EXPERIMENTAL INVESTIGATION OF VACUUM MEMBRANE DISTILLATION FOR FRESH WATER PRODUCTION

A PROJECT REPORT

Submitted by

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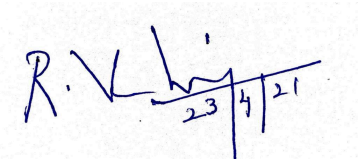
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APRIL 2021

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BONAFIDE CERTIFICATE

Certified that this project report "**EXPERIMENTAL INVESTIGATION OF VACUUM MEMBRANE DISTILLATION FOR FRESH WATER PRODUCTION**" is the bonafide work of **ASHWATH BALAJI (2017111112), KARTHIK VIGNESHWAR (2017111115), VENDHAN ARUNACHALAM (2017111120), and HARI SUNIL S (2017111134)** who carried out the project work under my supervision.



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ABSTRACT

Recently, the focus has shifted to water treatment and reuse of wastewater or raw water for producing drinking water. These interests are ascribed to the massive water consumption which has risen with population growth and the limiting of freshwater resources in many countries. Nowadays, separation processes based on membrane technologies are considered to be a powerful tool in many areas of applications, especially in desalination and wastewater treatment.

Vacuum membrane distillation (VMD) is a thermally driven membrane process with invigorating opportunities for seawater desalination by partial vaporization through the porous hydrophobic polymeric membrane. Unlike the conventional energy intensive desalination technologies, VMD can be fueled by low grade or alternative energy sources and is characterized by its lower operating temperature, lower operating hydrostatic pressure, less demanding membrane mechanical properties, and higher salt rejection rate for non-volatile solutes.

The purpose of this experiment is to provide an overview of the vacuum membrane distillation process in regard to its advantages, disadvantages and miscellaneous implementations. The role of operative conditions on the process performance is widely investigated in the case of aqueous mixtures containing impurities and different concentrations of sodium chloride.

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LIST OF ABBREVIATIONS

MD	Membrane Distillation
NaCl	Sodium Chloride
DCMD	Direct Contact Membrane Distillation
AGMD	Air Gap Membrane Distillation
VMD	Vacuum Membrane Distillation
SWGMD	Sweeping Gas Membrane Distillation
V-MEMD	Vacuum Multi-effect Membrane Distillation
PGMD	Permeate Gap Membrane Distillation
TDS	Total Dissolved Solids
R&D	Research and Development
LPM	Litres per minute
PSI	Pound-force per square inch
Mm Hg	Millimeter of Mercury
℃	Degrees in Celsius
AMPS	Ampere
RPM	Revolutions per minute
HP	Horsepower
P(feed)	Feed Pressure
LEP	Liquid Entry Pressure

CHAPTER 1
INTRODUCTION

1.1 WHAT IS MEMBRANE DISTILLATION

Membrane distillation (MD) is a separation process where a micro-porous hydrophobic membrane separates two aqueous solutions at different temperatures. The hydrophobicity of the membrane prevents mass transfer of the liquid, whereby a gas-liquid interface is created. The temperature gradient on the membrane results in a vapour pressure difference, whereby volatile components in the supply mix evaporate through the pores (10 nm – 1 μm) and, via diffusion and/or convection of the compartment with high vapour pressure, are transported to the compartment with low vapour pressure where they are condensated in the cold liquid/vapour phase. For supply solutions that only contain non-volatile substances, such as salts, water vapour will be transported through the membrane whereby demineralised water is obtained on the distillation-side and a further concentrated salt flow on the supply-side.

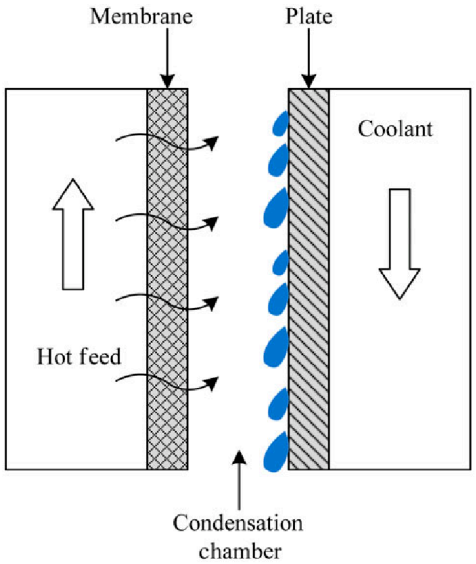


FIGURE 1.1.1 MEMBRANE DISTILLATION

1.2 TYPES OF MEMBRANE DISTILLATION PROCESSES

Many different membrane distillation techniques exist. The difference between these configurations depends on the way in which the vapor is condensed and/or removed from the membrane module. The following technologies are most common:

- Direct Contact MD (DCMD)
- Air Gap MD (AGMD)
- Vacuum MD (VMD)
- Sweeping Gas MD (SWGMD)
- Vacuum multi-effect membrane distillation (V-MEMD)
- Permeate Gap MD (PGMD)

1.2.1 DIRECT CONTACT MD

In DCMD, both sides of the membrane are charged with liquid- hot feed water on the evaporator side and cooled permeate on the permeate side. The condensation of the vapour passing through the membrane happens directly inside the liquid phase at the membrane boundary surface. Since the membrane is the only barrier blocking the mass transport, relatively high surface related permeate flows can be achieved with DCMD.

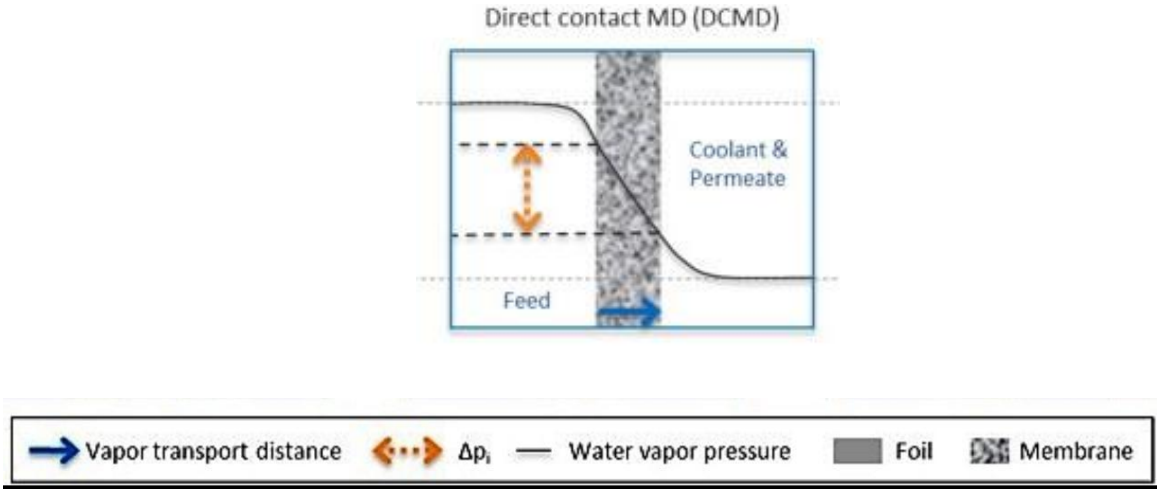


FIGURE 1.2.1.1 DIRECT CONTACT MD

1.2.2 AIR GAP MD

In air-gap MD, the evaporator channel resembles that in DCMD, whereas the permeate gap lies between the membrane and a cooled walling and is filled with air. The vapour passing through the membrane must additionally overcome this air gap before condensing on the cooler surface. The advantage of this method is the high thermal insulation towards the condenser channel, thus minimizing heat conduction losses.

