DIRECT CONTACT MEMBRANE DISTILLATION UNIT

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Bachelors of Mechanical Engineering

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ABSTRACT

The basic purpose of this project is to produce clean and pure water abundantly. A direct contact membrane distillation closed loop setup is used in this project to clean the brackish and sea water. The project uses a hydrophobic membrane that only allows vapors to pass through it. Solar collector can be integrated in the project to provide energy. A mathematical model is developed on the basis of heat and mass transfer inside the membrane module. The model used for this purpose was opted as Poiseuille and Knudsen. These models are then solved on EXCEL® and MATLAB® using iterative techniques. The results are then verified using finite element analysis on COMSOL 5.0®. The results of the software analysis shows the parameters that affect the performance of the distillation system. These parameters include feed temperature, feed velocity, porosity, permeate temperature, thickness etc. A small scale working prototype is also developed to validate the theoretical results.

PREFACE

Water is a basic human need. Every life on this earth needs water for its survival. But the world is now facing a problem of pure and clean water shortage. According to experts, next world war will be based on the sources of clean water.780 million people in the world lacks clean drinking water and by 2025, an estimated 1.8 billion people will live in areas plagued by water scarcity, with two-thirds of the world population living in water stressed regions. Now coming on the condition of pure and clean water in Pakistan, Pakistan lies 17th in the list of countries that is facing the problems of water shortage according to the reports of United Nation. So it is very important to solve this problem. Pakistan is also facing the problem of energy crisis. So a cheap method must be developed. Our project addresses this issue.

Our project "Direct Contact Membrane Distillation Unit" deals with the cleaning of the salty and brackish water in areas where the solar radiations is abundance. As membrane distillation needs lower operating temperature and can be achieved at lower cost as compared to some other distillation processes. Therefore, it can easily be integrated with solar energy. This technique removes about 99% of the salts from the sea water by using merely sunlight.

This technique produces clean and pure water at a cheap rate. This unit can be used not only for the production of drinking water in areas near sea but also for the treatment of chemically polluted and hazardous waste water produced from the industries in a very cost effective way. These small portable standalone units can easily produce enough water to fulfill the requirements of a house by putting it simply on the roofs even in hilly areas where lack of drinking water is a major issue now a days.

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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 and guidance of Dr. Zaib Ali 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 sheer responsibility if found otherwise**.**

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ABBREVIATIONS

AGMD	Air Gap Membrane Distillation
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CGMD	Conductive Gap Membrane Desalination
CNT	Carbon Nano Tubes
Conc.	Concentrated
DCMD	Direct Contact Membrane Distillation
FEM	Finite Element Method
F.W.T	Feed Water Tank
GOF	Graphic Oxide Framework
GPM	Gallon Per Minute
HABs	Harmful Algae Blooms
H.F.W.T	Hot Feed Water Tank
Ht	Heat Transfer
MD	Membrane Distillation
MEDINA	Membrane based Desalination: an Integrated Approach
MEDIRAS	Membrane Distillation in Remote Areas
MEMD	Multi Effect Membrane Distillation
MSF	Multi Stage Flash
PCM	Phase Change Material
PGMD	Permeate Gap Membrane Desalination

PI	Proportional Integral
PP	Polypropylene
PTFE	PolyTetraFluoroEthylene
PV	Photo Voltaic
PVDF	Polyvinylidenefluoride
RO	Reverse Osmosis
SGMD	Sweeping Gas Membrane Distillation
SMADES	Small-scale, Stand-alone Desalination system
Tds	Transport of Diluted Species
TPC	Thermal Polarization Coefficient
VMD	Vacuum Membrane Distillation
V-MEMD	Vacuum- multi effect Membrane desalination

NOMENCLATURE

General:

