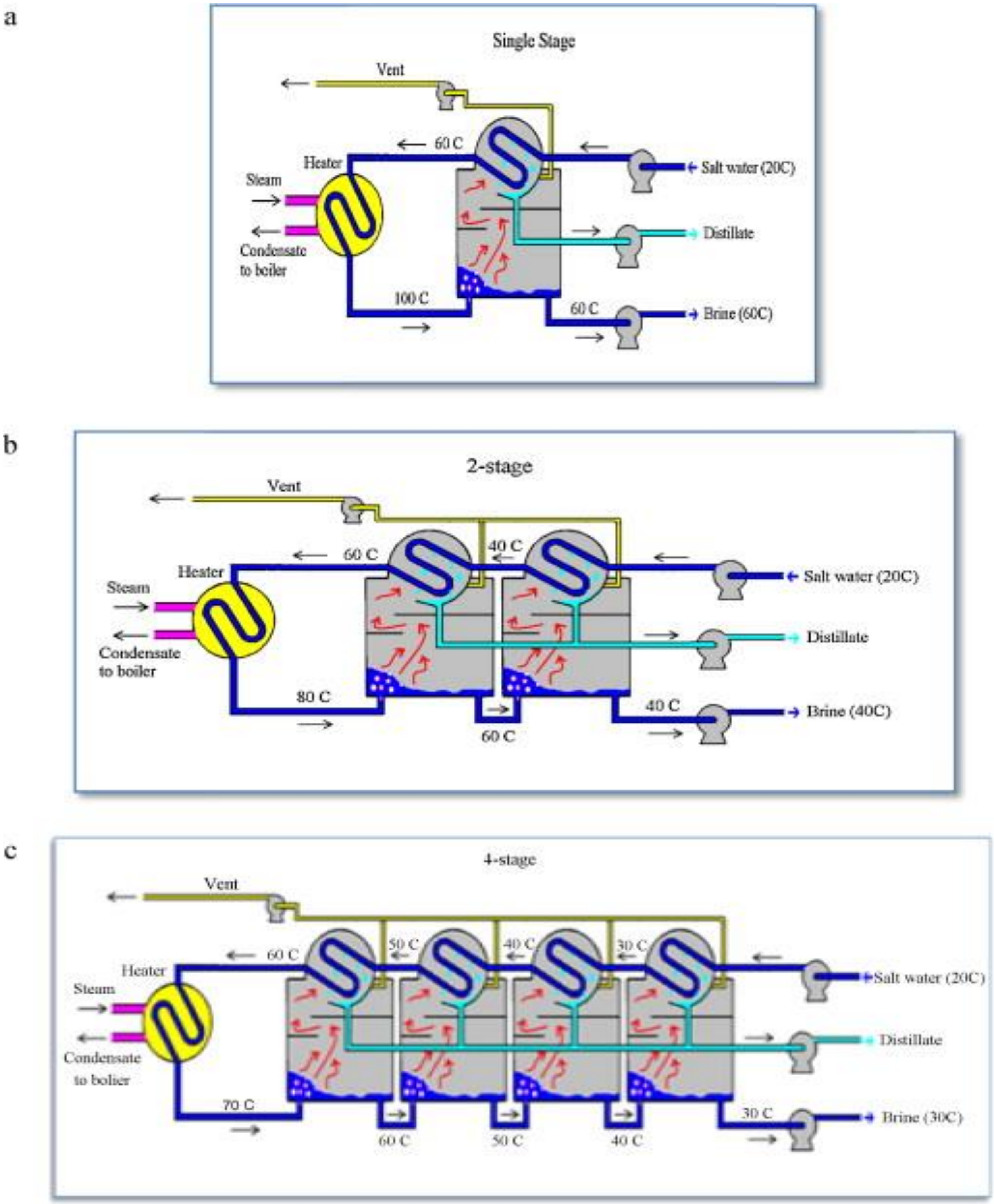


Figure 4.2: (a) 1 stage flash distillation. (b) 2 stage flash distillation. (c) 4 stage flash distillation (image_8, 2013).

4.1.2 Multiple-effect distillation

The multiple-effect distillation process consists of multiple stages (effects), where latent heat is reused. First the water is boiled in a boiler and converted into the hot steam, which is then used in boiling saline water in the first evaporator. The saline water in the second evaporator will be boiled by the hot steam coming from the first evaporator. The vapor from the second evaporator will boil water from the third evaporator and so on. At the same time boiling saline water from the third evaporator acts as a condenser for the second evaporator. So does the second evaporator for the first evaporator (Figure 4.3).

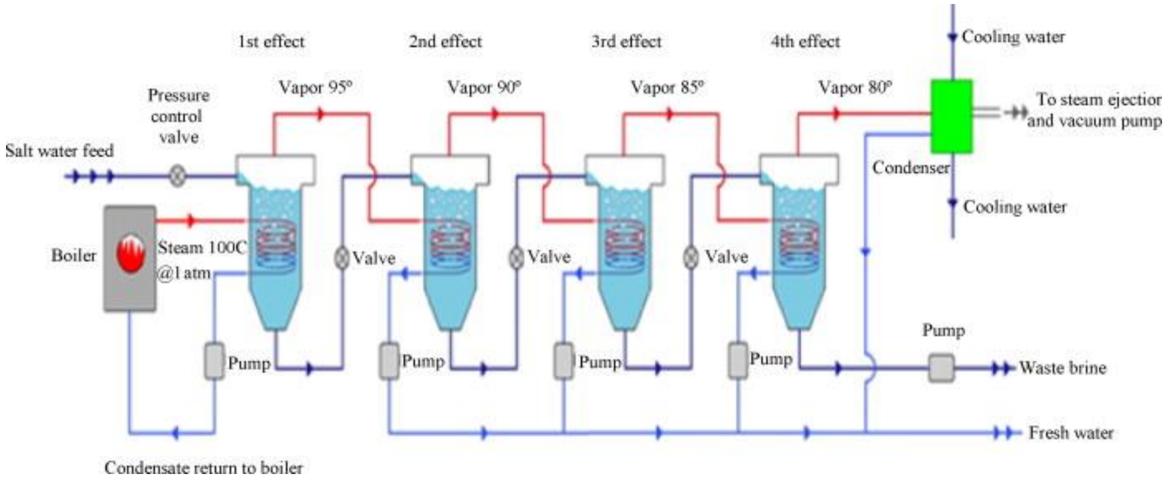


Figure 4.3: Multiple effect distillation (image_9, 2013).

The pressure and temperature differences in this process are an important factor. This means that the pressure vapor at the first effect has to be higher than the pressure vapor at the second effect, and so too the pressure vapor at the third effect has to be lower than in the second effect. Regulating pressure valves have to be installed to regulate the effects’ pressures. In MED vacuum pumps are required in order to eliminate oxygen and nitrogen, which can cause damage (Saidur et al., 2011).

4.1.3 Vapor-compression distillation (VCD)

The vapor-compression distillation shown in Figure 4.4 uses the mechanical source (vapor compressor) to warm up the saline water, whereas in the multiple-effect distillation and multi-stage flash distillation MSF methods the external heat sources are crude oil, natural gas, etc... The first step is to apply heat to the saline water by sending it through the heat exchanger outside the evaporator. The second step is boiling water inside the evaporator's tubes, which results in the water vapor being compressed. The compressed water vapor is sent back to the evaporator as an energy source for boiling. Vapor compression distillation is very efficient even at a small-scale (Saidur et al., 2011).

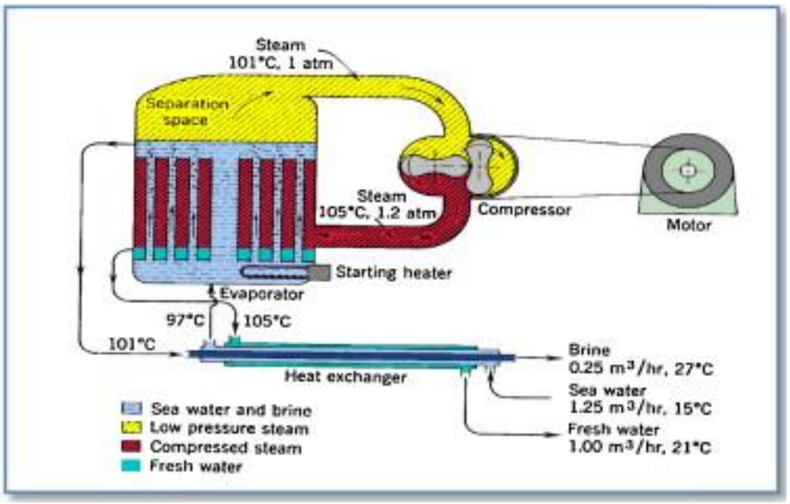


Figure 4.4: Vapor compression distillation (image_10, 2013).

4.2 Membrane processes.

Membranes are used in water desalination techniques like reverse osmosis and electrodialysis. Both of these methods use semi-permeable membranes for the separation of salts and other colloidal particles from water. The separation method is different in each of these techniques. In reverse osmosis pressure is applied in order to force separation. In Electrodialysis an electrical current is used in order to produce clean water (described in greater detail below).

Chapter five: Pilot plant design

5.1 Water quality indicators

The first step when it comes to water treatment is determining the quality of the water to be treated. This will provide the necessary information for maintaining a good functionality and performance of the membranes, while also prevent scaling, fouling and damage that could occur. When checking the water quality several parameters need to be taken into consideration:

- **Organic pollution:** algae, protozoa, bacteria and other microorganisms
- **Inorganic pollution:** metals, minerals, arsenic
- **Cosmetic pollution:** color, smell

Substandard water quality analyses are the reason why people in Africa or most of Asia are drinking substandard water, whereas people in America and Europe are drinking higher quality where water is treated.

5.1.1 Total Dissolved Solids (TDS)

In general, TDS is a measurement of both the organic and inorganic ions in water. Seawater mainly consists of inorganic salts (magnesium, bicarbonates, potassium, calcium, sodium, chlorides and sulfates), and small amounts of dissolved organic matter in water (WHO., 2004).

In a standard laboratory test (solid analysis), a 0.45μ filter is used to separate the TDS from the total suspended solids (TSS). Thus, the TDS particle size is much smaller and solved in the water phase. In order to determine the TDS, evaporation of the water is needed and the remnants are both organic and inorganic dissolved solids. If it is necessary to determine the inorganics, the remnants can be burned off in a muffle oven at 600^{o}C. The remaining ash will be the inorganic fraction while the missing weight will be the organic fraction. This analysis is time consuming and a TDS-meter can be used instead.

TDS is based on conductivity and is usually expressed as parts per million (ppm) or milligrams per liter (mg/L.) Most TDS meters convert total amount of dissolved solids such as NaCl ions, just for simplicity.

5.1.2 Water hardness

The term ‘hard water’ refers to the high content of dissolved salts (di- or trivalent cations) in the water (Rayner-Canham and Overton, 2006). Usually this problem is of concern when Ca^{2+} and Mg^{2+} are present. The minerals in the water are a result of millions of years of the weathering of bedrock (e.g. dolomite and calcite). In the industrialized world hard water has become a greater concern. Especially with regards to the increased scaling potential and reduced efficacy of soap when washing to name a few.

The water supplied by the municipal water treatment plant in this region where the pilot project experiment will be held contains very little dissolved minerals and total hardness is 3°dH German degrees (1 German degree = 10 mg/L CaO or 17.848 milligrams of $CaCO_3$ per liter of water, or 17.848 ppm (Dryden Aqua Technology, 2013)) and contains 20 mg/l Ca^{2+}(IVAR, 2012). Furthermore, the water quality is in excellent, with respect to the Norwegian regulations for potable water (Norwegian regulations for potable water, 2012).

5.1.3 pH

pH is a parameter that describes the activity of hydrogen ion and indicates if a solution is acidic or basic.

Measuring the pH of water is essential for making effective use of membrane processes. There is a range of membranes used in the desalination process, which operate in a specific pH range that is specific to each membrane. These ranges are provided by the manufacturer for each specific membrane. Changes in pH can cause membrane damage.

5.1.4 Turbidity

Suspended particles create an optical property in water, called turbidity. These particles, usually invisible to the naked eye, make water cloudy because they scatter and absorb light rays instead of transmitting light in a straight line. Turbidity indicates clarity of a water sample, which is an essential test for defining the quality of water quality. It is measured in nephelometric turbidity units (NTU) (Eric Dohner, 1997). Most manufacturers require a NTU less than 1 to prevent fouling of the membrane.

5.1.5 Silt Density Index (SDI)

Silt density index is a measurement used to identify the fouling potential of a given water supply (Metcalf. and Eddy., 2004). A high content of suspended solids (SS) in the feed water may promote growth of microorganisms, which will eventually clog the membrane(s). The SDI-number indicates how much pretreatment is required to achieve a high quality feed water. By having proper pre-treatment the lifetime of the membrane can be increased and the maintenance costs are reduced.

5.1.6 Temperature

Temperature changes affect membrane performance. High temperatures will give high salt diffusion through the membrane, whereas low temperatures will reduce the flux rate. Temperature can be controlled by adjusting operating pressure. Temperature also affects the membrane structure, because not all membrane types are able to tolerate high temperatures, which destroy the membranes.

5.1.7 Color

Color is byproduct of naturally occurring humic substances. Humic substances are divided into three groups of organic compounds: humic acid (dark brown to black), fulvic acid (yellow and yellow-brown) and humin (black). Color is measured by filtering the suspended matter. According to the APHA (American Public Health Association), it should be less than 3 (dimensionless unit of coloring) (Kucera, 2010). Color in the water must be removed due to danger of fouling the membranes.

5.1.8 Metals

Metals can affect the membrane filtration process. Some of these metals are iron, manganese and aluminum. Metal fouling is caused by oxidation of the membranes due to presence of metals in feed water. Manganese and iron are naturally occurring metals that can be found in well water and from some surface water sources. These metals are in a soluble form, before water is exposed to oxygen, at which point they will then form oxides. Metal oxides can damage the membrane surface.

Aluminum sulfate is usually used as coagulant in the pretreatment of water. Aluminum fouling can occur due to the formation of aluminum silicates from an over dosage of aluminum sulfate. By reducing the usage of chemicals in pretreatment processes aluminum fouling can be avoided.

Metal fouling can also be avoided by keeping the system oxygen free so that metals cannot form oxides and foul the membrane surface. To reduce iron fouling, pH and oxygen levels need to be reduced (Kuchera, 2010).

5.2 Fouling and scaling

Fouling and scaling are potential hazards to membrane materials. Fouling is caused by the organic material, whereas scaling is a result of an inorganic material’s impact on the membrane surface.

5.2.1 Fouling

Fouling refers to the adhesion of a substance which blocks the flow path of the membrane and permanently reduces its performance. A brand new membrane will always have a higher flux than a used element. Fouling of a membrane can be caused by the accumulation of different material:

- Particles larger than the Molecular Weight Cut-Off (MWCO).
- Suspended solids.
- Colloids (clay)
- Bio fouling (algae biofilms and biological colonies)
- Organics (proteins and fat acids).
- Organics (oil and grease)
- Color – tannins, humic acids (large chains of organic molecules)

In a membrane the fouling usually occurs on the feed side of the membrane. Each membrane material, membrane type and pore size is unique and they have different fouling tendencies (as seen in Table 5.1).

Table 5.1: Fouling tendency characteristics (Cipollina Andrea et al, 2009, Table 3-4)

	Tubular	Plate-and-frame	Spiral-wound	Capillary	Hollow fibre
Packing density	Low	→			High
Investment cost	High	←			Low
Fouling tendency	Low	→			High
Cleaning	Good	←			Poor

Larger pores will clog faster than small pores and the flux will decrease faster (Figure 5.1).

