Direct Contact Membrane Distillation (DCMD)

A dissertation

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In Partial Fulfillment

of the Requirements for the Degree of

Bachelors of Mechanical Engineering

by

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EXAMINATION COMMITTEE

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ABSTRACT

Direct Contact Membrane Distillation (DCMD) is one of the most commonly used configurations of membrane distillation technology for water desalination. Our project mainly comprised of making a working pilot model of DCMD. It contains two tanks; one for the feed water and the other for permeate water. Feed tank contains the saline water which is pumped into a membrane module for desalination. The membrane module consistsof four aluminum plates with a hydrophobic membrane sandwiched in between them. The membrane doesn’t allow water to pass through it while allows vapors to pass.

One side of the module contains the heated feed water while the other contains the clean distilled water (permeate) separated by the membrane. Permeate water is pumped by a small pump in the membrane module. The vapors from the feed water pass through the membrane and condense to become part of the permeate side.

The membrane module consists of a diffusion chamber engraved in the middle plates with the membrane sandwiched between them held in place by rubber cork, which acts as a sealing gasket as well as helps in keeping the module and membrane in place. The diffusion chamber prevented the water flowing into the module from striking the membrane directly and made the water flow in a laminar fashion across the membrane. This not only increases the membrane life but also provides higher permeate flux at lower temperatures.

PREFACE

Water is used for a lot of purposes; experts suggest that the next war can happen due to the shortage of clean water. Of the many conflicts between Pakistan and India, building of dams in India on the rivers that enter in Pakistan is one of the major dispute. Our project focuses on the treatment of water by a technique known as Direct Contact Membrane Distillation (DCMD). This project explores the cheap and more efficient alternatives of producing clean drinkable water.

Traditionally, reverse osmosis plants are used for the purpose of treating water but because of a huge installation and operational cost it is not widely used in developing countries where the problem is much worse than the rest of the world. DCMD is a cheaper alternative because it has lower power and pressure requirements. When combined with solar heating the electricity costs reduce drastically.

In this project, we have devised such a design of membrane module which increases the life of the membrane which in turns further reduces the costs. As a whole, this project has proposed a very cheap and extremely effective method of treating water.

ACKNOWLEDGMENTS

We are extremely thankful to our supervisor Dr. Muhammad Sajid who guided us from the very start. His invaluable advice and resourceful knowledge helped us to complete this project effectively on time.

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Finally we would like to thank Col. Naveed and his whole staff who helped us in the manufacturing of prototype and other workshop related equipment.

ORIGINALITY REPORT

We hereby declare that no portion of the work of this project or report is a work of plagiarism and the workings and findings have been originally produced. The project has been done under the supervision of Dr. Muhammad Sajid and has not been a support project of any similar work serving towards a similar degree's requirement from any institute. Any reference used in the project has been clearly cited and we take responsibility if found otherwise.

Direct Contact Membrane Distillation

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

DCMD: Direct Contact Membrane Distillation

RO: Reverse Osmosis

HABs: Harmful Algae Blooms

PES: Poly Ether Sulfone

PTFE: Poly Tetra Fluoro Ethylene

NOMENCLATURE

V= volume of permeate sample

A= effective membrane area

T=operating time

C_p= permeate concentration

C_t= feed concentration

xwf = mole fraction of water in feed

xNaCl = mole fraction of NaCl in feed

∝ = ratio of Kundsen to molecular diffusion

∝ = 5 x 10-5(Tf)3– 0.0085(Tf)2 + 0.455(Tf) – 7.05

δ = membrane thickness

ε = membrane porosity

R = universal gas constant

Tm = mean temperature across membrane surface

d_{pore} = pore diameter

Mol_w = molecular weight of water molecules

P = total pressure inside the pore

Dw,a = pressure independent molecular diffusion coefficient of water and air or diffusivity of vapors in air

τ = membrane tortuosity: 1/∈

h_f= connective heat transfer coefficient

T_{mf}=membrane surface temperatures in feed side

T_{mp}= membrane surface temperatures in permeate side

δ = membrane thickness

k_m = effective thermal conductivity of membrane

h_p = convective heat transfer coefficient in permeate side

k = average thermal conductivity of fluid in feed or permeate sides

D_h = the hydraulic diameters of flow channels

Nu = the dimensionless Nusselt number

L = the channel length

v = velocity of the fluid

l = the characteristic length

ν = kinematic viscosity of the fluid

Chapter 1

INTRODUCTION

Background:

Direct Contact Membrane Distillation (DCMD) is a thermal, membrane based separation process [1]. DCMD differs from the other membrane processes such as reverse osmosis in the aspect that the driving force across the membrane is the difference of vapor pressures and the concentration gradient across the membrane surfaces rather than the absolute applied pressure [2].

Membrane distillation was introduced in the 1960s [3]; however it was not commercialized at the time due to unavailability of membranes with the right characteristics to justify its cost. At that time, reverse osmosis (RO) was prevalent and was majorly used for desalination of water.

Need:

Pakistan has an impending water crisis and it is not getting the required attention that it deserves, which will cause problems not only for our generation but for the generations to come. The growing population and diminishing natural water resources estimate that Pakistan will run out of drinking water by the year 2025. Presently 50% of the world's total desalination capacity is based on membrane using the concept of reverse osmosis [4] but this cannot be adopted in Pakistan.

The reasons due to which reverse osmosis cannot be used efficiently in countries like Pakistan is the high feed salinity of the available water bodies and the high brine concentrations that make the membranes susceptible to fouling in the RO process. Secondly, there is a high occurrence of harmful algae blooms (HABs) in the Arabian Sea, our main water source for desalination. These HABs contain high concentrations of toxins that may pass through the membrane in the RO process and can cause illness on drinking and in some cases even death. [5]

Project Definition:

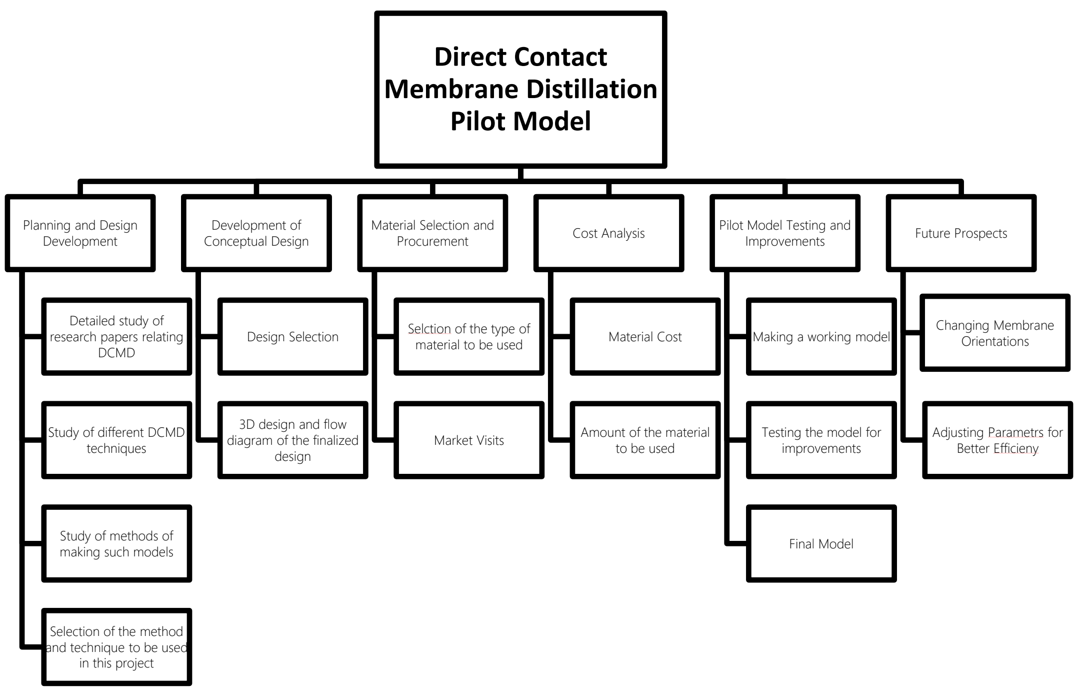
Our project was to design and fabricate a direct contact membrane distillation testing equipment.