Q	Heat flux	W m^{-2}
H	Heat transfer coefficient	W m^{-2} K^{-1}
T	Absolute temperature	K
J_w	DCMD flux	m s^{-1}
H	Enthalpy	J kg^{-1}
d_p	Mean pore size	N m
K	Thermal conductivity	W m^{-1} K^{-1}
Re	Reynolds number	
Nu	Nusselt number	
Pr	Prandl number	
D	Hydraulic diameter	m
C_p	Specific heat capacity	J kg^{-1} K^{-1}
V	Average velocity	m s^{-1}
P	Total pressure	Pa
P^v	Vapor pressure of water	Pa
P	Liquid pressure	Pa
P_a	Air pressure	Pa
B_m	Net DCMD permeability	s m^{-1}
R	Gas constant	J mol^{-1} K
K_n	Knudsen Number	

R	Mean pore radius	nm
M	Molecular weight of water	kg mol^{-1}
D	Water diffusion coefficient	m^{2} s^{-1}
TPC	Temperature polarization coefficient	
EE	Evaporation efficiency	
q_t	Total heat transfer	W
I	Specific enthalpy	J/kg
L	Analyzed collector length	m
$\dot{m}$	Mass flow rate	Kg/s
V	Volume	m^{3}
P	Tube pitch	m
W	Velocity of fluid	m/s

Greek symbols:

T	Tortuosity	
ϵ	Porosity	%
P	Density	kg m^{-3}
Δ	Total membrane thickness	µm
μ	Water dynamic viscosity	kg m^{-1} s^{-1}
Λ	Mean free path	nm
ΔH_v	Latent heat of vaporization	kJ mol^{-1}

Superscript:

C	Combined Knudsen/ordinary diffusion

Subscripts:

F	Feed
B	Bulk
M	Membrane
M.T.	Mass transfer
L	Liquid phase
P	permeate
G	Gas phase
In	Inlet
out	Outlet
V	Vapor phase

CHAPTER 1 INTRODUCTION

1.1 Motivation

Fresh water is viewed as the lifeblood of life and it is the privilege of every single individual in this world to get unadulterated and consumable water. Yet, the water emergency is a harsh issue and the undermining worry that exists around it is that it isn't getting the consideration which it merits thus culminating in water deficiency issue not for this age only but rather for the coming age too. The issue is getting significantly more astringent in developing nations like Pakistan where no less than 40 million individuals are running shy of consumable water. That is why as per diverse surveys, Pakistan will have insufficiency of clean drinking water till the year 2025. The issue is utterly replicated in the quote "Water is the new oil'. This issue is additionally made crumbled by Industrial part which are contaminating the lakes and streams by industrial waste and becoming cause of further casualties. As indicated by the UN report, about 70% of the aggregate waste created in the enterprises is being tossed into blue water [1]. There are around 250,000 youngsters who kick the bucket because of the water borne ailments and majority of these kids for sure belong to the rural areas and around 840,000 die every year particularly because they don’t get clean water for drinking. Notwithstanding that, over 80% of the illnesses in the underdeveloped nations is caused by water sanitation issues [2].

Thus, because of the above certainties and cases, it is greatly alluring to have a savvy desalination strategy or dependable process that can clean and purge the impurities from the water with the goal that remote communities can have access to this facility as interest of new water is rising exponentially. Around 72% of the aggregate area of Earth is secured with water and among this, around 97% of this is water [3]. So by utilizing this office, we could kill this spotless water issue. The extent of the water that is spotless in this world right currently is just 0.8% and available in limited forms like lakes, rivers etc. but this rate is amazingly low. In response to this, presently reverse osmosis holds around 50% share of purifying the water out of other desalination methods but due to its complications and difficulties this cannot be endorsed in Pakistan. The reasons due of which reverse osmosis can't be utilized effectively in nations like Pakistan is because of the high feed salinity of the accessible water bodies and the high brine concentrations that make the layers defenseless to fouling in the RO procedure. Furthermore, there is extremely elevated occurrence of harmful algae blooms (HABs) in the Arabian Sea, our main water source for desalination [4]. These HABs contain high convergences of poisons that may go through the layer in the RO procedure and can cause sickness on drinking and at times may prompt demise too. As about 97% of aggregate water is sea water, so this water could be utilized to get spotless and consumable drinking water by means of Membrane refining. The result of the undertaking will be spotless and unadulterated water on the opposite side. Moreover, to make it more economical and practical, integration with natural source like solar energy could be significantly more proficient and beneficial as opposed to driving it with counterfeit sources and energies.