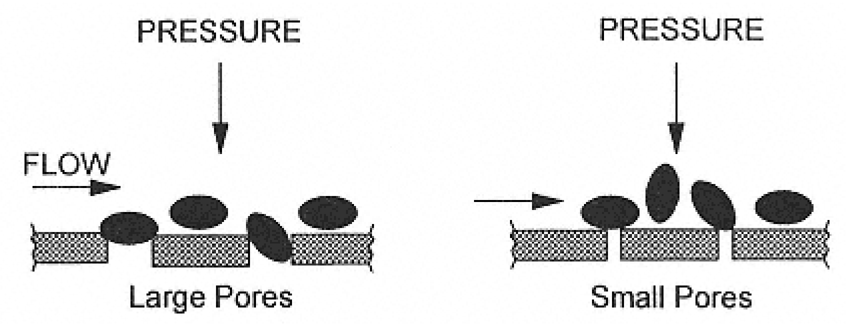


Figure 5.1: Mechanism of membrane fouling by particulates, showing the effect of pore size in relation to particle size (Cheryan, 1998, figure 6-11).

The high hydrophobicity (water repelling) of certain membrane materials tends make them foul more quickly than that of hydrophilic (water loving) membranes, because of the high non-specific adsorption ability (Cipollina Andrea et al., 2009).

By taking complete water analysis engineers can choose the correct pretreatment that would avoid fouling caused by agents that can clog the surface of the membranes. There is no one solution that is considered universal. A unique set-up is required in most situations as the conditions can be very different. For example, the separation of milk has its own particular properties that are different from that of seawater.

Flushing the membrane before and after use is important and will yield good results in fouling prevention, whether it is milk or seawater. When fouling agents are given enough time - that is no flushing before and after use - severe damage results on the membrane that can be irreversible.

Pretreatment can be viewed as a standalone part of a treatment plant, instead of being seen as only an appendix to the membrane. By maintaining a good pre-treatment system (fouling control) the membrane will last longer, keep an optimal flux rate, and reduce operational costs (require less manpower cleaning, chemical cleaning, etc…).

There are three major categories in fouling: bio fouling, colloidal fouling and organic fouling.

5.2.2 Bio fouling

Bio fouling is caused by microbes that adhere onto the membrane surface and start to grow. As the colony increases in size the area covered by microbes also increases, thus a reduction in passage for the water. This results in a reduced flow and the need for higher pressure to maintain a high flux. If the colony is given enough time biofilms will arise. A biofilm is more cohesive and difficult to remove. Another disadvantageous property of a biofilm is that the lower part of the biofilm is anoxic (without oxygen) and as a result of fermentation, acids will be a byproduct of the metabolic pathway. This is important as many membranes are not very tolerant of acids.

To prevent bio fouling a biocide can be added in the pretreatment (upstream the membrane). However, the biocide cannot be oxidizing or have high concentrations of chlorine which will both damage on the membrane. Different biocides are in use (e.g. ozone, UV, formaldehyde and other commercially available products). The biocides can either be injected continuously or as shock therapy with one single large dosage on occasion.

As microbes and viruses are too large to penetrate the NF or RO membrane, they are only found on the feed side of the membrane.

Due to imperfections or leakages on seals, gaskets and “O”-rings, microorganisms can be found on the permeate side. Therefore, a secure bacterial barrier for disinfection using Ultra-Violet radiation is the preferred method.

5.2.3 Colloidal fouling

Colloidal fouling is from colloidal particles (e.g. clays, solids >MWCO) adhering to the membrane surface. This type of fouling will cause a cake layer (also known as the CP-layer or concentration polarization), which makes diffusion of solutes very slow (macromolecules) and causes them to build up. Concentration polarization will decrease the efficacy of a membrane so much so that even if the pressure is increased, the flux is not increase accordingly (as seen for skim milk on Figure 5.2).

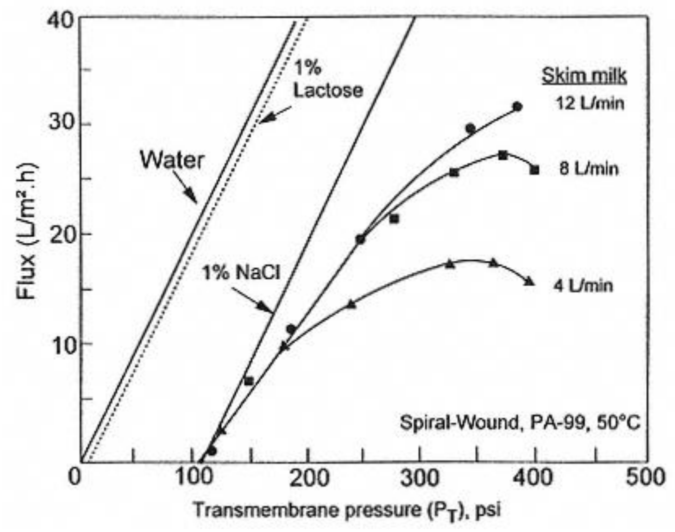


Figure 5.2: Reverse osmosis (of salt solution, sugar solution and a complex protein suspension), flux over transmembrane pressure (Cheryan, 1998 – Figure 1.12).

This adverse effect can be reduced either before (pretreatment) or after it adheres to the membrane (cleaning the MF/UF membrane with periodic backwashing or flushing the NF/RO membrane).

5.2.4 Organic fouling

Organic fouling is caused by organic macromolecules (e.g. sugars, lipids and proteins). Sugars with low molecular weight are known to cause little or no problems (Cheryan, 1998). Proteins and lipids are of more concern as they are stickier and/or can coagulate. Casein is a known example of a coagulating milk protein that can clog a membrane easily if preventative action is taken.

5.2.5 Scaling

The term “scaling” refers to chemical reactions where precipitation of dissolved inorganic ions in water. In other words, the ions present in the aqueous solution become a solid phase (as seen in example Equation (1)).

$$Ba^{2+}_{(aq)} + SO_4{}^{2-}_{(aq)} \rightarrow BaSO_{4\ (s)} \qquad (1)$$

This chemical phenomenon occurs in several situations under normal circumstance, e.g. crystallization of barium sulfate, calcium carbonate, etc… These crystal compounds are precipitated when the concentration is exceeds the solubility product constant (K_{sp}). However, temperature is also an important factor, because increased temperatures result in increased K_{sp} values.

Under an industrialized driven process it is not out of the ordinary to encounter the same problem (i.e. in oil and gas pipelines, in membrane installations or even in a house hold water heater).When precipitation occurs in a lake the solids sinks down (sedimentation) and stay on the bottom of the lake. But when this happens in a pipe line, on a membrane surface, or in a household water boiler the precipitation has nowhere to sink down to and blocks the pipes or membrane pores and becomes an unwanted problem (Figure 5.3).

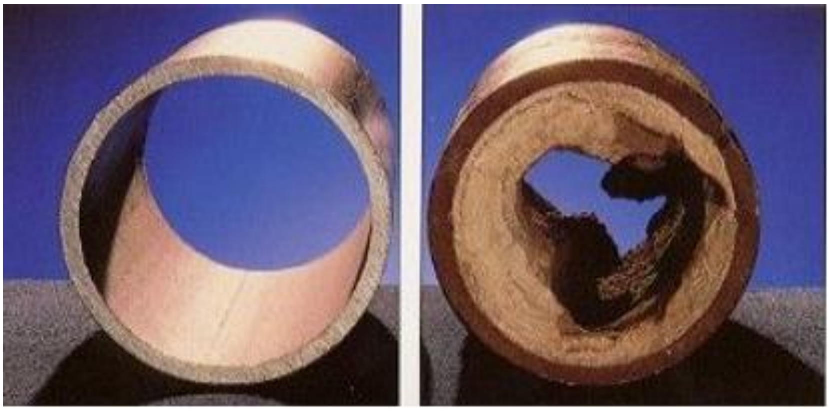


Figure 5.3: The crucial effects scale formation in a pipe (image_11, 2012).

In a membrane that has water passing from the feed side to the reject side, the concentration of salts on the reject side increases, whereas the concentration on the permeate side is very low. The concentration builds up until its solubility limit is exceeded. Then salts can then precipitate out as scale (precipitation) on the surface of feed side of the membrane (AMTA, 2007). Calcium carbonate, calcium sulfate, silica complexes, barium sulfate and calcium fluoride are common scales found to commonly form on membranes. A RO or NF membrane is designed to remove ions and not macromolecules. This is not the case when it comes to scale, because a membrane surface covered by scale will reduce the flow rate (flux) as the membrane pores become blocked. When there is a reduced flux through a membrane in a desalination plant, the plant will produce less clean water. To overcome this unfavorable problem the membrane has to be chemically cleaned. This cleaning requires downtime and increases the cost of operation. However, failing to remove scale can, in a worst case scenario, cause permanent damage to the membrane where the only solution is then the immediate replacement of the membrane. These variables should be included in the design of a treatment plant. However, if scaling still occurs after construction the operational protocol of the plant should be modified in order to counter act the scaling problem. A properly designed desalination plant should have a good pretreatment process which makes the scaling problem non-existent. In order to decide the best solution for handling this problem, it is important to know the water's properties (water quality and quantity). ATMA (America's Authority in Membranes Treatment) has proposed the minimum requirements needed for determining water quality (Table 5.2).

Table 5.2: Shows ATMA's minimum required water quality analysis (AMTA, 2007).

Minimum Required Water Quality Analysis				On Site Measurements
Aluminum	Chlorine	Manganese	Strontium	Temperature
Ammonia	Chromium	Nickel	Sulfate	pH
Arsenic	Color	Nitrate	Total Alkalinity	Carbon dioxide
Bacteriological (Total)	Conductivity	Ortho Phosphate	Total Dissolved Solids	Hydrogen Sulfide
Barium				
Bicarbonate	Copper	Potassium	Total Hardness	
Cadmium	Dissolved Iron	Selenium	Total Iron	
Calcium	Fluoride	Silica Colloidal	Total Organic Carbon	
Carbonate	Free Chlorine	Silica Soluble	Total Phosphate	
Carbonate Alkalinity	Lead	Silver	Total Suspended Solids	
Chloride	Magnesium	Sodium	Turbidity	

The different variables in Table 5.2 are needed in order to predict the scale potential, but the information given from these values can give an idea of how much fouling can be anticipated, how quickly the membrane will be degraded, and how often the membrane needs maintenance.

In principle, there are many different approaches for minimizing the problem scale formation. The pre-treatment methods for membranes (not limited to only membranes) should isolate the potential scale agents. The utilization of nanofiltration membranes prior to the RO-membrane can remove/minimize the ions. One of properties that nanofiltration membranes (also called softening membranes) possess is a charged surface; either positive or negatively charged.

Removal of sulfates can also be done by adding aluminum-bearing salts (Silva et al., 2010, Xu et al., 2004) (e.g. aluminum sulfate and aluminum chloride). The aluminum creates bonds with the sulfates in a complex way (Figure 5.4)

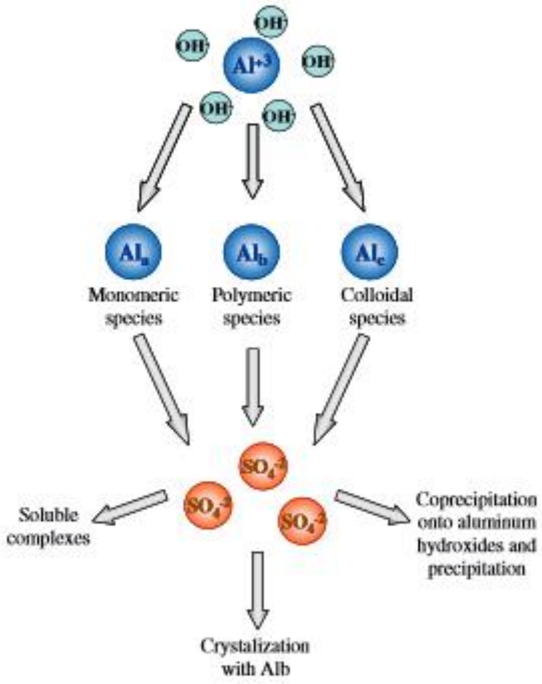


Figure 5.4: Aluminum species distribution and interaction with sulfate ions in solution (Silva et al., 2010).

Ozone is an excellent biocide for the removal of microbes, and has shown to be successful for the removal of minerals in environments with hard water (McGrane, 1992).

Other alternatives for scale removal/reduction are using agents upstream the RO-membrane such as: precipitation tanks (often with lime), biological digestion, injecting scale inhibitors, ion exchange, softening the water with a strong acid or dealkalization with a weak acid (Dow-Filmtec Form No. 609-02013-504).

5.2.6 Post removal of scale

If scale problems have already occurred there are also a ways to remove the deposited scale. Removal can be done either by mechanical/physical or chemical means. The chemical removal is done by treating the membrane with a strong acid that can remove soft scales (carbonates). The other method is through the use of mechanical/physical removal. This method can be applied to hard scales (sulfates), where acid does not help. Mechanical removal is done with tools such as a grinding bore with a steel brush mounted on it. However, when performing scale removal on membranes, they are very fragile in comparison to the steel piping, thus it is important to handle the membrane with care.

However, when scale has deposit on the membrane surface it will act as a catalyst for scale, thus increasing the scaling rate (AMTA, 2007). With this in mind it is favorable to reduce the scale potential upstream of the membrane to an absolute minimum.

Fouling and scaling occurs when the membranes see a variable pressure and flow rate. If both parameters can be avoided, an optimal system can be developed. High flow membranes are made of hydrophilic materials through which water can easily pass, but this also means that these membranes remove less salt than ordinary membranes.

5.2.7 Silt Density Index

For a successful RO operation, the supplier of the membranes used in this experimental Set-Up (Dow-filmtec) recommends a SDI-level of 5 as a maximum.

The SDI- analyzing instrument used in the actual RO set-up is produced by GE Infrastructure Water & Process Technologies (model Osmonics AutoSDI®). The AutoSDI kit is a mobile device and all components are installed in a suitcase (Figure 5.5).

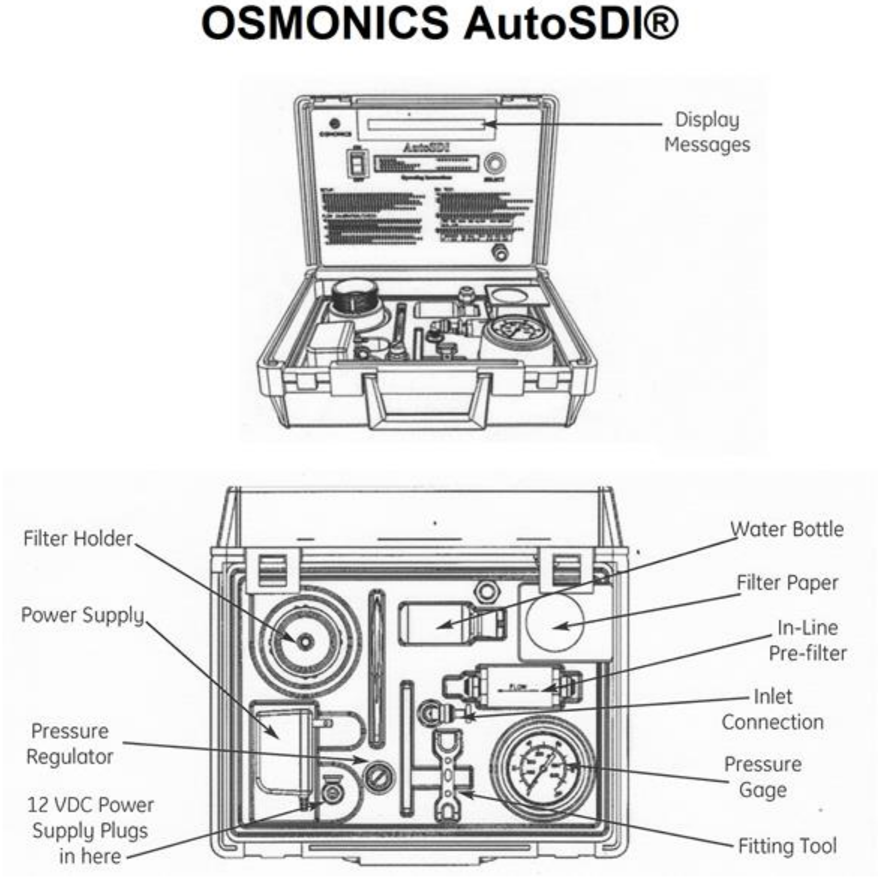


Figure 5.5: Shows the mobility of the AutoSDI-suitcase (image_12, N/A).