Objectives:

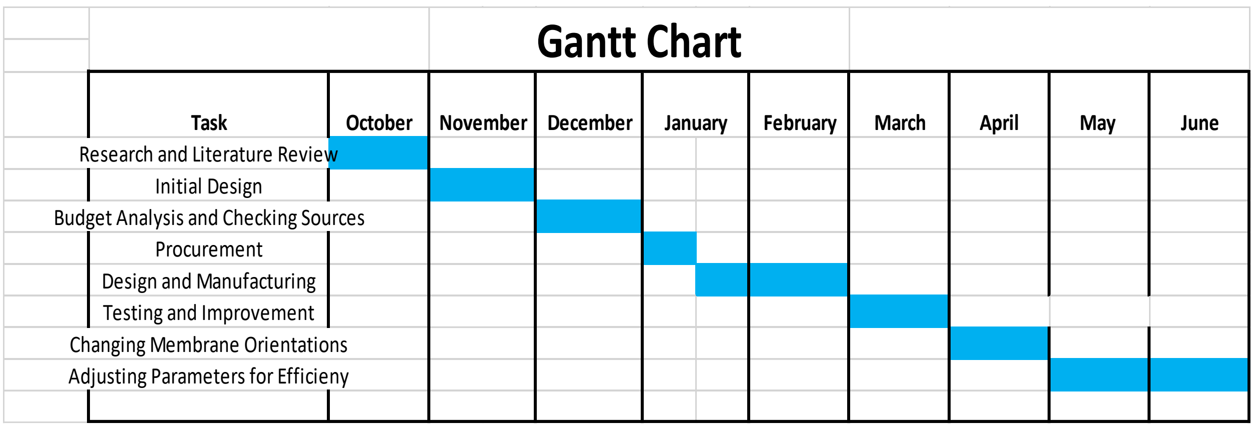
- Provide a cost effective solution to provide fresh water
- Optimum design of direct contact membrane distillation module
- Complete instrumentation of the module
- To study the permeate flux levels
- Comparative study on the permeate flux levels due to change in flow rates,

Project Plan:

Our project consisted of a number of steps which have been broken down into sub tasks as shown in the work breakdown structure.



How the tasks were divided were carried out over the course of the two semesters is shown in the Gantt chart below



Chapter 2

LITERATURE REVIEW

Desalination is being widely considered as a means to obtain fresh water from the sea or brackish water. This is due to the large amount of sea water which is available but cannot be consumed without treatment. This is where desalination comes into play. Different techniques for the treatment of saltwater are used around the world, the most popular of which is reverse osmosis. However, RO processes have already been given much attention and apart from improvements in feed spacer technology, and reduction of membrane fouling, there is little that can be done to further improve the process.

Another process being widely used in the Middle East is Direct contact membrane distillation. DCMD has a higher salt rejection factor (99%) than RO (96%). Having a higher salt rejection factor is essential for filtering water from the Arabian sea as it contains toxins (HABs) which are detrimental to health.

The major portion of power consumed by this process is in the form of heat, which requires an electric heater of 1500 Watts to heat the feed stream to around 70 degrees Celsius. The cost of heating can potentially be removed by introducing solar heating. Through this substitution, DCMD becomes the most cost effective method of large scale desalination.

Factors affecting permeate flux

Permeate flux is the filtrate that has passed from the feed stream to the permeate stream per unit time. The parameters of the experiment are varied one by one to observe the effect they have on the permeate flux.

Temperature difference across membrane:

The main driving force for vapors passing through the membrane is the difference in vapor pressure across the membrane, which is a function of the temperature difference across the membrane. This has been incurred by using a heating element at the feed side to raise its temperature as high as 90 degrees Celsius. The permeate side is incorporated with a cooling bath to reduce its temperature to a minimum value of 5 degrees Celsius. It must be noted however, that increasing the feed stream temperature is more effective in increasing the system flux as compared to decreasing the cold permeate stream temperature. One can report about 35% increase in flux, on average, when reducing permeate temperature from 25 °C to 5 °C, at constant hot feed temperature. On the other hand, increasing the feed temperature from 50 to 90 °C increases the flux by 302% to 560%, depending on the temperature of cold permeate stream. By varying the temperature difference, change in permeate flux is evident.

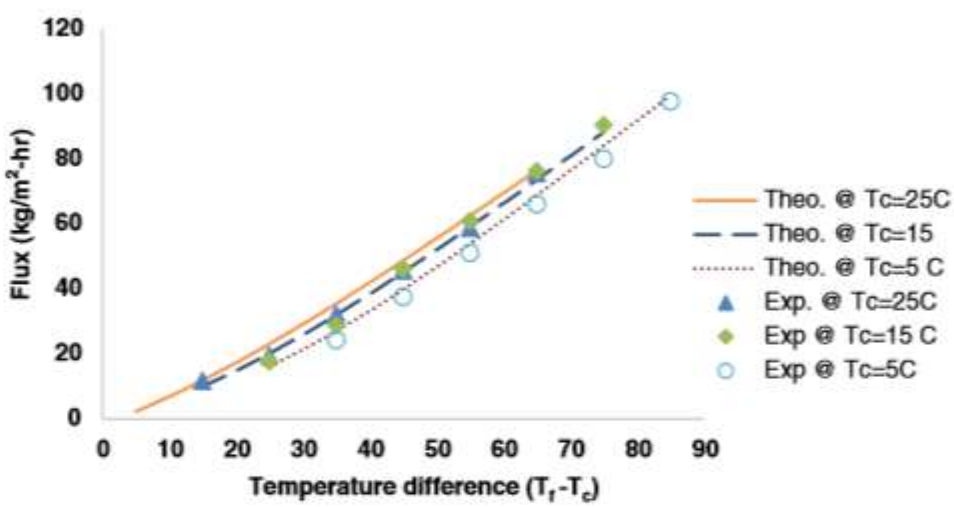


Figure 1: Effect of Operating Temperature Difference on Flux [6]

Feed and permeate volume flow rate:

Feed:

Another factor that affects the rate at which water is filtered is the flow rate of the feed side of the membrane. Although not as pronounced as the difference in permeate flux due to temperature, the effect of flow rate is significant at high temperatures. . For instant, at feed temperature of 90 °C, permeate flux increases from 55 to 72 kg/m2 ·h, by increasing the flow rate from 2.5 to 4.6 L/min, which is about 31% increase.

