WASTEWATER EFFLUENT TREATMENT PROGRAM FOR UTILIZATION IN INDUSTRY AS POLISHED WATER AND COOLING WATER

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CERTIFICATE

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ABSTRACT

Engro Polymers and Chemicals is currently treating the wastewater from its industrial processes to meet the NEQ limits. The effluent water is discharged to the Arabian Sea. However, water scarcity and environmental regulations demand effective recycling of this effluent water using green technologies so it can be utilized in one or more of the process on site.

This project designs a new unit for the treatment of wastewater effluent for utilization as polished water. As Engro Polymers and Chemicals uses the on-site steam generation for plant operations and distribution to the nearby fertilizer plants, recovering the wastewater effluent as polished water can be of significant importance.

The proposed design primarily uses membrane technology for water treatment along with a range of pre-treatment and secondary treatment facilities. By incorporating the principle of Zero Liquid Discharge (ZLD), the process recovers 100% of the effluent as polished water or cooling water. Finally, HAZOP study and economic analysis of the proposed solution is done to identify cost effectiveness and health and safety hazards involved.

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LIST OF ABREVIATIONS

VCM	Vinyl chloride monomer
NTU	Nephelometric turbidity unit
BOD	Biological oxygen demand
RO	Reverse osmosis
COD	Chemical oxygen demand
BFW	Boiler feed water
CW	Cooling water
TSS	Total suspended solids
MLD	Minimum liquid discharge
ZLD	Zero liquid discharge
TDS	Total dissolve solids
MMF	Multimedia filteration
VOC	Volatile organic chemical
PAC	Poly aluminium chloride
w.r.t	With respect to

CHAPTER 1

INTRODUCTION

1.1 About the Industry

Engro Polymers and Chemicals Limited (EPCL) is the subsidiary of Engro Corporation. It is the only fully-integrated facility of chloro-vinyl complex and the sole producer of PVC resin in Pakistan. The products of this industry are as follows:

- Polyvinylchloride (PVC)
- Caustic Soda
- Hydrochloric Acid (HCl)
- Sodium Hypochlorite
- Vinyl Chloride Monomer (VCM)

Among many others, one of the key value of EPCL that is highly relevant to this project is Health Safety and Environment. The company aims to operate in such a manner that it meets all the applicable environmental regulations while also maintaining an exceptional standard of health and safety for its employees.

Therefore, the treatment of wastewater effluent is of high importance to the company not only for business purposes but also for environmental concerns.

1.2 Operational Waste Water Treatment Plant in EPCL

The wastewater influent that is treated in EPCL comes from various sources. These primarily include the following:

- Decanters
- Laboratory
- Dehydrators
- Cooling Towers Blow Down
- Neutralization pit
- Dikes of VCM

The typical quality of influent water from all the four different streams are shown in the table below.

Parameter	Stream 1	Stream 2	Stream 3
Suspended Solids	310	10	50
pH	4	6	8
COD (Mn)	200	340	250
COD (Cr)	600	820	500
BOD	90	70	350

Table 1 Parameters of Stream 1, 2 & 3

	Stream 4
Caustic Soda	20%
Water	80%

Table 2 Parameters of Stream 4

Stream 1: Decanter Waste Water

Stream 2: Waste Water from Stripper

Stream 3: Waste Water from Laboratory

Stream 4: Caustic Waste Water

The influent wastewater from these four streams is sent to the wastewater treatment plant. The sequence of the physical and chemical treatments in this process is shown by the schematics below. [1]

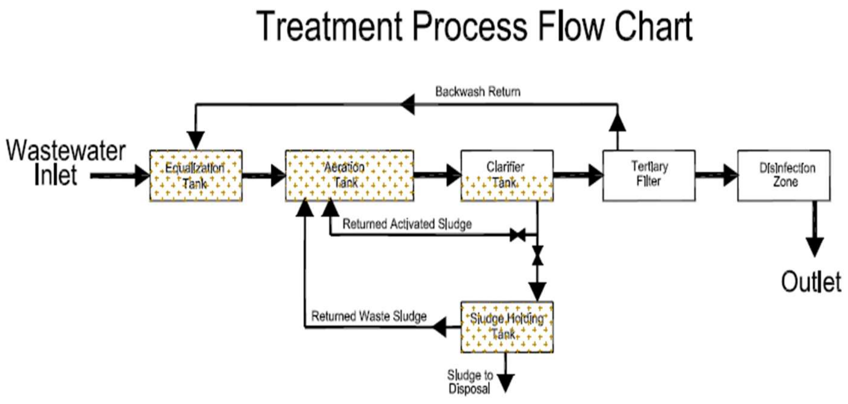


Figure 1 Treatment Process Flow Chart

1.3 Quality of Effluent Water and Desired Water

	Effluent Water			Boiler Feed Water	Cooling Water
Parameters	**Lower Limit**	**Upper Limit**	**Average Value**	**Recommended Values**	**Recommended Values**
BOD (ppm)	21.0	37.0	30.0	< 5.0	< 10 .0
COD (ppm)	0.0	130.0	87.4	0.05	50
Chlorides (ppm)	0.0	900.0	785.0	NIL	0.7
pH	6.5	8.5	7.7	8.0	8.0
TSS(ppm)	0.0	150.0	27.9	1.0	20
Total Dissolved Solids (ppm)	0.0	3000.0	1816.0	50.0	500
Total Iron (ppm)	0.0	1.0	0.4	0.01	0.1
Turbidity (NTU)	0.0	35.0	17.0	< 5.0	10.0

Table 3 Quality of effluent water, recommended values of BFW & CW

Based on the above data, we can make the following important conclusions at this stage:

- The effluent water quality does not fully adhere to the NEQ limits. The high average value of BOD indicates that the water contains organic pollutants even after wastewater treatment. This must be considered when choosing a suitable water treatment technology.
- A significant water softening capacity would be required to achieve 50.0 ppm or less amount of total suspended solids for boiler feed water. The system will be designed based on the upper limits of effluent water quality.
- The effluent treatment program must incorporate equipment to remove chemical oxygen, organic waste, chlorides, dissolved solids, and suspended solids by a significant percentage to achieve a reasonable quality of boiler feed water.

- For cooling tower make-up, the quality of water is not a significant issue due to the use of chemical treatment in cooling towers. However, feeding high quality, pure water would significantly reduce the chemical dosage fixed cost, and prevent scaling of equipment that use cooling water.

1.4 Available Technologies for Achieving the Desired Water Quality

Based on the effluent quality and required composition of water, the following technologies may be used to design the effluent treatment program. Note that these technologies are primarily for water softening applications. The project requires to produce high-quality demineralized water for use as boiler feed, so the choice of water softening method is of great importance. The other impurities may be removed in the pre-treatment stages depending on the technology adopted.

1.4.1 Reverse Osmosis

The working principle is based on the separation of dissolved solids or solute from water by using membranes that retain the salts and allow water to pass through them. [2] The effluent is introduced on the feed side through which permeate is obtained due to some driving force such as pressure gradient. The remaining feed flows to the retentate side of the membrane. Configuration of these systems is primarily based on the membrane modules. Normally, spiral wound modules are used in industrial applications due to the high surface area obtained in less floor space.

1.4.2 Membrane Bioreactor

MBR is a hybrid technology that combines the biological treatment of sludge and physical filtration using microfiltration and ultra-filtration membranes. The primary application of this technology is wastewater context is for municipal treatment which is conventionally done by Activated Sludge Process (APS). Membrane Bioreactor is a relatively new technology with limited industrial applications due to extensive membrane fouling. However, it is known to give a much better quality effluent that any other process. [3]

1.4.3 Ion Exchange

The working principle of this technology is primarily based on the exchange of ions between two resins or solutions. In wastewater treatment, the feed stream is in introduced to cation exchanger, which contains acidic resin. All the cations in the water are exchanged with hydrogen ions, making the water acidic. In the next step, the acidic stream is passed through anion exchange unit in which the added hydrogen ions are neutralized with hydroxide ions. Usually, cation-exchange resins are sulfuric acid or hydrochloric acid while sodium hydroxide is used as anion exchange resin. This technology can remove phosphates, nitrates, and organic matter. [4]

1.4.4 Lime Softening

This is a commonly used technique to remove the hardness of water by precipitating out magnesium and calcium salts as calcium carbonate and magnesium hydroxide. Depending on the alkalinity and total hardness of the feed, lime or excess lime and soda ash are added to the water. Calcium and magnesium ions react with the slack lime and form insoluble salts which are removed as lime sludge. The process takes place at pH as high as 10.8, so the soft water produced needs to be carbonated to lower the pH. Also, the treated water may contain unremoved precipitates and non-carbonate calcium hardness.

1.4.5 Comparison of Technologies and Preferred Choice

	Reverse Osmosis	**Membrane Bioreactor**	**Ion Exchange**	**Lime Softening**
Impurities Removed	Total dissolved solids including cations and anions	Organic and inorganic waste including suspended solids	Dissolved ionic solids – both cations and anions	Calcium carbonates and magnesium hardness
Waste Produced	Reject water which is 20% to 50% of the feed, concentrated salt solution	Highly toxic halogenated by-products, especially due to chemical cleaning of the membrane [5]	Exhausted resins of cations and anions which can be recovered	Lime sludge containing calcium carbonate, magnesium hydroxide, and lime

Table 4 Comparison of the water softening techniques

Given the quality of effluent and the desired output, it is evident that a rigorous water softening system is necessary. For that, a combination of RO and lime softening, along with the essential pre-treatment equipment will be preferred. From the comparison above, it is clear that Membrane Bioreactor is more appropriate for replacing the activated sludge treatment instead of effluent treatment. The resulting effluent quality may improve, but that would necessarily require to make the existing process obsolete, which is working well for the industry. As for ion exchange, the cost of resins and handling of harmful chemicals may cause serious HSE concerns – which is not the case with RO unit.

However, the two significant challenges of RO unit must also be considered, which are as follows:

1. The life of the membrane is limited, and the performance is likely to decline along with time due to fouling and concentration polarization. Therefore, membranes in RO must be replaced periodically to ensure reasonable efficiency of the system.
2. RO unit rejects 25% to 50% of feed, which is highly concentrated solution of dissolved salts. Such effluent cannot be discharged to the environment either due to strict regulations of governing bodies.

To address these issues,we will install lime softening equipment before the RO unit. Therefore, the feed of RO will have significantly lower TDS, hence better equipment life. Moreover, doing so would ensure that the permeate of membrane is suitable for boiler.

Secondly, the reject of RO will be treated using appropriate water softening technologies and then used as a make-up for cooling tower CT-I which is designed for 12 m^3/h.

1.5 Key Objectives

1. To study in detail the composition of effluent water stream and evaluate the potential treatment options available to utilize it for on-site utilities and operations.

2. To design a complete wastewater effluent treatment unit for achieving the desired quality of water essential for utilization on the site of Engro Polymers and Chemicals Ltd.

3. To conduct economic analysis and HAZOP study of the proposed design for evaluating the safety, environmental and economic concerns of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 The Concept of MLD and ZLD

The underlying principle of this project is the recovery of wastewater effluent which is otherwise disposed off into the environment. The two important concepts about effluent recovery are Minimum Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD).

While there are many technologies available for water softening and cleaning, RO filtration is the most widely used now at the industrial scale for its ease of operation, safety, and cost-effectiveness. Both MLD and ZLD are membrane-based processes that incorporate innovative ways to treat the reject water of RO. The main idea of minimum liquid discharge is to use a two-staged or even three-staged RO filtration to recover up to 95% of the effluent as permeate. This high quality permeate then can be processed further to be used as boiler feed water.

On the other hand, Zero Liquid Discharge goes a step further to recover even the remaining 5% effluent that exits as the reject of RO. The reject stream of RO unit is highly concentrated with dissolved solids. Therefore, it must undergo extensive softening treatment such as crystallization that that does not produce any hard water as a by-product. Such process require high amount of energy, and so the cost of recovering the last 5% effluent is at times even greater than the recovery of the initial 95%. For this economic reason, it is not implemented frequently in the industries, unless the problem of water scarcity is highly severe. [6]

Building upon these two concepts of effluent recovery, a complete process is build to not only cater for the economic issues of ZLD but to also recover 100% effluent produced from wastewater unit.

2.2 Process Selection for TDS

There are various softening technologies available at the commercial scale, which include ion exchange, RO filtration, bio membrane reactor, lime softening and crystallization. The main objective of this process is to achieve polished water, also known as demin water, which as minimum amount of total dissolved solids. Given the application of boiler feed water, such high quality water requires extensive treatment. Moreover, the volumetric flow rate in our process is also quite significant.

A comparison of the available technologies show that ion exchange has some major hazards associated with it. Due to the use to chemicals in this process, the operation is relatively unsafe, and requires frequent replacement of the ionic resins [7]. Therefore, the cost and operation of this particular process would be quite high. As for the bio-membrane reactor, it is usually used for treating water that is high contaminated with biological substances [8]. The quality of effluent from the wastewater treatment unit is not suitable to be processed in a bio membrane reactor. In the case of crystallization, it is a promising technology for building a process that follows the principle of ZLD. However, due to its high energy requirements, it would not be a feasible option to treat effluent as much as 220 m^3/h.

The remaining two choices of the processes are RO filtration and lime softening unit. While RO offers an easy operation with minimum safety and environmental hazards, it requires an extensive pre-treatment. This pre-treatment is essential to decrease the fouling and maintain the system efficiency for extended time. Given the high amount of TDS in the effluent stream, RO filtration can be combined with lime softening as a pre-treatment stage. Doing so would give a permeate that is polished water, and can be used as boiler feed.

2.3 Choosing the Right RO Pre-treatment

Having chosen RO as the primary technology for treating TDS, it is essential to install proper pre-treatment steps for effective operation of the membrane. The quality of effluent shows that suspended solids and organic content are the two main contaminations that must be treated. Moreover, the TDS level in effluent is quite high, and must be lowered for getting polished water as the permeate.

Therefore, a multimedia filter is used to remove TSS, while an aeration tank is installed to lower the BOD of effluent. Other membrane processes such as microfiltration could also have been used instead of multimedia filter. However, the pressure requirements and maintenance costs of microfiltration are greater than that of multimedia filter.

Finally, lime softening unit is installed for lowering the TDS value of the effluent. Soluble hardness is effectively removed, leaving behind insoluble hardness in the lime softening effluent. The non-soluble hardness is removed in the RO filtration.

2.4 Selection of Membrane Configuration

The term "membrane configuration" refers to the arrangement in which a single membrane element is placed. This arrangement has a significant role in the active surface area available for filtration, and the floor space the entire unit takes. Below are the four different configurations that may be used [9]:

1. Hollow Fibres: The membrane elements are attached to an epoxy block such that the fibrous membranes are hollow from inside. The fluid flows through the hollow section and is collected in the epoxy box as it moves forward.

2. Spiral wound: This configuration is typically used for nano filtration and RO unit. A perforated tube is used to pass the feed, and the membrane elements are folded over this sheet. The permeate is collected from each vessel of spiral wound through tubes.

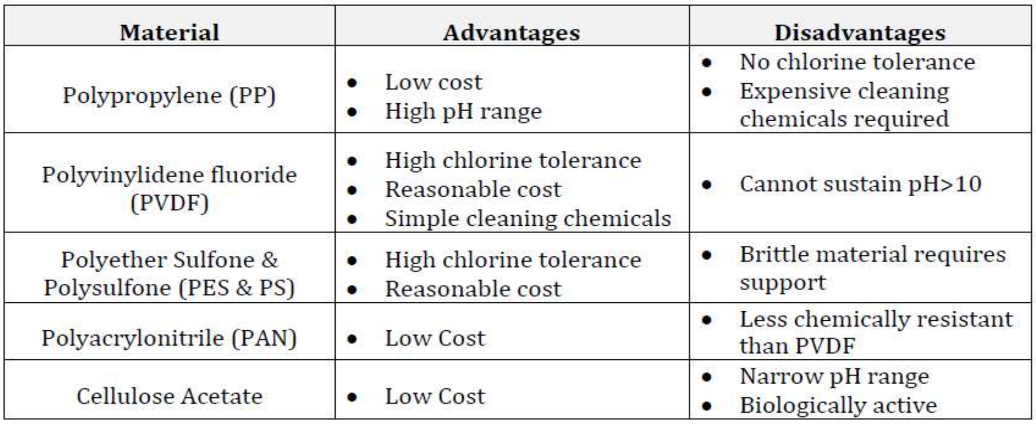
3. Plate and Frame: The elements of membrane are stacked on each other. The fluid passes over the elements. The clean permeate is collected on the other side while the reject stream on the opposite side of the permeate.

4. Tubular: Similar to hollow fibre, tubular configuration has the similar structure. The main difference lies in the diameter of each module.

From these configurations, spiral wound is chosen because of its high surface area, high packing density, and suitability for RO applications.

2.4.1 Selection of Membrane Material

The table shows a list of various materials that can be used for membranes. The advantages and disadvantages of each material are listed for comparison.