In order to measure the SDI water feed stream (with an available pressure of at least 3.4 bar) is required to supply the AutoSDI with samples. The device is rather simple to operate and little training is needed to achieve good results. The principle behind the AutoSDI Kit is using filtration to determine the amount of particulate contamination in a water sample. This is done by running a sample through the Millipore filter (0.45µm) with a 47mm internal diameter at 210 kPa. The main reason why the 0.45 µm micron filter is used, is because this filter has similar properties to that of a RO membrane (GE Infrostructure, N/A).

A wide variety of pretreatment methods can be used to reduce the SDI before feed water enters the RO membrane. For example, sand filtration, carbon filtration, and microfiltration to name a few. The pH adjustment is an important aspect in SDI measuring process. Running the test with or without a pH adjustment can indicate if it is affecting the SDI. The samples have to be taken at the beginning and the end of the test to determine the static measurement of resistance (silt density index).

5.2.8 SDI and Plugging Factor (PF) calculations

SDI can be calculated by equation 5.1 (Metcalf. and Eddy., 2004).

$$\boldsymbol{SDI = \frac{100\cdot(1-\left(\frac{t_i}{t_f}\right))}{t_{total}}} \tag{5.1}$$

Where:

t_i *= time to collect initial sample of 500 ml.*

t_f *= time to collect final sample of 500 ml.*

t_{total} *= total time for running the test.*

The PF (Equation 5.2) is another important parameter for the measurement of suspended solids (measured in %).

$$\boldsymbol{PF = \frac{SDI \cdot 100}{Max\ SDI}} \tag{5.2}$$

When a value of 100% is achieved, the membrane is plugged, whereas with 0%, the membrane is completely free for suspended solids.

The general procedure of the instrument (GE Infrastructure):

1. Attach the 5/8” tubing to the filter holder.
2. Ensure the pressure is 3.4bar and that the sample water is connected to the AutoSDI instrument.
3. Turn the machine on and adjust the pressure to 3.1 bar with the regulator. The test will run for 15 minutes and the SDI (T0, T5, T10 and T15) will be displayed in the display window (Figure 5.5). In addition PF will be shown on the display at 15-minuttes.
4. The procedure can be repeated by resetting the instrument (turning OFF/ON). Doing so will improve the test result quality.

5.2.9 Automatic flush system and TDS monitoring

The automatic flush system has to be installed on the membrane water treatment plant in order to reduce membrane fouling and scaling and also to reduce use of chemicals for cleaning the membrane elements. Membrane flush systems consist of a valve and a built-in mechanism, which controls when flushing starts/stops. There are different types of built-in flush mechanisms: volume controlled, timer mechanism and pressure sensor. Volume meter records how many liters that have passed through the membranes and is programmed to start / stop the flush period after a certain volume. A built-in timer mechanism is programmed to flush the membrane(s) with a specific time interval. There are also flush systems controlled by pressure sensors before and after the membrane(s).

It is essential to flush the membrane elements before start and in the end of the operation. The flush period is designed to be 3-5 minutes and is controlled by the built-in timer mechanism. TDS monitoring is also needed in order to monitor the TDS level.

5.3 Pretreatment

Pretreatment is the major component when designing the RO water treatment system. A proper pretreatment will increase the efficiency and the life time of membranes, as well as decrease the operational cost of the whole system and reduce the cost of the produced water, by preventing plugging of the membrane surface, colloidal fouling, biological fouling and scaling.

There are some main parameters affecting the design of pretreatment system such as feed water quality, variability of water quality from different water sources and RO/NF system operational parameters.

Three main options for pretreatment are presented in this chapter:

- Chemical pretreatment
- Mechanical/physical pretreatment
- Membrane pretreatment

5.3.1 Chemical pretreatment options

Chemical pretreatment options can be divided into coagulants and polymers, scale inhibitors, chlorination and pH adjustment.

5.3.2 Coagulants and polymers

Coagulants and flocculants are chemicals used in water treatment. The main objective for these chemicals is removal of unwanted species in the water phase. The coagulants and flocculants are usually organic or synthetic polymer, metal salts ($Al_2(SO_4)_3$ and $FeSO_4$) and prehydrolized metal salts (polyaluminum chloride (PACI) or polyiron chloride (PICI)). A coagulant is used to destabilize colloidal particles in water and form flocs, while a flocculent is used to enhance flocculation (Metcalf. and Eddy., 2004).

5.3.3 Scale Inhibitors (Anti-scalants)

Scale inhibitors are used to prevent scale formation on and/or in the equipment. Scale is unwanted due to reduction in water flux and lifespan of the equipment. Typical scale inhibitors used in water treatment are polyphosphates (Sodiumhexameta-phosphate (SHMP)), phosphonates (Bayhibit (PBTCA)) and polymers (Polymaleic acids (PMA). Small dose of 1-2 mg/l is enough to prevent scale formation and is found to be not harmful for the environment (Cipollina Andrea et al., 2009).

5.3.4 Chlorination

Chlorination is applied to reduce bacteria, ameobic cysts, algae, spores and viruses content in feed water. Chlorinators can be adjusted into the feed water in the range 50-3.600 kg/d. The most commonly used chlorinators are sodium hypochlorite (NaOCl) and chlorine gas (Cl_2). The sodium hypochlorite and chlorine gas is referred as free residual chlorine and its concentration should be reduced to 0.5-1.0 mg/l in the pretreatment section to avoid complications in the next step. Dechlorination is a pretreatment process used to prevent oxidation damage by residual chlorine. Sodium metabisulphite ($Na_2S_2O_5$) is commonly used dechlorination agent (Cipollina Andrea et al., 2009).

5.3.5 Acid addition/pH-adjustment

Feed water entering the system has a high pH value. To prevent calcium carbonate occurring, the pH value needs to be reduced to 7.5. Sulfuric acid is the most common chemical used in pH adjustment (Cipollina Andrea et al., 2009).

5.3.6 Mechanical/physical pretreatment options

Commonly used mechanical/physical pretreatment options are screens, dual media filters, cartridge filters and sand filters.

5.3.7 Screens

Screens are usually used as a first step in pretreatment of feed water. They consist of revolving wire mesh panels with 6-9.5 mm openings (Cipollina Andrea et al., 2009). Screens are applied to remove coarse solids in order to prevent water pumps and other process equipment from clogging.

5.3.8 Dual media filtration (DMF)

Dual media filters work under gravity flow and consist of fine sand bed covered with coarse anthracite coal. DMF are used to reduce the turbidity of feed water to about 0.4 NTU with an SDI of 2.5 or less (Cipollina Andrea et al., 2009), by removing suspended solids. Cleaning process applied on dual media filters is called backwashing, where surface scum and dirt in the filters are removed by flushing water the opposite direction from the filtration.

5.3.9 Cartridge filtration

Cartridge filters are applied in the systems with low contaminated water. There are two types of cartridge filters surface and depth filters. Surface filters block particle at the surface, while in depth filters particle are captured in the medium. Cartridge filters pore size is from 5 to 10 µm (Cipollina Andrea et al., 2009).

5.3.10 Sand filtration

Sand filters are used if water turbidity is less than 50 NTU. They can successfully remove organic and inorganic suspended matter as well as pathogenic organisms. The operating principle of sand filters is to pass water slowly through a bed of fine sand. Suspended matter is captured by the sand particles in upper 0.5-2 cm of the filter bed. Sand filters are also easy to clean by scraping of the top layer. Cleaning intervals depend on the feed water quality (Cipollina Andrea et al., 2009).

5.3.11 Microfiltration/ultrafiltration

Pretreatment by microfiltration and ultrafiltration is becoming widely used in water treatment industry. The process is low energy consuming and at the same time very effective. Microfiltration removes suspended solids and lowers the SDI to level below 5. Ultrafiltration is applied to remove suspended solids, bacteria, macromolecules and colloids. Advantages of MF/UF as a pretreatment technique (Cipollina Andrea et al., 2009):

- Increased recovery factor and flux
- Increase in the RO membrane lifespan
- Turbidity level is decreased
- Reduction of chemical use in pretreatment
- Space saving
- High quality permeate

MF/UF pretreatment option is called non-conventional pretreatment, while Chemical and mechanical/physical pretreatment is called conventional pretreatment. Conventional pretreatment option is considered to be more environmental friendly, due to reduced chemical use ease of operation.

5.4 Membrane process

Four main water treatment techniques are based on membranes process:

- Reverse osmosis
- Nanofiltration
- Ultrafiltration
- Electrodialysis

Membranes used with each water treatment technique have unique qualities (Figure 5.6). They have different pore size, structure, materials, modules, pressure tolerance, etc…

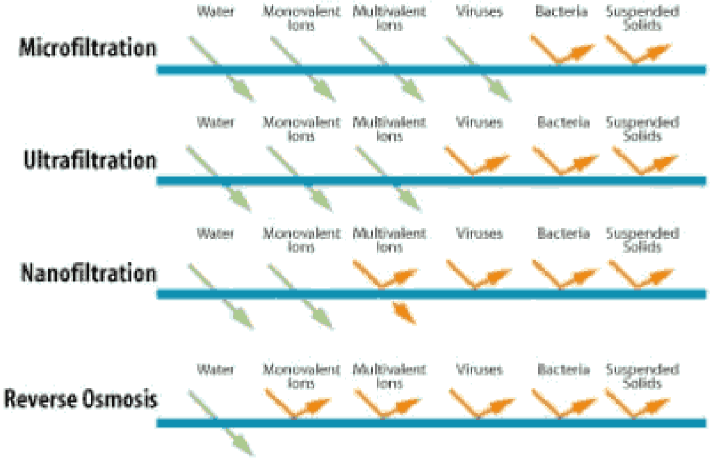
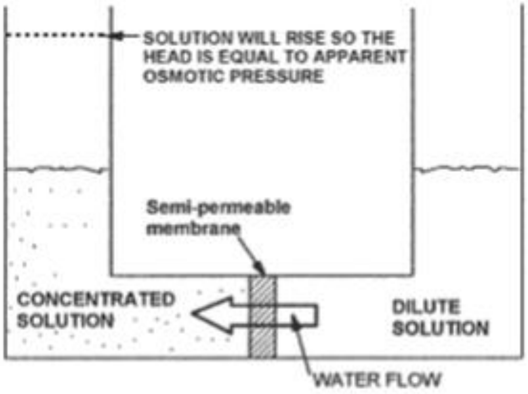


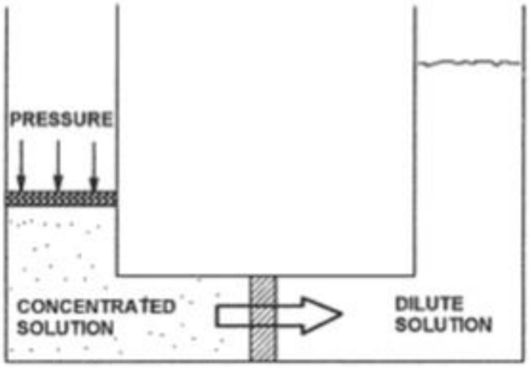
Figure 5.6: Various material sizes which can be removed by different membrane separation processes (image_13, 2013)

5.4.1 Osmosis

In Osmosis (Figure 5.7.a) a semi-permeable membrane, which separates two liquids with different concentrations, is used in order to achieve equilibrium of the liquid where the solutes will move from a high to low concentration site.



a) OSMOSIS



b) REVERSE OSMOSIS

Figure 5.7: a) Osmosis.; b) Reverse Osmosis (Cheryan_B., 1998).

5.4.2 Reverse Osmosis

In Reverse osmosis the solvent travels through the semi-permeable membrane from the low to the high solute concentration site, but only if the pressure applied exceeds the osmotic pressure. Abbe Nollet was one of the first who documented work with semi-permeable membranes and phenomenon of osmosis in 1748. Later Traube and Pfeffer had also worked on osmotic phenomena in 1850's. Modified technology was documented by Dr. Gerald Hassler who studied osmotic properties at the University of California at Los Angeles in 1948. Sidney Loeb and Srinivasa Sourirajan worked on reverse osmosis and development of first asymmetric cellulose acetate membrane in 1960. Their work made RO membranes commercially available (Kuchera, 2010).

Reverse Osmosis (Figure 5.7.b) is becoming more and more popular due to huge improvements regarding membrane materials and a much lower operating costs.

Semi-permeable membranes are capable of rejecting almost all colloidal and dissolved matter resulting in very clean fresh water. To achieve the good results with reverse osmosis the pressure has to be between 35-100 bar (Cheryan, 1998).

5.4.3 Osmotic pressure

Osmotic pressure (π) is a value that depends on the concentration of dissolved solids in solution. It can be calculated by applying either Van't Hoff's equation or Gibbs free energy equation (Cheryan, 1998). Gibbs free energy Equation illustrates the primary relationship between osmotic pressure and other thermodynamic properties (as stated in Equation (5.3) and (5.4)):

$$\boldsymbol{G = H - TS} \tag{5.3}$$

$$\boldsymbol{H = E + PV} \tag{5.4}$$

Where:

G = Gibbs free energy

H = enthalpy

T = absolute temperature

S = entropy

E = internal energy

P = pressure

V = volume

$$\boldsymbol{P = \rho \cdot g \cdot h} \tag{5.5}$$

Where

P = pressure

$\boldsymbol{\rho}$ *= density of the liquid*

$g = 9.8\ m/s^2$

h = depth of the liquid in meters

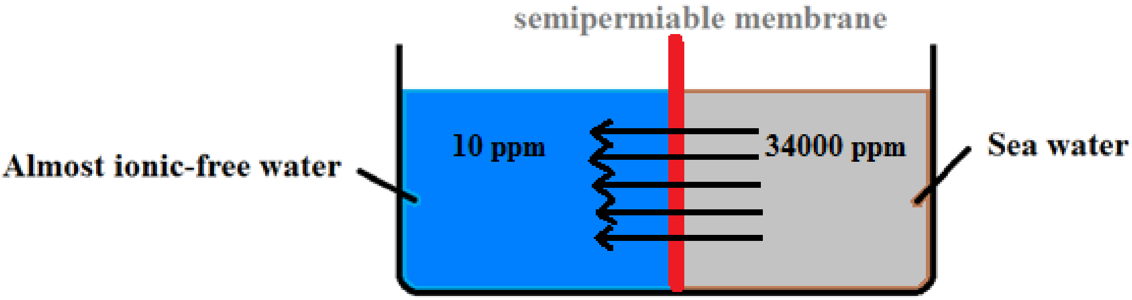


Figure 5.8: Shows water movement through the semipermeable membrane.

Example 1 (using Figure 5.8):

34000 ppm, 25°C, 1atm, 1bar:

$C = 3400\ ppm = 34\ g/L$

$M = 58.5\ g/mole$

$i = 2$

$T = 25^{o}C = 298.2^{o}K$

$R = 8.135\ m^3 \cdot Pa/mol \cdot {}^{o}K$

$1\ m^3 = 1000\ l$

$$P = \frac{2 \cdot 34\frac{g}{l} \cdot 8.135\frac{m^3 \cdot Pa}{mol \cdot {}^{o}K} \cdot 298.2^{o}K \cdot 1000l}{58.5\frac{g}{mol} \cdot 1m^3} = 2.82 \cdot 10^6 Pa$$

$$h = \frac{2.82 \cdot 10^6 Pa}{9.8\frac{m}{s^2} \cdot 1000\frac{kg}{m^3}} = 288\ \mathrm{m}$$

$$\pi = \frac{288\ m}{10\frac{m}{bar}} = \underline{\underline{28.8\ \mathrm{bar}}}$$

Van't Hoff equation (5.6) is used to determine the osmotic pressure of the solutions based on two assumptions: the solution has exhibits an ideal behavior and the liquid is incompressible:

$$\boldsymbol{\pi = \frac{iCRT}{M}} \tag{5.6}$$

Where:

π = osmotic pressure.

C = concentration of solutes in g/L of solution.

M = molecular weight of solute.

i = number of ions for ionized solutes

T = temperature of the solution in the absolute scale.

R = ideal gas constant.