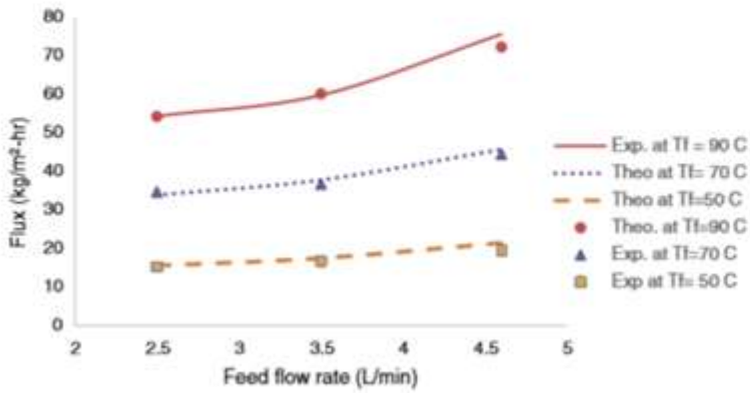


Figure 2: Effect of Feed Flow Rate on Permeate Flux. [6]

Permeate:

The effect of permeate side flow rate on permeate flux is close to negligible; therefore it is not worth increasing the velocity of the fluid for such a small increase of flux. In the figure below it is shown that increasing the coolant flow rate from 2 to 3.65 L/min resulted in only 4.6% increase in permeate flux at feed temperature of 90 °C

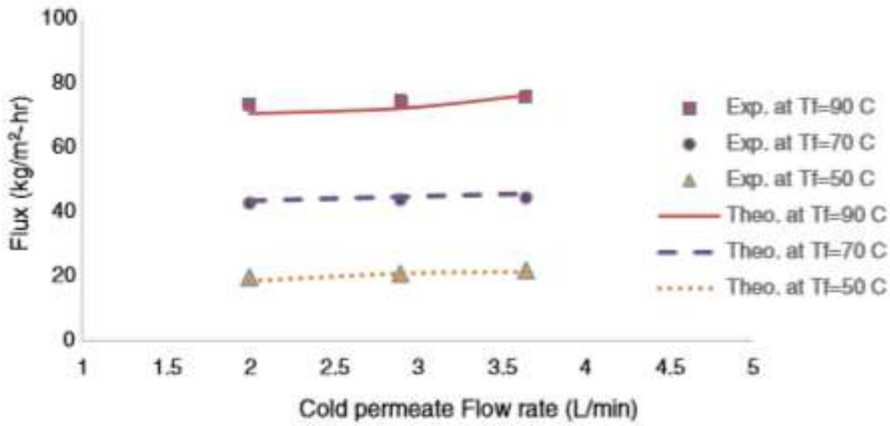


Figure 3: Effect of Cold Permeate Flow Rate on Permeate Flux. [6]

Feed concentration:

The following figure shows that the permeate flux is continuously decreasing as the feed salinity increases. The flux reduction with increasing the feed concentration is mainly due to the increasing effect of the salt concentration polarization, which adds more resistance to vapor permeation across the membrane

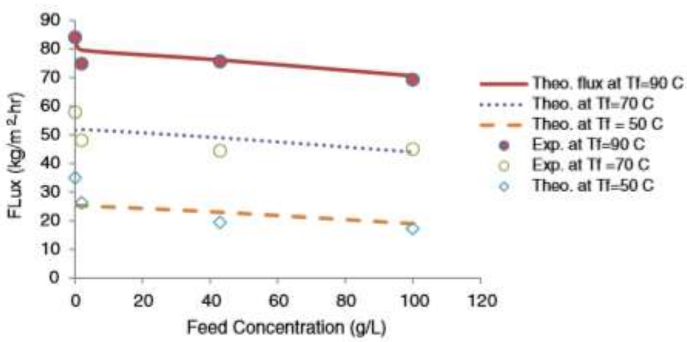


Figure 4: Effect of Feed Concentration on Permeate Flux [6]

Our Project:

The main focus of our project was to set up a pilot model for DCMD, and compare the price of its supply of water to local rates of bottled water. We added a diffusion chamber to the test section, where the membrane is located. By incorporating this feature the water transitions from the pipe to the membrane surface more smoothly. Water is evenly distributed across the membrane as the angular cut section directs the flow of water in a less turbulent manner.

Chapter 3

METHODOLOGY

Flow circuit

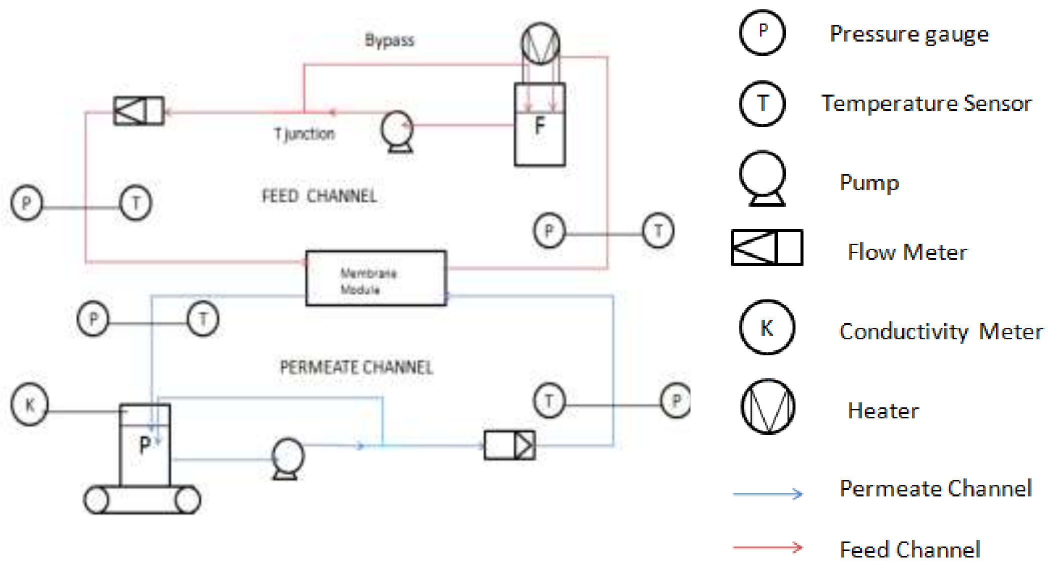


Figure 5: Flow Circuit

Test section design

The membrane size available to us was found to be in accordance with literature review examples. It was small enough for laboratory use, yet large enough to yield results which can provide guidelines for large scale modeling. The membrane was procured from PCSIR Lahore with the specifications provided by us. The requirement of our project was a hydrophobic membrane. The hydrophobic membrane does not allow liquid to pass through it and only vapors can travel through it. This differs from the membrane used in RO process which is hydrophilic in nature in the aspect that it does not allow liquid to pass through. The membrane used in our project is the PES (Polyethersulfone) membrane. Another substitute for this is the PTFE (Polytetraflouroethylene) membrane but PES was easily available to us and was used in our project.

The characteristics of the membrane used are:

Thickness: 259.09 micrometers

Porosity: 69%

Dimensions: 6 x 3 inches.