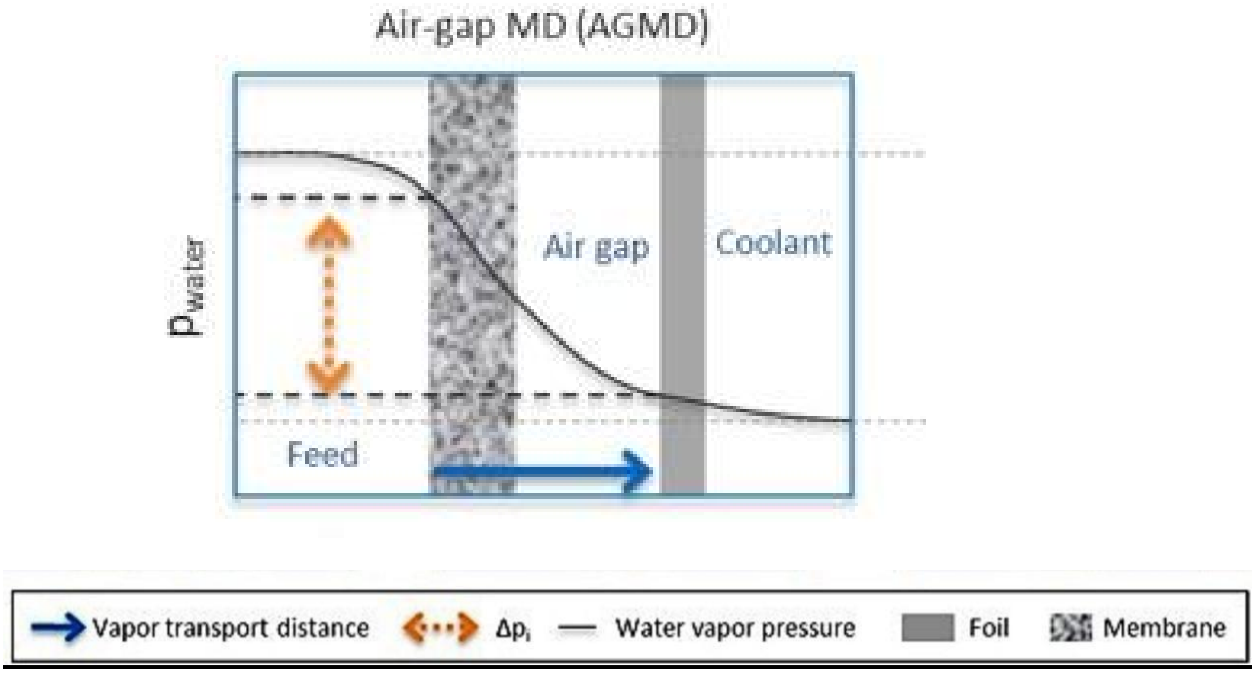


FIGURE 1.2.2.1 AIR GAP MD

1.2.3 SWEEPING GAS MD

Sweeping-gas MD, also known as air stripping, uses a channel configuration with an empty gap on the permeate side. This configuration is the same as in AGMD. Condensation of the vapour takes place outside the MD module in an external condenser. As with AGMD, volatile substances with a low surface tension can be distilled with this process.

1.2.4 VACUUM MULTI-EFFECT MD

The typical vacuum multi-effect membrane distillation module consists of a steam raiser, evaporation–condensation stages, and a condenser. Each stage recovers the heat of condensation, providing a multiple-effect design. Distillate is produced in each evaporation–condensation stage and in the condenser.

1.2.5 PERMEATE GAP MD

Membrane distillation (MD) as a thermally driven process with moderate operating temperatures is a known effective technology for salt-water desalination. In this research, the permeate gap membrane distillation configuration (PGMD), as a novel sustainable MD design having internal heat recovery characteristics, is introduced, designed and the system performance investigated in terms of permeate water flux rate and specific thermal energy consumption (STEC).

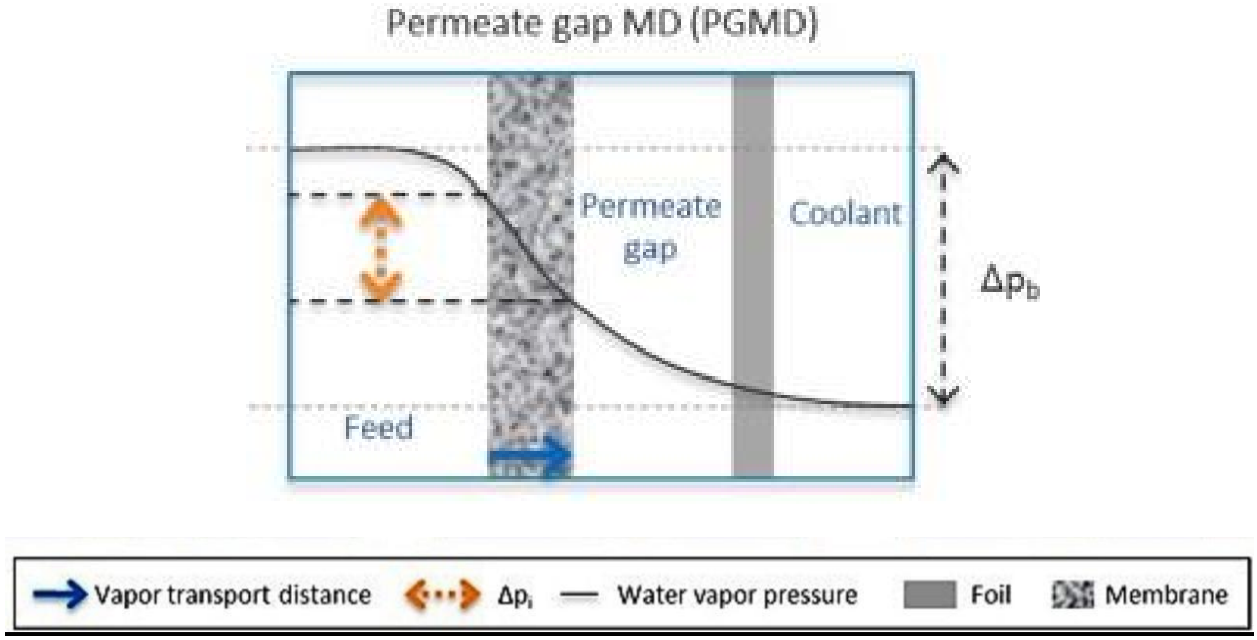


FIGURE 1.2.5.1 PERMEATE GAP MD

1.3 VACUUM MEMBRANE DISTILLATION

Vacuum membrane distillation is a membrane‑based separation process considered here to remove volatile organic compounds from aqueous streams. Microporous hydrophobic membranes are used to separate the aqueous stream from a gas phase kept under vacuum. The evaporation of the liquid stream takes place on one side of the membrane, and mass transfer occurs through the vapor phase inside the membrane.

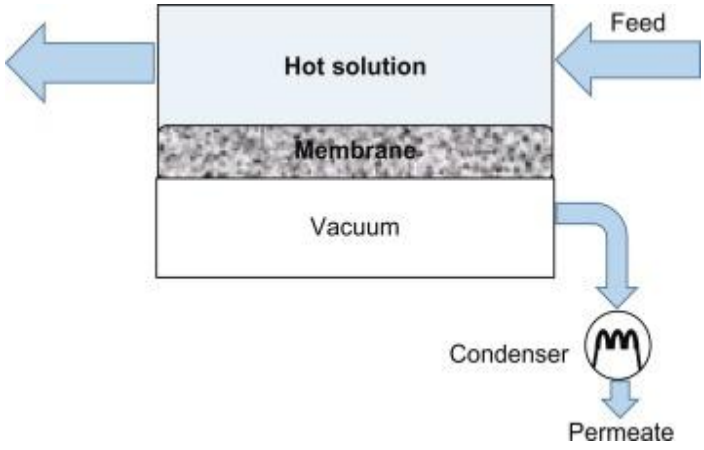


Figure 1.3.1 MEMBRANE DISTILLATION PROCESS

1.4 TOTAL DISSOLVED SOLIDS

Water is a good solvent and picks up impurities easily. Pure water -- tasteless, colorless, and odorless -- is often called the universal solvent. Dissolved solids" refer to any minerals, salts, metals, cations or anions dissolved in water. Total dissolved solids (TDS) comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and some small amounts of organic matter that are dissolved in water.In general, the total dissolved solids concentration is the sum of the cations (positively

charged) and anions (negatively charged) ions in the water. Therefore, the total dissolved solids test provides a qualitative measure of the amount of dissolved ions but does not tell us the nature or ion relationships.