Example 2 (using Figure 5.8):

34000 ppm, 25^{o}C, 1atm, 1bar:

C = 3400 ppm = 34 g/L

M = 58.5 g/mole

i = 2

T = 25^{o}C = 298.2^{o}K

R = 0.082 atm-L/gmole·^{o}K

$$\boldsymbol{\pi = \frac{2\cdot 34\ (\frac{g}{L})\cdot 0.082\ (atm{-}L/gmole\cdot {}^{o}K)\cdot 298.2^{o}K}{58.5\ g/mole}} = \underline{\underline{\textbf{28 bar}}}$$

5.4.4 Comparison of Van’t Hoff and Gibb’s equations

By comparing Van’t Hoff’s and Gibb’s equation mathematically, it can be shown which components make these two formulas different and why we get a different result from each.

Van’t Hoff equation:

$$\boldsymbol{\pi = \frac{iCRT}{M}}$$

Gibb’s equation:

$$\boldsymbol{P = \frac{i*C*R*T*1000l}{M}} \textbf{ (*)}$$

$$\boldsymbol{h = \frac{P}{g*\rho}} \quad \rightarrow \quad \boldsymbol{P = h*g*\rho} \textbf{ (**)}$$

$$\boldsymbol{\pi = \frac{h}{10m/bar}} \quad \rightarrow \quad \boldsymbol{h = 10\,\pi} \textbf{ (***)}$$

Set (***) in (**)

$$\boldsymbol{P = 10\,\pi*g*\rho} \text{ (****)}$$

Set (****) into (*)

$$\boldsymbol{\frac{i*C*R*T*V}{M} = 10\,\pi*g*\rho}$$

$$\boldsymbol{\frac{i*C*R*T*V}{10M} = \pi*g*\rho}$$

$$\frac{\boldsymbol{i * C * R * T * V}}{\mathbf{10}} = \boldsymbol{\pi * g * \rho * M}$$

$\boldsymbol{\pi} = \frac{\boldsymbol{i * C * R * T * V}}{\boldsymbol{10 * g * \rho * M}}$ **(Gibb's*)**

Van't Hoff = Gibb's*

$$\frac{\boldsymbol{iCRT}}{\boldsymbol{M}} = \frac{\boldsymbol{i * C * R * T * V}}{\boldsymbol{10 * g * \rho * M}}$$

$$\mathbf{1} = \frac{\boldsymbol{V}}{\boldsymbol{10 * g * \rho}} \rightarrow \boldsymbol{\rho} = \frac{\boldsymbol{m}}{\boldsymbol{V}} \rightarrow \mathbf{1} = \frac{\boldsymbol{V}}{\boldsymbol{10 * \frac{m}{V} * g}} \rightarrow \mathbf{1} = \frac{\mathbf{1}}{\boldsymbol{10 * m * g}}$$

This implies that Gibb's equation includes the variables m*g, which Van't Hoff does not. This can indicate that the answers from the two equations will not be the same.

Some examples under a variety of realistic conditions are summarized in Table 5.3.

Table 5.3: Osmotic pressure of aqueous sucrose solutions in bar.

Conditions	Concentration (ppm)	Gibbs Equation Osmotic pressure (bar)	Van't Hoff Equation Osmotic pressure (bar)
25^{o}C, 1 atm, 1 bar	34000	28.8	28
	10	$8.7\cdot10^{-3}$	$8.4\cdot10^{-3}$
25^{o}C, 1 atm, 1 bar	5000	4.3	4.2
	10	$8.7\cdot10^{-3}$	$8.4\cdot10^{-3}$
4^{o}C, 1 atm, 1 bar	5000	3.9	3.9
	10	$7.9\cdot10^{-3}$	$7.7\cdot10^{-3}$
25^{o}C, 1 atm, 1 bar	40000	34.6	33.9
4^{o}C, 1 atm, 1 bar	40000	32.2	31.5
25^{o}C, 1 atm, 1 bar	45000	39	38
4^{o}C, 1 atm, 1 bar	45000	36.2	35.5
25^{o}C, 1 atm, 1 bar	50000	42.4	42.4
4^{o}C, 1 atm, 1 bar	50000	40.2	39.4
25^{o}C, 1 atm, 1 bar	55000	47.6	46.6
4^{o}C, 1 atm, 1 bar	55000	44.3	43.4
25^{o}C, 1 atm, 1 bar	60000	52	51
4^{o}C, 1 atm, 1 bar	60000	48.3	47.3
25^{o}C, 1 atm, 1 bar	65000	56.3	55.2
4^{o}C, 1 atm, 1 bar	65000	52.3	51.3
25^{o}C, 1 atm, 1 bar	70000	60.6	59.4
4^{o}C, 1 atm, 1 bar	70000	56.3	55.2

Both the Gibb’s and Van’t Hoff equations can be used to arrive at similar results, but a slight difference appears under higher concentrations. From experience, the theoretical value acquired from Gibb’s equation is more accurate (Cheryan_C., 1998). This phenomenon can be explained by the lack of important variables in the Van’t Hoff equation. Jacobus Henricus Van 't Hoff was a chemist working with gases, while Josiah Willard Gibbs was a mathematician working with gas and liquids. Gibb’s goal was to find a suitable formula for both phases (liquid and gas). However, there are some differences between the liquid and gas phases, where gas is compressible and a liquid is incompressible. This is an another reason why one cannot use the Van’t Hoff equation for both phases, because calculating the osmotic pressure of liquids is through the semi permeable membrane (Berg, 2006).

Calculating the osmotic pressure with Van’t Hoff’s equation is used only for theoretical practices, since it is based on the assumptions that the liquid is incompressible and the behavior of the solution is ideal. Gibb’s equation for calculating the osmotic pressure is applied in practice, because the numbers are more similar to the numbers one would get from the operation of an actual RO plant.

5.4.5 Nanofiltration

Nanofiltration, an environmental friendly process, is a cross-flow pressure driven purification technology that falls between reverse osmosis and ultrafiltration. However, this technology is quite new and has not been explored or studied as much as RO. “Nanofiltration membranes can be used in the separation of salts and mixtures containing small organic solutes” (Bowen and Mohammad, 1998).

Nanofiltration membranes can reduce the number of dissolved multivalent ions, color, and some heavy metals. Other advantages with this technology is its reduced pressure when compared with RO, which reduces its operating costs, eases the requirement for operational maintenance, allows for high quality permeate flow, etc…

Nanofiltration was discovered during the 1970's. Low pressure RO membranes were developed using relatively high fluxes and the energy costs were reduced. These low pressure membranes were called nanofiltration membranes. One decade later NF membranes were found in many applications such as treatment of wastewater, ground water (color reduction) and for pretreatment in desalination. (Hilal et al., 2004)

Nanofiltration uses charged membranes with small pores that range in size from 100 to 1000 Daltons (0.0001 to 0.001 microns) (Nath, 2008) for their molecular weight cut off (MWCO).

In NF membranes monovalent ions pass through the membrane, and divalent ions are removed. The membrane surface can be positively or negatively charged. The charge causes interactions between ions and the membrane surface. NF membranes are also called softening membranes, because of their ability to remove positively charged cations (calcium, magnesium, etc.) from hard water when the membrane surface is negatively charged. (Cipollina Andrea et al., 2009) Water is termed as "hard" when the mineral content is high. Another advantage in NF membrane properties is that the permeate level is high when compared to RO membranes where permeate level is low.

In Nanofiltration, the pressure applied to the membranes while operating is significantly lower(10-34 bar) (Yacubowicz and Yacubowicz, 2005) than the operating pressure used in Reverse Osmosis (35-100 bar (Cheryan_B., 1998)) systems. Thus NF is a much more energy efficient process. In NF membranes, the permeate flow is high and the concentrate flow is low, whereas with RO membranes the permeate flow is low and the concentrate flow is high. When NF membranes are used in pretreatment of seawater, they reduce scale formation within the equipment (Hilal et al., 2005). The Softening of water by Nanofiltration allows some minerals to pass through the membrane to the permeate side, which makes the water less corrosive and prevents the corrosion of the equipment.

5.4.6 Pretreatment-Fouling

Proper pretreatment is very important for the prevention of fouling. As in any other membrane treatment technology, nanofiltration membranes have problems with fouling, which leads to flux reduction. High flux and high surface roughness in NF membranes increase possibility of fouling. (Hilal et al., 2005) Size, shape, ion charge and the density of the particles are the main parameters in calculating the risk of fouling that occurs with NF membranes. To avoid fouling the NF processes can be performed by putting a pre-filter before the membrane, which will prevent most fouling agents from reaching the membrane.

5.4.7 Membrane materials

Homogeneous asymmetric nanofiltration membranes are mostly made of cellulose acetate (CA) and polysulfone (PS). Thin film composite NF membranes are made of polysulfone, polyethersulfone (PES), polyvinyledene fluoride (PVDF), polycrylonitrile (PAN), and Polyether ether Kethone (PEEK) (Yacubowicz and Yacubowicz, 2005). CA is one of the most used membrane materials, because of its low cost and hydrophilicity. Its hydrophobic properties make it more resistant to fouling. However, CA is very attractive material for bacteria in feed water, which can cause bacterial fouling and shorten the membranes lifetime. The surface of CA membranes is smooth and uniform, whereas polyamides have protuberances (Figure 5.9). There is a risk of fouling if the protuberances catch and retain matter suspended in the feed (Cheryan, 1998).

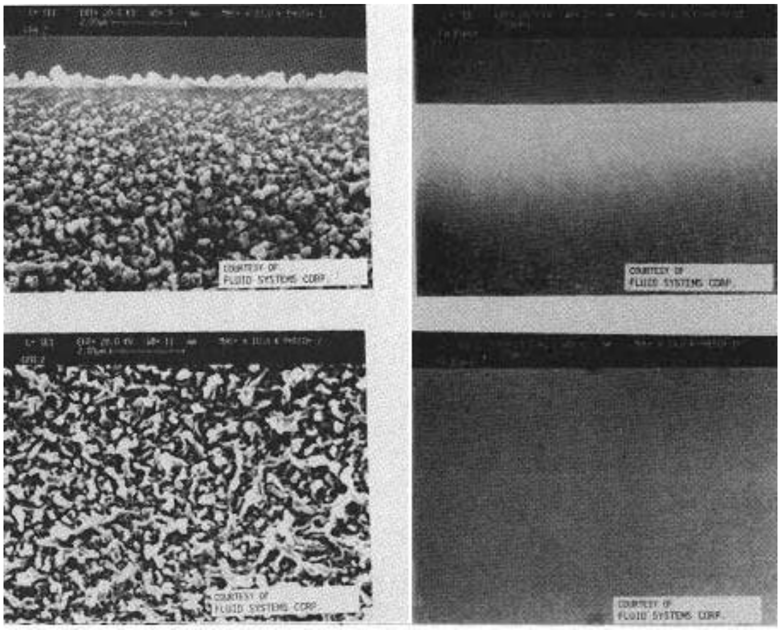


Figure 5.9: Examples of surface structure of Cellulose Acetate (right) and Polyamide (left) membrane materials (Cheryan, 1998).

Thin film composite (TFC) membranes are one of the most widely used in nanofiltration applications. TFC consist of an asymmetric porous support with an ultra-thin layer that is polymerized onto the asymmetric porous support. The biggest manufacturer of TFC is DOW-Filmtec.

5.4.8 Applications

Because of its unique features, NF is used in many different applications. The ability of nano-filters to remove viruses, color and soften water has made it a suitable technology for some municipal applications. The NF membranes are used in removal of effluents from industrial effluents and in making waste discharges less toxic for the environment. Because of the rapid development of nanofiltration technology, NF membranes are quickly becoming a substitute for reverse osmosis membranes in desalination of seawater. NF is also applied in paper, diary, textile industries, etc... (Yacubowicz and Yacubowicz, 2005)

5.4.9 Ultrafiltration

The first Ultrafiltration membrane was made in 1907 using nitrocellulose by Bechhold (Kuchera, 2010). Ultrafiltration (UF) (Figure 5.10) uses a membrane separation process with pore sizes in the range of 0.001 to 0.1 microns (Nath, 2008).

Figure 5.10: Ultrafiltration membrane with the membrane house.

UF membranes can remove high molecular-weight substances, colloidal materials, bacteria as well as organic and inorganic polymeric molecules. UF membranes are not capable of removing low molecular weight organics and ions.

The operational pressure used in Ultrafiltration processes is low (1-10 bar) when compared to that of reverse osmosis and nanofiltration, which makes ultrafiltration energy saving treatment technique (Nath, 2008).

5.4.10 Types of membranes

Ultrafiltration membranes are made by phase inversion. There are four main polymers used in this process: polysulfone (PSU), polyethersulfone (PES), polyimide (PI) and polyacrylonitrile (PAN). Polysulfone and polyethersulfone are hydrophobic materials. The hydrophobicity of these materials can lead to fouling, which affects membrane performance and reduces the membrane lifetime. This can be avoided by mixing these materials with hydrophilic polymers such as polyvinylpyrrolidone or polyethyleneglycol. Polyimide has a high chemical tolerance and high thermal stability. It is often used in UF asymmetric membrane production (Cipollina Andrea et al., 2009).

5.4.11 Applications

There are many different applications where ultrafiltration membranes can be applied. One of the most common applications is as a pretreatment in RO systems to reduce SDI value of the feed water to 2 or 3, thus prolonging the membrane’s life and reducing the necessity for chemicals (Cipollina Andrea et al., 2009).

Humic acid is especially unwanted in drinking water, because it discolors water and gives it an unwanted smell. Ultrafiltration can be used to remove humic acids from the drinking water (Lowe and Hossain, 2008). UF is also used in the textile and dairy industries.

5.4.12 Electrodialysis

Electrodialysis is a water desalination technique, that has been on the market since 1952 (Cipollina Andrea et al., 2009). The main characteristic of Electrodialysis is that it makes use of voltage or electromotive force to help separate charged ionic species.

An Electrodialysis consists of a stack of two types of membrane pairs, anion and cation. In one end of the stack there is an anode and in the other end a cathode. When an electrical current, from an external source, is sent through the solution the ions with positive charges migrate to the electrode with the negative charge (anode), and the ions with the negative charges migrate to the electrode with a positive charge (cathode). When the anions pass through the anion exchange membrane their movement is further blocked by the cation exchange membrane, and when the cations pass through the cation exchange membrane their movement is blocked by the anion exchange membrane. In this way, ionic movement through a charged membrane concentrate and permeate is created in the spaces between the membranes (Figure 5.11).

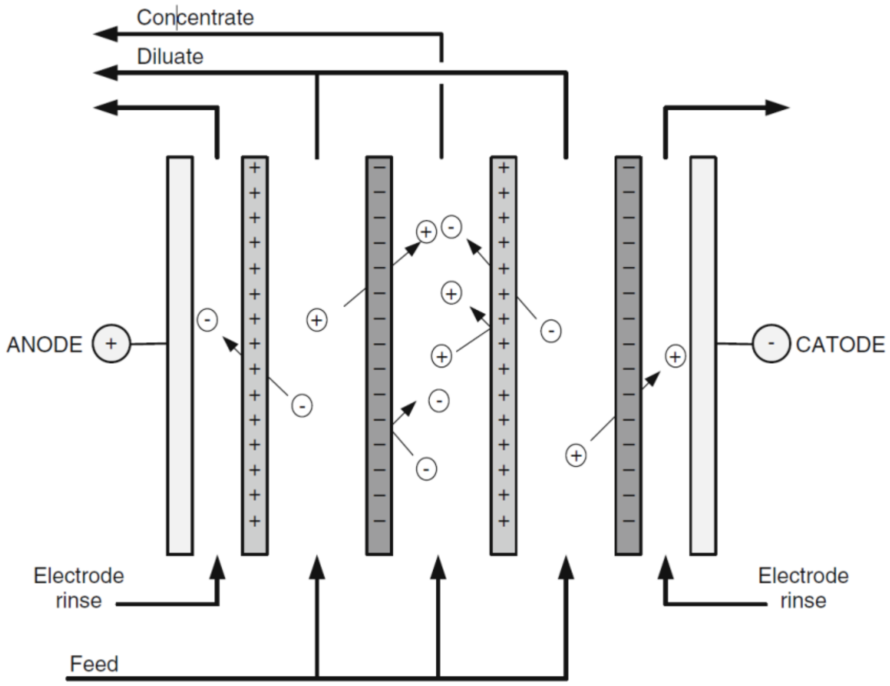


Figure 5.11: Electrodialysis (Cipollina Andrea et al., 2009).