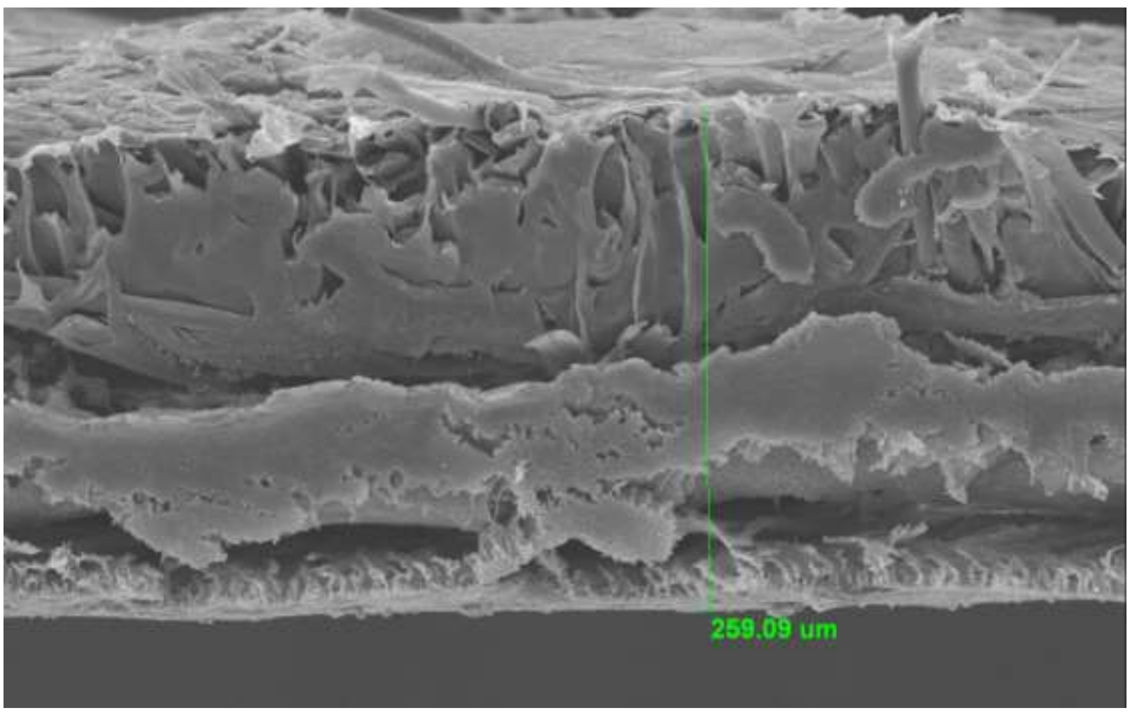


Figure 6: Standard Electron Microscopy of Membrane.

The design for the membrane module was proposed by our supervisor. It included two plates on both ends, two plates in the middle to hold the membrane, and two plates between the end and middle plates which were to have the angular cut section for the diffusion chamber. This configuration consisted of a total of 6 plates.

The material chosen for the plates was aluminum. It has high tensile strength. It is practically rust proof and corrosion resistant owing to the hard, inert coating of Al2O3. The fact that aluminum is rust proof plays a vital role in this experiment as the high salinity of the feed water would have corroded stainless or mild steel much faster. The delicate composition of feed and permeate streams also requires that there must be no added pollutant, such as rust, which may disturb this composition and effect TDS (total dissolved salts) measurement of the streams.

After consulting with our supervisor, we decided to get rid of the extra two plates in between, by incorporating the diffusion chamber into the plates holding the membrane. By doing this the number of plates was reduced to 4, thereby reducing total cost of material used. Another benefit of this modification was that now there were lower chances of leakage in the system.

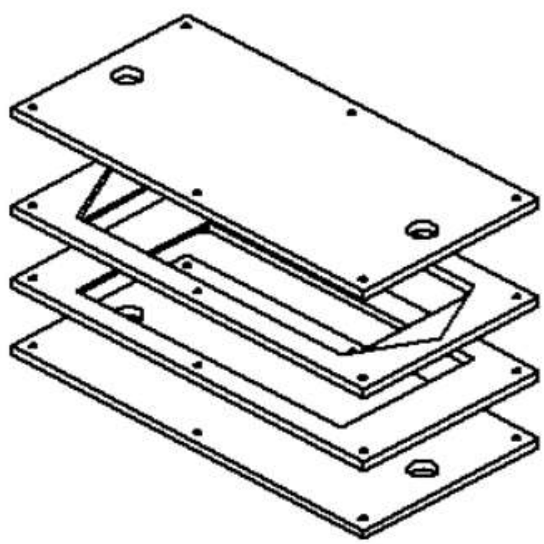


Figure 7: Exploded View of Test Section

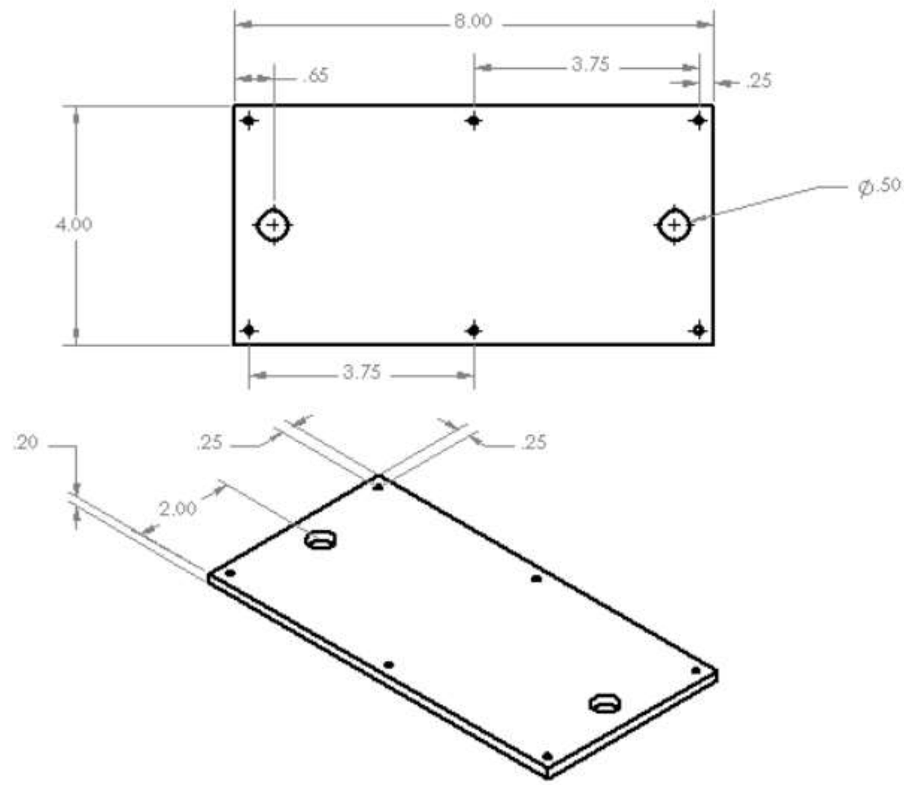


Figure 8: CAD Drawings of Top and Bottom Plate.