1.5 NEED FOR DESALINATION

Desalination is a water supply option that is used widely around the world and involves taking the salt out of water to make it drinkable. Many countries use desalination as a way of creating a more reliable water supply that is not dependent on rain. With more than 20,000 plants now contracted around the world, desalination is enabling countries to provide water security for future generations amid growing climate concerns. By converting saline water, the process can offer freshwater in areas lacking natural groundwater, or surface water supplies. Together with water reuse, desalination can offer solutions to water scarcity and in some countries, provides over 90 per cent of total water supply. The rapidly growing advance in water reuse, particularly direct and indirect potable reuse of municipal wastewater, uses desalination membrane technology.

Globally, more than 300 million people rely on desalinated water for some or all of their daily needs. In total, desalination is practised in 150 countries around the world with a total of 20,516 desalination plants now contracted.

In the future, the demand for fresh water will increase in tandem with the world's expanding populations. However, available freshwater supplies are in limited supply and poorly distributed. With climate change intensifying droughts and floods, desalination can provide a guaranteed source of potable water from seawater to ensure water supply sufficiently meets water demand. Desalination and water reuse are non-conventional, environmentally sound

water supply solutions in keeping with the circular water economy and offer solutions to water scarcity.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, we discuss the literature survey done to explore more on the different configurations of the VMD process and different energy consumption profiles, also to get a deep knowledge on different case studies done on the topics.

2.2 LITERATURE REGARDING PURIFICATION:

Amr Omar, et al., (2021) gives an overview of the vacuum membrane distillation process. Different configurations for the VMD process were also briefly discussed in this report.

This study reveals that the development of VMD represents a promising direction for thermal desalination technologies, particularly for high saline water applications. Experimental and numerical evaluation of the energy requirement of multi-stage vacuum membrane distillation designs.

P. Wang and T.-S. Chung (2015) This review aims to summarize the recent advances in membrane distillation (MD) and provide perspectives for its future R&D. The development of MD membranes was reviewed from different aspects as material, micro-structure and macro-geometry. The traditional and new configuration designs with improved energy efficiency were summarized.

2.3 LITERATURE REGARDING ENERGY CONSERVATION:

M. A. Eltawil, et al., (2009) gives an overview of how energy is an essential ingredient of socio-economic development and economic growth.

Renewable energy provides a variable and environmentally friendly option and national energy security at a time when decreasing global reserves

of fossil fuels threatens the long-term sustainability of the global economy. The integration of renewable resources in desalination and water purification is becoming increasingly attractive.

2.4 CASE STUDIES:

Chaohuan Yang, et al., (2019) investigated the performance of VMD and AGMD systems for separating water from copper containing solutions. The impacts of various operating parameters and module parameters on VMD performance were studied in terms of permeate flux, rejection rate, total water production, specific thermal energy consumption, pressure drop and thermal efficiency.

M. Sivakumar, et al., (2013) discussed design configuration and demonstrated the response of flux rate to various process operating parameters, including vacuum pressure, feed water temperature, flow rate and feed salinity concentration for mine water treatment. It is concluded that the quality of permeate meets the water quality standards for potable use, but may however, require mineralization efforts before direct human consumption.

Alessandra Criscuoli, et al., (2013) analyzed the potentialities of Vacuum Membrane Distillation for treating water containing arsenic, both in the trivalent and pentavalent form with the aim of producing a purified permeate working at low feed temperatures.

Adnan Alhathal Alanezi, et al., (2016) investigated the performance of O-Ring Vacuum Membrane Distillation for water desalination and interpreted the reason for why low operating temperatures are adequate for the VMD process. He states that there is negligible heat conduction across the membrane module due to a very low pressure (i.e, high vacuum degree) on the permeate side.

CHAPTER 3

METHODOLOGY AND PROGRESSION

3.1 INTRODUCTION

This chapter deals with the methodology which has been adopted to investigate the applicability of vacuum membrane distillation to produce freshwater from various impaired water sources

3.2 EXECUTED METHODOLOGY

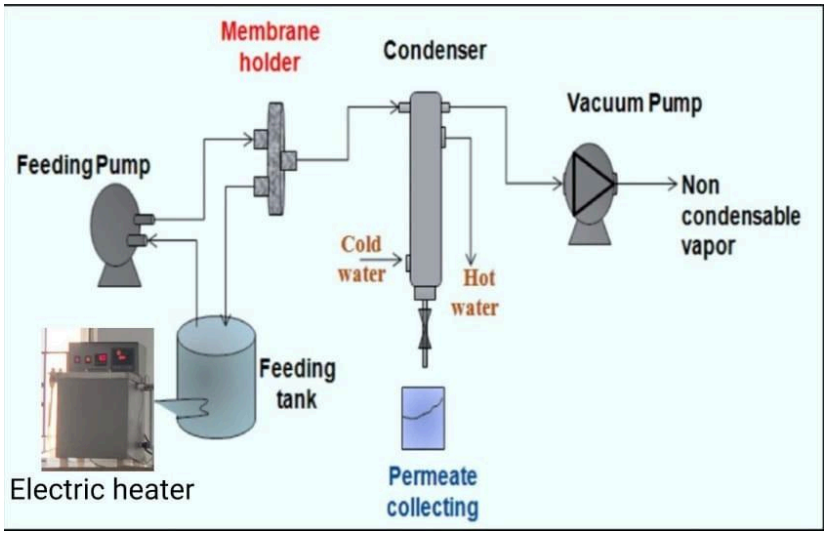


FIGURE 3.2.1 SCHEMATIC DIAGRAM FOR VACUUM MEMBRANE DISTILLATION SYSTEM

The experimental setup comprises a hot side (thermostatic hot water bath, circulating pump, rotor flow meter, thermometer, pressure gauge and control valve) connected to a hydrophobic porous membrane module and in turn a vacuum side (freshwater collection tank, electronic balance, vacuum pump).

The feed solution under investigation is heated using an electric heater provided with a temperature controller to the predetermined temperature, then

it is pumped into the hollow fiber membrane module using the circulating pump after the flow is adjusted by a rotameter .

The membrane is in direct contact with the feed solutions and it acts as a selective barrier between the feed in the liquid phase and the permeate in the vapor phase. The hydrophobic nature of the membrane prevents the water from entering the pores of the membrane and only allows vapor to pass through the membrane.

Therefore, a vapor pressure difference is maintained between both sides of the membrane pores to allow volatile vapor molecules to pass through the VMD and retain non-volatile compounds on the retentate stream. The permeated volatile vapors are then condensed and collected outside the membrane module. The vacuum pump is used to maintain a vacuum on the permeate side of the membrane. The degree of separation is controlled by the membrane and fluid properties.

3.3 COMPONENTS AND SPECIFICATIONS



FIGURE 3.3.1 EXPERIMENTAL SETUP

3.3.1 HEATING UNIT

The hearing unit consists of:

- Water tank
- Water heater
- Circulating pump
- Connecting tubes

The water heater heats up the water in the heating unit's tank. The circulating pump circulates hot water into a jacket around the water tank in the distillation kit through an entry valve. Heat transfer takes place resulting in rise of temperature of feed water.