Material	Advantages	Disadvantages
Polypropylene (PP)	• Low cost • High pH range	• No chlorine tolerance • Expensive cleaning chemicals required
Polyvinylidene fluoride (PVDF)	• High chlorine tolerance • Reasonable cost • Simple cleaning chemicals	• Cannot sustain pH>10
Polyether Sulfone & Polysulfone (PES & PS)	• High chlorine tolerance • Reasonable cost	• Brittle material requires support
Polyacrylonitrile (PAN)	• Low Cost	• Less chemically resistant than PVDF
Cellulose Acetate	• Low Cost	• Narrow pH range • Biologically active

Table 5 List of various membrane materials & their pros and cons

The application in our process has a pH less than 10 for the RO feed. Therefore, PVDF is used for the RO unit.

2.5. Treatment of RO Reject

The reject stream of RO primarily contains a high level of dissolved solids. Instead of treating it extensively to achieve the quality of polished water, it can be softened to be used as a cooling tower make up. The requirements for a cooling tower makeup are not strict, given the chemical treatment used in cooling towers to address fouling, scaling and microbial activity.

For this reason, a pellet reactor is used to soften the reject of RO. Pellet reactor is a relatively water softening technology that uses soda ash and NaOH to remove dissolved solids in water [10]. The dissolved solids are removed as small pellets that can be used for other applications. The basic working principle is of crystallization on a fluidized bed vessel. Most importantly, there is no sludge produced in a pellet reactor as in lime softening unit. Moreover, it is very well suited to treat low flow rates of water as is the case in this process.

The softened water from pellet reactor is alkaline due to the action of sodium hydroxide. Such high pH is not suitable for cooling tower, as it increases the tendency of fouling and scaling. Therefore, the water from pellet reactor is sent to pH adjustment tank. Sulfuric acid is dosed in a measured quantity to lower the pH of water near to 7. After that, it is sent to cooling tower as make-up.

The low level of TDS in this make-up water and almost negligible amount of organic substance and suspended solids make it an excellent resource for the cooling tower. The need for chemical treatment is also reduced, ultimately reducing the utility costs of the entire plant.

CHAPTER 3

PROCESS DESCRIPTION

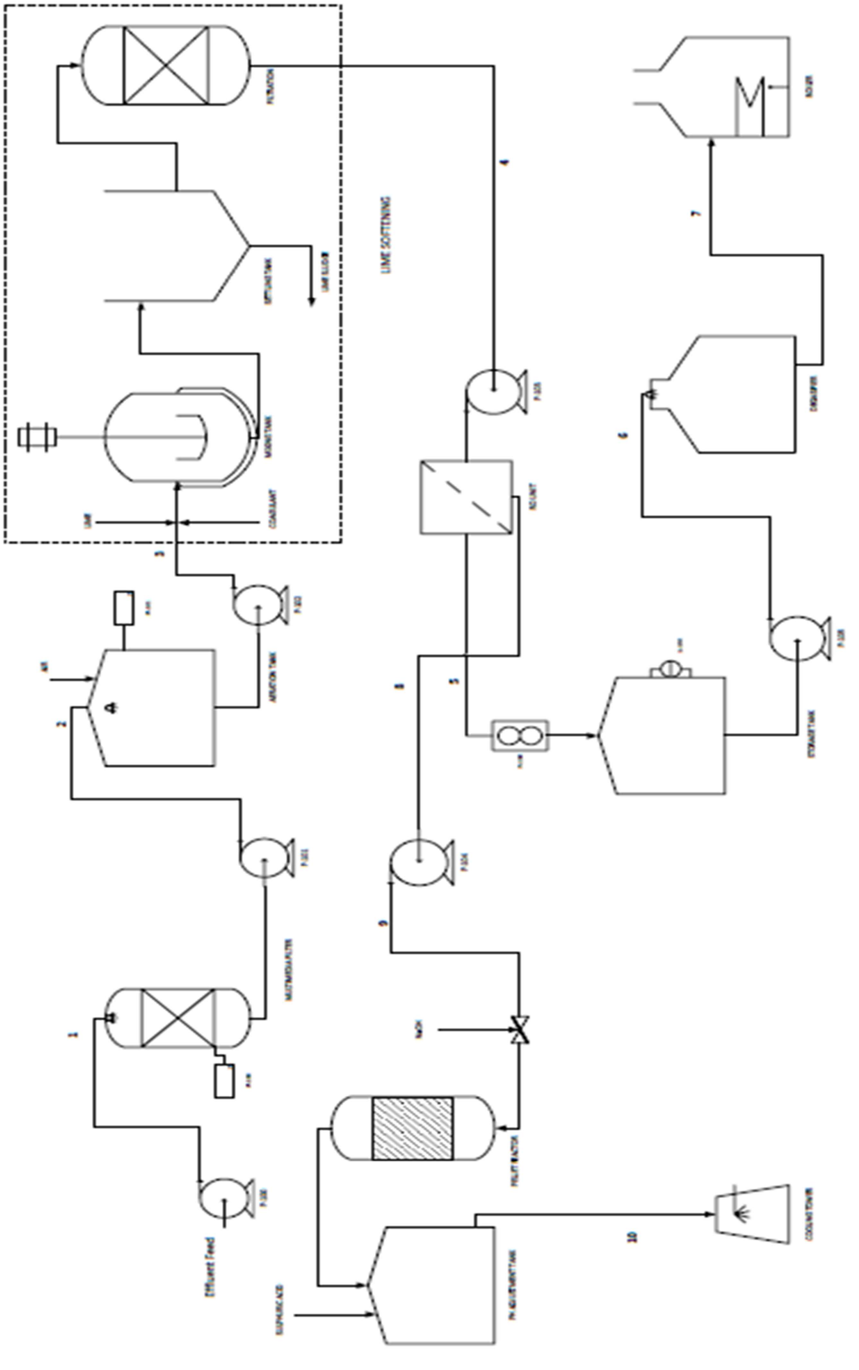


Figure 2 Process Flow Diagram

3.1 Multimedia Filteration

Multimedia filtration is used to filter the suspended solids mixed in the processing water. These small solid particles includes slit, grit, clay, algae and micro-organisms. Degree of filtration of MMF depends on the filter media and flow rate of the liquid.

As opposite to the sand filtration (single stage filtration) multi-media filter is a pressure vessel and it is usually made of stainless steel. While the vessel contains three layers of different media, one of **Anthracite**, **Sand** and **Garnet**. The purpose of using these different layers is the difference in their filtration capabilities based on their densities. Also, the idea behind using different layers of the varying density is that during backwash the lightest media (Anthracite) should stratify at the top of the tower followed by sand which would settle in the middle while garnet being the heaviest material would settle at the bottom.

Processing water is introduced from the top of the tank and passed through the multiple layers of the beds. Anthracite separate the coarse dirt particles or the large particles which makes a bed at the top of the tower during filtration. While the smaller size particles are separated in the following two layers with relatively smaller one or fine particles are separated by garnet bed and less fine particles by sand bed. A simple sand filter can filter the particles of size range of 25-50 microns while a multi-media filter can separate 10-25 microns size particles approximately.

When the bed get saturated with the trapped particles and the turbidity of the effluent has increased from 10% or pressure drop has increased to 10 psi then the tower needs to be cleaned and for this purpose it requires backwash of the tower. During backwash, water is introduced from the bottom of the tower and it lifts the beds of the filter media. Due to the water pressure bed is lifted upward and trapped particles are get released from the top of the tower. The supporting gravel will not lift and helps to distribute the backwash evenly throughout the bed. Also, the backwash flow rate is always greater than the processing water inline flow rate.

3.2 Aeration Tank

Aerators are used in the water treatment to remove the trapped gases in the water, odor, hydrogen sulphide gas, VOC, or carbon dioxide gas, also it reduces the odor, BOD, and contaminants from the water.

Small droplets of air can be introduced to the water in a close contact. These air bubbles will rise on the upper side of the tank as it will be injected from the bottom. Aeration will remove the dissolved gasses. For the removal of metals, oxygen will react to the metals in air and will oxidized the materials which are undesirable.

In this project Aeration tank is used to remove biological oxygen demand. When oxygen is supplied to the aeration tank where wastewater is present, it will produce the bacteria. BOD is consumed by the bacteria, so that these bacteria grow in a large manner. These will settle down in the tank and will be removed. To maintain the concentration of bacteria, some of the sludge is send back to the aeration tank.

3.3 Lime Softening

It is a water treatment process in which process water is treated with either sodium hydroxide or limewater to soften water by removing calcium and magnesium ions. This process basically *increases the PH* of the process water which in turn makes the materials (Ca & Mg bicarbonates) causing water hardness to settle down. This process not only softens the water but also removes the harmful microorganisms, TDS, dissolved organic matter and certain metals such as Iron, Arsenic, Radium and Manganese, and act as a pretreatment to make the boiler feed.

If lime softening is done at ambient temperature it is known as *cold lime softening*. In this process, temporary hardness is removed by the reaction of lime with calcium or magnesium bicarbonates (water soluble) forming calcium or magnesium carbonates (water insoluble) by following the reactions given below:

$$Ca(OH)_2 + Ca(HCO_3)_2 \rightarrow 2CaCO_3 + 2H_2O$$

$$Ca(OH)_2 + Mg(HCO_3)_2 \rightarrow MgCO_3 + CaCO_3 + 2H_2O$$

$$Ca(OH)_2 + MgSO_4 \rightarrow CaSO_4 + Mg(OH)_2$$

On the other hand, permanent hardness is not removed by using only lime instead it is used in combination with other chemicals.

When water has been softened then the precipitated solids are required to be separated from the soft water. For this purpose, soft water is passed through the filter press and lime slurry generated is separated by pressure filtration. The filter cake, consisting of primarily lime, is separated and the filtrate or soft water is then sent for the further water treatment.

This lime softening process is most suitable for ZLD or MLD and used for very high hardness.

3.4 Reverse Osmosis

“It is a process by which a solvent pass through a porous membrane in the direction opposite to that of natural osmosis when subjected to a hydrostatic pressure greater than the osmotic pressure.”

It is a water purification technology that utilizes a semi-permeable membrane to remove ions, molecules and larger particles from the processing water. In reverse osmosis, an applied high pressure is used to overcome the osmotic pressure. Reverse osmosis can remove many types of dissolved and suspended solids from water, including bacteria, and is used in both industrial processes and the production of potable water. The result is that the solute is retained on the pressurized side of the membrane and the pure solvent is allowed to pass to the other side. To be "selective", this membrane should not allow large molecules or ions through the pores (holes), but should allow smaller components of the solution (such as solvent molecules) to pass freely.

The main part of RO vessel is their membranes which filters the raw water with low TDS water to permeate and rejecting the high TDS water to drain. RO membrane can filter the water with 70–90 % efficiency which mainly depends on the feed water TDS. These membranes can reject up to 99.8% salts. The membranes used in RO are spiral wound. These membranes are mostly made of polymeric materials.

Also, membrane is used in the form of ***Modules*** which are defined as it consist of membranes, feed inlet, concentrate outlet and permeate outlet. These membrane modules contain different configuration of the membranes such as plate and frame, spiral wound, tubular and hollow fiber. But spiral wound is mostly used for wastewater treatment as it provides high surface area for the filtration.

Raw water is introduced from the feed inlet pipe in the spiral wound membrane module and because of the high-pressure water having low TDS permeates through the membrane and collected on the other side of the membranes as ***permeate***. While the high TDS rejected water, which is known as the ***Concentrate,*** is drained.

A major problem associated with the RO is the ***membrane fouling*** which greatly reduces the membrane efficiency as well as the life of the membranes. There are four types of membrane fouling as scaling, bio fouling, organic and colloidal. However, fouling can be avoided by using disinfectants and anti-scalant. Also, the membranes are backwashed at high flow rate after every 2-3 hrs to remove the trapped particles in the pores of the membrane.

Another concern is that RO membranes are very sensitive towards the presence of Chlorine in the feed water and it can tolerate maximum 0.1 ppm of chlorine. If chlorine dosage increases the defined limit, then RO membrane gets damaged greatly. That’s why activated carbon tank is used before RO unit to remove the added chlorine.

However, efficiency of the membrane may decrease due to the dissolved solids in water, metal ions (Ca, Mg, Fe, Mn), active chlorine, active oxygen and microbes.

3.5 Deaerator

It is a device which is used to remove oxygen and other dissolved gasses from the water. For boiling feedwater, it is used to remove all the dissolved gasses.

If oxygen present in the feedwater, is not removed, will cause corrosion within the tubes of boiler and all piping’s through which it will pass. If Carbon dioxide is present in water, it will chemically react with water to form carbonic acid, which also causes corrosion.

Spray type deaerator is horizontal device, having preheated section, and deaeration section. Steam having low pressure enters by sparger which is present at bottom of vessel. The feed will be spared in the preheating section and will preheated. The purposes of preheating are to reach at its saturation temperature so that gasses which are dissolved in the water, stripped out easily.

For proper designing, hydrodynamics must be considered. There must be good contact between water and the steam. This will improve the efficiency of the mass transfer of dissolved gasses from the water. This will follow the Henry’s Law. When water will attain its saturation temperature, solubility of oxygen is zero in water. So, there will be transfer of oxygen from the water to the steam side.

This stream will go the deaerator section where deaeration process will begin. The gasses will be removed by the vent at the top from water.

3.6 Pellet Reactor

Pellet reactors are being used in water treatment plants which has Impurities of calcium. Pellet reactor remove calcium through the precipitation of calcite. This is done in fluidized pallet reactor, I which base of strong nature is added to the effluents to increase the PH of the effluents and making precipitation feasible. If the amount of calcium and magnesium is high in the water, it will eventually produce scaling

Pellet reactor has cylindrical vessel which is filled with sand up to some level. The Diameter for seeding grain is usually kept low and surface for crystallization is large. Water is pumped from the upward direction with high speed for maintaining the fluidized condition of material which is seeding. At the lower end, dosing of chemicals including, soda ash/lime and caustic soda is done. As in this process crystallization is the main part for softening the water, will depend upon the temperature, quality of feed water and concentration of chemicals which are being dosed at the bottom.

As the temperature will be low, rate of reaction will be low, resulting a higher crystallization rate. Pallet removal is controlled by the pressure drop phenomena i.e. through fluidized bed hydraulic resistance.

In pellet reactors there is flow distribution controller which distributes the total flow over the reactor in optimum conditions. For optimizing the caustic soda dose, by-pass ration is always adjusted while dosing.

To obtain best performance pellet reactor, surface area which is ratio of area of pellet surface to the volume of the reactor. Crystallization occurs on the surface if the reactors only. Modern pallet reactors operate in continuous manner by frequently adding the dose of seed material and removing the batches of pallets. Optimum diameter of the pellet is necessary which helps to obtain the maximum surface for the crystallization.

3.7 PH adjustment tank

PH adjustment is alteration of concentration of hydrogen Ions. If PH of any solution is high, then for adjusting the PH, strong Acid like sulphuric acid or hydrochloric acid is used. Wastewater is placed in the tank in a specific volume. In this reaction tank, there will be one mixer for the continuously movement of water. Then, dosing chemicals will be added to the wastewater and to maintain the specific PH.

In this project, the reject of RO goes to the pellet reactor where the PH of the system increases, and for BFW, the required PH is 9 and to maintain that PH we have to add strong acid to reduce the effect of base. When we obtain the desired PH, the water will exit through the exit point and will supplied to the cooling tower.

CHAPTER 4

MATERIAL BALANCE

4.1 Multimedia Filter

- Multimedia filter removes suspended solids in the effluent stream while allowing all the effluent water to pass through.
- 95% efficiency for TSS filtration is considered for this equipment.
- $\text{In}_{TSS} - \text{Out}_{TSS} = \text{Retained}_{TSS}$
- Basis = 1 hour

Flow Rate of Effluent Water	220 cmh
Amount of TSS present	150 ppm
Amount of TSS in kg	33 kg
TSS retained (95% of inlet)	31.35kg
Amount of TSS in outlet	1.65 kg
Amount of TSS in outlet (ppm)	7.5 ppm

Table 6 Effluent water Quality at inlet to MMF

4.2 Aeration Tank

From Literature, [11] The standard air flow rate required in aeration tank is given by:

$$SCFM = \frac{mgd}{OTE}\,(1.1BOD + 4.6NH_3)$$

- SCFM is the standard air flow rate in ft^3/min
- mgd is the flow rate of wastewater in million gallons per day
- OTE is the Oxygen transfer efficiency
- BOD and NH_3 are in ppm.

Flow Rate of Effluent Water	**1.4 mgd**
Oxygen Transfer Efficiency	0.6
BOD	30 ppm
Ammonia	NIL
SCFM	76.5 cfm
Standard Air Flow Rate	130 cmh
BOD (outlet)	5 ppm

Table 7 Water quality at inlet to Aeration tank

4.3 Lime Softening Unit

All balances are based on stochiometric amounts assuming 90% reaction extent.