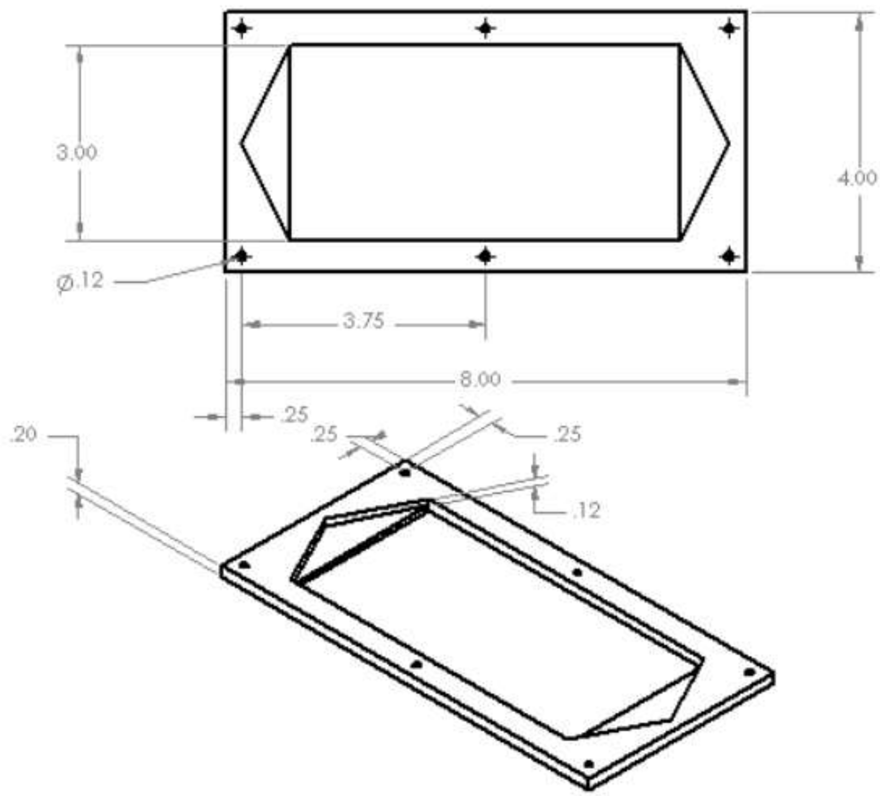


Figure 9: CAD Drawings of Plates with Diffusion Chamber.

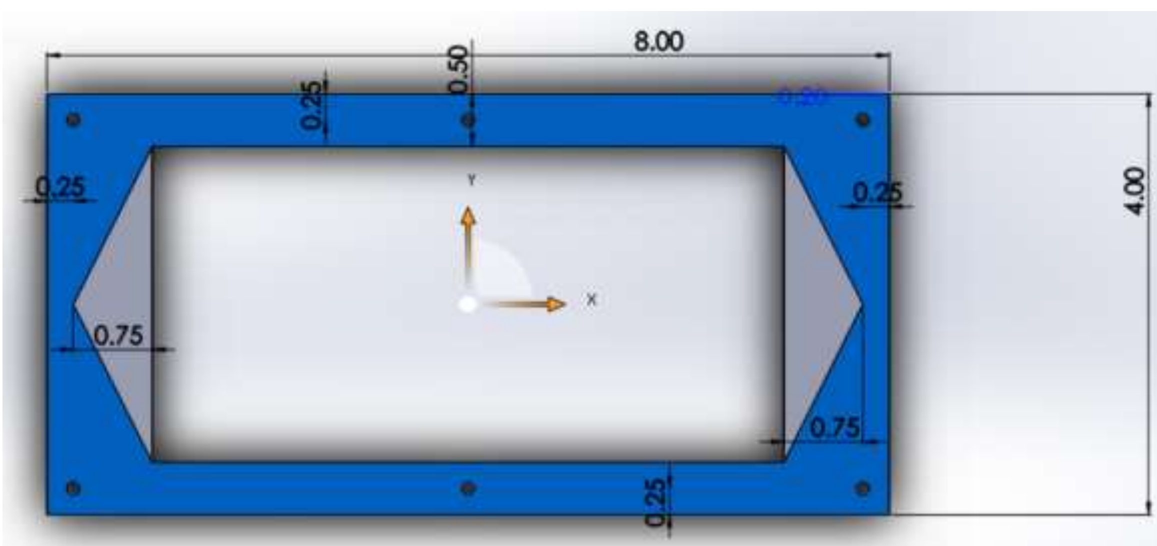


Figure 10: CAD Drawing of Diffusion Chamber.

For prevention of leakage within the module, rubber cork gaskets were used. 4 pieces of 4 mm thickness gaskets were used. Two were placed between the outer and inner plates. the remaining two were sandwiched between the center plates, holding the membrane between them.

All 4 plates and 4 gaskets were drilled with 6 holes at the longer edges; 3 holes on each side. Nuts and bolts were fitted tightly into each hole, holding the test section into place while. However, this arrangement proved inadequate to prevent the leakage of water. Facing this problem we decided to increase the total number of holes to 10, adding 2 on each side of all plates and gaskets. This was finally sufficient to stop the leakage altogether, even with the pumps turned on.

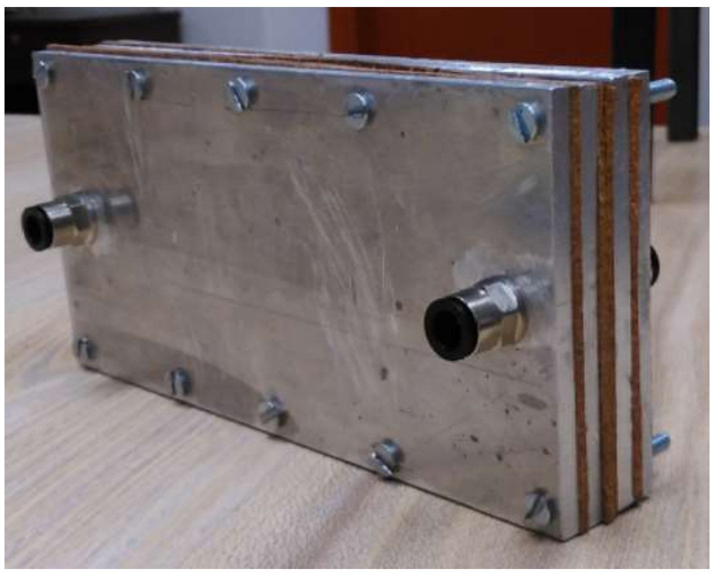


Figure 11: Membrane Module.

The top and bottom plates are drilled with two threaded holes on each plate. These holes are to be fitted with connectors which will be the inlets and outlets of the feed and permeate streams.

Instrumentation:

Instrumentation plays a key role in this project. For monitoring and regulating the parameters affecting the permeate flux, we designed an intricate system which consists of pressure gauges, thermocouples and flow meters, all connected to one LCD, for displaying the measured values.

Pressure gauges:

The pressure gauges are screwed into the cross joints. Teflon tape was wrapped over the threads to prevent leakage. There are four cross joints, two at the inlets, and two at the outlets of the feed and permeate streams. The gauges we are using have a range of 0 – 0.7 bar. The gauge pressure of the feed and permeate streams goes up to a maximum of 0.3 bars with the pumps we are using, which lies well within the gauge range.

Pumps:

We are using two pumps in our system. The larger one being used for the feed stream has a pressure head of 5 meters and power consumption of 10 Watts. This pump provides a maximum flow rate of 10 L/min. The pump being used at the permeate stream has a pressure head of 2 meters, consuming 8 Watts and flow rate of 2 L/min.