3.3.2 WATER CIRCULATING PUMP



FIGURE 3.3.2.1 KEMFLO BOOSTER PUMP

We utilized the Kemflo Booster Pump to circulate feed water throughout the machine. This pimp provides a nominal flow rate of 1.8 LPM. The maximum pressure it can handle is 110 PSI and the maximum inlet pressure it can handle is 60 PSI.

3.3.3 HYDROPHOBIC POROUS MEMBRANE

A hydrophobic membrane is used for the separation process. The hydrophobic nature of the membrane prevents penetration of the aqueous solution into the pores, resulting in a vapour–liquid interface at each pore entrance. A vacuum pump is used to impose a pressure difference across the membrane to drive the flux. The membrane is characterized by the following factors:

1. Liquid Entry Pressure (LEP)
2. Porosity
3. Thermal Conductivity
4. Water Contact Angle
5. Membrane thickness

To abstain from membrane wetting, the MD membrane should have three major properties, simultaneously: high water contact angle, high hydrophobicity, and narrow pore size distribution. However, membrane wetting may take place and affect membrane performance when the feed solution is in direct contact with the membrane surface. When the hydraulic transmembrane pressure oversteps LEP, aqueous solution components will prevail over the surface tension and wet membrane pores. Generally, LEP is the maximum pressure value applied onto the feed solution to be treated before the membrane pore wetting happens.

Porosity of MD membranes must be as high as possible until the wetting phenomenon does not occur. Porous surface can lead to higher permeate flux. Generally, the ratio of free volume to total volume of the membrane is called porosity.

Thermal conductivity of MD membranes must be as low as possible. Heat loss in various MD configurations is attributed to the membrane material and existing gases in the membrane pores. Increasing thermal conductivity

could reduce mass flux which is undesirable for MD process. Since the water vapor thermal conductivity is one order of magnitude lower than polymeric materials to be used in MD, increasing membrane surface porosity could lead to heat loss reduction. So, the presence of macrovoids in the membrane surface will result in reducing thermal conductivity.

Tendency of membrane surface to be wetted by liquids is often measured by liquid contact angle analysis. In MD, because water is the major component of the feed solution, water contact angle is calculated for determining surface tendency to water droplets. In this technique, the angle between water droplet and membrane surface is calculated. To minimize the errors of calculation, various locations of membrane surface are selected randomly, and the average contact angle is reported as water contact angle. Due to the lack of time constraint, we were unable to delve into the experimental aspects of water contact angle, porosity, and liquid entry pressure in the VMD process.

The membrane thickness is one of the most effective characteristics on MD membrane performance. The membrane thickness and membrane permeate flux are inversely related to each other. As the membrane becomes thinner, the permeate flux enhances due to the reduction of mass transfer resistance. On the other hand, when the membrane thickness increases, the heat loss decreases. So, there is a trade-off between advantage (lower heat loss) and disadvantage (lower permeate flux) of thicker membranes.

3.3.4 MEMBRANE DISTILLATION KIT

The membrane distillation kit forms the heart of the apparatus. This unit consists of an insulated, jacketed water tank which circulates hot water continuously in order to heat the feed solution under investigation.

The membrane distillation kit consists of:

- Water circulating pump
- Connecting tubes
- 5L water tank
- A series of gauges for changing the different parameters



FIGURE 3.3.4.1 MEMBRANE DISTILLATION KIT



FIGURE 3.3.4.2 MEMBRANE DISTILLATION KIT CONNECTIONS

3.3.5 VACUUM PUMP

The Vacuum pump forms an integral part of the condensing circuit as it provides the necessary suction at the required pressure for the steam to condense into the collector tank. A vacuum pump of the following specifications was used:

MODEL	TID-75-S
FLOW	45 LPM
VACUUM	27” Hg
PRESSURE	55 PSl
TEMPERATURE	55 ℃
CURRENT	0.8 AMPS
SPEED	1440 RPM
MOTOR	¼ HP
VOLTAGE	230 VOLTS

TABLE 3.3.5.1 SPECIFICATIONS OF VACUUM PUMP

3.3.6 CONDENSING UNIT

The condensing unit consists of:

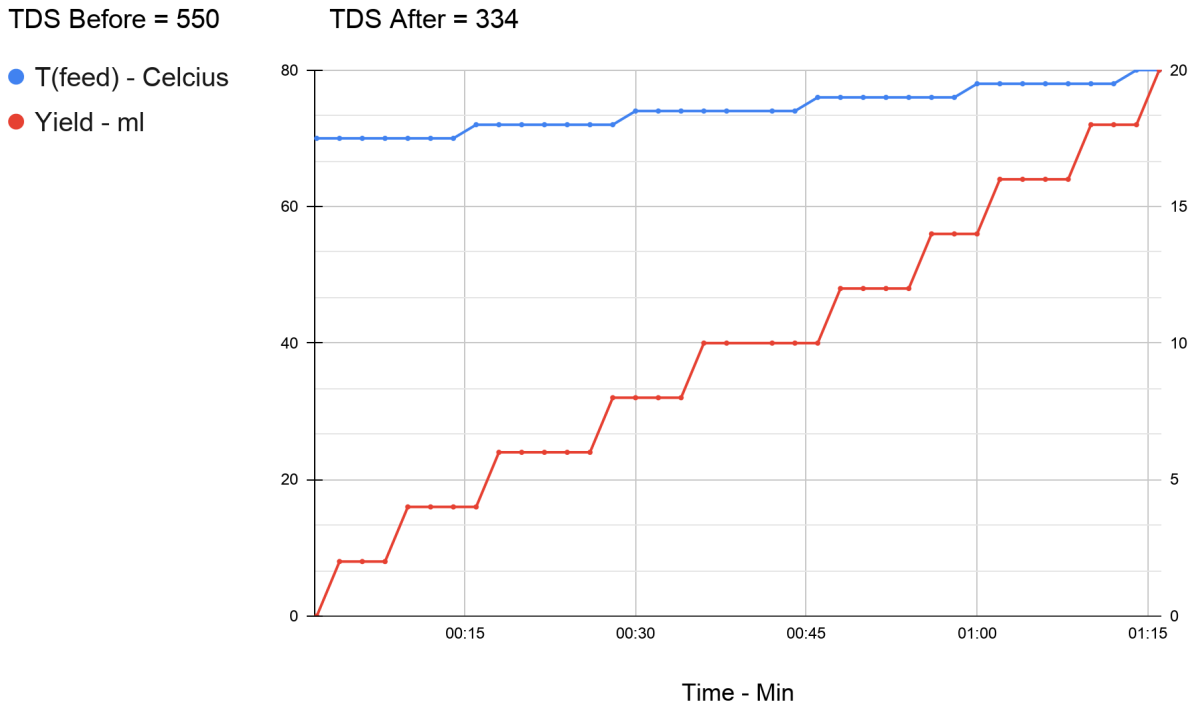
An ice bath: The ice bath is used to bring down the temperature of water vapour for condensation.

A collector unit: The collector unit is placed in the ice bath. The outlet from the membrane and the vacuum pump are connected to the collector unit.

A weighing scale: Both the ice bath and collector unit are kept on a weighing scale to measure the weight of fresh water condensed and collected in the collector unit.