Hydrolysis and scaling also need to be controlled in the electrodialysis process to ensure the stable operation. Hydrolysis can reduce the efficiency of electrodialysis when the concentration of Na^+ and Cl^- at the membrane surface becomes very low. In this case, H^+ and OH^- ions pass through the cation and anion exchange membranes into the concentrate, where $Mg(OH)_2$ may occur as scale. At the same time, if the concentration of NaCl in the concentrate is too high it may lead to scaling.

In Electrodialysis, water recovery can be increased by increasing the NaCl concentration. The selection of the right membranes for Electrodialysis is based on membrane resistance and physical strength. It is also important to check the quality of the raw water so as to prevent a high concentration of organic acids from entering.

Processing brackish water gives the highest recovery rate (90%) when applying Electrodialysis. Long membrane lifetime, membrane resistance to strong acids and alkaline conditions as well as low installation and operational costs makes electrodialysis a effective membrane desalination technique (Cipollina Andrea et al., 2009).

5.5 Membrane modules

A membrane module is a device in which is installed a membrane filter. There are different shapes of membranes such as flat sheets, tubes and hollow fibers. These are four main membrane module designs most commonly used (Figure 5.12).

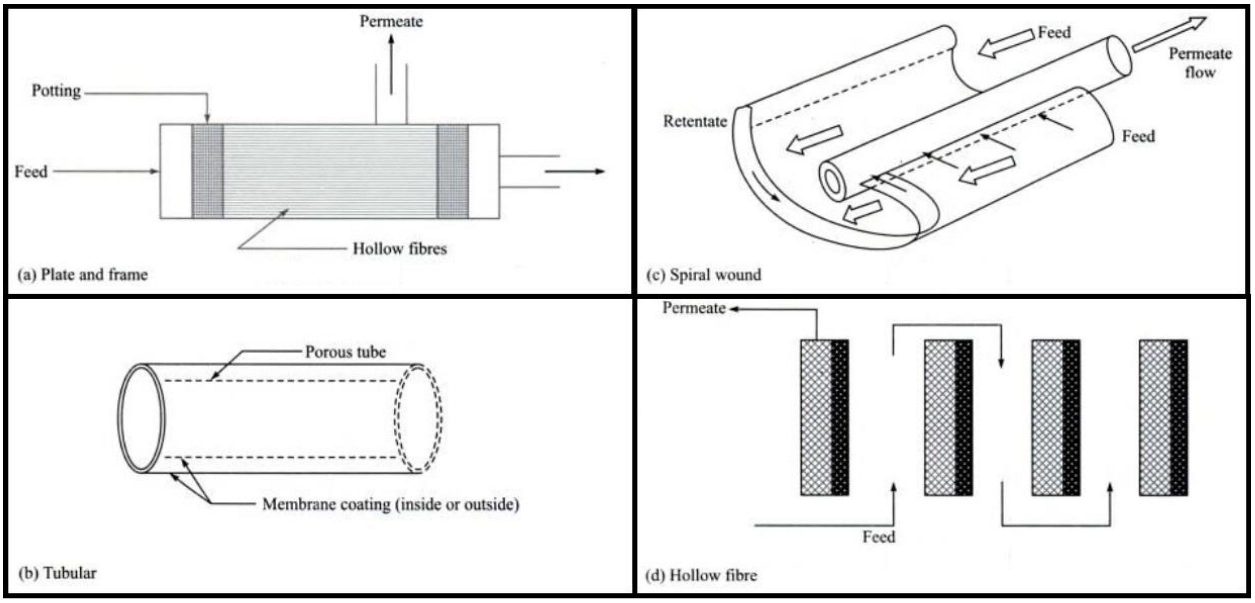


Figure 5.12: Membrane module designs (Kaushik Nath, 2008).

5.5.1 Plate-and-frame modules

A plate and frame membrane module can be variable, but in general they have a series of flat membrane sheets (Figure 5.12.a). Membranes cover thin plastic plates on both sides, while sealing prevents any leakage. The permeate flows through the small grooves situated on plate’s flat surface. Plate-and-frame modules are also easy to take apart for cleaning.

5.5.2 Tubular modules

Tubular modules (Figure 5.12.b) are built of shells and tubes. In tubular modules the feed flows through the tubes and the permeate passes through the wall at the end of the tube, which is on the shell side. The tubes in these tubular devises are walled, porous or perforated. Simple pretreatment of feed water eases the operation of tubular modules. Mechanical cleaning is applied by using a sponge ball.

5.5.3 Spiral wound modules

The membrane elements are designed around flat sheets (Figure 5.12.c). Two flat sheets are placed together with their active sides facing away from each other. They are separated by a thin, mesh-like spacer material and are glued together on three sides.

5.5.4 Hollow fiber modules

A hollow fiber module (Figure 5.12.d) consists of large number long and narrow hollow fibers tubes. A pressure vessel usually contains a certain number of U-shaped hollow fibers, where the open end of the fibers is pointing into a head plate. Feed water enters the vessel under high pressure and flows along the outside of the fibers, while the permeate passes through the base of the fibers. In hollow fiber modules two way filtration is possible (inside-out or outside-in).

5.6 Post-treatment

The permeate produced by the RO water treatment plant does not meet the drinking water requirements; it is poor of minerals, corrosive and have risk of growing bacteria an microorganisms. Thus, the post-treatment must be applied on produced water. There are various types of post-treatment:

- Disinfection (ultraviolet, ozonation and chlorination)
- Re-mineralization
- Corrosion control

5.6.1 Disinfection

The term disinfection or the deactivation of organisms living in the water is done by either destroying or impairing vital parts of the organism that will prevent cell growth or interfere with their energy yielding mechanisms. This is done to prevent the spreading of pathogens and also to prevent bioaccumulation in membranes. Different methods of disinfection are used such as chlorine, chloramine, chlorine, dioxide, UV, ozone; to name a few. Other processes can be done for the purification of drinking water. The three most commonly used methods for disinfection in water desalination systems are Ultraviolet (UV), ozonation and chlorination.

Gas striping is used for the removal ammonia, VOC's, odorous gas, and other gases that include CO_2, O_2, H_2S. It is the opposite of gas adsorption. Added as a separating agent gas stripping materials obey Henry's law.

Along with disinfection, water quality can also be improved through the use of ion exchange, advanced oxidation processes, distillation and membranes.

5.6.2 Ultraviolet

One of the most effective post-treatments in a water treatment plant is disinfection using ultraviolet light. In Ultraviolet disinfection, the UV light is used to deactivate bacteria, pesticides and viruses that may be present in the treated water.

A typical UV system contains UV lamps within a closed chamber (Figure 5.13). The UV lamps are made of quartz sleeves, which make it possible for the UV light to travel through them. The approximate lifetime of an UV lamp is one year, at which point it must be replaced. The UV lamps have to be continuously cleaned either mechanically by wire brushes or Teflon rings, or chemically. During chemical cleaning the UV lamps are taken out of the chamber and the reactor is cleaned with dilute citric or phosphoric acid.

Figure 5.13: UV disinfection system (image_14, 2013).

When water passes through the UV chamber, the microorganisms present are exposed to UV light. The wavelength this light is in the range of 210 to 300 nm, which is damaging for nucleotides in the microbial DNA/RNA. This makes it impossible for microorganisms to reproduce after leaving the UV chamber and eliminates the risk of diseases (Erin D. Mackey, 2001).

Advantages of UV disinfection:

- It does not affect water taste, color, or pH.
- It does not produce toxic by-products.
- It is easy to install, operate and maintain.
- It does not require much space.
- It is an inexpensive technology with low operational costs.

5.6.3 Chlorination

Disinfection using chlorine is a simple and common post-treatment method. It is very effective in deactivating bacteria, algae, spores, ameobic cysts and viruses.

There are several chlorinators used in this process. It is important to know how much organic material is present in the water in order to add the correct amount of disinfectant. The most commonly used disinfectant is sodium hypochlorite (NaOCl). The following reaction (2) shows how sodium hypochlorite behaves in a solution:

$$NaOCl + H_2O \rightarrow HOCl + NaOH \qquad (2)$$

Another widely used disinfectant is a chlorine gas. It dissolves easily in water and can be injected directly into the flow stream. The reaction (3) between the chlorine gas and the water can be written as:

$$Cl_2 + H2O \rightarrow HOCl + HCl \qquad (3)$$

This type of disinfection is most effective in deactivating viruses and bacteria. However, it is not common to inject a chlorine gas directly into the flow. When employing this method for chlorine injection, the gas is fed into a chlorine contact tank where it must have a contact time with the water for about 30 minutes. Chlorine can be applied in gas, liquid or solid form (Cipollina Andrea et al., 2009).

Chlorine is also an important disinfectant, because of its ability to provide a residual. The chlorine residual has the ability to disinfect treated water from the desalination plant by continuing on in the water distribution system until it reaches the consumer.

5.6.4 Ozonation

Ozone is considered a good disinfectant because of its high oxidation potential. Ozone has a low solubility in water; therefore, the effectiveness of its disinfection is dependent upon the application method, pH and temperature. Ozone can be produced by applying a high voltage current through oxygen. Ozonation (Figure 5.14) removes taste, odor and color from drinking water. Also it has a low number of by-products and requires only small dosages (1-2mg/L) for a high level of disinfection.

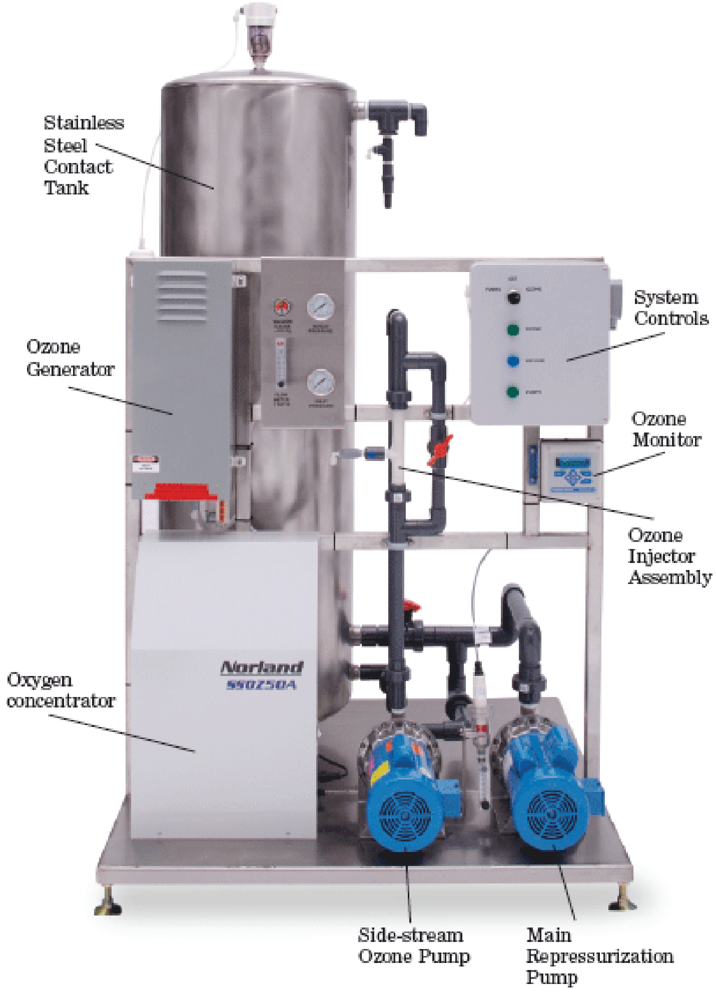


Figure 5.14: Ozone disinfection system (image_15, 2013).

There are some disadvantages with ozone disinfection. It is very unstable and has a short lifespan (less than an hour) in aqueous solutions. Thus, it cannot provide a residual and requires an additional disinfectant, like chlorine or chloramine. If an additional disinfectant is not used there arises the risk of bacterial regrowth. It is difficult to store ozone, because of its reactivity. Furthermore, there is a high capital cost for the instillation and production of an ozone disinfection system (Kawamura Susumu, 2000).

5.6.5 Re-mineralization

Water produced by a RO system is highly purified, corrosive, unhealthy and soft, because there are so few minerals present in the product. The re-mineralization process is used to increase the salinity and hardness of the produced water to protect the water distribution system and pipes from corrosion, and to improve the color and taste of the purified water. During the process of re-mineralization, CO_2 acidified permeate needs to come into contact with a bed of limestone. Thus, saturating permeate with calcium and providing alkalinity through bicarbonate to the water. The chemical reaction (4) is presented below (Hasson and Bendrihem, 2006):

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO^-_3 \qquad (4)$$

The only disadvantage in the limestone process is that reaction is slow and does not reach completion. As a result NaOH and Na_2CO_3 are added to neutralize excess CO_2.

Chemical addition to the permeate flow is also used as a means of re-mineralization. It includes addition of calcium and magnesium salts. Post-treatment with lime ($Ca(OH)_2$) is an effective way to increase pH and to provide hardness and alkalinity to the permeate. The chemical reaction (5) is presented below (Voutchkov Nikolay, 2012):

$$2CO_2 + Ca(OH)_2 \rightarrow Ca(HCO_3)_2 \tag{5}$$

The tank that is filled with lime is fed by permeate from the RO membrane, where water is mixed with lime to create a saturated limewater. This saturated limewater is then injected into the permeate flow that did not pass through the tank filled with lime. The combined product is then distributed to the consumer. Moreover, calcium is added to control corrosion from the produced water, while magnesium is added to enhance the nutrition of the product.

Lime processes require equipment for the preparation and dosing of lime slurries, which makes it less cost effective than equipment used for handling limestone.

5.6.6 Corrosion control

Corrosion is described as the degradation of metal into ions, which is essentially due to the redox reactions occurring in the solution (e.g. Fe (iron) reacts with water or air moisture creating rust).

Corrosion increases the operational costs. That is to say, that more maintenance would be needed to combat corrosion. In the event of excessive corrosion, with little or no maintenance, the membrane could be destroyed. Corrosion could also be combated using better materials, but that would also increase costs. This is because the equipment would have to be made of high cost alloys that can handle the corrosion. In the end, the detriment is to the consumer either by reduced water quality (health problems) and/or increased tax.

To produce a non-corrosive and non-scaling forming water (stable water), it is important to find the exact balance between pH, alkalinity and hardness. Corrosion control (i.e. chemical agents/high quality alloys/ceramic membranes) is a much cheaper option, than reinstalling the whole new system.

To determine if water is corrosive or scale-forming, Baylis curve and Langelier index (Equation 5.7) can be used (Delion et al., 2004):

$$LI = pH - pHs \quad (5.7)$$

If LI < 0, water is corrosive; if LI > 0, water is scale forming; if LI = 0, water is stable.

The Baylis curve is used to indicate the properties of produced water from the relationship between alkalinity and pH values of calcium carbonate (Figure 5.15).

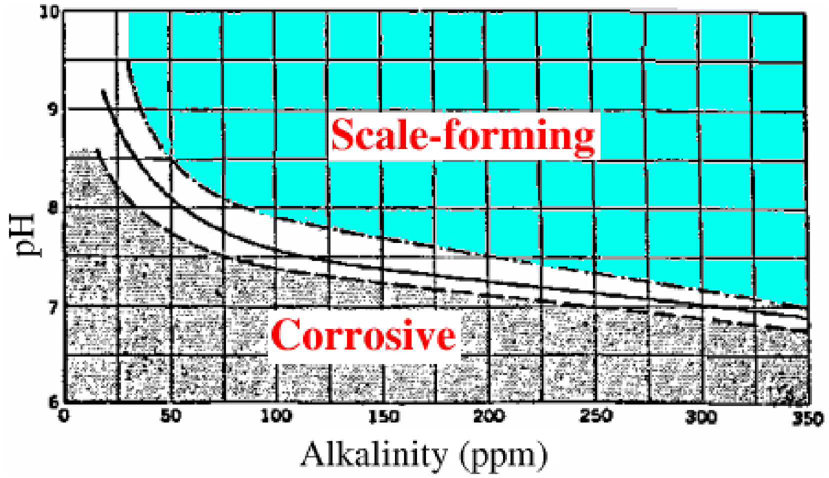


Figure 5.15: Baylis Curve (image_16, 2013).