Thermocouples:

The same cross joints in which the pressure gauges are fitted, have one K-type thermocouple each screwed into them as well. Sleeves have been specifically designed to fix the thermocouples into the cross joints. The sleeves are Inner and outer threaded to fill the void between the smaller diameter thermocouple and the larger diameter hole of the cross joint. The heating rod that heats up the permeate stream is controlled by the thermocouple at the feed inlet. The thermocouple reads the current temperature before the inlet of the test section. If this temperature is at a lower value than the temperature that is set in the arduino program, the heating coil is consequently turned on using a 5-volt relay connected to the arduino. The heating coil is kept on until the temperature reading of the thermocouple is at a higher value than the one that is set in the program. When this happens the arduino transmits a 'low' signal to the relay which, in turn, switches the heating rod off. This keeps on happening until the temperature variation finally falls within 1 degree Celsius around the set temperature.

In our experiment we have decided to increase the temperature difference by raising the feed stream temperature only. Increasing the temperature difference by reducing the permeate stream temperature consumes a lot of energy. Therefore, it can be said that increasing the feed stream temperature is more effective in increasing the system flux as compared to decreasing the cold permeate stream temperature.

Flow meters:

Two flow meters have been used, one to monitor each of the flow rates at the feed and permeate sides. The flow meters were calibrated through a series of experiments in which a stopwatch was used to measure the time taken for the water to fill a 2 liter beaker. The initial error of the flow meters was calculated this way. Values were rectified using correction factors known as K and M-factors.

Arduino settings:

The programming for data acquisition of temperature and flow rate was relatively simple using the "Arduino MEGA". The temperature control for the heating rod was done using a simple "if "command.

What we found a bit challenging was to connect 4 thermocouples and 2 flow meters, all on one arduino board. This however was managed by searching for the correct libraries to be downloaded.

Libraries

- #include <LiquidCrystal.h> // for LCD display
- #include <SPI.h> // for multiple thermocouple connections
- #include <Thermocouple.h> // thermocouple library
- #include <FlowMeter.h> // flow meter library

Digital mass balance:

Using this balance at the permeate stream allows us to measure the mass of water added to the cold permeate side. Using the density of water lets us calculate the volume of water that has been distilled through the membrane. If the time is measured during this process, the permeate flux can also be calculated.

TDS (total dissolved solids) meter:

This device is able to read the temperature and TDS in ppm (parts per million), of a fluid. The temperature range is from 0-100 degrees Celsius. The range of TDS in ppm is 0-9900ppm. 9900ppm is equal to 11.5g of salt per liter of water, which is close to the composition of brackish water (10g/L).

By measuring the TDS of the permeate stream and feed stream before and after running he experiment, the SRF (salt rejection factor) of the process can be calculated. This can also tell us the quality of the water, for example, whether or not it is fit for consumption.

Operating parameters:

Table 1: Components and Their Specifications

Component Name	**Specifications**
Membrane	Polyethersulphone(PES, 69%porosity)
Module plates	Aluminum
Gaskets	Rubber cork
Pressure Gauges	0.0 to 0.7 bar
Feed Pump	10 liters/min (5 meters head)
Permeate Pump	2 liters/min (2 meters head)
Temperature Sensor	K type Thermocouple (-270 to 1260 ℃)
Conductivity Meter	0 to 9,900 microsiemens/cm
Flow Meter	0.3 to 6 liters/minute

Mathematical modeling

Three main models of transfer mechanism across the membrane:

1. Mass transfer
2. Momentum transfer
3. Energy transfer

Mass transfer takes place through the membrane layer. Momentum transfer takes place in the feed and permeate channel while the energy transfer takes place in all three. However, in our study we will only be focusing on the mass transfer mechanism because our main aim is to calculate the flux through the membrane, and this will help us do just that.

Three basic diffusion models for mass transfer across membrane:

1) Knudsen diffusion model
2) Poiseuille flow model
3) Molecular diffusion model

The detailed derivation of equations is given in the appendix.

Chapter 4

RESULTS

Theoretical:

Mass flux:

Porosity

$$\text{Porosity} = \frac{\text{Total Volume} - \text{Volume of Solid}}{\text{Total Volume}} \qquad \text{Equation 1}$$

Membrane Dimensions = 2cm by 2cm

Membrane Thickness = 259.09 μm

ρ_{PES} = 1.37 g/cm^3

Dry Weight = 0.044 grams

Total Volume = 0.103636 cm^3

Volume of Solid = 0.0321167883 cm^3

Porosity = 69%

Calculation of heat transfer coefficient For 70 ^oC feed stream:

$$Pr = \frac{\text{Dynamic viscosity} \times \text{Specific Heat}}{\text{Thermal Conductivity}}$$

$$Pr = \frac{(0.404\times10^{-3})\times4189.5}{0.6631} = 2.5525$$

$$\dot{m} = \Delta A v \qquad \text{Equation 2}$$

Rearranging it,

$$v = \frac{\dot{V}}{A} = \frac{2.933\times10^{-5}}{7.62\times10^{-4}} = 0.0385 \text{ m/s}$$

$$R_e = \frac{\text{Velocity} \times \text{Length of Channel}}{\text{Kinematic Viscosity}}$$

$$R_e = \frac{0.0385 \times 0.1524}{0.413 \times 10^{-6}} = 14206.78$$

$$N_{uf} = \frac{(2.5525 \times 14206.78 \times 0.01768)^{0.33}}{0.1524} \times 1.86 = 29.202$$

$$h_f = \frac{29.202 \times 0.6631}{0.01768} = 1095.26$$

Calculation of heat transfer coefficient For 30 ºC permeate stream:

$$Pr = \frac{(0.798 \times 10^{-3}) \times 4178.4}{0.6154} = 5.4182$$

$$\dot{m} = \Delta A v$$

Rearranging it,

$$v = \frac{\dot{V}}{A} = \frac{2.5833 \times 10^{-5}}{7.62 \times 10^{-4}} = 0.0339 \text{ m/s}$$

$$R_e = \frac{0.0339 \times 0.1524}{0.801 \times 10^{-6}} = 6449.89$$

$$N_{up} = \frac{(5.4182 \times 6449.89 \times 0.01768)^{0.33}}{0.1524} \times 1.86 = 28.848$$

$$h_p = \frac{28.848 \times 0.6154}{0.01768} = 1004.15$$

Calculation for thermal coefficient k_m :

$$k_m = \left(\frac{0.69}{0.016} + \left(\frac{1-0.69}{0.16287}\right)\right)^{-1} = 0.022$$

T_{mf} and T_{mp} can now be calculated using the iterative process described in the appendix

Experimental:

By varying the feed stream temperature we were able to obtain favorable results for the corresponding permeate flux. In agreement with past experiments it was observed that the permeate flux not only significantly increased by increasing the temperature, but the diffusion chamber also played a key role in increasing the flux.

In the current experiment the following parameters were kept constant:

- Membrane size = 3in x 6in
- Feed flow rate = 1.83 L/min
- Permeate flow rate = 1.58 L/min

Three experiments were conducted with the temperature set at 50, 60, and 70 degrees Celsius.