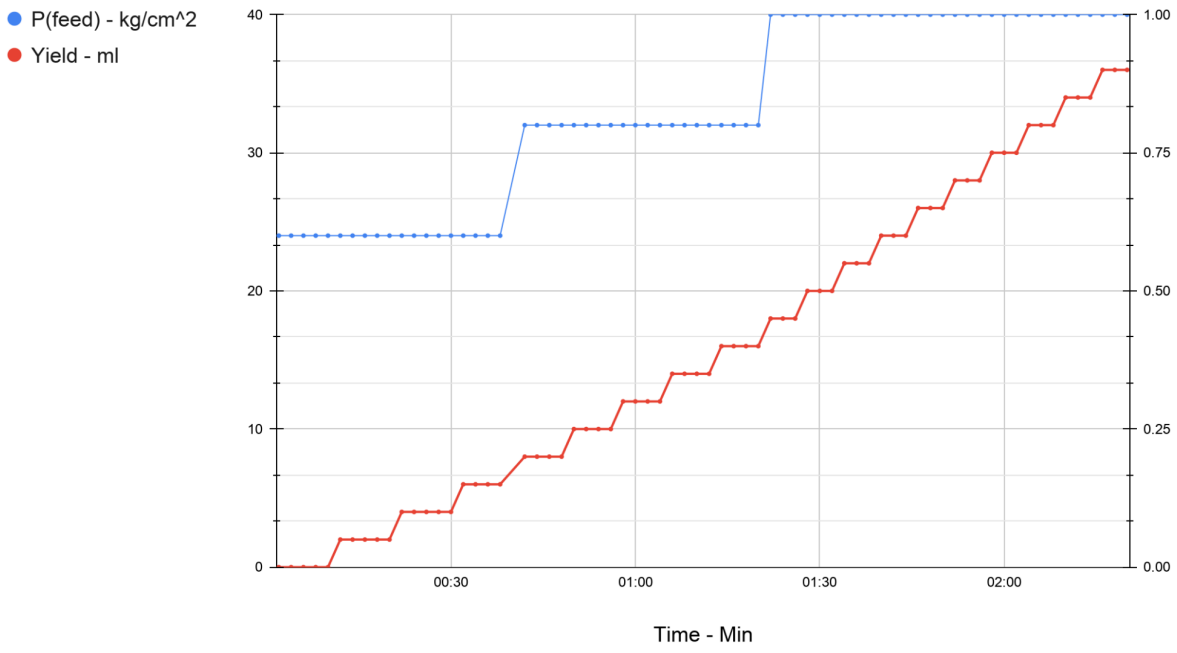
3.4 GRAPHICAL REPRESENTATION

3.4.1 EFFECT OF TEMPERATURE - TAP WATER



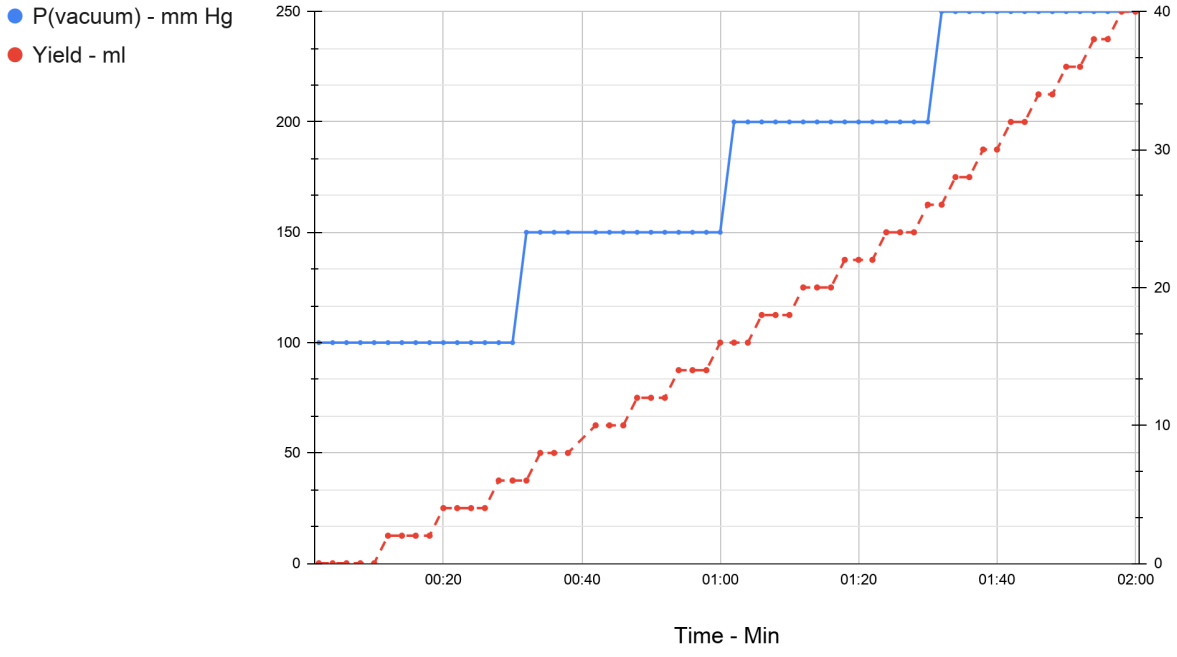
3.4.2 EFFECT OF FEED PRESSURE - TAP WATER

TDS Before = 554 TDS After = 315

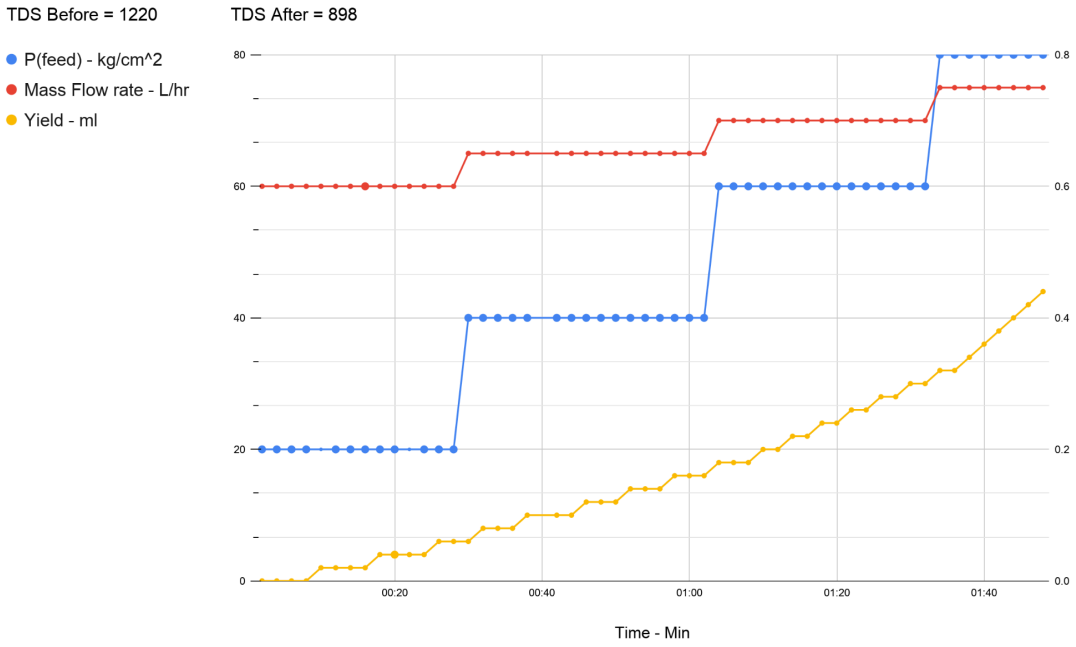


3.4.3 EFFECT OF VACUUM PRESSURE - TAP WATER