By plotting the alkalinity and pH values on a graph water conditions can be defined. If the crossing point of pH and alkalinity is below the curve, it means that water is corrosive. When the crossing point is above the curve, it means water is scale-forming and pH needs to be lowered, whereas alkalinity needs to be decreased in order to make water stable. The problem of corrosion can be avoided by adjusting the pH and applying corrosion inhibitors, such as silicates, polyphosphates, and zinc phosphates.

Chapter six: Description of RO/NF pilot plant

6.1 Water treatment pilot plant set-up

The purpose of this thesis was to demonstrate a fully operational system that could actually produce safe, clean and fresh drinking water powered by a relatively small wind turbine fitted with an electric generator.

For this Prototype all parts and components were installed on a 1 (height) by 0.8 (wide) by 0.6 meter (length) modified laboratory table, which the university no longer needed.

A schematic of the membrane set-up (Figure 6.1) and all of the system components in the water treatment pilot plant are described below.

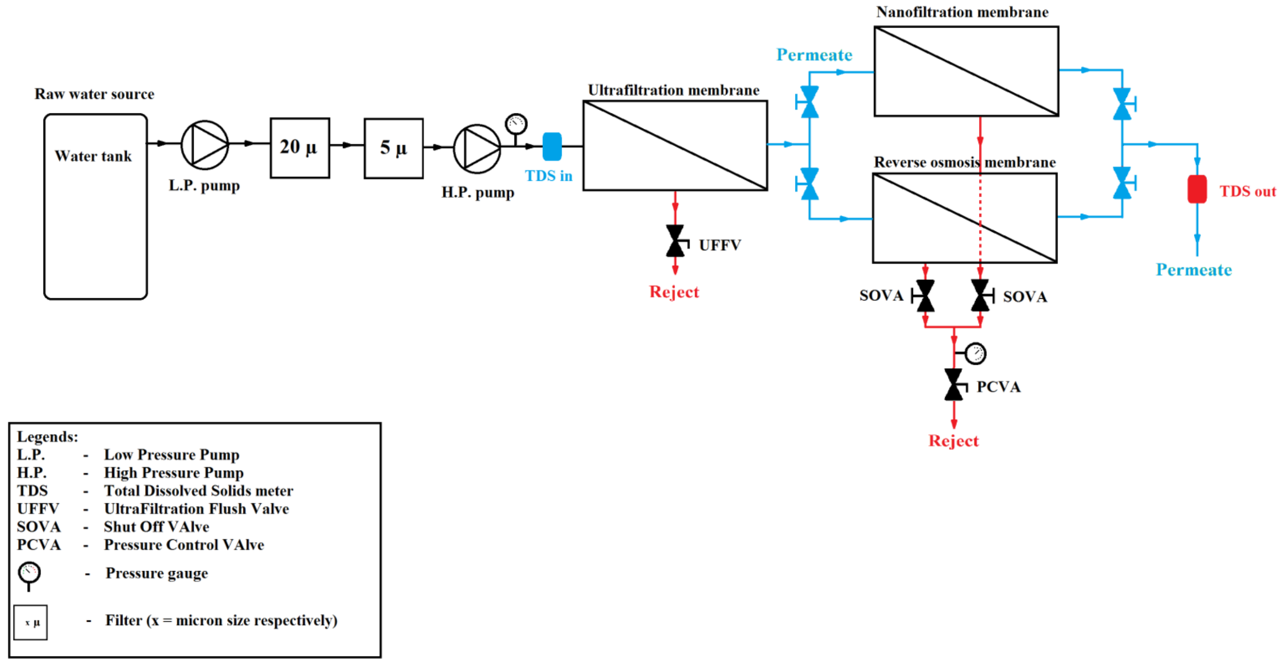


Figure 6.1: Shows the membrane schematic.

6.1.1 Low pressure pump.

For this pilot plant the low pressure pump was bought from a local hardware store. The low pressure pump was a Coltech Submersible, 220 Volt, 1 phase 400 Watts low-pressure pump. In this study, the pump was used to collect untreated, raw water from the bottom of a polypropylene tank. When applied in other applications this pump could be placed in seawater or in any other water source that is deemed unfit for human consumption.

The purpose this pump is merely to feed raw water into two separate pre-filters that are connected in series. The first has a 20 micron replaceable filter cartridge inside of a filter housing made of polypropylene, and the second has a 5 micron replaceable filter cartridge installed in a similar housing.

These two filters, 20 µ and 5 µ, remove all particles larger than 5 microns before the influent water is fed to the UF, NF, and reverse osmosis membranes.

6.1.2 Filters

The filter housings were produced by PENTEK. The changing of filter cartridges was easily performed, and if needed, cleaning or disinfection of the inside of the filter housings could be done in a few minutes. The filter cartridges used were Aqua Pro 20 microns and 5 microns. They were made of a pleated filter material constructed using woven Polypropylene fibers that created a very large filter area supported by an internal perforated core. Raw water was first filtered through the 20 micron filter to remove larger particles and then through the 5 micron filter to achieve a good water quality before it was fed to the membranes. Effective pre-filtration was a very important step in order to reduce the raw waters SDI (Silt Density Index), which helped to prevent the clogging of the membrane(s) and had a great impact on them by optimizing their performance and extending their lifespan. The main purpose of using filters is to prevent fouling and to keep the flux rate high.

6.1.3 High pressure pump

The high pressure pump was produced by PROCON PUMPS, Series 200 constructed in stainless steel. It is designed to boost the feed water pressure up to 15.8 bars. It is a one stage impeller pump specially designed for 800 gallon (3020 liter per day) RO systems. This pump was chosen due to its high reliability and ruggedness.

6.1.4 Reverse Osmosis/Nanofiltration Membranes.

For this Prototype, Filmtec (Dow) TFC “TW-2540” and “NF-2540” membranes were chosen (Table 6.1).

Table 6.1: Shows the dimensions of the Dow-Filmtec membrane in inches (mm) (data obtained from the manufacturer) (Dow-Filmtec, 2012):

Name	A (Length)	B (Diameter)	C (Diameter)	D (Diameter)
TW30-2540	40.0 (1,016)	1.19 (30.2)	0.75 (19)	2.4 (61)
NF90-2540	40.0 (1,016)	1.19 (30.2)	0.75 (19)	2.4 (61)

These membranes are tape-wrapped (Figure 6.2).

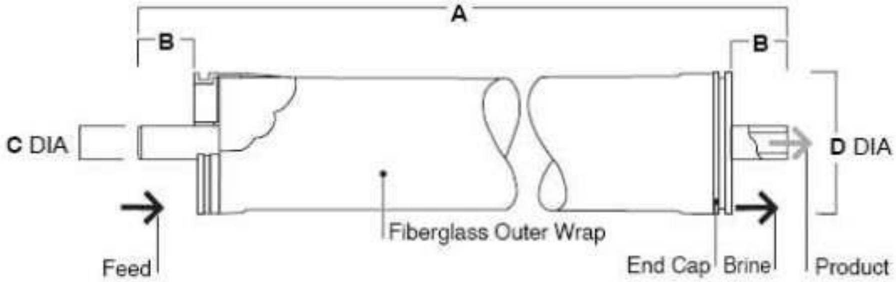


Figure 6.2: FILMTEC RO element TW30-2540 (Dow-Filmtec, 2012).

TFC - Thin-Film composite membranes are frequently used for purification of tap-water. The material used in these is polyamide (PA). There are three main types of composite membranes; thin-film, ultrathin, or thin-layer composite membranes. They are widely used in both RO and nanofiltration applications. A thin, dense polymer skin is formed over a microporous support film in the composite membranes. The manufacturing process typically includes two or more steps (Cheryan, 1998), due to the complexity of manufacturing the two layers together. The supporting film decreases the risk that the membrane pores will clog. PA membranes tolerate a wide pH range (2-11). The free chlorine tolerance level of the PA TFC membranes is < 0.1 ppm. In order to prevent possible damage to the membrane during operation, the pressure-drop should not exceed 13 psig (0.9 bar). The maximum operational pressure is 600 psig (41 bar). The membrane’s lifetime can be prolonged if the temperature is held below 45°C. The membrane should then yield a rather high rejection rate of 99.5 % (Dow-Filmtec, 2012).

6.1.5 TDS measurement

The Dual Inline TDS monitor used in this set-up was used to define the total dissolved solids content in the two different water lines, before water entered the first membrane feed water and on the permeate side of second membrane. The installed TDS monitor showed if the filter cartridge or the membranes were or were not functioning properly.

The used TDS monitor is a HM-Digital™ - DM2 commercial In-Line Dual TDS monitor (Figure 6.3). The TDS monitor dimensions were 11.6x6.8x1.8cm.

Figure 6.3: HM-Digital DM2 dual TDS monitor (image_17, 2012).

The TDS-monitor was powered by batteries (lifetime ~two years) and had a range from 0-9990ppm (where 0-999ppm has a resolution of 1ppm and 1000-9900ppm has a resolution of 10ppm). It was equipped with two cables (in-red and out-blue), with ¼” T-fittings. TDS levels can be read both from the feed and product side so it is easy to determine whether the filtration system is working properly or not. The TDS-monitor is simple to install and operate, and provides readings that are fairly accurate (±2%).

The TDS meter measures the conductivity level of the solution. Conductivity describes the ability of the ions in the water to conduct an electrical current between two or more electrodes.

Negatively charged ions are attracted to the positively charge electrode and positively charged ions are attracted to the negatively charged electrode. Conductivity (G) is the inverse of resistivity (R), which can be defined with Ohm's law (Equation 3.1):

$$\boldsymbol{R = \frac{V}{I}} \tag{3.1}$$

Where:

R = Resistance of the solution (ohms)

V = Voltage (volts)

I = Current (amperes)

And equation for conductivity will look like (Equation 6.1):

$$\boldsymbol{G = \frac{1}{R}} \tag{6.1}$$

Where:

G = Conductivity (Siemens)

R = Resistance of the solution (ohms)

The conductivity of the solution is usually measured in μS (micro-Siemens)**.** The conductivity level of the solution can be affected by the change in temperature of the solution (SAS., 2004).

6.1.6 Pressure Gauges

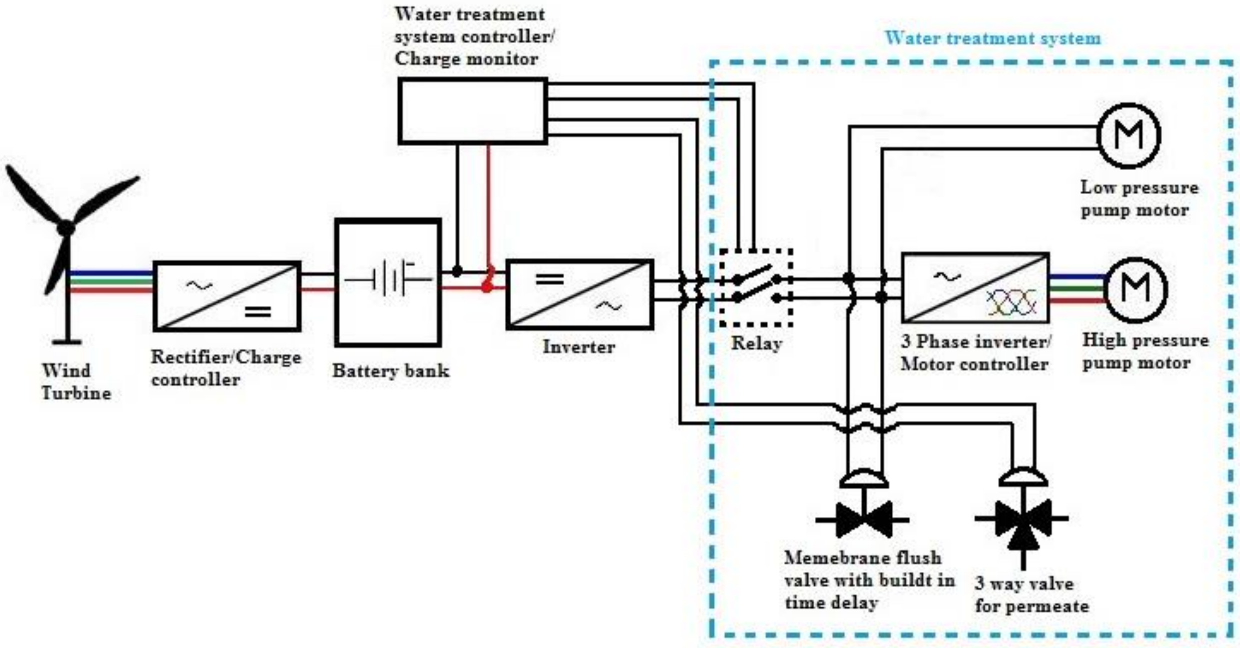
Two pressure gauges were installed on this RO system; their function is to show the pressure in the system (Figure 6.4). There is one for the pressure input (feed) before the first membrane and one for the pressure on the rejection side of the second membrane. The water pressure indicated by the second pressure gauge is for the operating pressure inside the membrane pressure vessels and can be adjusted using a pressure control valve (PCVA).

Figure 6.4: Liquid pressure gauges.

A pressure drop may indicate fouling of the membrane. The reject flow rate can indirectly affect membranes and indicate fouling. Pressure control valve on the reject side is installed to adjust pressure across the semipermeable membrane(s).

6.2 Pilot plant electrical set-up

A schematic of the electrical set-up of the entire system excluding the membrane components in the water treatment pilot plant was made in order to provide map and guide for the electrical flow in the system (Figure 6.5). When adjustments needed to be made it was useful to see what order the components were connected in in the system so as to avoid confusion. The water treatment section was more elaborately depicted in figure 6.1 above.



Legends:
~ Alternating current (AC)
= Direct current (DC)

Figure 6.5: A schematic of the electrical set-up.

6.2.1 Wind turbine and inverter

The wind turbine is equipped with an alternative current generator that cannot be connected directly to the rechargeable batteries. The alternating current must first be routed through semiconductors or diodes that rectify the current. The most widely used rectifiers are called “bridge rectifiers”. A charge controller (Figure 6.6) is also needed so as not to “overcharge” the batteries. In some more advanced models these controllers may even stop the wind turbine generator when the batteries are fully charged.

Figure 6.6: 600W wind turbine rectifier/charge controller (image_18, 2013).

Electrical power can be calculated from the following equation 6.2:

$$\boldsymbol{P = V \cdot I} \tag{6.2}$$

Where:

P = power (Watts)

V = voltage (Volts)

I = current (Ampere)

The Wind Turbine is a three-phase generator that generates alternating current in three phases with 120 degree shift between each of them (Figure 6.7).

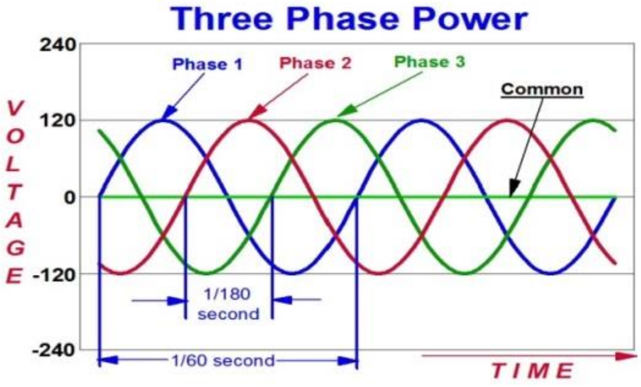


Figure 6.7: Three phase power (image_19, 2012).

This method is the most efficient way of using alternating current. The alternating current is divided into three wires, which make use of size, dimension and thickness to makes the current conduction more energy efficient.

6.2.2 Galvanic elements

The galvanic element (Figure 6.8) is an electrochemical element that takes chemical energy and transforms it into electricity. It consists of two electrodes immersed in an electrolyte. The energy released by the electrolyte acts on one or both of the electrodes. It then dissolves and converts them chemically. The primary element was invented by the Italian Luigi Galvani (Hess, 2013).

He introduced the term galvanic current on flow from such items. Volta's original element consisted of a copper and zinc plate immersed diluted sulfuric acid.