	Calcium Hardness(ppm)	**Magnesium Hardness(ppm)**
Carbonate	650	800
Non-Carbonate	500	1050
Total	1150	1850

Table 8 Quality of water at inlet to Lime Softening

4.3.1 Reactions:

$$Ca(OH)_2 + Ca(HCO_3)_2 \rightarrow 2CaCO_3 + 2H_2O$$

Component	**Input (gmol)**	**Output (gmol)**	**Generation or Consumption (gmol)**
$\boldsymbol{Ca(OH)_2}$	896	89.6	-806.4
$\boldsymbol{Ca(HCO_3)_2}$	896	89.6	-806.4
$\boldsymbol{CaCO_3}$	0	1612.8	+1612.8
$\boldsymbol{H_2O}$	0	1612.8	+1612.8

Table 9 Material Balance summary of Reaction 1

$$Ca(OH)_2 + Mg(HCO_3)_2 \rightarrow MgCO_3 + CaCO_3 + 2H_2O$$

Component	Input (gmol)	Output (gmol)	Generation or Consumption (gmol)
$Ca(OH)_2$	1202	120.2	-1081.8
$Mg(HCO_3)_2$	1202	120.2	-1081.8
$CaCO_3$	0	1081.8	+1081.8
H_2O	0	2163.6	+2163.6
$MgCO_3$	0	1081.8	+1081.8

Table 10 Material balance summary of reaction 2

$$Ca(OH)_2 + MgSO_4 \rightarrow CaSO_4 + Mg(OH)_2$$

Component	Input (gmol)	Output (gmol)	Generation or Consumption (gmol)
$Ca(OH)_2$	1920	192	-1728
$MgSO_4$	1920	192	-1728
$CaSO_4$	0	1728	+1728
$Mg(OH)_2$	0	1728	+1728

Table 11 Material balance summary of reaction 3

Hence,

Slacked Lime Feed: 1202 + 896 + 1920 = 4017 gmol = 217 kg

To precipitate Calcium Carbonate and Magnesium salts, alkaline environment is needed i.e. pH = 10.2. For that, additional slacked lime is added at rate of 1.25 meq/l.

This equals 10.175 kg excess lime

To ensure complete reaction, 10% excess lime is added, which makes **total lime feed as 250 kg /hr**

Coagulant added: Poly-aluminium Chloride (PAC)

Amount added: 5 ppm

= **1.1 kg / hr**

4.3.2 Sludge Produced:

Calcium Carbonate: 2694.6 mol = 269.5 kg

Magnesium Hydroxide = 1728 mol = 100.80 kg

Magnesium Carbonate = 1081.8 mol = 90.80 kg

Calcium Sulfate = 1728 mol = 235.50 kg

Slacked Lime: 33 kg + 29.73kg = 62.73 kg

Water: 3776.4 mol = 67.97 kg

Total Stream Flow rate: 827.3 kg / hr

4.3.3 Output Stream of Lime Softening Unit:

Magnesium Sulfate = 192 mol = 23.12 kg

Magnesium Bicarbonate = 120.2 gmol = 17.6 kg

Calcium Bicarbonate = 89.6 gmol = 14.5 kg

Calcium non-carbonate (primarily $CaCl_2$) = 110 kg

Hence, RO feed quality is:

Parameters	Value
Flow rate	220 m^3/hr
TDS	750 ppm
TSS	< 10 ppm
BOD	5 ppm

Table 12 Outlet stream quality of lime softening

4.4 RO Unit

- 30% of the feed exits as reject while 70% as permeate.
- 95% efficiency in removing TDS from effluent stream
- Feed = Permeate + Reject

Feed	**220 cmh**
Permeate	154 cmh
Reject	66 cmh

Table 13 Overall balance on RO

Stream	Mass (kg)	Concentration (ppm)
Feed	165 kg	750
Permeate	8.25	37.5
Reject	156.75	2375

Table 14 Material Balance of TDS

4.5 Crystallization Pellet Reactor

- Feed Stream contains 2375 ppm TDS in 66 m^3/h RO reject
- For calculating the required amounts of NaOH and Na_2CO_3, 90% reaction extent is considered
- 15 kg/h NaOH and 85 kg/h Na_2CO_3 is required based on the calculations below.

$$Ca(HCO_3)_2 + 2\,NaOH \rightarrow CaCO_3 + \ Na_2CO_3 + 2H_2O$$

Component	Input (gmol)	Output (gmol)	Generation or Consumption (gmol)
$\boldsymbol{Ca(HCO)_3}$	89.6	9.0	-80.6
$\boldsymbol{NaOH}$	179.2	18.0	-161.2
$\boldsymbol{CaCO_3}$	0	80.6	80.6
$\boldsymbol{Na_2CO_3}$	0	80.6	80.6
$\boldsymbol{H_2O}$	0	161.2	161.2

Table 15 Material balance w.r.t reaction 1 in pellet reactor

$$Mg(HCO_3)_2 + 2\,NaOH \rightarrow MgCO_3 + Na_2CO_3 + 2H_2O$$

Component	Input (gmol)	Output (gmol)	Generation or Consumption (gmol)
$\boldsymbol{Mg(HCO_3)_2}$	99.0	9.9	-89.1
$\boldsymbol{NaOH}$	198.0	19.8	-178.2
$\boldsymbol{MgCO_3}$	0	89.1	89.1
$\boldsymbol{Na_2CO_3}$	0	89.1	89.1
$\boldsymbol{H_2O}$	0	178.2	178.2

Table 16 Material balance w.r.t reaction 2 in pellet reactor

$$CaCl_2 + Na_2CO_3 \rightarrow CaCO_3 + 2NaCl$$

Component	Input (gmol)	Output (gmol)	Generation or Consumption (gmol)
$\boldsymbol{CaCl_2}$	991	118.3	-872.7
$\boldsymbol{Na_2CO_3}$	969.7	97.0	-872.7
$\boldsymbol{CaCO_3}$	0	872.7	872.7
$\boldsymbol{2NaCl}$	0	1745.4	1745.4

Table 17 Material balance w.r.t reaction 3 in pellet reactor

4.5.1 Output Water

All the $CaCO_3$ and $MgCO_3$ crystals are filtered out from the output stream of pellet reactor, giving the feed to Cooling Tower of the following quality:

TDS = 500 ppm

pH = 10.8 (based on the concentration of NaOH)

Component	Moles (gmol)	Mass (kg)
$Ca(HCO_3)_2$	9	1.5
NaOH	37.8	1.5
$Mg(HCO_3)_2$	9.9	1.4
$CaCl_2$	118.3	13.1
Na_2CO_3	97	10.3

Table 18 Outlet stream compsition of pellet reactor

4.6 pH Adjustment Tank

Ideal pH for Cooling Tower Makeup 8.0. To neutralize NaOH, we therefore need to add sufficient amount of H_2SO_4.

The required $[OH^-]$ is 1×10^{-6}. For that, we must neutralize 5.7×10^{-4} mol/litre of NaOH. This equals to 37.7 mol of NaOH.

$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$

Hence, we must add 18.85 mol of H_2SO_4 (or 1.8 kg/hr).

4.7 Deaerator

- Feed is the permeate stream of RO, containing 69 ppm dissolved oxygen and 154 m^3/h raw water.
- 1.3% of the steam introduced is released as vent gas
- Input streams: RO permeate (m_w), superheated steam (m_s)
- Output streams: vent (m_v) , deaerated boiler feed water (m_o)
- $m_wH_w + m_sH_s = (m_w + m_s) H_o$
- Enthalpies are taken from steam tables at corresponding temperatures and pressures
- Basis = 1 hour

4.7.1 Required Steam Input

$$m_s = \frac{m_w(H_o - H_w)}{H_s - H_o}$$

m_w = 154,000 kg

H_w = 356 kJ/kg

H_s = 2781 kJ /kg

H_o = 440 kJ/kg

Substituting these values,

m_s = 5525.8 kg /h steam required

4.7.2 Vent

$m_v = 0.013m_s$

m_v = 71.8 kg/h

4.7.3 Deaerated Boiler Feed

Applying overall material balance,

$m_w + m_s = m_v + m_o$

m_o = 154,000 + 5525.8 – 71.8

m_o = 159,454 kg /h or 159.5 m^3/h boiler feed water produced

4.8 Important Conclusions from Material Balance Calculations

1. By treating 220 m^3/h effluent wastewater, 159.5 m^3/h polished water and 65 m^3/h cooling tower make-up is produced.
2. The condensation of steam in deaerator adds 5.5 m^3/h water to polished water stream. 1 m^3/h water is evaporated in pellet reactor during crystallization.
3. The following raw materials are required for this plant

Raw Material	Amount	Purpose
Standard Air Supply (cmh)	130	Aeration Tank
Ca(OH) (kg/h)	250	Lime Softening Unit
PAC (kg/h)	1.1	Cogulant in Lime Softening
NaOH (kg/h)	15	Pellet Reactor
Soda Ash (kg/h)	85	Pellet Reactor
Sulfuric Acid (99.9% purity) (kg/h)	1.8	pH Adjustment Tank
Superheated Steam (kg/h)	5525.8	Deaerator

Table 19 List of raw materials needed in this wastewater treatment

CHAPTER 5

ENERGY BALANCE

5.1 Pump P-100

- Steady-state, open system
- No heat flow, Q = 0
- $H_{out} – H_{in} = W$
- $\Delta P = 0.04$ MPa

Effluent water flows at 25^0C and 0.1 MPa (1 atm). At the given conditions,

$H_{in} = 104.92$ kJ / kg

For $\Delta P = 0.04$ MPa, outflow conditions of 25^0C and 0.14 MPa give,

$H_{out} = 104.96$ kJ /kg

Hence, W = 0.04 kJ/kg

For a flow rate of 220,000 kg/h effluent,

W = 8800 kJ/h

For ή = 0.75,

$W_{act} = 8800/0.75 = 11{,}733.3$ kJ /h

Hence, required power = 3.26 kW

5.2 Multimedia Filter

- Steady-state, open system
- W = 0, Q = 0
- $H_{in} = H_{out}$

$H_{in} = 104.96$ kJ /kg

$H_{out} = 104.96$ kJ /kg

5.3 Pump, P-101

- Steady-state, open system
- Q = 0

- $H_{out} - H_{in} = W$
- $\Delta P = 0.02$ MPa

Water inflows at 25^0C and 0.1 MPa (1 atm). At the given conditions,

$H_{in} = 104.92$ kJ / kg

For $\Delta P = 0.02$ MPa, outflow conditions of 25^0C and 0.14 MPa give,

$H_{out} = 104.94$ kJ /kg

Hence, W = 0.02 kJ/kg

For a flow rate of 220,000 kg/h effluent,

W = 4400 kJ/h

For ή = 0.75,

$W_{act} = 4400/0.75 = 5866.6$ kJ /h

Hence, required power = 1.63 kW

5.4 Aeration Tank

- Steady-state, open system
- W = 0, Q = 0
- $H_{in} = H_{out}$

$H_{in} = 104.94$ kJ /kg

$H_{out} = 104.94$ kJ /kg

5.5 Pump P-102

- Steady-state, open system
- Q = 0
- $H_{out} - H_{in} = W$
- $\Delta P = 0.02$ MPa

Water inflows at 25^0C and 0.1 MPa (1 atm). At the given conditions,

$H_{in} = 104.92$ kJ / kg

For $\Delta P = 0.02$ MPa, outflow conditions of 25^0C and 0.14 MPa give,

$H_{out} = 104.94$ kJ /kg

Hence, W = 0.02 kJ/kg

For a flow rate of 220,000 kg/h effluent,

W = 4400 kJ/h

For ή = 0.75,

W_{act} = 4400/0.75 = 5866.6 kJ /h

Hence, required power = 1.63 kW

5.6.1 Lime Softening Reactor

- Agitator ensures proper mixing and chemical reaction
- $H_p = H_f + Q + W$

Chemical Reactions involved:

$$Ca(OH)_2 + Ca(HCO_3)_2 \rightarrow 2CaCO_3 + 2H_2O \quad (1)$$

$$Ca(OH)_2 + Mg(HCO_3)_2 \rightarrow MgCO_3 + CaCO_3 + 2H_2O \quad (2)$$

$$Ca(OH)_2 + MgSO_4 \rightarrow CaSO_4 + Mg(OH)_2 \quad (3)$$

Data of standard heats of formation:

$Ca(OH)_2$ = -986.6 kJ/mol

$Ca(HCO_3)_2$ = -1925.2 kJ/mol

H_2O = -285.8 kJ/mol

$Mg(HCO_3)_2$ = -1844.2 kJ/mol

$MgCO_3$ = -1113 kJ/mol

$CaCO_3$ = -1207.0 kJ/mol

$MgSO_4$ = -1278.2 kJ/mol

$CaSO_4$ = -1432.7 kJ/mol

$Mg(OH)_2$ = -924.7 kJ/mol

Using the above data and mass balance calculations,

$H_r = H_p - H_f$

For reaction (1)

H_p = (-1207.0 x 1612.8) + (-285.8 x 1612.8) = -2407.6 MJ

H_f = (-986.6 x 896) + (-1925.2 x 896) = -2609.0 MJ

H_r = +201.4 MJ

For reaction (2)

H_p = (-1113.0 x 1081.8) + (-986.6 x 1081.8) + (-285.5 x 2163.6) = -2889.1 MJ

H_f = (-986.6 x 1202) + (-1844.2 x 1202) = -3402.6 MJ

H_r = +513.5 MJ

For reaction (3)

H_p = (-1432.7 x 1728) + (-924.7 x 1728) = -4073.6 MJ

H_f = (-986.6 x 1920) + (-1278.2 x 1920) = -4348.4 MJ

H_r = +275.4 MJ

Therefore,

Q = 201.4 + 513.5 + 275.4 = +990.3 MJ heat is added to the reactor

Power Required by agitator,

Power = $N_p.\rho.N^3.D^5$

where N_p = 1.370

ρ = 1000 kg/m^3

N = 20.18 rpm

D = 2600 mm

P = 6.40 kW

for efficiency of 80%,

P = 8.00 kW

5.6.2 Lime Softening Settling Tank

- $H_{in} = H_{out}$

H_{out} = -9370.3 MJ

5.6.3 Lime Softening Filtration Unit

- $H_{in} = H_{out}$

$H_{out} =$ -9370.3 MJ

5.7 RO Unit Pump P-103

Pressure of outlet water = 10.2 bar

Pressure of inlet water = 1.014 bar

Efficiency (η) = 75 %

Expansivity Coefficient (β) = 0.000248

Temperature of water (T) = 25 °C

Inlet water flow rate = 220 m^3/hr

RO Pump Energy = $\frac{Inlet\ water\ flow\ rate\ (Pout-Pin)(1-\beta T)}{\eta}$

RO pump Energy = $\frac{220\ (10.2-1.014)(1-0.000248*298)}{.75}$ => 151 KW

5.8 RO Unit:

Water flow rate at inlet = 220 m^3/hr

Permeate flow rate = 154 m^3/hr

Retentate flow rate = 66 m^3/hr

Energy of water at inlet = 151 kW

Permeate Energy (E_P) = $\frac{Permeate\ flow\ rate}{Feed\ water\ flow\ rate} * Inlet\ water\ energy$

$E_P = \frac{150}{220} * 151$ = 102.96 kW

Similarly,

Energy of Retentate (E_R) = Energy of feed water – Energy of Permeate

E_R = 151 – 102.96 = 48.04 kW

5.9 Pellet Reactor

- $H_p = H_f + H_r$

- H_r indicates the total heat of reaction

Chemical reactions involved:

$$Ca(HCO_3)_2 + 2\ NaOH \rightarrow CaCO_3 + \ Na_2CO_3 + 2H_2O \qquad (1)$$

$$Mg(HCO_3)_2 + 2\ NaOH \rightarrow MgCO_3 + \ Na_2CO_3 + 2H_2O \qquad (2)$$

$$CaCl_2 + \ Na_2CO_3 \rightarrow CaCO_3 + \ 2NaCl \qquad (3)$$

Required data of heats of formation:

$NaOH$ = -426.7 kJ /mol

Na_2CO_3 = -1130.9 kJ/mol

$NaCl$ = -425.93 kJ/mol

$CaCl_2$ = -795.0 kJ/mol

$Ca(HCO_3)_2$ = -1925.2 kJ/mol

H_2O = -285.8 kJ/mol

$Mg(HCO_3)_2$ = -1844.2 kJ/mol

$MgCO_3$ = -1113 kJ/mol

$CaCO_3$ = -1207.0 kJ/mol

For reaction (1)

$H_{r,1}$ = [(-1207 x 80.6) + (-1130.9 x 80.6) + (285.8 x 161.2)] – [(-1925.2 x 89.6) + (-425.93 x 179.2)]

$H_{r,1}$ = 106.5 MJ

For reaction (2)

$H_{f,2}$ = [(-1113.0 x 89.1) + (-1130.9 x 89.1) + (-285.8 x 178.2)] – [(-1113 x 99.0) + (425.93 x 198)]

$H_{f,2}$ = -225.0 MJ

For reaction (3)

$H_{f,3}$ = [(-1207 x 872.7) + (-425.93 x 1745.4)] – [(-1113.0 x 991) + (-425.93 x 969.7)]

$H_{f,3}$ = -280.8 MJ

Net Heat of Reactions: -399.3 MJ (heat liberated)

5.10 Deaerator

- $Q_f = m_oH_o - m_wH_{w;}$ heat absorbed by feed water
- $Q_s = m_sH_{s;}$ heat available as steam
- $Q_v = Q_s - Q_{f;}$ heat released as vent

Q_f = (159454 x 440) – (154000 x 356) = 15,335,760 kJ /h

Q_s = 5525.8 x 2781 = 15,367,249.8 kJ/h

Q_v = 31, 489.8 kJ/h

CHAPTER 6

EQUIPMENT DESIGN

6.1 Reverse Osmosis Membrane

6.1.1 Feed and Permeate Specifications

Feed source: Wastewater Effluent

Feed flowrate: 220 m^3/h = 968 gpm

Feed TDS concentration: 750 ppm

Permeate flowrate: 154 m^3/h = 678 gpm

Permeate TDS concentration: 37.5 ppm

$$Recovery = \frac{Permeate\ Flowrate}{Feed\ Flowrate} x\ 100$$

$$Recovery = \frac{154}{220} x\ 100$$

$$= \mathbf{70}\%$$

6.1.2 Flow configuration and Number of Passes

Flow configuration: plug flow in spiral wound configuration

Number of passes: 1

6.1.3 Membrane Module Element Type

The table below shows the typical specifications of different membrane elements.