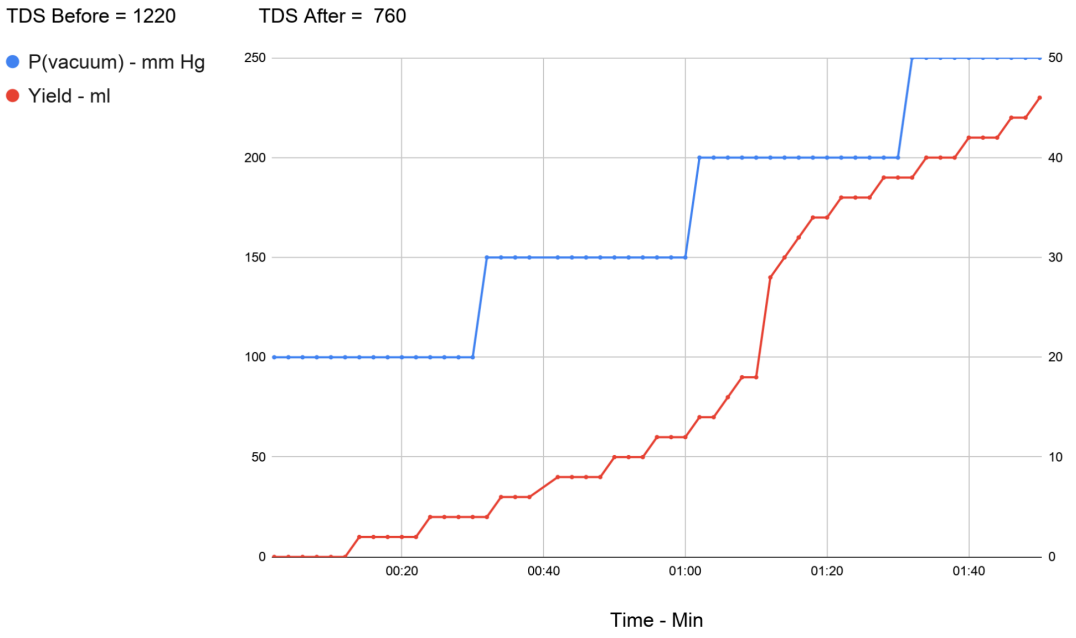
TDS Before = 554 TDS After = 360



3.4.4 EFFECT OF FLOW RATE & FEED PRESSURE - LAUNDRY WASTEWATER

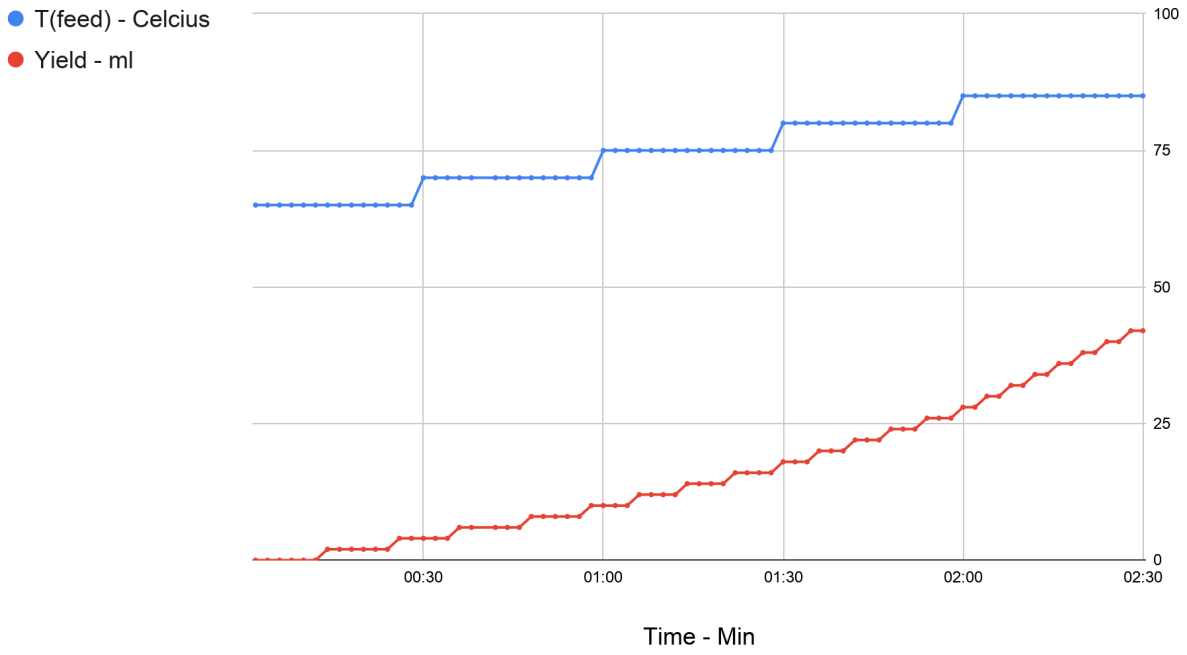


3.4.5 EFFECT OF VACUUM PRESSURE - LAUNDRY WASTEWATER



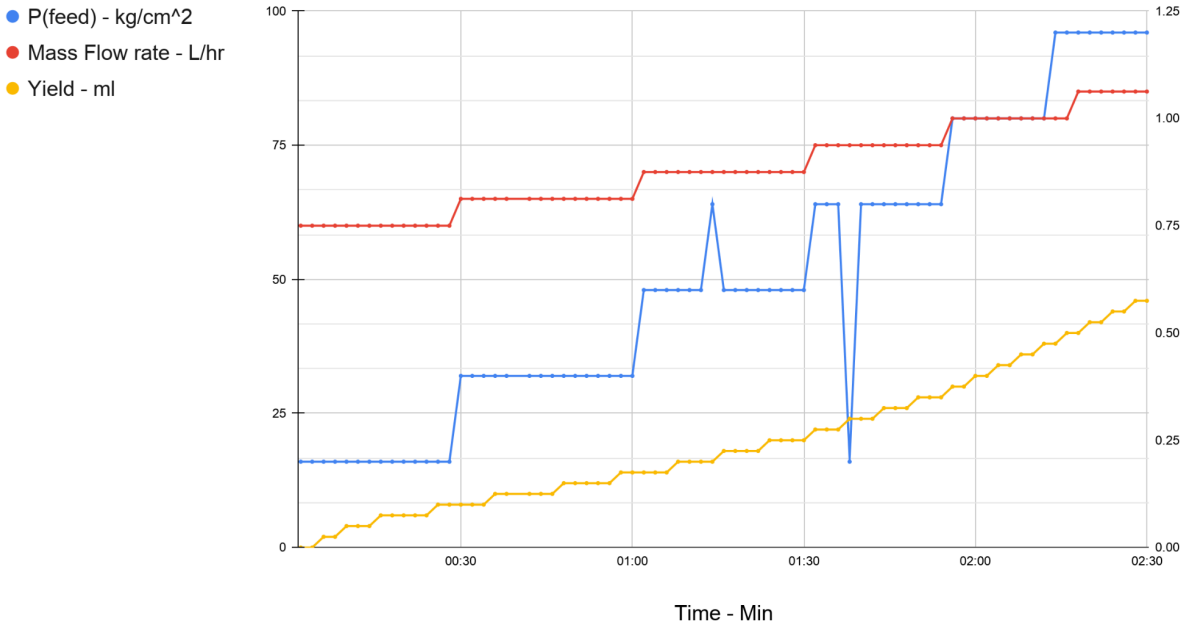
3.4.6 EFFECT OF TEMPERATURE - 0.25M NaCl