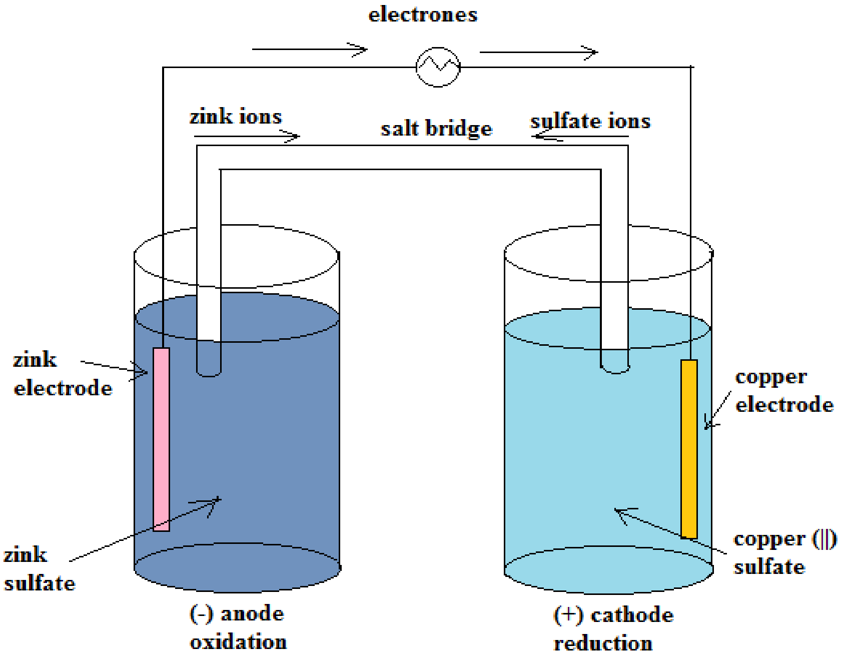


Figure 6.8: Galvanic element.

When the zinc plate comes into contact with the electrolyte, positively charged zinc ions are liberated, the zinc plate then gains an excess of electrons and becomes negatively charged. When the copper plate comes into contact with the electrolyte hydrogen ions attract electrons from copper and are then excreted as hydrogen gas. This results in the copper plate becoming positively charged. At both electrodes, the electric potential is rapidly established from a predetermined value. From the zinc plate (the negative pole) the ions are released but the positive zinc ions will gradually return, whereas the copper plate (the positive pole) repels each of the positive hydrogen ions. Connecting the two plates externally with an electrical conductor will create a current from the positive to the negative pole (i.e. electrons move in the opposite direction). This eliminates the electrons from the zinc plate and zinc ions can then be re-emitted to the electrolyte. Similarly, the copper plate provides electrons so that the hydrogen ions are neutralized.

6.2.3 Battery bank

In a battery bank, one should stick with the same chemistry (in this case lead-acid) so that the lifetime of the battery bank can be increase (Batteries, 2012). By having different Ampere (chemistry), the battery with lowest number will be discharged faster. The sealed lead-acid batteries were used because of their low cost and higher capacity. The normal concerns of a high weight and the necessity for a large amount of space were not important in this experiment, as the pilot project was performed at the university campus. The main purpose of using batteries in this project was to provide a continuous flow of electricity. Since the weather can be very hard to predict, the wind turbine may not be running during certain periods of time. This lack of power can cause severe damage to the membranes and also results in the system not producing water when required.

The sealed lead-acid batteries are made from five major components (Figure 6.9): a plastic container made of polypropylene, internal lead plates, plate separators, electrolyte (battery acid), and connection points made of lead (batteries., 2012).

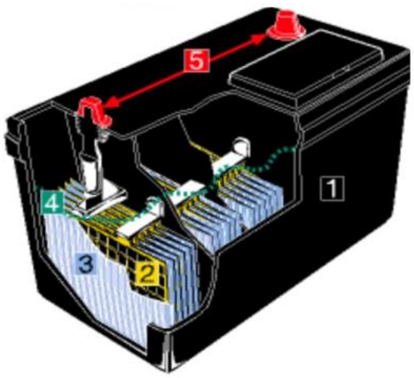


Figure 6.9: The sealed lead-acid battery (image_20, 2012).

The initial plan was to use eight sealed lead-acid batteries 110 A each, connected in parallel, and two batteries (the same type as in parallel circuit) in series (Figure 6.10).

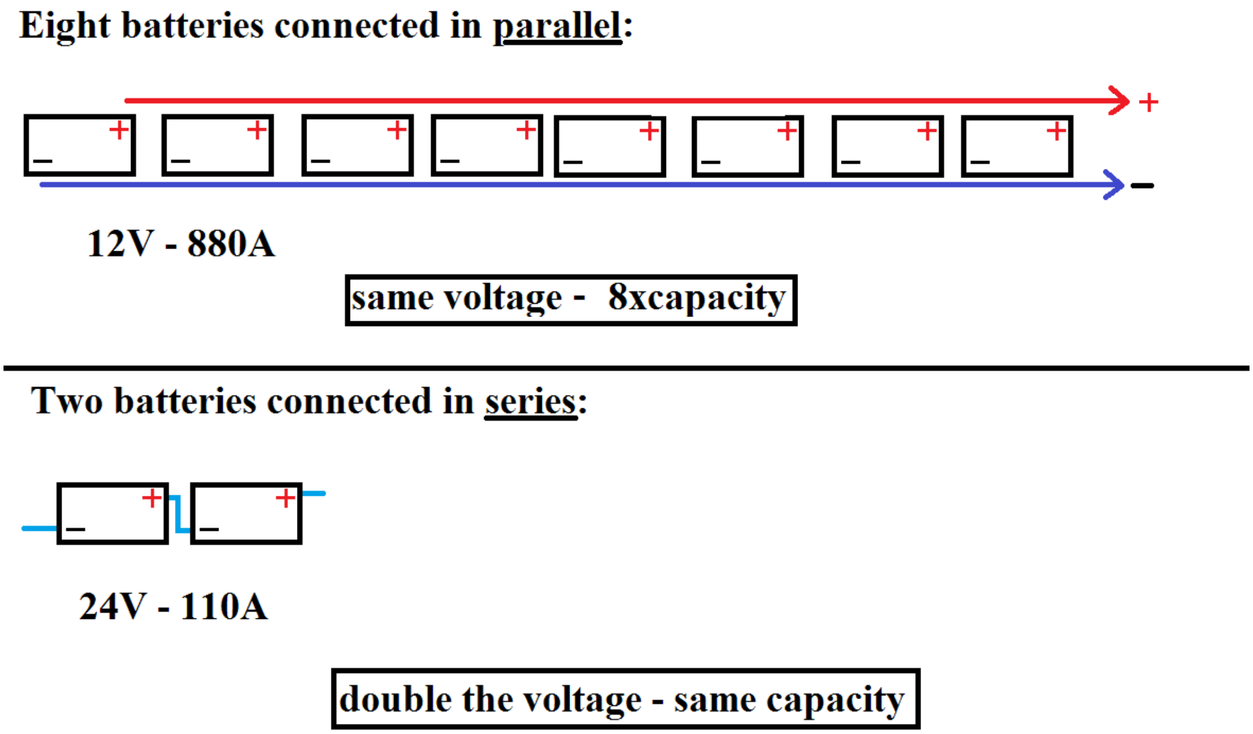


Figure 6.10: Batteries connected in parallel and in series.

However, when testing the second hand batteries they didn't charge 100%. In order to provide enough electricity to run the desalination pilot plant for an extended period, the battery pack set-up was changed to be ten batteries in parallel and with none in series (Figure 6.11).

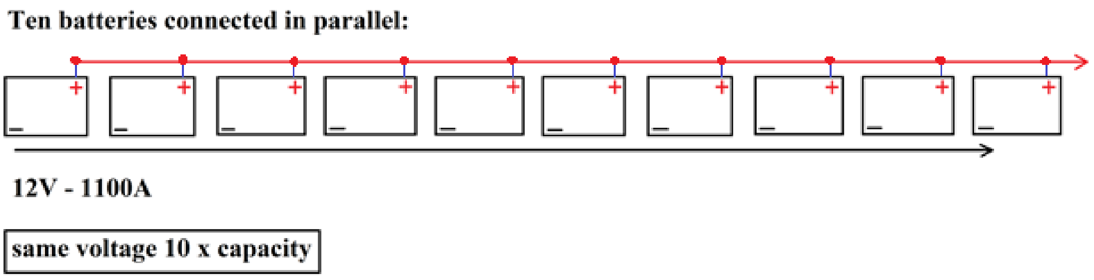


Figure 6.11: Batteries connected in parallel.

Specially designed fuses were installed on each of the ten batteries (Figure 6.12).

Figure 6.12: Specially designed fuse.

If one or more batteries had been discharged too much, it affected all the others, and even short-circuited the parallel connection. To avoid this, these fuses were melted and the affected batteries were disconnected from the rest.

There are other types of rechargeable batteries suitable for pilot plant utilization, such as Li-Ion (Lithium-Ion) and Ni-Cad (Nickel-Cadmium) batteries; however, these were not used.

Lithium-Ion batteries have a high nominal voltage of 3.7V. The anode in lithium rechargeable batteries is made of a carbon material and the cathode is made of a lithium metal oxide (Figure 6.13). The electrolyte in these kinds of batteries are liquid and have a polymer matrix (McDowall, 2000).

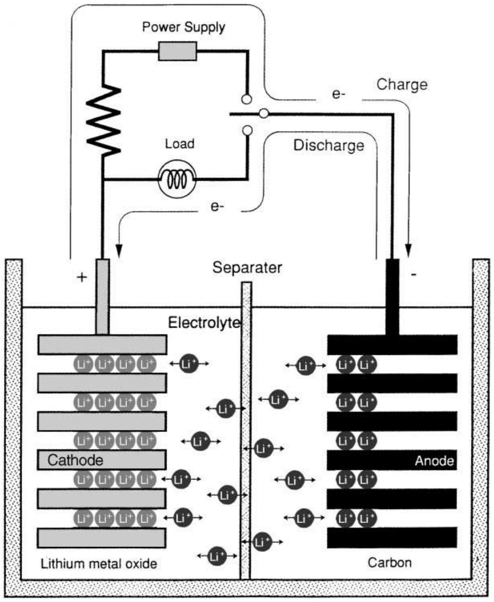


Figure 6.13: The Lithium-Ion battery (Wakihara, 2001).

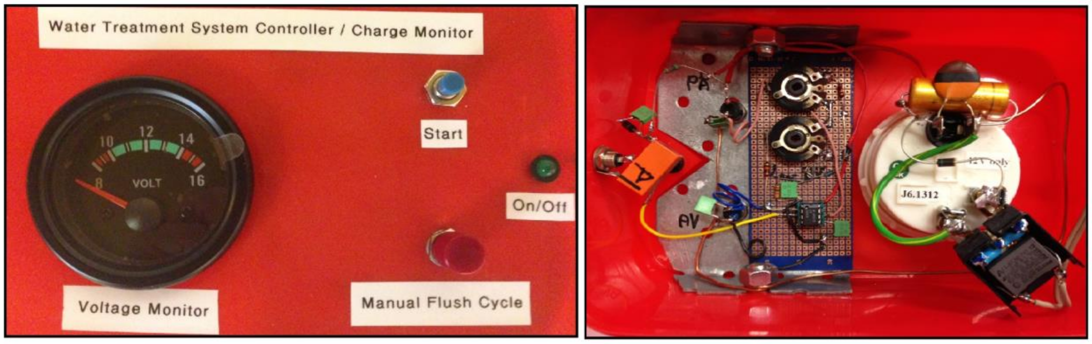
Lithium-Ion batteries are non-toxic and seem to be the most environmental friendly solution. They have good performance at high-temperatures, are recyclable, have a high specific energy and do not suffer from the so called “memory effect”. The “memory effect” is the total charge a battery can retain, which is set by the first time it is charged. If not properly charged the first time this can cause the battery to hold less charge. A long battery life of 2000 cycles is one of the advantages of Li-Ion batteries (Alireza Khaligh, 2010). The disadvantage of using Li-Ion batteries is that they are more expensive than lead acid or Ni-Cad batteries. They also cannot tolerate a full discharge, because they have a mechanism installed that controls the charge/discharge rate (Rashidi et al., 2009).

Nickel-Cadmium batteries are a well-known battery type. They have a long lifetime, can tolerate being discharged completely, are resistant to abuse and can be recycled. The operating voltage of the Ni-Cad batteries is 1.20 V, which is low when compared to that of Li-Ion batteries (Dell, 2000). The electrodes in Ni-Cad batteries consists of nickel oxide hydroxide and metallic cadmium (Rashidi et al., 2009).

There are some disadvantages when using Ni-Cad batteries, the main being the difficulty of recycling them. The cadmium is a heavy metal, and if not properly disposed it can cause severe environmental pollution (Alireza Khaligh, 2010). They also suffer from the “memory effect,” mentioned above, which initiates a high self-discharge. The cost of the Ni-Cad batteries is also quite high when compared to lead acid batteries (McDowall, 2000).

6.2.4 Water treatment system controller/charge monitor

The water treatment system controller/charge monitor has two main functions. The first is to protect the batteries from discharging below 11.5 Volts. This is done by automatically disconnecting the main power from the water treatment system. However, this function can be overridden by pressing the start button, even though this should be avoided and only used during an emergency situation. The second function is to automatically power up the water treatment system when the battery bank is fully charged. On the front panel a voltmeter continuously displays the true voltage of the battery bank (Figure 6.14).



Outside **Inside**

Figure 6.14: The water treatment system controller/charge monitor. This build was made specifically for this water treatment system.

Flow Diagram for the Water Treatment System Controller/Charge Monitor was made to describe the principle how controller/monitor works (Figure 6.15).

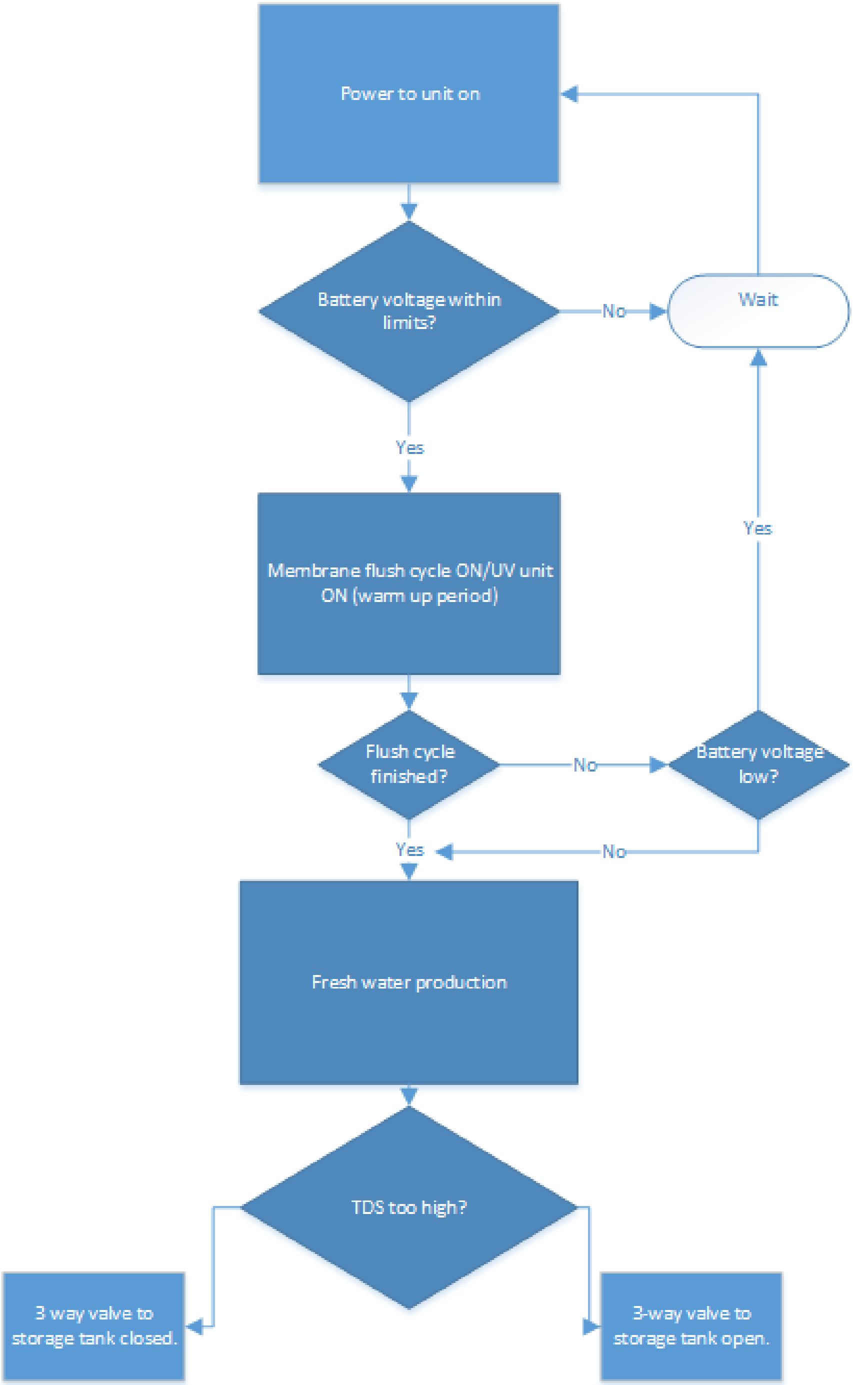


Figure 6.15: Battery voltage monitor/membrane flush controller.