1.2. Membrane Distillation

Membrane desalination works on the basis of partial pressure difference on the shell and lumen side which arises due to the temperature difference. Vapors that are formed on the feed side pass through hydrophobic membrane gets condensed on the other hand and thus converted into the liquid form which is actually the clean water. Water cannot pass through membrane because membrane resists and thus blocks the water due to surface tension forces. Development of the pressure across the hydrophobic membrane also depends on the type of configuration of membrane distillation.

1.3 Background

Figure 1: Chronological Background

1.4 Problem Statement

To obliterate the problem of clean and pure water shortage by design and fabrication of a Membrane Distillation setup which can be incorporated with Solar Energy to make a **Self-operating Solar powered direct contact membrane distillation unit.**

1.5 Objectives of the Project

- Optimum design of distillation module.
- Complete instrumentation of the module.
- Mathematical modelling of the system.
- Performing the parametric analysis and observing the trends on permeate flux in any simulation software.
- Performing the experimental comparative study by varying different parameters and recording the water flux.

1.6 Advantages

Following are the notable advantages of membrane distillation [6]:

- This membrane process can be integrated easily with other processes or natural resources like solar, wind etc.
- It can easily operate on lower temperature and pressure.
- Carrying out the separation of pure water can occur in normal conditions.
- Less stringent mechanical properties are needed for the operation.
- Characteristics of Membrane can be controlled and varied easily. So if it is used in a proper way, this could enable the access of clean water easily.
- By comparing it with other similar process for cleaning water, it is considered to be less susceptible to the limitations of flux by concentration polarization.
- More than 99% of salt rejection is achievable.

1.7 Gantt Chart

The project is divided is several milestones and planned accordingly:

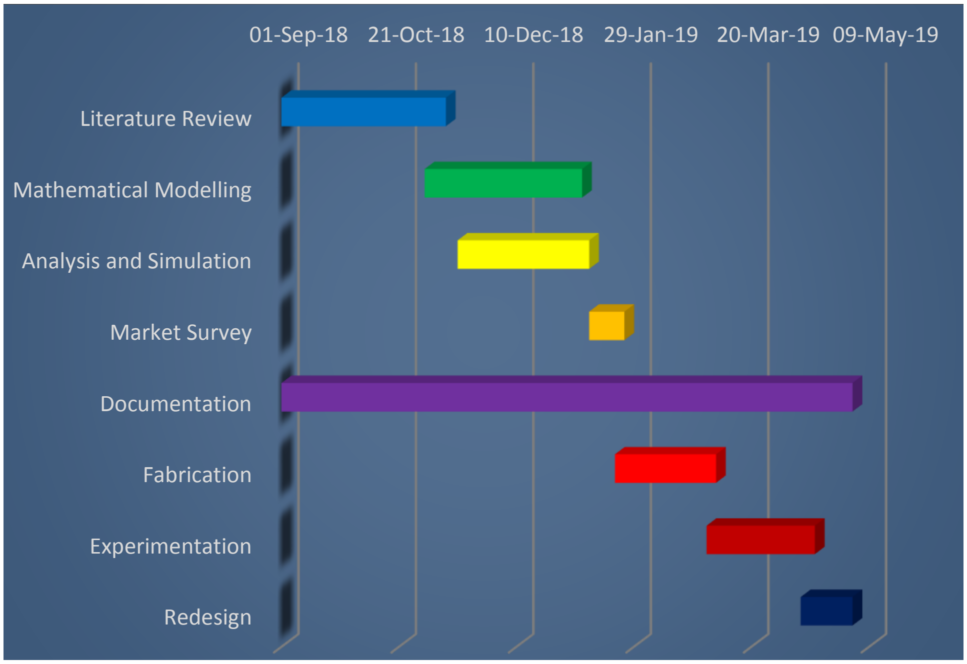

Figure 2: Gantt chart

CHAPTER 2: LITERATURE VIEW

2.1 Membrane distillation

Membrane distillation (MD) is a potential mean of water desalination. MD is a thermally driven desalination technology that has been employed in four basic configurations. One of these configuration is Direct Contact Membrane Distillation (DCMD). In DCMD, both hot and cold solution is maintained in direct contact with micro porous hydrophobic membrane material. It is regarded as one of the most atypical and nonpareil technologies that can succeed and replace the conventional methods that includes Multi stage flash (MSF), Reverse Osmosis etc. It is a topic of consideration since 1960 and a lot of versatile researches has been done on this premier method till today.