TDS Before = 10075 TDS After = 7858.5



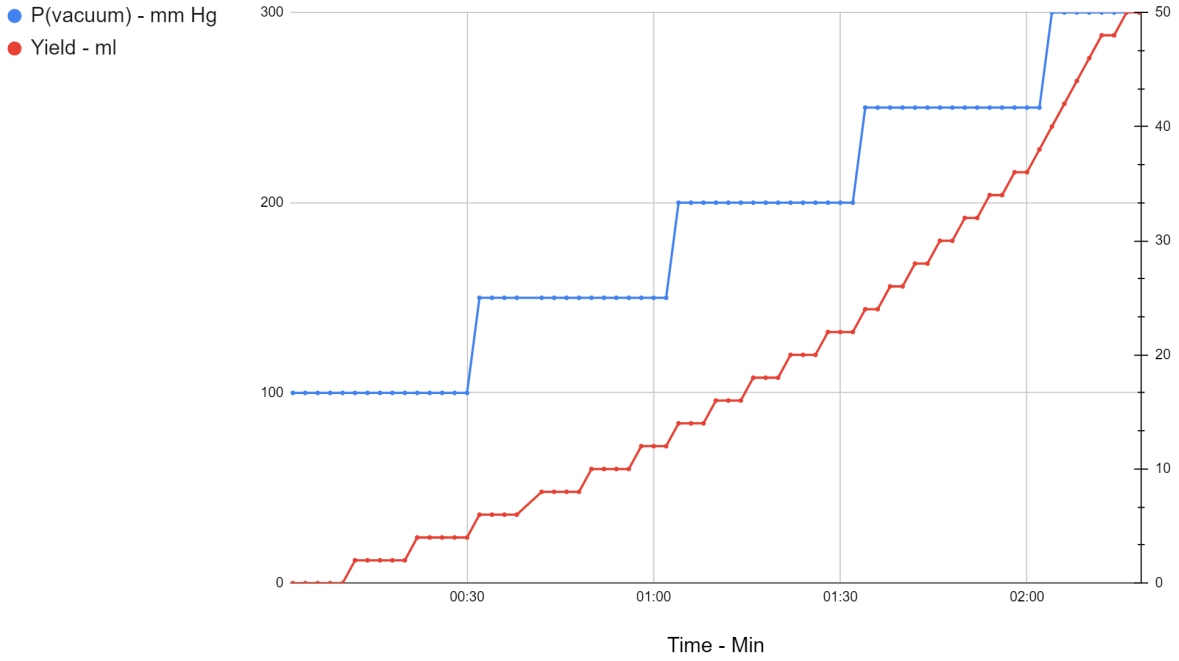
3.4.7 EFFECT OF FLOW RATE & FEED PRESSURE - 0.25M NaCl

TDS Before = 10075 TDS After = 7760.2



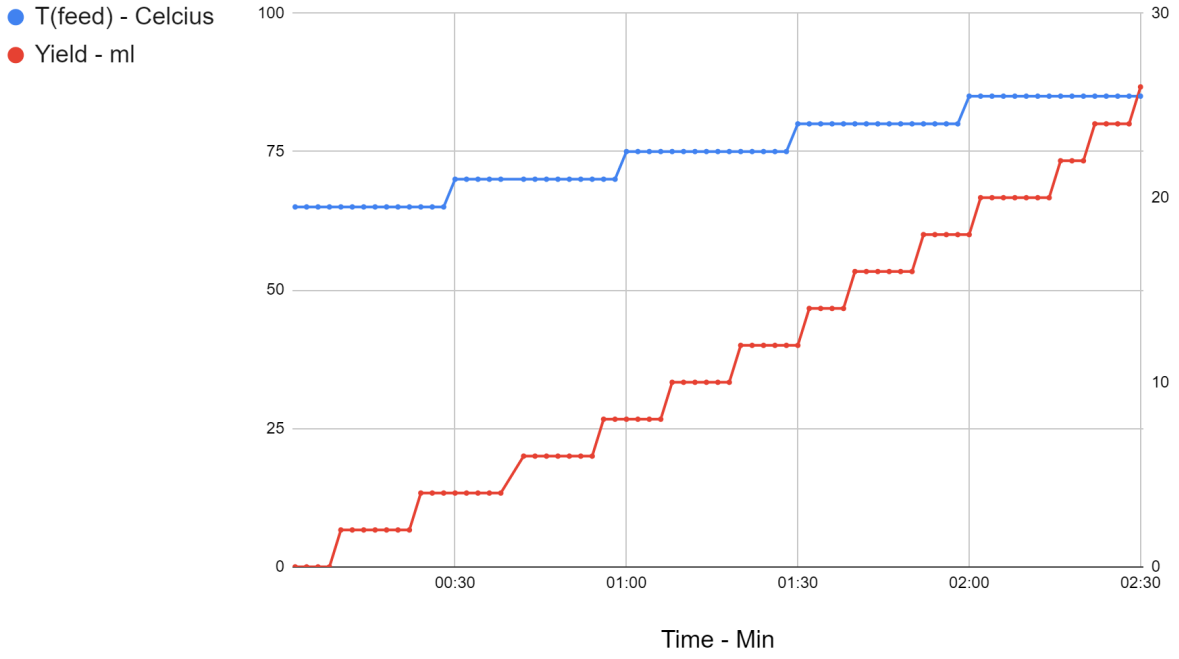
3.4.8 EFFECT OF VACUUM PRESSURE - 0.25M NaCl