Membrane Type	Feed TDS (ppm)	Permeate Quality (ppm)
TW	<5000	<50
XLE, LE	<1000	<50
BW, FR	<5000	<50
SW	3000 - 15000	<150
SWHR, SWHR LE	10000 - 50000	Varies (<500)
NF	<1000	<150

Table 20 Types of membrane module elements

Membrane element BW30-400/34i is selected given the brackish feed water and large scale application. The active area of this element is 34 m^2.

6.1.4 Average Membrane Flux

Flux = 22 L/m^{2}h (based on the effluent feed to the RO unit passing through conventional pre-treatment)

6.1.5 Number of elements required

$$N_e = \frac{Q_p}{F \ x \ A}$$

where N_e is the number of elements

Q_p is the permeate flow rate

F is the average membrane flux

A is the active element area

$$N_e = \frac{154 \frac{m^3}{h} x \ 1000 \frac{L}{m^3}}{22 \frac{L}{m^2 h} x \ 34m^2}$$

$$N_e = 205.9$$

Hence, the total number of elements required is <u>206.</u>

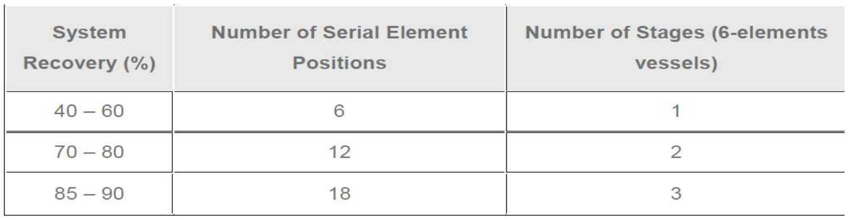
6.1.5 Number of Pressure Vessels

A single pressure vessel can contain maximum of 8 elements. Therefore,

$$Number \ of \ pressure \ vvessels = \frac{206}{8} = 25.75$$

Hence, 26 pressure vessels are required.

6.1.6 Number of stages



System Recovery (%)	Number of Serial Element Positions	Number of Stages (6-elements vessels)
40 – 60	6	1
70 – 80	12	2
85 – 90	18	3

Table 21 System recoveries w.r.t number of stages & no. of serial element positions

Given that our system has a recovery of 70% with 8 elements in a single pressure vessel, we can reasonably assume that we would require a 2-stage RO system.

6.1.7 Staging Ratio

$$R = \left[\frac{1}{1 - Y}\right]^{\frac{1}{n}}$$

Where R is staging ratio,

Y is the recovery in fractions

And n is number of stages

$$R = \left[\frac{1}{1 - 0.7}\right]^{\frac{1}{2}} = 1.83$$

N_1 is the number of vessels in first stage

N_2 is the number of vessels in second stage

$$N_1 = \frac{N}{1 + R^{-1} + R^{-2}} = 14$$

$$N_2 = N - N_1 = 12$$

6.1.8 Pressure Vessels

Diameter of each element, D_e = 7.9 inch

Diameter of vessel = D_e + allowance = 8.9 inch

Length of single element = L_e = 40.5 inch

Length of pressure vessel = L_e x number of elements in a vessel + allowance = 325 inches

Hence, volume of a pressure vessel = 0.331 m^3

6.2 Spray Tray Deaerator

6.2.1 Length of Pre-Heater

According to the Flownex model, the length of the pre-heater section of a spray tray type deaerator depends upon the total residence time for the condensate inside the vessel. The length is given by:

$$L_{preheater} = t_{res} v_{droplet} \cos\theta$$

where $v_{droplet}$ is the velocity of condensate droplet, and

t_{res} is the total residence time of condensate droplet given by:

$$t_{res} = t_{ht} + t_{mt}$$

where t_{ht} is the time needed to heat the condensate droplets to saturation and t_{mt} is the time allowed for mass transfer.

$$t_{ht} = \frac{F_0 . c_{p\,mc.avg} D_{32}^2 \rho_{mc.avg}}{4k_{mc.avg}}$$

where

$$F_0 = -\frac{\ln(1-\theta_m^2)}{\pi^2}$$

and t_{mt} can be calculated by using the following equation for oxygen diffusivity in water:

$$\omega_{o2}(t) = \omega_{o2.in} e^{-6\frac{Sh\,D_{o2.mc}}{D_{32}^2} t_{mt}}$$

6.2.1.1 Droplet Diameter D_{32}

$$D_{32} = 2.25\sigma^{0.25}\mu^{0.25}m^{0.25}\Delta P^{-0.5}\rho^{-0.25}$$

Variable	**Value**
Surface tension at nozzle outlet, $\boldsymbol{\sigma}$	0.05 N/m
Viscosity of main condensate, $\boldsymbol{\mu}$	8.9 x 10^{-4} Pa.s
Mass flowrate of condensate, m	42.78 kg/s
Pressure drop across nozzle, $\boldsymbol{\Delta P}$	0.2 bar
Density of steam, $\boldsymbol{\rho}$	1.5 kg /m^3
Sauter Mean Diameter, $\boldsymbol{D_{32}}$	**3 x 10^{-3} m**

Table 22 Values of multiple parameters for droplet diameter calculation

6.2.3.2 Oxygen Diffusivity in Water

$$D_{o2.mc} = \left(\frac{117.3\ x\ 10^{-18}(\phi.M)^{\frac{1}{2}}\left(\frac{T}{K}\right)}{\left(\frac{V_{mo}^{0.6}}{\frac{1000cm^3}{mol}}\right)\left(\frac{\mu}{\frac{kg}{\frac{m}{s}}}\right)} \right)\left(\frac{m^2}{s}\right)$$

Variables	Values
Solvent association parameter, ϕ	2.26
Molecular weight, M	18 g/mol
Temperature of mixture, T	150 ^{0}C
Molal volume of oxygen, V_{mo2}	31.2 cm^3/mol
Viscosity of main condensate, μ	8.9 x 10^{-4} Pa.s
Oxygen Diffusivity, $D_{o2.mc}$	**2.85 x 10^{-9} m^2/s**

Table 23 Values of multiple parameters for oxygen diffusivity in water calculation

6.2.1.3 Sherwood Number

$$Sh = Sh_0 + 0.347\left(ReSc^{\frac{1}{2}}\right)^{0.62}$$

For initial Sherwood Number, Sh_0

$$Sh_0 = 2 + 0.569(Gr.Sc)^{0.25}\ if\ Gr.Sc \le 10^8$$

$$Sh_0 = 2 + 0.0254(Gr.Sc)^{\frac{1}{3}}.Sc^{0.244}\ otherwise$$

$$Gr = \frac{d_{32}^3\rho_{dea.out}g(\rho_{dea.out} - \rho_{s.dea})}{\mu^2}$$

Variable	Value
Droplet Diameter, d_{32}	3 x 10^{-3} m
Condensate density at deaerator outlet, $\rho_{dea.out}$	1000 kg/m^3
Gravitational acceleration, g	9.81 m/s^2
Average steam density, $\rho_{s.dea}$	1.5 kg/m^3
Condensate viscosity, μ	8.9 x 10^{-4} Pa.s
Grasshof Number, Gr	3.34 x 10^5

Table 24 Values of multiple parameters for initial Sherwood number calculation

$$Sc = \frac{\mu}{\rho D_{o2}}$$

Variable	Value
Condensate viscosity, μ	8.9 x 10^{-4} Pa.s
Condensate density, ρ	1000 kg./m^3
Oxygen Diffusivity, D_{o2}	2.85 x 10^{-9} m^2/s
Schmidt Number, Sc	312.3

Table 25 Values of multiple parameters for Sherwood number calculation

Therefore, $Gr.Sc = 1.04\ x\ 10^8$

So Initial Sherwood Number is given by:

$$Sh_0 = 2 + 0.569(Gr.Sc)^{0.25} = 59.5$$

Reynolds Number is given by:

$$Re = \frac{\rho_{s.dea} v_{droplet d_{32}}}{\mu_s}$$

For droplet velocity:

$$v_{droplet} = \frac{\frac{m}{N_{noz}}}{\rho_{noz} A_0 (1 - X)}$$

Variable	**Value**
Condensate flowrate, m	42.78 kg/s
Number of nozzles, N_{noz}	1
Condensate density across nozzle, ρ_{noz}	1000 kg/m^3
Nozzle flow area, A_0	0.4 m^2
Nozzle X factor, X	0.6
Droplet velocity, $v_{droplet}$	0.21 m/s

Table 26 Values of multiple parameters for droplet velocity calculation

Therefore, Reynolds Number = 94.5

Sherwood Number = 102.7

6.2.1.4 Mass Transfer time t_{mt}

Outlet oxygen concentration $\omega_{o2}(t)$ = 0.1 ppm

Inlet oxygen concentration $\omega_{o2.in}$= 69 ppm

Sherwood Number $Sh = Sh_0 + 0.347 \left(ReSc^{\frac{1}{2}}\right)^{0.62}$ = 102.7

Oxygen diffusivity, D_{o2} = 2.85 x 10^{-9} m^2/s

Mean droplet diameter, d_{32} = 3 x 10^{-3} m

Substituting these values into oxygen continuity equation, and solving for t_{mt} gives:

$$t_{mt} = -\frac{\ln(\omega_{o2}(t) - \omega_{o2.in}) d_{32}^2}{6 Sh D_{o2}} = 21.7\ s$$

6.2.1.5 Heating time, t_{ht}

$$t_{ht} = \frac{F_0 . c_{p\ mc.avg} D_{32}^2 \rho_{mc.avg}}{4 k_{mc.avg}}$$

where

$$F_0 = -\frac{\ln(1 - \theta_m^2)}{\pi^2}$$

θ_m is the mean dimensionless temperature given by:

$$\theta_m = \frac{T_{Target} - T_{dea.in}}{T_{dea.out} - T_{dea.in}} = \frac{149.95 - 25}{150 - 25} = 0.996$$

Therefore, $F_0 = 0.579$

$t_{ht} = 8$ s

6.2.1.6 Total residence time, t_{res}

$$t_{res} = t_{ht} + t_{mt} = 29.7\ s$$

6.2.1.7 Length of Preheater

$$L_{preheater} = t_{res} v_{droplet} \cos\theta$$

$$= 29.7\ x\ 0.21\ x \cos 60 \ = \mathbf{3.12\ m}$$

6.2.2 Packing Size and Diameter

The packing or tray box is included in a tray deaerator to increase the contact surface area between steam and condensate. Regarding the working principle, the design calculations are performed as that for a direct contact heat exchanger.

6.2.2.1 Vertical section diameter

Diameter and packing size are design variables and one of them must be specified to calculate the other. Therefore, a diameter of 2.0 m is taken based on the standard dimensions available in commercial deaerator.

6.2.2.2 Number of Diffusion Units, n_d

Floor area: $\pi r^2 = 3.14\ m^2$

Liquid loading, L = $\frac{154{,}000}{3.14} = 49{,}044 \frac{kg}{hm^2}$

Gas loading, G =$\frac{5508}{3.14} = 1754 \frac{kg}{hm^2}$

Gradient of operating line: $\frac{L}{G} = 28$

$$n_d = \frac{K_x aV}{L} = \frac{dT}{H' - H}$$

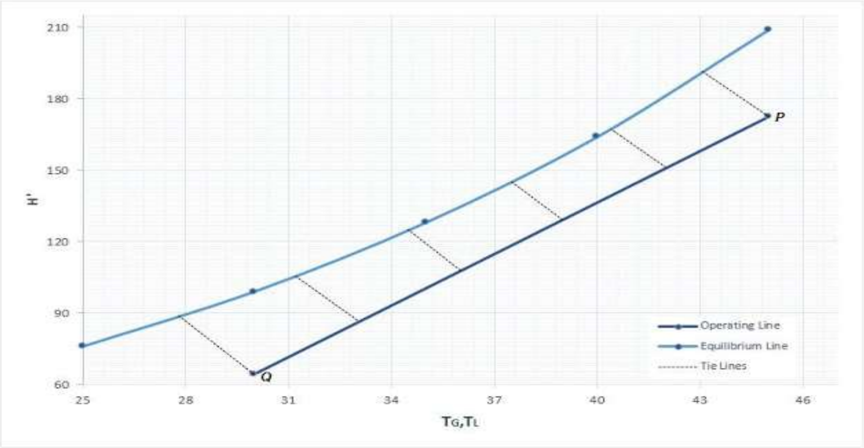


Figure 3 H-T Diagram

Calculating log mean difference over the range of 93^{0}C to 178^{0}C using the corresponding enthalpies of inlet condensate, outlet condensate, inlet steam, and outlet steam:

$$H_{cond.in} = 389.6\frac{kJ}{kg}$$

$$H_{cond.out} = 410.66\frac{kJ}{kg}$$

$$H_{steam.in} = 2745.9\frac{kJ}{kg}$$

$$H_{steam.out} = 2775.5\frac{kJ}{kg}$$

$$logarithmic\ mean = \frac{H' - H}{2.3\log\frac{H'}{H}} = 2206.2\frac{kJ}{kg}$$

$$n_d = \frac{Temperature\ range}{logarithmic\ mean} = 0.020$$

6.2.2.3 Packing height

$$Z = \frac{n_d L}{K_x a}$$

Variable	Value
Number of diffusion units, n_d	0.020 m
Liquid loading, L	49,044 $\frac{kg}{hm^2}$
Mass Transfer coefficient for stainless steel trays, $K_x a$	376.3 $\frac{kg}{hm^2}$
Packing height. Z	2.6 m

Table 27 Values of multiple parameters for packing height calculations

Hence, the height of tray box is 2.6 m

6.3 Lime Softening Unit

6.3.1 Reactor Design

Equation of CSTR is:

$$\frac{V}{F_{Ao}} = \frac{X_A}{-r_A} = \frac{\tau}{C_{Ao}} \qquad \text{(A)}$$

Reaction 1:

Hard water flow rate = 220 m^3/hr

Extent of Reaction = 90 %

F_{Ao} = 896 gmol/hr

C_{Ao} = 896/220 => 4.07 gmol/m^3

F_{Bo} = 896 gmol/hr

Volumetric flow rate = 896 * 74 => 66304 g/hr => $\frac{66.304\ Kg}{hr} * \frac{\text{m3}}{2211\ Kg}$ => 0.03 m^3/hr

C_{Ao} = (66.304 Kg/hr)/ 0.03 m^3/hr => 2210000 g/m^3 => 29864 gmol/ m^3

Conversion (X) = $\frac{4.07 - 3.66}{4.07}$ => 0.1

Rate constant (K_1) = 3.29 hr^{-1}

Order of 1st reaction = 1

So, putting the values in Eq (A) gives:

$$V = \frac{(0.1)(896)}{(4.07)(3.29)} \Rightarrow \mathbf{6.691\ m^3}$$

Reaction 2:

Extent of Reaction = 90 %

F_{Ao} = 1202 gmol/hr

C_{Ao} = 1202/220 => 5.46 gmol/m^3

F_{Bo} = 1202 gmol/hr

Volumetric flow rate = 1202 * 74 => 88948 g/hr => $\frac{88.948\ Kg}{hr} * \frac{\text{m3}}{2211\ Kg}$ => 0.04 m^3/hr

C_{Ao} = (88.948 Kg/hr)/ 0.04 m^3/hr => 2223700 g/m^3 => 30050 gmol/ m^3

Conversion (X) = $\frac{5.46 - 4.914}{5.46}$ => 0.1

Rate constant (K_2) = 3.02 hr^{-1}

Order of 2nd reaction = 1

So, putting the values in Eq (A) gives:

$$V = \frac{(0.1)(1202)}{(5.46)(3.02)} \Rightarrow \mathbf{7.289\ m^3}$$

Reaction 3:

Extent of Reaction = 90 %

F_{Ao} = 1920 gmol/hr

C_{Ao} = 1920/220 => 8.73 gmol/m^3

F_{Bo} = 1920 gmol/hr

Volumetric flow rate = 1920 * 74 => 142080 g/hr => $\frac{142.080\ Kg}{hr} * \frac{\text{m3}}{2211\ Kg}$ => 0.064 m^3/hr

C_{Ao} = (142.080 Kg/hr)/ 0.064 m^3/hr => 2220000 g/m^3 => 30000 gmol/ m^3

Conversion (X) = $\frac{8.73 - 7.857}{8.73}$ => 0.1

Rate constant (K_3) = 2.52 hr^{-1}

Order of 3rd reaction = 1

So, putting the values in Eq (A) gives:

$$V = \frac{(0.1)(1920)}{(8.73)(2.52)} \Rightarrow \mathbf{8.693\ m^3}$$

6.3.1.1 Total Volume of Reactor:

Total volume of reactor = 6.691 + 7.289 + 8.693 => **22.6 m^3**

6.3.1.2 Space Time:

As this is a constant density system so space time becomes equal to residence time and we consider residence time for mixing tank which is calculated as:

Residence time = (Reactor volume/volumetric flow rate) => (22.6/220) => **369.81 sec**

6.3.2 Settling Tank

Discharge flow rate = 220 m^3/hr

Let us assume that the detention time is 2.5 hrs. So

Volume of tank = Discharge flow rate * Detention time

= 220 m^3/hr * 2.5 hrs => 550 m^3

Moreover, let us assume that the 'depth' of tank is '3 m' and its length to width ratio is 4:1 which is equal to 4W = L. Here W is width and L is length.