A.S Jonsson et al. [7] stated that Findley was the first to link the separation techniques now known as membrane distillation (MD). The role of operating conditions in membrane desalination process is extremely critical and thus was studied by Sulaiman et al. [8] in Direct Contact Membrane Desalination. They found that thermal efficiency and Transmembrane flux were found to be extremely delicate to feed temperature, feed flow rate and concentration of feed solution as increase in the first two properties enhanced thermal efficiency and Transmembrane flux and the latter one decreased the thermal efficiency and Transmembrane flux which was carried out on the modules named as MD020CP2N, MD020TP2N and MD080CO2N. They also studied the properties of hydrophobic membrane and found that increasing the thermal conductivity, thickness and decreasing the membrane porosity lessen the Tran's membrane flux and thermal efficiency. Similarly, different micro porous hydrophobic membranes of flat type of polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) were examined [9]. Drioli et al. [10] showed that low thermal conductivity, high liquid entry pressure, high thermal and chemical stability are the most favorable and suitable properties for hydrophobic membranes for the purpose of distillation.

Initially when membrane desalination was discovered in late 1960s, it was not commercialized particularly due to the fact that favorable and adequate properties of the membrane were an issue. So people started to look into the materials that can satisfy their needs for the purpose of distillation. Hence, further research has been carried on to Nano materials by Daer et al. [11] and their studies have shown that they are superlative in salt rejection and contribute to high flux especially Zeolites, CNT's and Graphene. This can be extended to Reverse osmosis as well which can be carried out efficiently using GOF (Graphic Oxide Framework) rendered by molecular dynamics simulations [12].

Stand-alone membrane desalination process was constructed using mathematical model to investigate its potential by Alklaibi [13]. He developed the mathematical model which comprised of mass and heat transfer analysis. He proved that variation of different parameters and putting them in different equation yielded the outcome that polarization coefficient is minimum at relatively high Reynolds number. Drioli et al. [10] have explained that different nature of fouling occurs for different type of Membrane desalination methods.

A mathematical model was developed as well by Qtaishata et al. [14] using heat and mass analysis for locating the heat transfer coefficients values and interface temperature of the liquid/membrane. Model was evaluated on the basis of experimental evidences. It was solved using MATLAB and hence derived the result that permeate flux is highly dependent on average temperature. Similar results were deduced by Cai et al. [15] that feed temperature plays the most influential role on permeate flux. Also the dependency of mass transfer on heat transfer and relation between them was deliberated extensively. It was found using Dufour effect that it was insignificant at permeate and feed side under certain conditions whereas study of its effect is remarkable inside the membrane [16].

2.2 Comparisons of Different Membrane Configurations

There are different types of Membrane configurations. First is VMD Vacuum Membrane Desalination was first used by Bodell [17]. VMD model is suggested considering the bulk flow of temperature, velocity, mass fraction and pressure distribution as function of module length by Gil et al. [18]. VMD has been experimentally studied by M. Khayet et al. [19] and has determined the heat transfer coefficients in both the lumen and shell side of hydrophobic membrane.

Other two types of membrane desalination i.e. Air gap membrane desalination (AGMD) and Sweeping gas membrane desalination (SGMD) have been examined by Khalifa et al. [20]. A novel method of AGMD using series and parallel connectors was analyzed by Khalifa el al. [21]. Similarly, Garcia et al. [22] modified the process with hollow fiber membrane made up of alumina. SGMD has been studied by modelling and optimization of different parameters [23, 24]. Sweeping gas MD using hollow fiber is comprehensively studied by Karinikola et al [25].

The fourth type is DCMD which is already explained.