TDS Before = 10075 TDS After = 7790.6



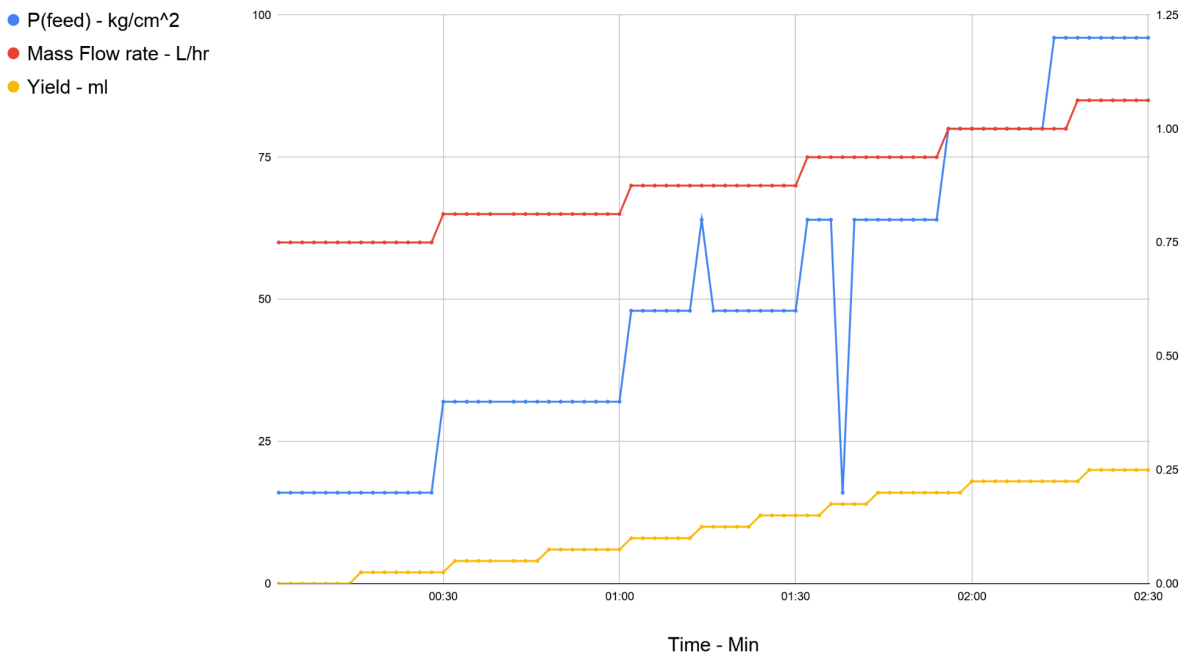
3.4.9 EFFECT OF TEMPERATURE - 0.5M NaCl

TDS Before = 29,786 TDS After = 23,233



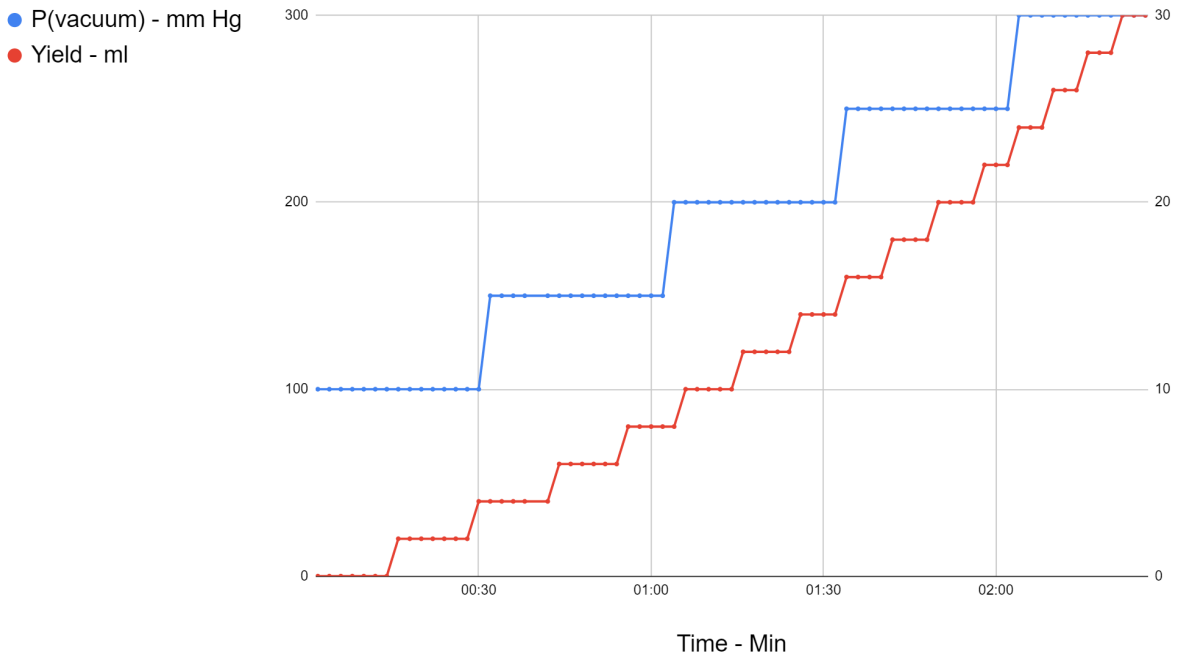
3.4.10 EFFECT OF FLOW RATE & FEED PRESSURE - 0.5M NaCl

TDS Before = 29,786 TDS After = 22,903



3.4.11 EFFECT OF VACUUM PRESSURE - 0.5M NaCl

TDS Before = 29,786 TDS After = 29,396



CHAPTER 4
RESULTS AND DISCUSSION

4.1 WORK DONE

Experiments were carried out by varying the following parameters:

1. Feed solution
    a. Tap Water
    b. Laundry wastewater
    c. Sodium Chloride Solution
2. Feed Concentration
    a. 0.25M Sodium Chloride Solution
    b. 0.5M Sodium Chloride Solution
3. Physical Parameters
    a. Feed Temperature
    b. Feed Pressure
    c. Vacuum Pressure
    d. Flow Rate

Data were collected on individual or various combinations of the above mentioned parameters and further analysed by plotting graphs against the specified parameters.

Total dissolved content (TDS) values of the obtained permeate solutions were measured and compared with those of the corresponding feed solutions.

The readings were analysed to investigate its potential to mass produce on a large scale. The most efficient parameters to obtain flux from the vacuum membrane distillation process were interpreted.

4.1 INTERPRETATION

The efficiency of the process for was affected in the following order of intensity for the mentioned feed solutions:

1. Tap Water:

Feed pressure > Vacuum Pressure > Temperature > Flow Rate

2. Laundry Wastewater:

Flow Rate > Vacuum Pressure > Feed Pressure > Temperature

3. 0.25M NaCl Solution:

Vacuum Pressure > Feed Pressure > Temperature > Flow Rate

4. 0.5M NaCl Solution:

Vacuum Pressure > Feed Pressure > Flow Rate > Temperature

It was observed that the more saline feeds such as the 0.25 and 0.5 molarity sodium chloride salt solutions had the greatest increase in yield due to the effect of pressure. More specifically, vacuum pressure had the greatest impact on solutions of higher dissolved salt content followed by feed pressure that is given to the membrane unit.

The feed with the greater concentration of hard impurities, such as the laundry waste water which had a TDS level of 1220 and impurities visible to the naked eye, yielded the greatest increase in output due to flow rate rather than the effect of pressure. Nevertheless, the effects of pressure were still considerable. This can be deduced to the fact that water needed to be pushed at a more aggressive and faster rate through the membrane pores on account of the impurities which might create a barrier across the microscopic pores.

The effect of temperature and flow rate had the least effect throughout the experimentation process regardless of feed concentration and feed solution except for laundry wastewater. This can be accounted on behalf of the negligible heat conduction across the membrane due to a very low pressure

(i.e, a high vacuum degree) on the permeate side, which is in accordance with the statement of Adnan Alhathal Alanezi et al. [1]

At a feed temperature of 80℃, 0.8 kg/cm^2 feed pressure, flow rate of 80 L/hr and a vacuum pressure of 300 mm Hg, the apparatus yielded 50 millilitres of water in 2 hours and 18 minutes. The graph yielded flux at a rate of 11n ml/hr where n is a positive integer. The VMD process has lesser prospects in the production of freshwater than its potential for treating industrial effluents on an industrial scale.

[1] Authors of a research article who investigated the performance of O-Ring Vacuum Membrane Distillation process.

CHAPTER 5
CONCLUSION

The Vacuum membrane distillation process is potentially a cost-competitive and energy saving membrane separation technology that has its greatest prospects in treating industrial effluents on a large scale. It has the added advantage of being able to desalinate the water at very low hydrostatic pressures in both the boiler as well as the condenser side. Since the membrane module is unaffected by heat conduction, temperatures lower than the boiling point are sufficient to vaporize the feed water. By the use of heat exchangers in industries of high waste heat generation, the VMD process can be reinforced to be extremely low cost as a means for treating effluents from textile, chemical and other industries. This in turn reduces the hardness of water being released into the environment which can be used for agricultural and irrigation purposes.

The VMD process has the ability to harness renewable energy sources such as solar and geothermal energy for heating, circulating and condensing purposes. If the setup is integrated with renewable energy sources or waste heat at low pressures, this process has prospects for being a highly energy efficient method in contributing to solve the fresh water shortage problem, especially in remote areas and advocates for a more environmentally friendly planet.

5.1 APPLICATIONS & FUTURE WORK

VMD is used in environmental, textile, food, pharmaceutical, and nanotechnology industries. Also, VMD can be used as a single-step process or can be combined with other separation techniques as a last stage.

Some applications of VMD are the following:

- Seawater desalination

- Brackish water desalination
- Desalination brine treatment
- Process water treatment
- Water/Groundwater purification
- Removal/Concentration of ammonium

It is especially employed in industrial wastewater treatment including concentration of nonvolatile acids, volatile acid recovery from industrial effluents, salt recovery and textile industry effluents. This process is also used in the preparation of distilled water for medical and pharmaceutical purposes.

The major advantage of vacuum membrane distillation over other conventional processes such as desalination is its lower operating temperature and pressure. This in turn enables the possibility of utilizing renewable energy sources such as solar or geothermal energy to power the process. Waste heat generated from factories and industries can be put to use in this process by the use of heat exchangers.

VMD has its primary prospects in the application of desalinating wastewater which is highly saline and filled with microscopic impurities in a manner suitable for safe discharge into the environment or to produce water that is fit for consumption. The theoretical 82% rejection of nonvolatile solutes, colloids, and biological matters by VMD guarantees the elimination of all unwanted solutes that are often existing in water sources.

The flux produced consists of purified water capable of being reutilized inside the production plant or for agriculture and irrigation purposes. Other positive performances are those related to the treatment of olive mill

wastewaters and the recovery of fully demineralized water starting from brackish waters, seawaters, and reverse osmosis brines

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