Surface area of tank = $\frac{Volume\ of\ tank}{Depth}$ => $\frac{550}{3}$ => 183.33 m^2

Area = L * W = 4W * W = 183.33

$\sqrt{4W^2} = \sqrt{183.33}$

2W = 13.54

Width (W) = **6.77 m**

Thus,

Length (L) = 4 * 6.77 => **27.1 m**

6.3.2.1 Settling Velocity:

Given Data:

Density of calcium hydroxide (ρ) = 2340 m^3/hr

Density of water (ρ) = 1000 kg/m^3

Viscosity of water (μ) = 0.00091 Ns/m^2

Diameter of particle (d) = 20 µm

Calcium hydroxide being the lightest particle among all the other particles, having density of 2340 Kg/m^3, will settle after all the other particles. So, it is considered for the calculations of settling velocity.

Moreover, as the diameter of particle is less than 0.1mm so the flow will be laminar and for laminar flow settling velocity is given by:

$$V_s = \frac{g(\rho_S - \rho)d^2}{18\mu}$$

Putting values in the above equation gives:

$$V_s = \frac{9.8(2340 - 1000)(20e - 6)^2}{18(0.00091)}$$

$V_s = 3.21 * 10^{-4}$ m/sec

6.3.2.2 Overflow Velocity:

$$V_o = \frac{Discharge}{W * L} \Rightarrow \frac{220}{6.77 * 27.1} \Rightarrow 1.2 \text{ m/hr}$$

$V_o = 3.33 * 10^{-4}$ m/sec

6.3.2.3 Flow Through Velocity:

$$\text{Flow through velocity} = \frac{Discharge}{W * H} \Rightarrow \frac{220}{6.77 * 3} \Rightarrow 10.83 \text{ m/hr}$$

Flow through velocity = 0.003 m/sec

6.3.2.4 Efficiency of Settling Tank:

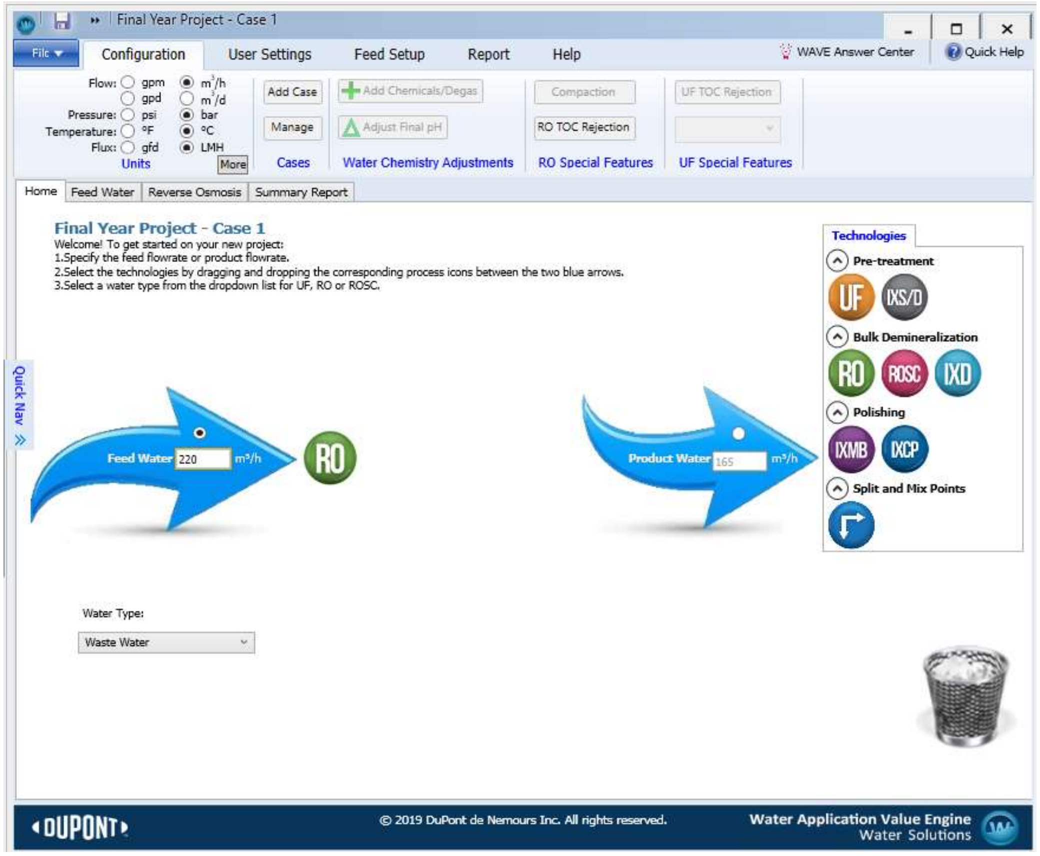
$$\text{Efficiency} = \frac{V_S}{V_O} * 100 \Rightarrow \frac{3.21 * 10^{-4}}{3.33 * 10^{-4}} * 100 \Rightarrow \mathbf{96.4\ \%}$$

CHAPTER 7

PROCESS SIMULATION

7.1 RO Simulation

7.1.1 Home Screen



Final Year Project - Case 1

Flow: ○ gpm ● m³/h ○ gpd ○ m³/d
Pressure: ○ psi ● bar
Temperature: ○ °F ● °C
Flux: ○ gfd ● LMH

Final Year Project - Case 1

Welcome! To get started on your new project:
1.Specify the feed flowrate or product flowrate.
2.Select the technologies by dragging and dropping the corresponding process icons between the two blue arrows.
3.Select a water type from the dropdown list for UF, RO or ROSC.

Feed Water 220 m³/h

Product Water 165 m³/h

Water Type: Waste Water

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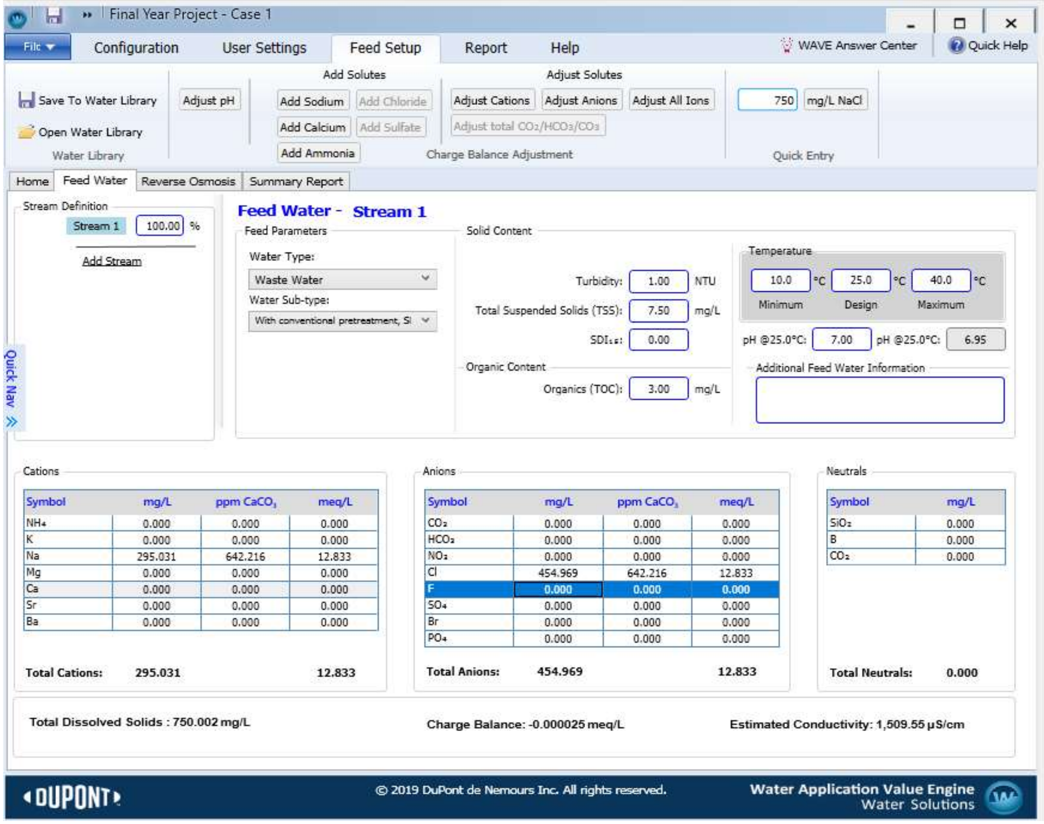
Figure 4 Home screen of DUPONT for RO simulation

We used DOW WAVE software to simulate the RO unit in our wastewater treatment plant as shown above.

The flowrate of RO feed is 220 m^3/h and the water type is chosen as waste water as per the project requirements.

7.1.2 Feed Water Composition



Quick Entry: 750 mg/L NaCl

Stream Definition: Stream 1 100.00 %

Feed Water - Stream 1

Feed Parameters

Water Type: Waste Water

Water Sub-type: With conventional pretreatment, SI

Solid Content

Turbidity: 1.00 NTU

Total Suspended Solids (TSS): 7.50 mg/L

SDI_{15}: 0.00

Organic Content

Organics (TOC): 3.00 mg/L

Temperature: 10.0 °C Minimum; 25.0 °C Design; 40.0 °C Maximum

pH @25.0°C: 7.00 pH @25.0°C: 6.95

Additional Feed Water Information

Cations

Symbol	mg/L	ppm $CaCO_3$	meq/L
NH_4	0.000	0.000	0.000
K	0.000	0.000	0.000
Na	295.031	642.216	12.833
Mg	0.000	0.000	0.000
Ca	0.000	0.000	0.000
Sr	0.000	0.000	0.000
Ba	0.000	0.000	0.000

Total Cations: 295.031 12.833

Anions

Symbol	mg/L	ppm $CaCO_3$	meq/L
CO_3	0.000	0.000	0.000
HCO_3	0.000	0.000	0.000
NO_3	0.000	0.000	0.000
Cl	454.969	642.216	12.833
F	0.000	0.000	0.000
SO_4	0.000	0.000	0.000
Br	0.000	0.000	0.000
PO_4	0.000	0.000	0.000

Total Anions: 454.969 12.833

Neutrals

Symbol	mg/L
SiO_2	0.000
B	0.000
CO_2	0.000

Total Neutrals: 0.000

Total Dissolved Solids : 750.002 mg/L

Charge Balance: -0.000025 meq/L

Estimated Conductivity: 1,509.55 µS/cm

Figure 5 Feed stream input screen

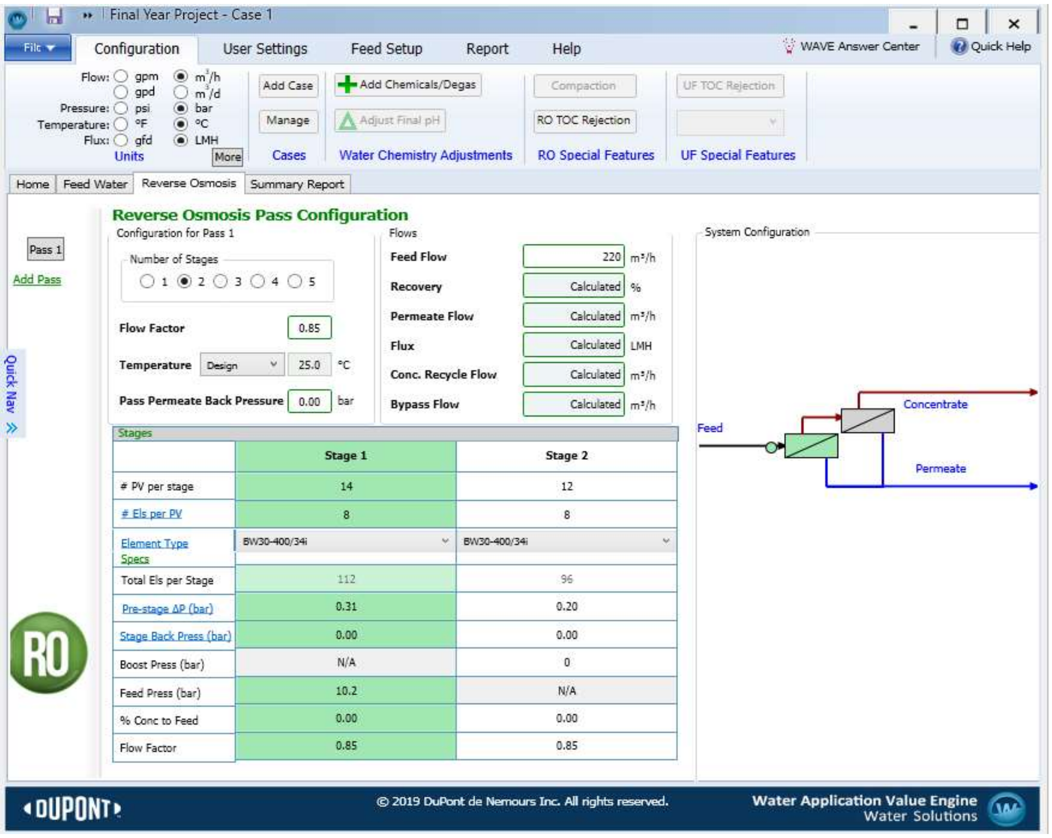
The feed parameters are selected based on the material balance calculations performed earlier.

Turbidity corresponds to the water after being passed through multimedia filter.

TOC shows the total organic content after aeration tank.

For TDS, 750 ppm NaCl is specified as an equivalent amount of the total TDS that were present in the feedwater after lime softening. NaCl is the common salt present in water, and gives a good approximate of water quality especially when the exact composition is not known.