6.2.5 Inverter

The inverter connected the battery bank and the motor. The inverter was used to convert direct current to alternating current via an oscillator, which cut the direct current into high frequency electronic pulses. The input from direct current was at 12V/24V and the output for alternating current was at 110V/220V with a frequency of 50Hz. There are two types of inverters: one-phase and three-phase. The one-phase inverters are mostly used for low-energy demanding purposes, whereas the three-phase inverters are used when higher energy amounts are required (Khanna, 2004). The ideal situation would be to produce alternating current with pure sine waves. This is the case for many motors.

Additionally, two electrical sockets were installed downstream of the inverter (Figure 6.5). These two electrical outlets allowed for both the electrical low-pressure pump and the three-phase motor with a high-pressure pump to be run simultaneously.

Chapter seven: Results

7.1 Theoretical calculations of electricity consumption

The power consumption of the motor was calculated by multiplying the motor current and the motor voltage. The relationship between power, current and voltage is given in equation 6.3:

$$\boldsymbol{P_{motor} = 5.2\ A \times 220\ V = 1.144\ kW}$$

The system consists of three units that consume electrical power: a motor, a low pressure pump and a flush valve. The total amount of electrical power required is shown in equation 7.1.

$$\boldsymbol{P_{demand} = \left(P_{motor} + P_{low\ pressure\ pump} + P_{flush\ valve}\right)} \qquad (7.1)$$

$$\boldsymbol{P_{demand} = 1.144\ W + 0.400\ W + 0.020\ W = \underline{\underline{1.564\ kW}}}$$

If the unit runs for one hour the power consumption would be 1.564 kW/hour (hereafter written as h).

7.2 Theoretical calculation of battery bank power capacity

The battery bank consisted of ten batteries connected in parallel. Each battery had an electrical current of 110 A. The parallel connected system had a combined voltage of 12 V. The power capacity of one battery was calculated using equation 6.3. Equation 7.2 was used for calculating the theoretical battery bank power capacity.

$$\boldsymbol{P_{one\ battery} = 110\ A \times 12\ V = 1.320\ kW}$$

$$\boldsymbol{P_{battery\ bank\ theoretical} = 10\ batteries\ \times P_{one\ battery}} \tag{7.2}$$

$$\boldsymbol{P_{battery\ bank\ theoretical} = 10\ batteries\ \times 1.320\ kW = 13.200\ kW}$$

It was estimated that the battery bank could only utilize 90% of its maximum power, due to the loss of 12V DC to the 220V AC Inverter.

The P_{input} is the realistic battery bank power capacity where a 10% loss was taken into account. It was calculated by multiplying the maximum theoretical power capacity with the coefficient 0.9, as shown in equation 7.3.

$$\boldsymbol{P_{total} = P_{battery\ bank\ theoretical} \times 90\%} \tag{7.3}$$

$$\boldsymbol{P_{total} = 13.200\ kW \times 90\% = 11.880\ kW}$$

The run time (equation 7.4) of the system is defined as the amount of time the pilot desalination system can run with a fully loaded battery bank, without any external force charging the battery bank.

$$\boldsymbol{Run\ Time = \frac{P_{total}}{P_{demand}}} \tag{7.4}$$

$$\boldsymbol{Run\ Time = \frac{11.880\ kW}{1.564\ kW} = \ 7.596\ hours}$$

7.596 hours is approximately 7 hours and 36 minutes.

The water treatment system has a daily capacity of a total 800 GPD, which is equivalent to 3040 liters per day. If there is no wind present to recharge the batteries, a running time of 7 hours 36 minutes is expected.

$$\boldsymbol{Hourly\ capacity = \frac{3040\ litres/day}{24\ hours} = 127\ litres/hour}$$

To calculate the battery's backup capacity in the pilot plant, the hourly capacity was multiplied with the running time:

$$\boldsymbol{127\ litres/hour \times 7.596\ hours = 962\ litres}$$

7.3 Solution for the ideal set-up

The ideal set-up would power the water treatment system for 24 hours (equation 7.5). The actual power demand was 1,564 kW/hour, which in a period of 24 hours represents a total power demand of 37,536 kW.

$$\boldsymbol{P_{24h} = P_{demand/hour} \times 24\ h} \tag{7.5}$$

$$\boldsymbol{P_{24h} = 1.564\ kW/h \times 24h = \underline{37.536\ kW}}$$

After running for 24 hours the water treatment system had consumed 37,536 kW.

The number of batteries (equation 7.6) required for a 24 hour non-stop operation was determined by taking into account a 10% power loss from the inverter. To calculate the power loss from inverter it was necessary to multiply the equation with a coefficient 1.10.

$$\boldsymbol{Number\ of\ batteries = \frac{37.536\ kW}{1.320\ kW} \times 1.10\ = 31.28 \approx \underline{\underline{32\ batteries}}} \tag{7.6}$$

24 hours of normal operation requires 32 batteries to run the system continuously. It would be necessary to have more than 31 batteries, in this case 32, because 31 would not be capable of fully powering the system for 24 hours.

7.3.1 Assumption

By increasing battery current, the number of batteries could be decreased, e.g. replacing 110 A batteries with 500 A batteries. This was calculated by applying equation 6.3, followed by equation 7.6.

$$\boldsymbol{P_{one\ battery} = 500\ A \times 12\ V = 6\ kW}$$

$$\boldsymbol{Number\ of\ batteries = \frac{33.792\ kW}{6\ kW} \times 1.10 = 6.195\ \approx 7\ batteries.}$$

7.4 Wind turbine power calculation

Defining the size or power output of the wind turbine is not an easy task. The wind turbine used in this project had a maximum power output of 600 W. The amount of electricity needed to run all of the power consuming electrical components in this system was 1.564 kW/h. Using a simple calculation (equation 7.9), the size of the wind turbine could be defined as:

$$\frac{\mathbf{1.564}\ \boldsymbol{kW}}{\mathbf{0.6}\ \boldsymbol{kW}} = \mathbf{2.667} \approx \mathbf{3} \tag{7.9}$$

From the above calculation, it was obvious that the power output generated by wind turbine would have to be three times larger than the 600 Watts (0.6 kW) produced by the wind turbine used in this project. Assuming that the wind turbine provides 1.564 kW to all of the water system's electrical components, the batteries must also be simultaneously charged with the same amount of power:

$$\mathbf{1.564}\ \boldsymbol{kW}(\boldsymbol{water\ treatment\ system}) + \mathbf{1.564}\ \boldsymbol{kW}(\boldsymbol{battery\ charge}) = \mathbf{3.128}\ \boldsymbol{kW}$$

This indicated that a total power output of 3.128 kW was required from the wind turbine's electrical generator. This amount was the minimum needed to run both the water treatment system and to provide enough energy to keep the battery bank fully charged at all times.

Since wind turbines rarely produce the power stated by the manufacturer, it is safe to assume that the said output was, in reality, approximately 50 to 60% of the stated output. With this in mind, a wind turbine with twice the output would be a better choice:

$$\mathbf{3.128}\ \boldsymbol{kW} \cdot \mathbf{2} = \mathbf{6.256}\ \boldsymbol{kW}$$

The minimum power output of the wind turbine required for this project was 6.256 kW, but such wind generators were not available. However, 7.5 kW generators were easy to find, being made by a number of manufacturers – which in turn creates sound competition price wise. In fact, there was very little difference in pricing when comparing 5 kW and 7.5 kW wind turbines.

Chapter eight: Discussion

The main purpose of this study was to develop a membrane system that could run on green energy. The choice of components was very important. All of the components had to fit together so that the system would work as intended.

8.1 Wind turbine

The wind turbine used in this project showed a low charge capacity. Additionally, through the use of theoretical calculations it was proven that the wind generator had to be at least 6.256 kW in order to produce enough electricity to run the water treatment plant non-stop for a minimum of 24 hours. Moreover, a more powerful wind turbine would require a charge controller and inverter that corresponded to its power output.

8.2 Battery bank

In this pilot plant, the battery bank backup system consisted of lead acid batteries. Use of Li-Ion batteries was not possible, because of the project’s budget constraints; such batteries are quite expensive. However, Li-Ion batteries would be the most suitable power solution when constructing the ideal pilot plant. They are environmentally friendly, performance well at high temperatures, do not suffer from the “memory effect,” and have a long battery life of 2,000 cycles.

In addition to results found about the battery backup system, this project proved that charging batteries on pure wind energy would not guarantee a continuous power supply. For this reason a diesel generator would have to be installed as a backup power source, in the case that the weather conditions were uncooperative with very little wind or in the case of a full battery discharge. Calculations made for determining the battery bank’s full capacity showed that the system required several more batteries, or a higher battery current from each cell in order to be sufficient.

8.3 Why use three phase system instead of one phase system

In the beginning of the project a single phase motor was installed at the high pressure pump in order to create enough pressure for the RO membranes. However, the single phase motor was not powerful enough. In addition to its low capacity, the single phase motor became very warm, which indicated that a lot of electricity was being wasted away in form of heat. Single-phase motors consist of a starter, a rotor, a shaft and a condenser. When alternating current is applied it has no rotating magnetic field. Connecting it in series with a condenser with one field winding a weak rotating magnetic field could be obtained, which would result in a rotation of the shaft. A single phase motor is simple (Figure 8.1), robust and cheap.

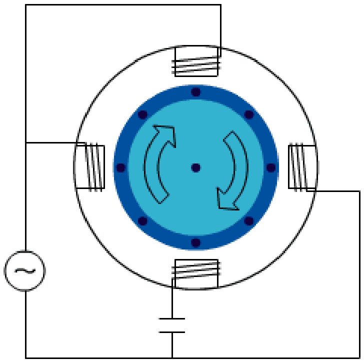


Figure 8.1: Single Phase motor (image_21, 2013).

Single phase motors are mostly used for low power demanding devices such as vacuum cleaners, refrigerators, heat pumps, etc…The efficiency is not as good as with three-phase motors, but it has a very simple and robust construction. This combined with a single electrical system makes this kind of motor more widely used in applications where there are relatively smaller outputs. In a three phase system the power source consists of three sinusoidal voltages. For a balanced three-phase system, these three sources are different wavelengths and are displaced by 120 electrical degrees (Figure 8.2).

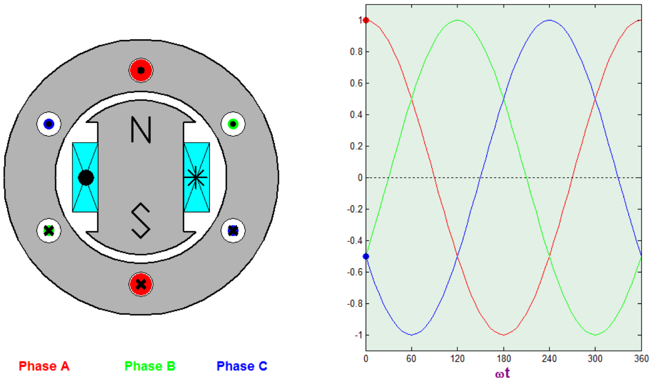


Figure 8.2: Three phase system (image_22, 2013).

When using a balanced three phase system, the power delivered to the load is always constant, and does not experience periodic interruptions; such is the case in a single phase motor.

Three-phase motors have a rotating magnet in the middle of three fixed coils. It will always rotate in one direction, but if two of the three wires are swapped, the shaft will turn in the opposite direction. This is because the electromagnetic rotating field in the motor would change direction.

Three phase motors are typically used only in larger engines in the industry where efficiency is important. Three phase motors can be very efficient, and can run for long periods of time without stopping.

8.4 Ultrafiltration as pretreatment option

The pilot plant was designed with an ultrafiltration membrane - as part of the pretreatment - ahead of the reverse osmosis membranes. The ultrafiltration membrane decreased the raw water’s SDI number, thereby decreasing the necessity for the use of cleaning chemicals as a pretreatment. Applying ultrafiltration also reduces the operational costs and increases the membrane lifetime for an RO system.

8.5 Nanofiltration vs. reverse osmosis

There were three membrane types installed in the plant: a nanofiltration membrane, a reverse osmosis membrane and an ultrafiltration membrane.

The raw water had a low TDS level that was between 40 to 50 ppm. It was expected that the reverse osmosis membrane would reduce the TDS to less than 1 ppm. However, when measuring the TDS levels leaving the NF membrane, the TDS was seen to be 0 ppm. This was a surprise, but the raw water's TDS was mostly caused by cations, which are removed by NF membranes. This effectively showed that NF membranes soften water that passes through it.

8.6 Automatic flushing system/ TDS monitoring

In order to avoid fouling and scaling, automatic flushing systems and TDS monitors had to be installed on membrane water treatment systems. If reverse osmosis membranes were not in use for a while, the TDS on the permeate side would be noticeably higher during the first minutes of operation. This phenomenon was due to small leakages on O-rings, seals and gaskets. Following a flush cycle, the TDS level also had a tendency to increase a little.

Chapter nine: Conclusions and recommendations

Experience gained from building this system resulted in the following recommendations:

1. To determine the proper size of a wind turbine, wind data acquisitions must be taken over an extended period of time in the area where the wind turbine is to be installed. The wind turbine must be selected based on the power curve readings and not from how much power it supplies at its maximum wind speed. The power curve is unique for each wind turbine. It is beneficial to conduct preliminary research on the different suppliers and/or models available in order to determine the most effective wind turbine size. Power curves help to decide the actual power output of the wind turbine based on the actual wind speed at the location where it is mounted.

2. The power that is generated from the wind turbine needs appropriately sized electrical cables to prevent any power loss from the circuit.

3. The battery bank used in this project was unable to perform the task for which it was designed because its capacity was insufficient. Thus, the battery bank in a future project should have a higher capacity. This would enable the system to run for at least 24 hours.

4. As shown in this project, three phase electrical motors provide a more energy efficient performance and turn out to be a more reliable solution than single phase motors. Thus, this is the preferred motor to run a pump on in a water treatment plant.

5. Prior choosing the membranes for the water treatment plant, it is wise to build a pilot water treatment plant. Tests should be performed on the different membranes based taking into account the water characteristics specific the site where water treatment will occur. This will help determine the most suitable membrane type for water purification. Based on the desired water quality the number of necessary membranes can also be determined.

6. The pretreatment must be selected based on a thorough water analysis and SDI measurements. These measurements should be from sampling performed over an extended period of time.

7. Water produced using membranes process requires disinfection to maintain a certain standard. There are three main methods of disinfection: UV, ozonation and chlorination. They can be used either separately or in combination.

8. The membranes must be flushed periodically to prevent the formation of deposits on both sides of the membrane surface. The automatic flushing system should be used when in operation, when in standby mode, during start-up, and prior to “Stand-by” mode.

Electricity production by using wind turbines is a well-known and reliable technology. Desalination by reverse osmosis uses less power than any other desalination technology. Both technologies have become less expensive. The work performed in this study proved that it is possible to power a membrane water treatment plant using wind turbines. With improved design parameters and components, it should be possible to build similar treatment plants that would help to alleviate the problems presented by a growing demand for clean drinking water.

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