Table 2: Temperature and corresponding Permeate flux readings

Temperature (C)	**Flow Rate (l/hr)**
50	0.882
60	0.984
70	1.2
80	1.359
90	1.518

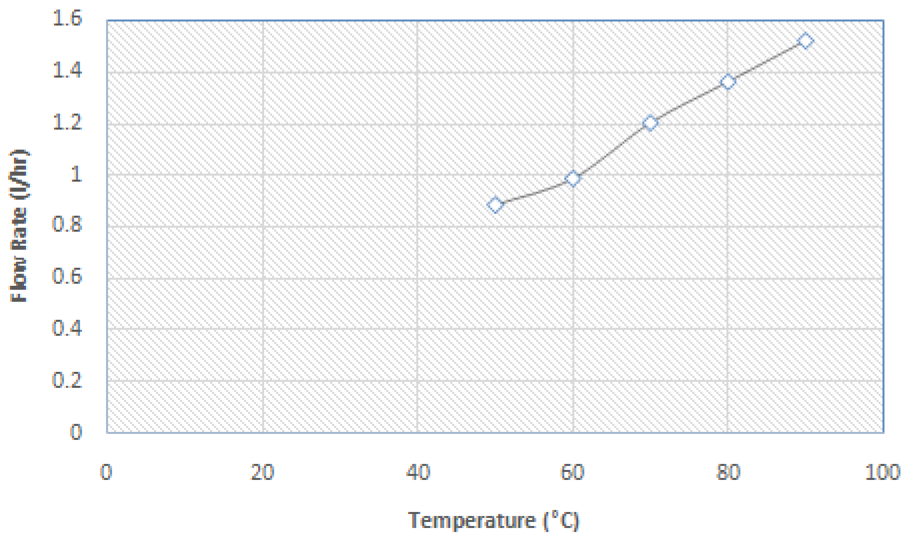


Figure 12: Temperature versus Permeate Flux Plot.

Chapter 5

CONCLUSION:

To determine the feasibility of our DCMD setup, we decided to compare the cost per liter of the plant's production of water to normal bottled water.

The bottled water chosen for comparison is NESTLE`. Its cost and TDS properties are as follows:

- Cost per liter: Rs 13.16
- Total dissolved solids: 50 – 86 ppm

DCMD pilot model produces 1 liter of water in 50 minutes when the feed temperature is set to 70 degrees Celsius. Under these operating conditions the 1.5kW heater runs for 30 minutes while the two pumps totaling 20W run for 50 minutes. The rate of electricity is taken to be Rs 11.50 taking into account the peak and off peak hours. Cost of electricity consumed by heater is Rs 8.63, while the cost incurred by the pumps is a meager Rs 0.19. This adds up to a total of Rs 8.82 to produce 1 liter of water. The TDS for this water is 120 ppm, which is higher than that of NESTLE`, but still well within acceptable limits of Pakistan Standards Quality Control Authority, which requires drinking water to have less than 1000 ppm per liter.

Table 3: Comparison between Nestle water bottle and DCMD

	NESTLE`	DCMD
Cost(Rs)/ Liter	13.16	8.82
TDS (ppm)	50-86	120

On the face of it, DCMD looks like the much more favorable option. However, there are other costs which have not been taken into account for the production of water through DCMD. This includes the total cost to setup the model which is close to Rs20000. Another factor that has been overlooked in these calculations is the cost of membrane which will need to be eventually replaced. Although the membrane can be used for up to 40 hours, even after which it can be reused once it has been backwashed to remove fouling, the fact stands that membranes are not easily available and are quite costly.

Recommendations:

DCMD can be made even more cost effective with the introduction of solar heating. As mentioned before, the main cost was incurred by the heating element which accounts for almost 97% of the cost of producing water by DCMD. If this is replaced by solar heaters, such as parabolic trough collectors, DCMD can bring a revolutionary change to combat water shortage in countries which get a lot of sun for solar heating.

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Appendix 1

Mathematical Equations

Mass flux (permeate):

$J_w = D_e \times \Delta p = D_e \times (P_{wf}^0 - P_{wp}^0)$ Equation 3

Antoinne `D equation to calculate saturated pressure:

$P_{wf}^0 = \exp(23.1964 - \frac{3816.44}{Tf - 46.13})$ Equation 4

$P_{wp}^0 = \exp(23.1964 - \frac{3816.44}{Tp - 46.13})$

Considering the effect of salinity:

$J_w = D_e \text{ x } (P_{wf}^0 . \gamma_{wf} . x_{wf} - P_{wp}^0)$ Equation 5

$\gamma_{wf} = 1 - (0.5 \text{x } x_{NaCl}) - (10 . x_{NaCl}^2)$

x_{wf}= mole fraction of water in feed

x_{NaCl}= mole fraction of NaCl in feed

Kundsen Coefficient:

$D_k = ((\frac{3 * \delta * \tau}{2 * \varepsilon * dpore}) \text{x} (\frac{\pi R \overset{m}{T}}{8 Molw})^{0.5})^{-1}$ Equation 6

Poiseuille Coefficient:

$D_m = (\frac{RT\delta\tau Pair,pore}{Molw.\varepsilon.PDw,a})^{-1}$ Equation 7

D_e has the combined effect of D_k and D_m:

$D_e = ((\frac{\propto}{Dk}) + (\frac{1-\propto}{Dm}))^{-1}$ Equation 8

$\propto$ = ratio of Kundsen to molecular diffusion

δ = membrane thickness

ε = membrane porosity

R = universal gas constant

T_m = mean temperature across membrane surface

d_{pore}= pore diameter

Mol_w= molecular weight of water molecules

P = total pressure inside the pore

$D_{w,a}$= pressure independent molecular diffusion coefficient of water and air or diffusivity of vapors in air

τ = membrane tortuosity: $\frac{1}{\epsilon}$

$PD_{w,a}$= 1.895 x 10^{-5} . $T_m^{2.072}$

P_{pore}= $\frac{Pf+Pp}{2}$

$P_{air,pore}$= P_{pore}– $P_{w,r,p}$

Calculate using Antoinne `D equation by putting T as T_m=$\frac{Tmf+Tmp}{2}$

Calculation of T_{mf} and T_{mp}

Where, T_{mf} and T_{mp} are membrane surface temperatures in feed and permeate side respectively

The temperatures of the membrane surfaces at feed and permeate sides are calculated as,

$$T_{mf} = \frac{Km*\left(Tbp+\frac{hf}{hp}*Tbf\right)+((\delta*(hf*Tbf-Jw*\Delta Hv)))}{(km)+(hf*\left(\delta+\frac{km}{hp}\right))} \qquad \text{Equation 9}$$

$$T_{mp} = \frac{Km*\left(Tbf+\frac{hp}{hf}*Tbp\right)+((\delta*(hb*Tbp+Jw*\Delta Hv)))}{(km)+(hp*\left(\delta+\frac{km}{hf}\right))} \qquad \text{Equation 10}$$

T_{bp} is the permeate stream temperature

T_{bf} is the feed stream temperature

h_p is the convective heat transfer coefficient in permeate side

h_f is the convective heat transfer coefficient in feed side

k_m is effectivethermal conductivity of membrane

$$k_m = ((\frac{\varepsilon}{Kgas}) + (\frac{1-\varepsilon}{Kmem}))^{-1} \qquad \text{Equation 11}$$

$$\Delta H_v = ((1.7535 \text{ x } T_{mf}) + 2024.3) \qquad \text{Equation 12}$$

By definition, the convective heat transfer coefficient is calculated as:

$$h = \frac{Nu*k}{Dh} \qquad \text{Equation 13}$$

k is the average thermal conductivity of fluid in feed or permeate sides

D_h is the hydraulic diameters of flow channels

N_u is the dimensionless Nusselt number.