7.1.3 RO System Specifications



Units

Flow: ○ gpm ● m^3/h ○ gpd ○ m^3/d

Pressure: ○ psi ● bar

Temperature: ○ °F ● °C

Flux: ○ gfd ● LMH

Reverse Osmosis Pass Configuration

Configuration for Pass 1

Number of Stages: ○ 1 ● 2 ○ 3 ○ 4 ○ 5

Flow Factor 0.85

Temperature Design 25.0 °C

Pass Permeate Back Pressure 0.00 bar

Flows

Feed Flow 220 m^3/h

Recovery Calculated %

Permeate Flow Calculated m^3/h

Flux Calculated LMH

Conc. Recycle Flow Calculated m^3/h

Bypass Flow Calculated m^3/h

Stages

	Stage 1	**Stage 2**
# PV per stage	14	12
# Els per PV	8	8
Element Type Specs	BW30-400/34i	BW30-400/34i
Total Els per Stage	112	96
Pre-stage ΔP (bar)	0.31	0.20
Stage Back Press (bar)	0.00	0.00
Boost Press (bar)	N/A	0
Feed Press (bar)	10.2	N/A
% Conc to Feed	0.00	0.00
Flow Factor	0.85	0.85

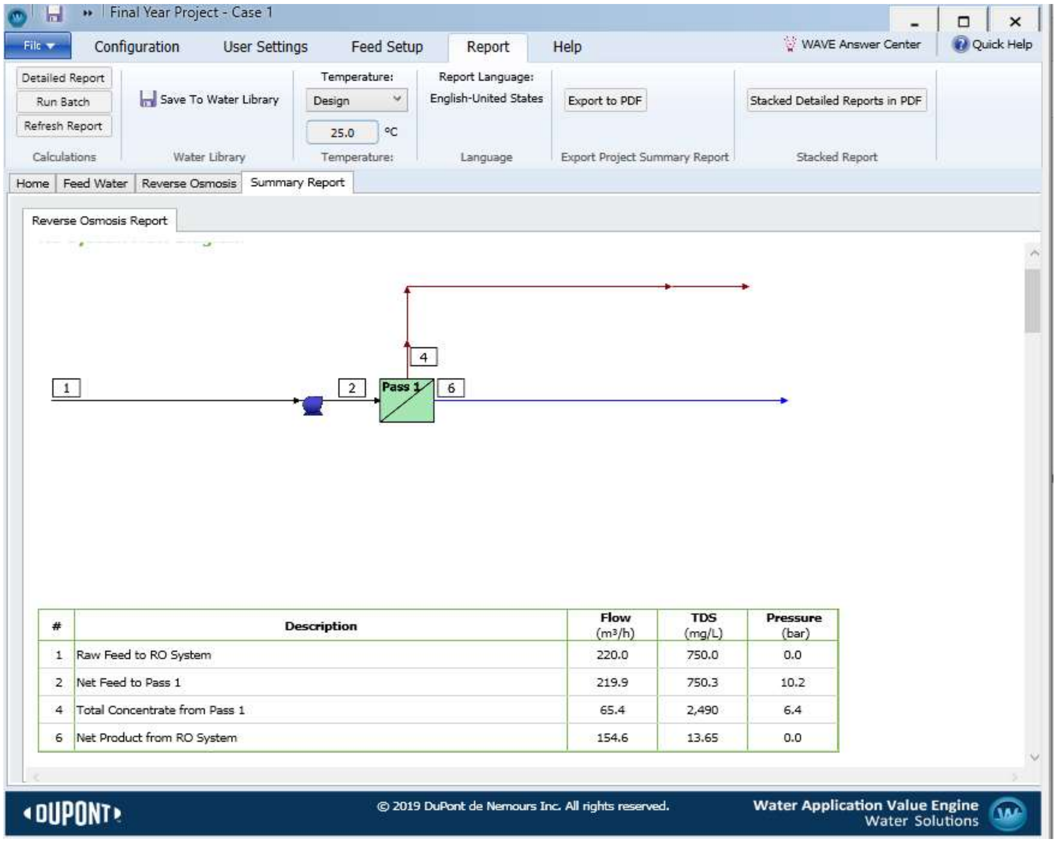
Figure 6 RO system specifications

The feed pressure is taken as 10.2 bars as calculated in energy balance calculations. The design calculations show that we need a two-staged RO system for treating this flowrate of water to the desired quality.

Moreover, the element type and number of elements per pressure vessel, BW30-400/34i and 8 respectively, are also according to the design calculations.

The number of pressure vessels for stage 1 are 14 and for stage 2 they are 12 as determined in design calculations.

7.1.4 Summary Report

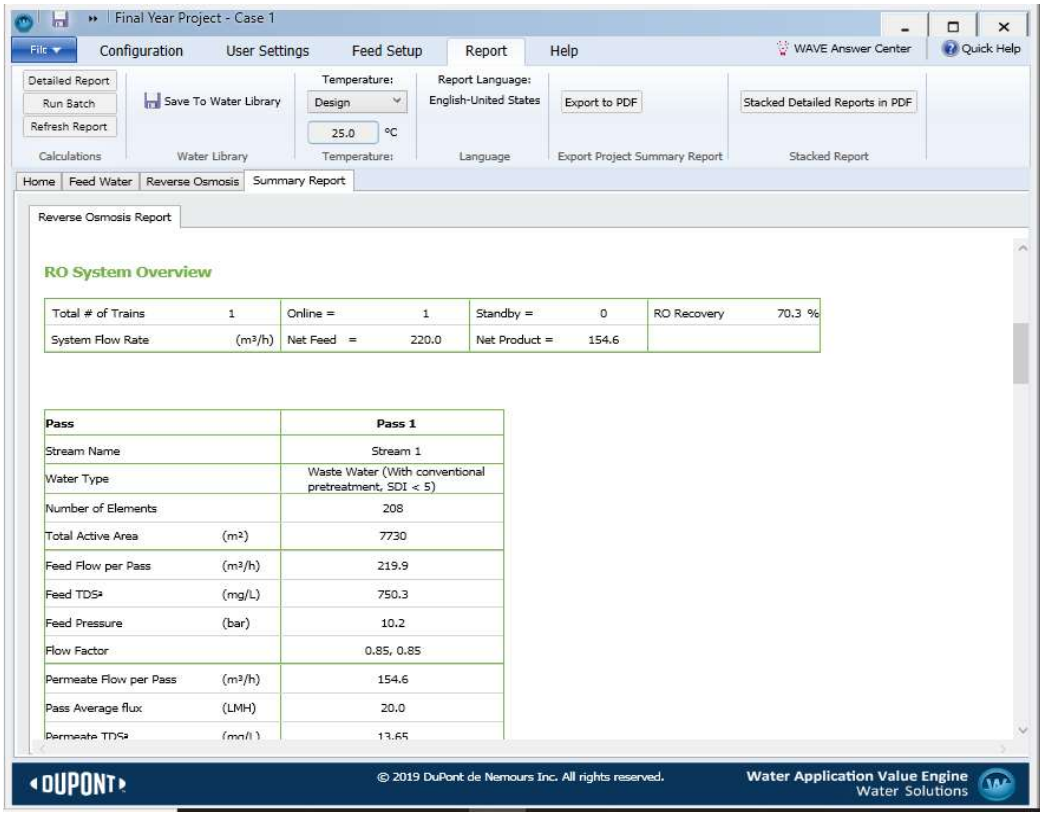


Temperature: Design, 25.0 °C

Report Language: English-United States

#	Description	Flow (m³/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	220.0	750.0	0.0
2	Net Feed to Pass 1	219.9	750.3	10.2
4	Total Concentrate from Pass 1	65.4	2,490	6.4
6	Net Product from RO System	154.6	13.65	0.0

Figure 7 Summary screen of RO



Temperature: Design

25.0 °C

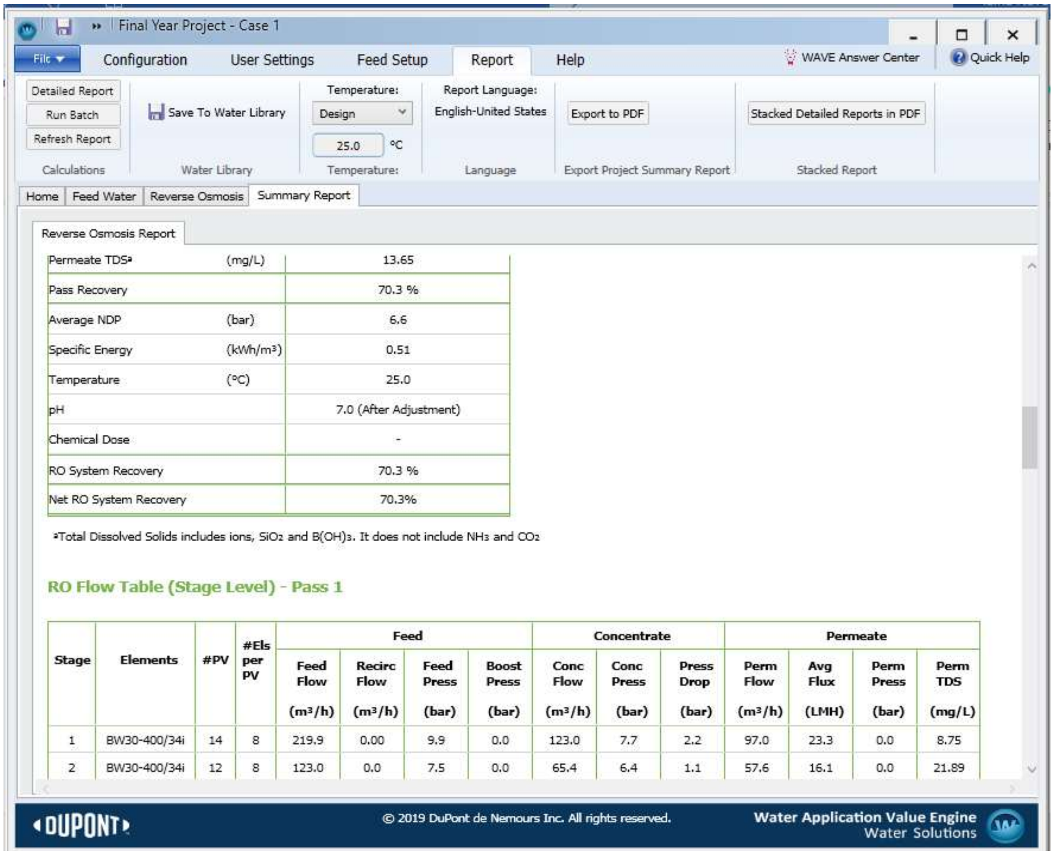
Report Language: English-United States

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	70.3 %
System Flow Rate	(m^3/h)	Net Feed =	220.0	Net Product =	154.6		

Pass		**Pass 1**
Stream Name		Stream 1
Water Type		Waste Water (With conventional pretreatment, SDI < 5)
Number of Elements		208
Total Active Area	(m^2)	7730
Feed Flow per Pass	(m^3/h)	219.9
Feed TDS^a	(mg/L)	750.3
Feed Pressure	(bar)	10.2
Flow Factor		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	154.6
Pass Average flux	(LMH)	20.0
Permeate TDS^a	(mg/L)	13.65

Figure 8 Summary report of RO (1)



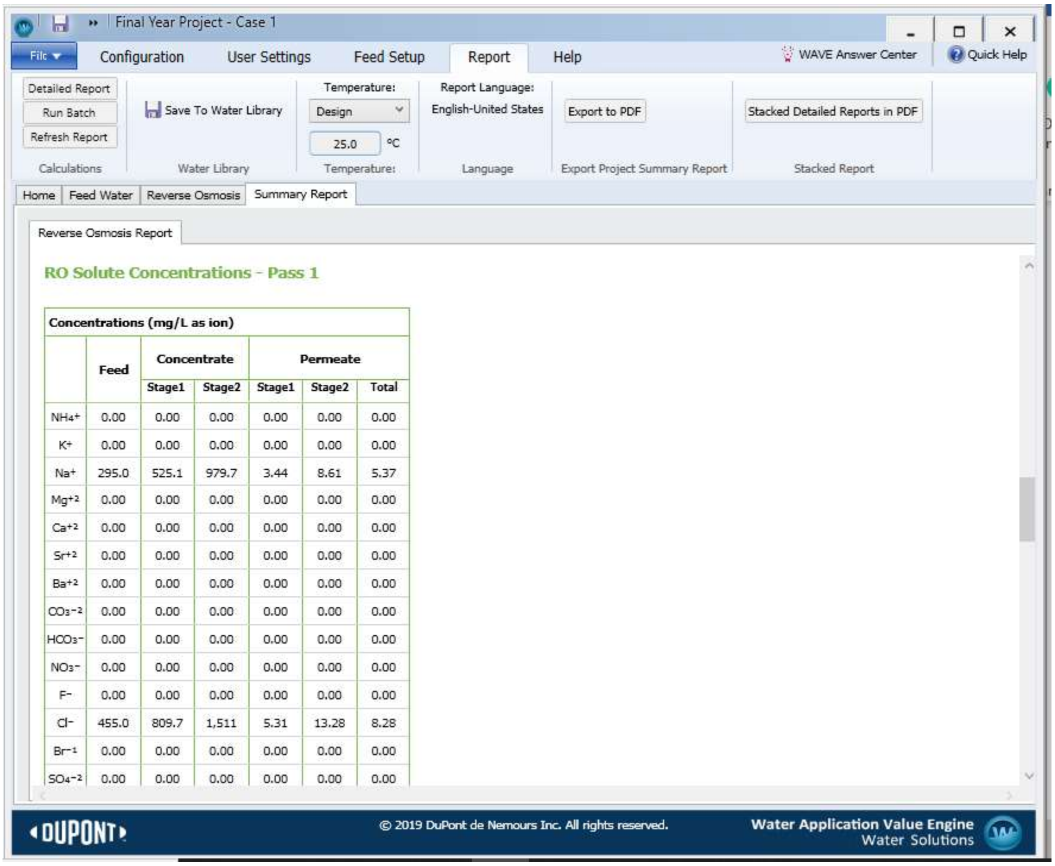
Permeate TDS[a]	(mg/L)	13.65
Pass Recovery		70.3 %
Average NDP	(bar)	6.6
Specific Energy	(kWh/m³)	0.51
Temperature	(°C)	25.0
pH		7.0 (After Adjustment)
Chemical Dose		-
RO System Recovery		70.3 %
Net RO System Recovery		70.3%

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m³/h)	Recirc Flow (m³/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m³/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m³/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	BW30-400/34i	14	8	219.9	0.00	9.9	0.0	123.0	7.7	2.2	97.0	23.3	0.0	8.75
2	BW30-400/34i	12	8	123.0	0.0	7.5	0.0	65.4	6.4	1.1	57.6	16.1	0.0	21.89

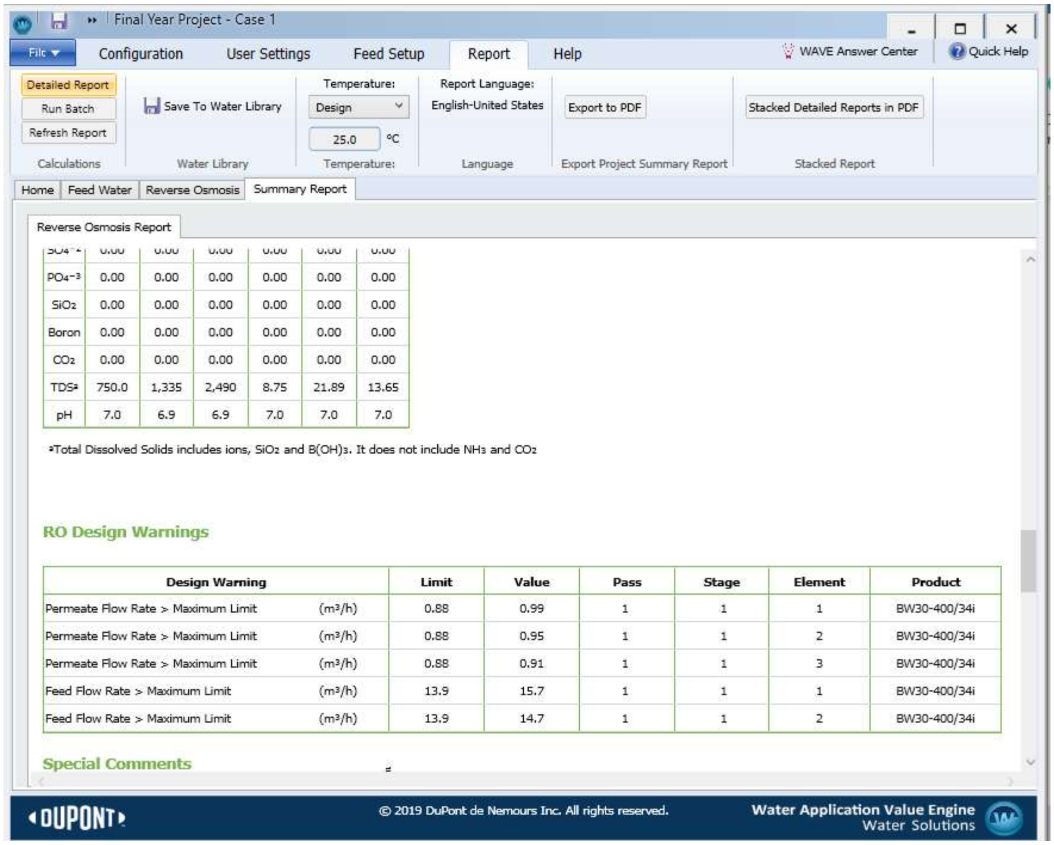
Figure 9 Summary report of RO (2)



RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)						
	Feed	Concentrate		Permeate		
		Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	0.00	0.00	0.00	0.00	0.00	0.00
Na^+	295.0	525.1	979.7	3.44	8.61	5.37
Mg^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ca^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Sr^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
CO_3^{-2}	0.00	0.00	0.00	0.00	0.00	0.00
HCO_3^-	0.00	0.00	0.00	0.00	0.00	0.00
NO_3^-	0.00	0.00	0.00	0.00	0.00	0.00
F^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	455.0	809.7	1,511	5.31	13.28	8.28
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	0.00	0.00	0.00	0.00	0.00	0.00

Figure 10 RO solute concentrations for single pass (1)