In case of laminar channel flow, Graetz-Lévéque proposed the following correlation for Nusselt Number, which is valid for flows in both feed and permeate sides:

$N_u = 1.86 * (\frac{Re*Pr*Dh}{L})^{0.33}$ Equation 14

where, D_h is the channel hydraulic diameter

L is the channel length

And Pris Prandtl number; which is the ratio of viscous diffusion rate to thermal diffusion rate and is defined as;

$Pr = \frac{\nu}{\alpha} = \frac{\mu*cp}{k}$ Equation 15

$Re = \frac{vl}{\nu}$ Equation 16

Where, v = velocity of the fluid

l = the characteristic length

ν = kinematic viscosity of the fluid

This is an iterative process. Initial values of T_{mf} and T_{mp} are predicted. These values are plugged into the equations 2, 4 and 5 to solve for the permeate flux. Once the flux is calculated its value is inserted into equations 7 and 8 to calculate the new values of T_{mf} and T_{mp}. This process goes on until the values of temperature converge to a reasonable variation. The final values of temperature are then used to calculate the theoretical permeate mass flux of the system

Appendix 2

Arduino codes

```
#include <LiquidCrystal.h>

// initialize the library with the numbers of the interface pins

LiquidCrystal lcd(13, 12, 11, 10, 9, 8);

#include <SPI.h>                //http://arduino.cc/en/Reference/SPI

#include <Thermocouple.h>       //http://github.com/JChristensen/Thermocouple

//MAX6675 SPI pin definitions

#define csTC1  22                 //chip select for MAX6675 #1

#define csTC2  4              //chip select for MAX6675 #2

#define csTC3  5               //chip select for MAX6675 #1

#define csTC4  6              //chip select for MAX6675 #2

//Additionally, connect the MAX6675s as follows:

//MISO  Arduino pin 12          //master in slave out

//SCK   Arduino pin 13          //serial clock

Thermocouple tc1 = Thermocouple(csTC1);    //instantiate the thermocouple objects

Thermocouple tc2 = Thermocouple(csTC2);

Thermocouple tc3 = Thermocouple(csTC3);

Thermocouple tc4 = Thermocouple(csTC4);

  #include <FlowMeter.h>     // https://github.com/sekdiy/FlowMeter

int vccPin = 9;

int gndPin = 8;
```

```
FlowSensorProperties MySensor = {6.0f, 73.0f, {1.11708, 0.885567, 0.88277, 0.8550,
0.8019, 0.7783, 0.7547, 0.7312, 0.7076, 0.6840}};

FlowSensorProperties MySensor2 = {6.0f, 73.0f, {1.11708, 0.885567, 0.88277, 0.8550,
0.8019, 0.7783, 0.7547, 0.7312, 0.7076, 0.6840}};

FlowMeter Meter = FlowMeter(3, MySensor);

FlowMeter Meter2 = FlowMeter(2, MySensor2);

long period = 1000;   // one second (in milliseconds)

long lastTime = 0;

// define an 'interrupt service handler' (ISR) for every interrupt pin you use

void MeterISR() {

  // let our flow meter count the pulses

  Meter.count();

}

  // define an 'interrupt service handler' (ISR) for every interrupt pin you use

void Meter2ISR() {

  // let our flow meter count the pulses

  Meter2.count();

}

const int analogPin = A0;    // pin that the sensor is attached to

const int relay = 40;

const int threshold = 35    ;
```

```
void setup() {
 // initialize the LED pin as an output:
  pinMode(relay, OUTPUT);
  // initialize serial communications:
  Serial.begin(9600);
  // set up the LCD's number of columns and rows:
  lcd.begin(16, 2);
 Serial.begin(115200);       //initialize Serial
  Serial.begin(9600);
     pinMode(vccPin, OUTPUT); digitalWrite(vccPin, HIGH);
  pinMode(gndPin, OUTPUT); digitalWrite(gndPin, LOW);
  delay(500);
    // enable a call to the 'interrupt service handler' (ISR) on every rising edge at the
interrupt pin
    attachInterrupt(INT0 , MeterISR, RISING);
    // sometimes initializing the gear generates some pulses that we should ignore
    Meter.reset();
    Serial.begin(9600);
     pinMode(vccPin, OUTPUT); digitalWrite(vccPin, HIGH);
  pinMode(gndPin, OUTPUT); digitalWrite(gndPin, LOW);
  delay(500);
attachInterrupt(INT1 , Meter2ISR, RISING);
    // sometimes initializing the gear generates some pulses that we should ignore
```

```
    Meter2.reset();
}

void loop() {
int test = tc1.readC();
if (test > threshold) {
    digitalWrite(relay, HIGH);
  } else {
    digitalWrite(relay, LOW);
  }
  delay(1);
   long currentTime = millis();
    long duration = currentTime - lastTime;
    // wait between display updates
    if (duration >= period) {
        // process the counted ticks
        Meter.tick(duration);
        // prepare for next cycle
        lastTime = currentTime;
    }
    if (duration >= period) {
        // process the counted ticks
        Meter2.tick(duration);
```

```
      // prepare for next cycle
      lastTime = currentTime;
  }
// set the cursor to column 0, line 1
// (note: line 1 is the second row, since counting begins with 0):
lcd.setCursor(0, 0);
lcd.print("Temp1");
// print the number of seconds since reset:
lcd.setCursor(8, 0);
lcd.print(tc1.readC());
 lcd.setCursor(0, 1);
lcd.print("Flow1");
// print the number of seconds since reset:
lcd.setCursor(8, 1);
lcd.print(String(Meter.getCurrentFlowrate()));
 lcd.setCursor(12, 1);
lcd.print(" L/min, ");
delay(2000);
 lcd.clear ();
 lcd.setCursor(0, 0);
lcd.print("Temp2");
// print the number of seconds since reset:
lcd.setCursor(8, 0);
```

```
lcd.print(tc2.readC());
 lcd.setCursor(0, 1);
lcd.print("Flow1");
// print the number of seconds since reset:
lcd.setCursor(8, 1);
lcd.print(String(Meter.getCurrentFlowrate()));
 lcd.setCursor(12, 1);
lcd.print(" L/min, ");
delay(2000);
lcd.clear ();
  lcd.setCursor(0, 0);
lcd.print("Temp3");
// print the number of seconds since reset:
lcd.setCursor(8, 0);
lcd.print(tc3.readC());
 lcd.setCursor(0, 1);
lcd.print("Flow2");
// print the number of seconds since reset:
lcd.setCursor(8, 1);
lcd.print(String(Meter2.getCurrentFlowrate()));
 lcd.setCursor(12, 1);
lcd.print(" L/min, ");
delay(2000);
```

```
lcd.clear ();
  lcd.setCursor(0, 0);
lcd.print("Temp4");
// print the number of seconds since reset:
lcd.setCursor(8, 0);
lcd.print(tc4.readC());
 lcd.setCursor(0, 1);
lcd.print("Flow2");
// print the number of seconds since reset:
lcd.setCursor(8, 1);
lcd.print(String(Meter2.getCurrentFlowrate()));
 lcd.setCursor(12, 1);
lcd.print(" L/min, ");
delay(2000);
lcd.clear ();
}
```