PO_4^{-3}	0.00	0.00	0.00	0.00	0.00	0.00
SiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00
TDS[a]	750.0	1,335	2,490	8.75	21.89	13.65
pH	7.0	6.9	6.9	7.0	7.0	7.0

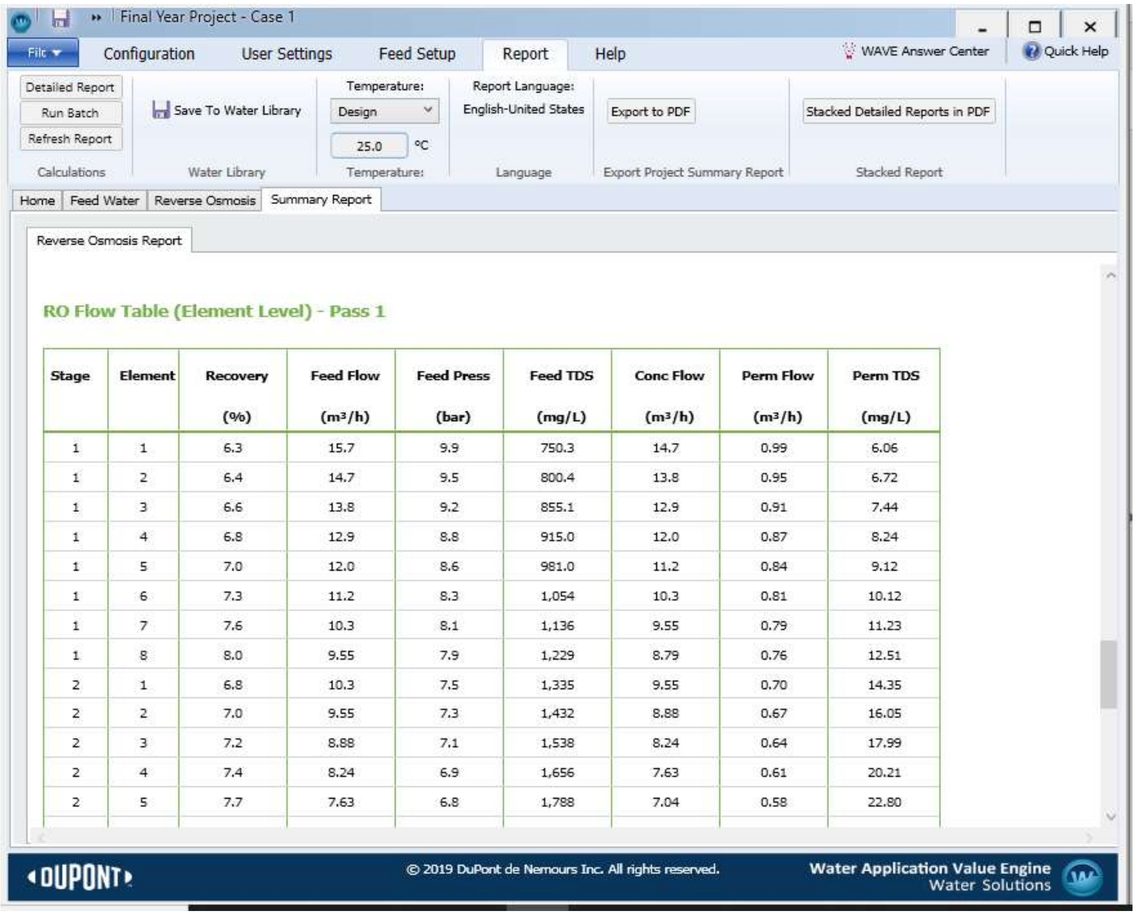
[a] Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Design Warnings

Design Warning		Limit	Value	Pass	Stage	Element	Product
Permeate Flow Rate > Maximum Limit	(m^3/h)	0.88	0.99	1	1	1	BW30-400/34i
Permeate Flow Rate > Maximum Limit	(m^3/h)	0.88	0.95	1	1	2	BW30-400/34i
Permeate Flow Rate > Maximum Limit	(m^3/h)	0.88	0.91	1	1	3	BW30-400/34i
Feed Flow Rate > Maximum Limit	(m^3/h)	13.9	15.7	1	1	1	BW30-400/34i
Feed Flow Rate > Maximum Limit	(m^3/h)	13.9	14.7	1	1	2	BW30-400/34i

Special Comments

Figure 11 RO solute concentrations for single pass (2)



RO Flow Table (Element Level) - Pass 1

Stage	Element	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm TDS (mg/L)
1	1	6.3	15.7	9.9	750.3	14.7	0.99	6.06
1	2	6.4	14.7	9.5	800.4	13.8	0.95	6.72
1	3	6.6	13.8	9.2	855.1	12.9	0.91	7.44
1	4	6.8	12.9	8.8	915.0	12.0	0.87	8.24
1	5	7.0	12.0	8.6	981.0	11.2	0.84	9.12
1	6	7.3	11.2	8.3	1,054	10.3	0.81	10.12
1	7	7.6	10.3	8.1	1,136	9.55	0.79	11.23
1	8	8.0	9.55	7.9	1,229	8.79	0.76	12.51
2	1	6.8	10.3	7.5	1,335	9.55	0.70	14.35
2	2	7.0	9.55	7.3	1,432	8.88	0.67	16.05
2	3	7.2	8.88	7.1	1,538	8.24	0.64	17.99
2	4	7.4	8.24	6.9	1,656	7.63	0.61	20.21
2	5	7.7	7.63	6.8	1,788	7.04	0.58	22.80

Figure 12 RO flow table for signle pass

The summary report shows results that are very close to our design calculations. With a recovery 70.2%, it has calculated total 208 elements required with the permeate containing 13.65 ppm TDS.

These results are comparable with our calculations of design, mass balance and energy balance.

7.2 Mixing Tank

7.2.1 Main Flow sheet

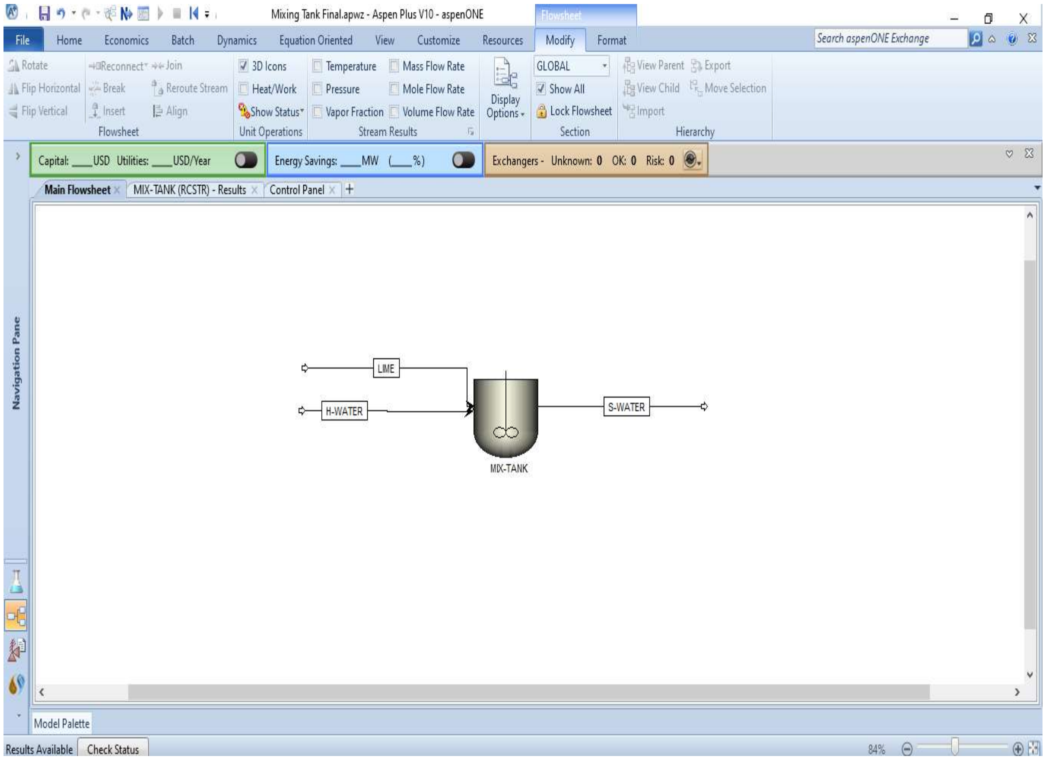


Figure 13 Main flowsheet of mixing tank

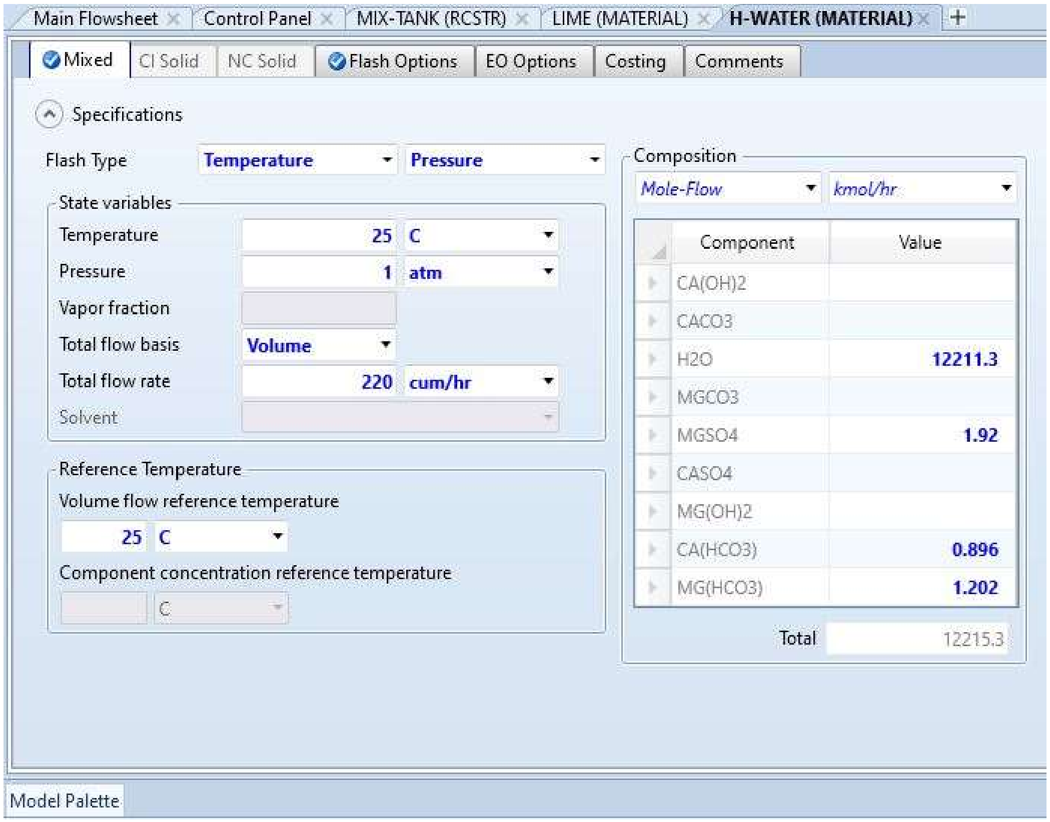
We used Aspen Plus for the simulation of Mixing tank by assuming it as a CSTR as its fuction is similar to that of the a continuous stirred tank reactor. Its simulation is shown in the above figure.

7.2.2 Inlet Streams

In the figure shown below, all the parameter such as temperature, pressure, mole fractions and mass flow rates of both the inlet streams (LIME & H-WATER) were provided.

The feed parameters are selected based on the material balance calculations performed earlier.

7.2.2.1 H-Water Stream



Specifications

Flash Type: Temperature, Pressure

State variables

Temperature: 25 C

Pressure: 1 atm

Vapor fraction:

Total flow basis: Volume

Total flow rate: 220 cum/hr

Solvent:

Reference Temperature

Volume flow reference temperature: 25 C

Component concentration reference temperature: C

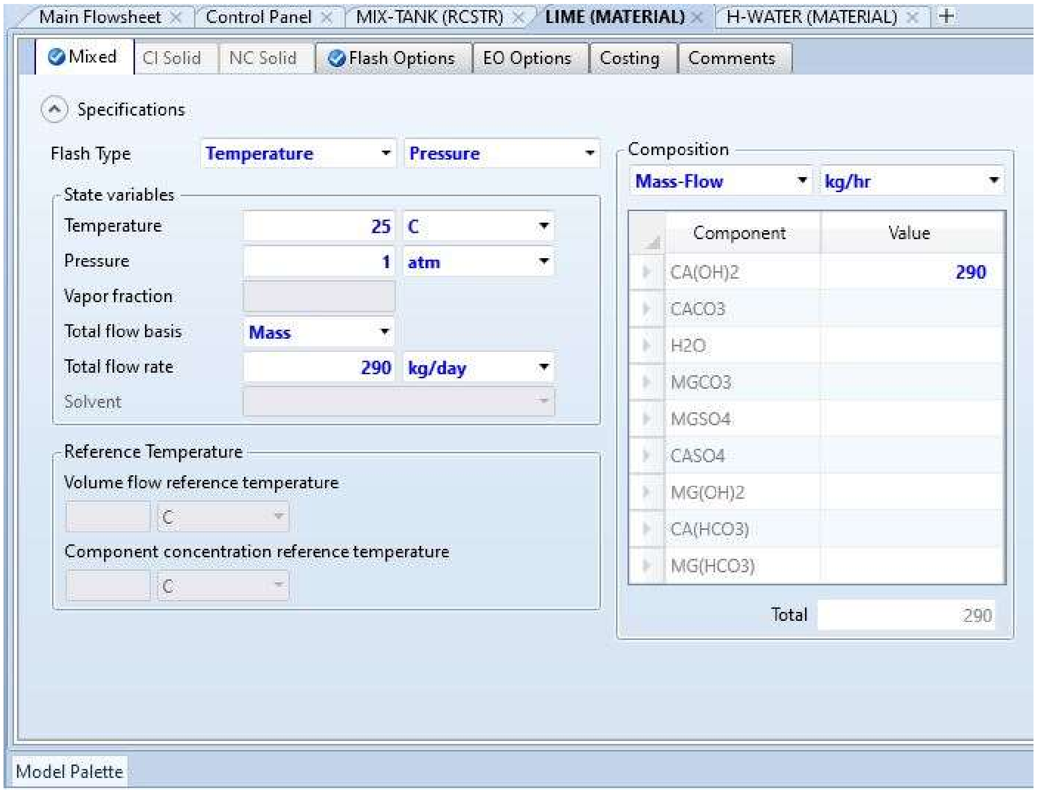
Composition: Mole-Flow, kmol/hr

Component	Value
CA(OH)2	
CACO3	
H2O	12211.3
MGCO3	
MGSO4	1.92
CASO4	
MG(OH)2	
CA(HCO3)	0.896
MG(HCO3)	1.202

Total: 12215.3

Figure 14 H-WATER stream input data screen

7.2.2.2 LIME Stream



Flash Type: Temperature, Pressure

State variables

Temperature: 25 C

Pressure: 1 atm

Vapor fraction:

Total flow basis: Mass

Total flow rate: 290 kg/day

Solvent:

Reference Temperature

Volume flow reference temperature: C

Component concentration reference temperature: C

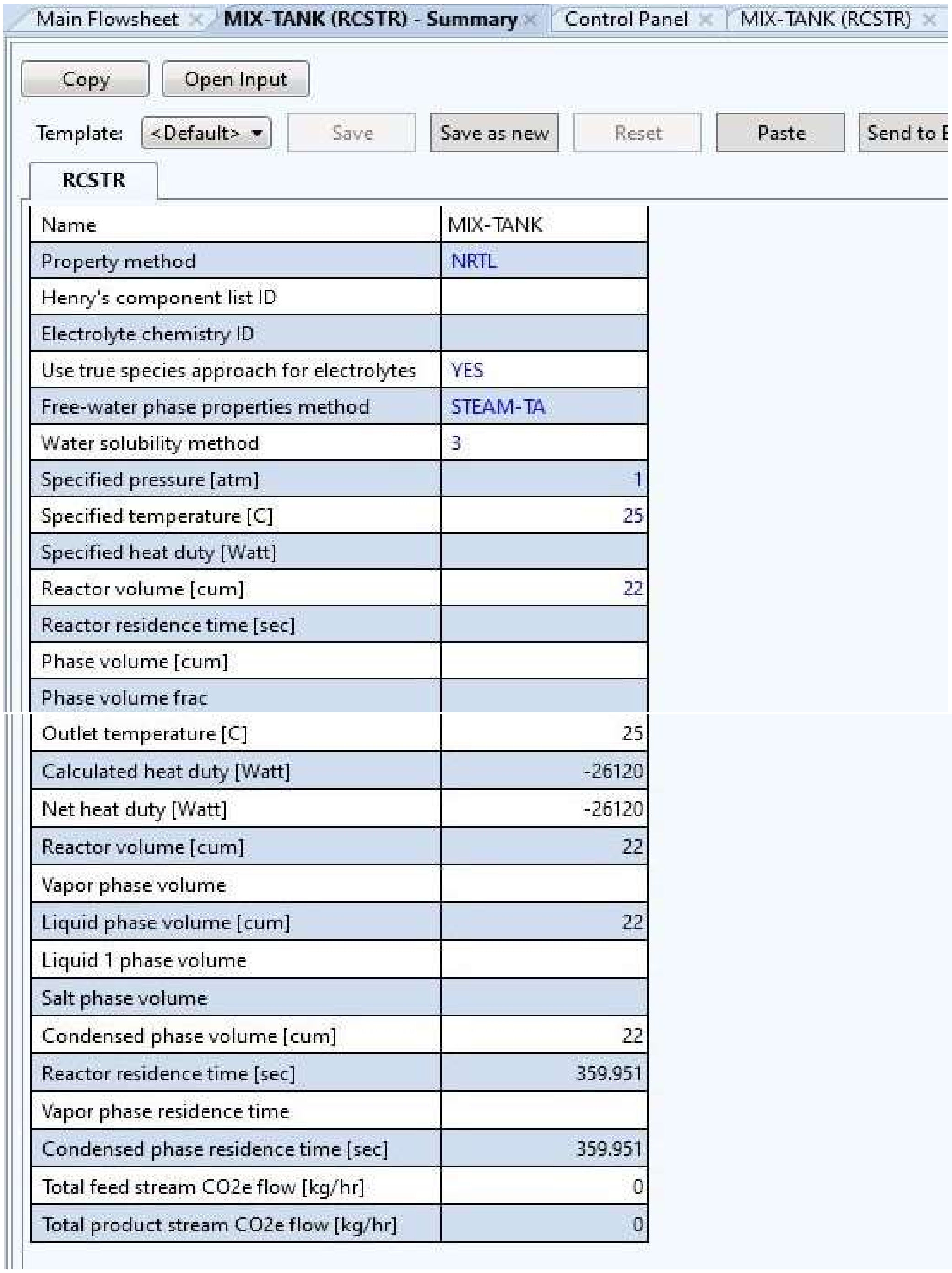
Composition: Mass-Flow, kg/hr

Component	Value
CA(OH)2	290
CACO3	
H2O	
MGCO3	
MGSO4	
CASO4	
MG(OH)2	
CA(HCO3)	
MG(HCO3)	

Total: 290

Figure 15 LIME stream input data screen

7.2.3 Results Summary



Name	MIX-TANK
Property method	NRTL
Henry's component list ID	
Electrolyte chemistry ID	
Use true species approach for electrolytes	YES
Free-water phase properties method	STEAM-TA
Water solubility method	3
Specified pressure [atm]	1
Specified temperature [C]	25
Specified heat duty [Watt]	
Reactor volume [cum]	22
Reactor residence time [sec]	
Phase volume [cum]	
Phase volume frac	
Outlet temperature [C]	25
Calculated heat duty [Watt]	-26120
Net heat duty [Watt]	-26120
Reactor volume [cum]	22
Vapor phase volume	
Liquid phase volume [cum]	22
Liquid 1 phase volume	
Salt phase volume	
Condensed phase volume [cum]	22
Reactor residence time [sec]	359.951
Vapor phase residence time	
Condensed phase residence time [sec]	359.951
Total feed stream CO2e flow [kg/hr]	0
Total product stream CO2e flow [kg/hr]	0

Figure 16 Results summary of mixing tank

After successfully converging the simulation of CSTR, the above figure shows the results summary of the simulation. The results have shown that when reactor volume was 22 cubic meter then at the same time residence time was calculated to be 359.951 seconds.

CHAPTER 8

ECONOMICAL ANALYSIS

8.1 Total Initial Investment

8.1.1 Costing of Pumps

Equipments	Power (hp)	Cost ($)
P-100	4.4	2,100
P-101	2.2	1,750
P-102	2.2	1,750
P-103	202.2	19,000
P-104	2.2	1,750
P-105	2.2	1,750
Total		**28,100**

Table 28 Costing of all the pump

8.1.2 Multimedia Filter:

$S = 1\ m^3$

$C = 2400$

$n = 0.6$

$Ce = CS^n = \$\ 2400$

Thus, the calculated cost of Multimedia filter is **$ 2400**.

8.1.3 Aeration Tank:

$S = 150\ m^3$

$C = 2400$

$n = 0.6$

$Ce = CS^n = \$\ 48,500$

Thus, the calculated cost of Aeration Tank is **$ 48,500**.

8.1.4 Mixing Tank:

S = 226 m^3

C = 15000

n = 0.4

Ce = CS^n = $ 131,140

Thus, the calculated cost of Mixing tank is **$ 131,140**.

8.1.5 Settling Tank:

S = 550 m^3

C = 2400

n = 0.6

Ce = CS^n = $ 105,790

Thus, the calculated cost of Settling tank is **$ 105,790**.

8.1.6 Filtration Tank:

S = 1 m^3

C = 2400

n = 0.6

Ce = CS^n = $ 2400

Thus, the calculated cost of Filtration tank is **$ 2400**.

8.1.7 RO Unit:

Capacity of a single pressure vessel (S) = 0.331 m^3

C = 2900

n = 0.6

Ce = $CS^n = (2900)(0.331)^{0.6}$ = $ 1500/vessel

Total cost of pressure vessel = 26 * 1500 => $ 39,000

Pressure factor = 39,000 * 1.2 => $ 46,800

Number of elements needed = 206

Cost of elements = 206 * 545 => $ 112,270

Total calculated Cost of RO unit = 46,800 + 112,270 => **$ 159,070**

8.1.8 Storage Tank:

S = 50 m^3

C = 4350

n = 0.55

Ce = CS^n = $ 25,100

Thus, the calculated cost of Storage tank is **$ 25,100**.

8.1.9 Deaerator:

Height = 3.12 m

Diameter = 2.0 m

Cost of vessel = $ 14000 * 2 * 1.0

= $ 28,000

Cost of Trays = 5700 * 1.7 => $ 1190/plate

Total number of trays needed = 50 trays

Total cost of trays = 50 * 1190 => $ 59,500

Total calculated cost of deaerator = 28,000 + 59,500 = **$ 87,500**

8.1.10 Pellet Reactor:

S = 50 m^3

C = 15000

n = 0.6

Ce = CS^n = $ 71,800

Thus, the calculated cost of Pellet reactor is $ **71,800**.

8.1.11 PH Adjustment Tank:

S = 50 m^3

C = 2400

n = 0.6

Ce = CS^n = $ 25,100

Thus, the calculated cost of PH adjustment tank is **$ 25,100**.

Total Purchasing Cost of Equipments (PCE)	
Equipments	Cost ($)
Pumps	28,100
Multimedia Filters	2,400
Aeration Tank	48,500
Mixing Tank	131,140
Settling Tank	105,790
Filtration Tank	2,400
RO Unit	159,070
Storage Tank	25,100
Deaerator Tank	87,500
Pellet Reactor	71,800
PH Adjustment Tank	25,100
Total Cost	**686,900**

Table 29 Total purchasing cost of all the equipments

Physical Plant Cost		
	Factors	Value
f_1	Equipment Erection	0.45
f_2	Piping	0.45
f_3	Instrumentation	0.15
f_4	Electrical	0.10
f_5	Buildings	0.10
f_6	Utilities	0.45
f_7	Site development	0.05
f_8	Storages	0.20
f_9	Auxiliary buildings	0.20
Total		**2.15**

Table 30 Physical plant cost factors

PPC = PCE(1 + 2.15)

PPC = 686,900(3.15) => **$ 2,163,135**

8.1.12 Fixed Capital:

Total = 0.4

Fixed capital cost = PPC (1 + 0.4) => $ 3,029,229

8.1.13 Working Capital:

Working capital = 5% * fixed capital => 0.05 * 3029229

Working capital = $ 151,461

8.1.14 Total Investment:

Total investment = fixed capital + working capital

T. Investment = 3,029,229 + 151,461 => **$ 3,180,690**

8.2 Annual Operating Cost:

8.2.1 Operating Time:

Plant Attainment = 95% * 365 days => 347 days per annum

Or

Plant attainment = 8328 hours per annum

Fixed Operating Cost		
Type of Cost	Calculation Method	Cost ($)
Maintenance	5% of Fixed capital	151,461
Operating Labour	Manning Estimate	100,000
Lab Cost	20% of operating labour	20,000
Supervision	20% of operating labour	20,000
Plant overheads	50% of operating labour	50,000
Capital Charges	10% of Fixed capital	302,922
Insurance	1% of Fixed capital	30,292
Local Taxes	2% of Fixed capital	60,586
Royalties	1% of Fixed capital	30,292
Total		**765,555**

Table 31 Fixed operating cost

Variable Cost:

Variable Operating Cost		
Type	Calculation Method	Cost ($)
Raw Materials	$Ca(OH)_2$ (250 Kg/hr) = 0.120 * 250 * 8328 = $ 250,000	552,475
	NaOH (15 Kg/hr) = 2.6 * 15 * 8328 = $ 32,500	
	Soda Ash (85 Kg/hr) = 0.380 * 85 * 8328 = $ 269,000	
	Sulphuric Acid (1.8 Kg/hr) = 0.065 * 1.8 * 8328 = $ 975	
Misc. Materials	10% of maintenance cost	15,146
Utilities	0.015 * 23,161.4 * 8328	2,893,322
Total		**3,460,943**

Table 32 Variable operating cost of various items

8.2.2 Annual Operating Cost:

Annual operating cost = Fixed Cost + Variable Cost

= 765,555 + 3,460,943 => $ 4,226,500

8.3 Net Cost Per m³ of Water:

Amount of water as BFW, annually = 154 m^3/hr * 8328 => 1,282,512 m^3

Amount of water as Cooling water makeup, annually = 66 m^3/hr * 8328 => 549,648 m^3

Thus,

Cost of water as BFW, annually = $\frac{4,226,500}{1,282,512}$ => **$ 3.3/m^3 of BFW**

Cost of water as CW makeup, annually = $\frac{4,226,500}{549,648}$ => **$ 7.7/m^3 of CW makeup**

CHAPTER 9

HAZOP ANALYSIS

9.1 Introduction

The purpose of HAZOP analysis is to study thoroughly a new process or an existing process undergoing major design modifications for any operation difficulties or risks due to deviations from the design conditions. After having developed and documented a robust design of the process, each line and equipment of the process is considered. The ideal operating conditions of that hardware are considered and possible deviations from those conditions are studied. Once the deviations are identified, their potential causes, consequences, and solutions are suggested.

In the industrial practice, the HAZOP team consists of experts from various parts of the operations. They all share their knowledge about the different operations involved in the process, and identify the hazards and operational risks that may occur in the lifetime of the plant. With this study, any essential design changes are made in the process flow diagram to make the plant safer.

This section documents the results of HAZOP study of the entire PFD.

9.2 Terminology

Term	Definition
Operating steps	The procedure under analysis
Study Nodes	The points where deviations from process parameters are considered
Intention	The routine operations expected on the study node
Process Parameters	The defining characteristics of a physical or chemical process
Cause	The reason behind the deviation from routine operations
Deviation	Change in routine operations

Table 33 HAZOP Terminologies

9.3 Multimedia Filter

Deviation	Causes	Consequences	Actions
(i) No inlet flow	Feed pump not working	Loss of feed to aeration tank	Ensure good communication with the operator of Wastewater treatment unit
	Blockage in effluent line / line isolated	Reduced production of BFW	Install low-level alarm on multimedia filter
	No discharge from waterwater unit		Troubleshoot the effluent feed pump P-100
(ii) Reduced or No outlet flow	Too much fouling in the filter	Same as (i) and Filter vessel overflow	Backflow for washing the filter or mechanical cleaning
	Low pressure on the feed side		Troubleshooting of feed pump
Increased feed flowrate than design	Excess discharge from wastewater unit	Ineffective filteration of TSS	Ensure good communication with the operator of Wastewater treatment unit
		Excessive pressure on filters	Install flow control valve on effluent line
Increased TSS in inlet flow	Ineffective wastewater treatment	Poor quality BFW	Ensure good communication with the operator of Wastewater treatment unit

Table 34 . HAZOP analysis of MMF

9.4 Aeration Tank

Deviation	Causes	Consequences	Actions
(i) No Air inlet	Blocked or isolated line from air tank	No removal of organic content	Troubleshoot air supply system
	Empty air storage		Ensure sufficient ait storage
(ii) Reduced or No outlet water flow	Blockage or leakage in outlet line	Loss of feed to lime softening unit	Check outlet line for leakage or blockage
	Pump P-102 Malfunctioning	Reduced production of BFW	Troubleshooting of pump P-102
(i) Increased air supply than design	Excess valve opening of air storage tank	Increased oxygen content in water	Install flow control valve on air supply line
		Poor quality BFW produced	
(ii) Increased outlet flow of water	Excess valve opening of outlet line	Increased feed to lime softening reactor	Install flow control valve on outlet line
		Ineffective water softening	

Table 35 HAZOP analysis of aeration tank

9.5 Lime Softening Unit

Deviation	Causes	Consequences	Actions
Continuous Turbid effluent with high hardness	Sludge carryover	Damage to RO unit	Adjust feed flow rate
		High fouling of membranes	Increase sludge blowdown
			Increase coagulant feed
Sporadic turbid effluent with high hardness	Water surges due to filter backwash	High fouling of RO membranes	Install a holding tank and investigate recirculation of effluent
High soluble hardness with minimal turbidity	Insufficient feed of lime	Reduced efficieny of RO unit	Adjust lime feed and check lime for impurities

Table 36 HAZOP analysis of lime softening process

9.6 High Pressure RO Pump

Deviation	Causes	Consequences	Recommendations
Pressure	• Feed overflow high pressure • restricted flow low pressure	• Pump damage. • Recirculation. • More pump powers. • Cavitation in pump	Ensure Flow regulation
Temperature	High or low temperature	• Increased risk of cavitation.	• Temperature regulation and control of columns. • Flow regulation and control of tank
Flow	More or less flow	• Reduced pump efficiency • Chances of cavitation • Chances of recirculation	Ensure Flow regulation

Table 37 HAZOP analysis of high pressure pump

9.7 RO Membrane

Deviation	Causes	Consequences	Recommendations
No pressure at inlet	• Blocked inlet and outlet of the pump • Pump Failure • Fouling of check valves • Manual valve failure	• Line Trip, and no produce permeate water	• Install switch on manual valve as safety lock • Install auto vent on the line
Low pressure at inlet	•Decrease in level of Raw Water Vessel regard to inlet suction • Strainer blockage • Pump Corrosion	• Line Trip, and no produce permeate water	• Controlling of manual valves • Installing moisture sensor near sand filter pump
Low flow at inlet	• No regular manual valve in outlet of Raw Water Pump, Concentrate of Reverse Osmosis, High Pressure Pump • Failure in pump suction • Check valve blockage	• Line Trip, and no produce permeate water	• Controlling of manual valves • Regular backwash of sand filter. • Periodical inspection & maintenance
High flow at outlet	• No regularize manual valve. • Mechanical failure in flange. • Start accidental pump	• Line Trip, and no produce permeate water and cracking pipe	• Programming on PLC that no start additional pump when one pump is running
Service failures	• Acid Pump corrosion. • Mechanical failure in Acid instrument	• No unloading of Acid, diffusion of Acid on place	• Maintenance & periodical repairing

Table 38 HAZOP analysis of RO membrane

9.8 Deaerator

Deviation	Causes	Consequences	Actions
Reduced pressure	Low steam inlet	Ineffecient deaeration	Install pressure controller on deaerator
	Leakage in inlet pipes or vessel	Corrision in Boiler due to dissolved oxygen	
Reduced Tempature	Poor insulation of vessel	Non condensable gases not removed	Ensure temperature regulation
	Reduced temperature of steam or condensate		Cleaning of heat transfer surface
Reduced flow	Bloackage in spray nozzles	Reduced production of BFW	Ensure proper flow regulation
	Fouling on heat transfer surface		Mechanical cleaning of nozzles and trays
	Flow rate variations of condensate or steam		

Table 39 HAZOP analysis of deaerator

9.9 Pellet Reactor

Deviation	Causes	Consequences	Actions
Continuous Turbid effluent	Pellets carryover	Poor quality cooling water makeup	Ensure proper filteration of effluent
High hardness in effluent	Low NaOH feed		Adjust NaOH feed

Table 40 HAZOP analysis of pellet reactor

CHAPTER 10

CONCLUSION

The proposed design produces high quality polished water and cooling water at market competitive costs. The total capital investment and annual operating cost of the process is justified by the reduction in the cost of chemical treatmrent in cooling tower. The high quality cooling water make-up reduces the dependency of the industry on well and canal as well.

The HAZOP study proves the effectiveness of the process in terms of safety and operability. The quality of effluent that was provided by the industry is converted to the desired quality, while meeting all three objectives of the project.

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