The table [10] below will provide the distinguishing feature of each four of them:

Configuration	**Pros**	**Cons**
Vacuum Membrane Distillation	• High flux • Improved mass transfer • Negligible conductive heat loss	• Higher risk of Membrane wetting • Electricity consumption vacuum pump • Limited heat recovery
Direct Contact Membrane Distillation	• High flux • Simplicity in design • Lesser fouling tendency	• High heat loss by conduction • Sensitive to membrane wetting
Air Gap Membrane Distillation	• Relatively high flux • Low thermal losses • No wetting on permeate	• Provides resistance to vapors • Difficult module designing • Lowest gained output ratio
Sweeping Gas Membrane Distillation	• Lower Thermal polarization • No wetting on permeate	• Additional complexity • Heat recovery is difficult • Low flux,

Table 1: Pros and Cons of Different Membrane Configurations

2.3 Other Advancements

Also there are other various advancements done in Membrane configuration and system for the purpose of improving the efficiency [26]. First of them is Vacuum enhanced DCMD in which setting the distillate pump right after the DCMD module causes an increase in the flux. The second innovation is Multi effect MD (MEMD). It is derived from AGMD having porous fibers arranged in the parallel form and dense wall fibers having an internal heat exchanging in the counter current direction. The other one is Vacuum- multi effect Membrane desalination (V-MEMD). It consists of both Multi effect distillation and Vacuum membrane desalination. Also Multi stage MD which is responsible for lowering the energy consumption. Osmotic MD requires a special mention in which vapor pressure difference is created with the help of water activity difference between the feed solutions.

Many renewable sources have been proposed to solve the energy problems [27]. Like the Solar energy which is the most abundant form and has been integrated in many of the MD related projects. Primarily the use of solar collector and PV cells have gained a lot of reputation in the recent years due to their enhanced ability to overcome cost and improve economical factor in Membrane desalination. Also Banat et al. has used solar still for producing potable water [28]. Geothermal energy which can offer the continuous thermal energy. However its extraction is little bit costly. Wind energy can serve the desalination plants in the form of electricity. Wave energy can serve as an ideal platform for membrane desalination plants. Similarly there are other forms of energy which can prove to play a vital role for solving the energy crisis related to MD and bring a revolution in future.

2.4 Analysis of Membrane Desalination in different software's

As membrane desalination involves heat and mass transfer and dependency of mass transfer on heat transfer has been extensively studied under various conditions by Phattaranawik [16] that involve very complex PDE and ODE equations that have been solved using limited number of softwares only. Like DCMD equations have been first simplified by Qtaishat et al. [14] and thus solved using MATLAB. Also equations in the PDE form have been solved using COMSOL by Hasanizadeh et al [29] as it is a multiphysics software and thus can integrate heat and mass transfer at the same time in the same module as well.

On the other hand, for simulations, ANSYS Fluent and CFD have been extensively used. Like fluid flow effect on the permeate flux has been studied by Soukane et al. [30] in Fluent with turbulence model. Similarly, CFD analysis of DCMD has been done by H.Yu et al. [31] and have achieved very promising results that can be compared with experimental results. VMD analysis in CFD has been done by Hayer et al. [32] on the basis of fluid mechanics as well as heat and mass transfer.

2.5 Fouling and Wetting complications

Fouling of membranes is still one of the problems that torments the extensive stability of membranes and declines the flux. Its most common type is scale fouling. Its magnitude varies from one type of membrane desalination to another. Various methods were proposed to get rid to the maximum level by Tijing et al. [33] such as pre-treatment, membrane flushing, gas bubbling etc.

Various versatile projects have tried to integrate the solar energy with Membrane desalination technology and have strived to provide new sagacity for diverse possible applications [34]. First commercial plant for MD was installed in Maldives in year 2014. Since then, a lot of plants have been established in various parts of the world to produce clean water. So Membrane desalination is an effective technique that if employed, can produce the clean and pure water safe for drinking and thus can solve the drinking issues at present and in future as well.

CHAPTER 3: METHODOLOGY

3.1 Schematic Diagram:

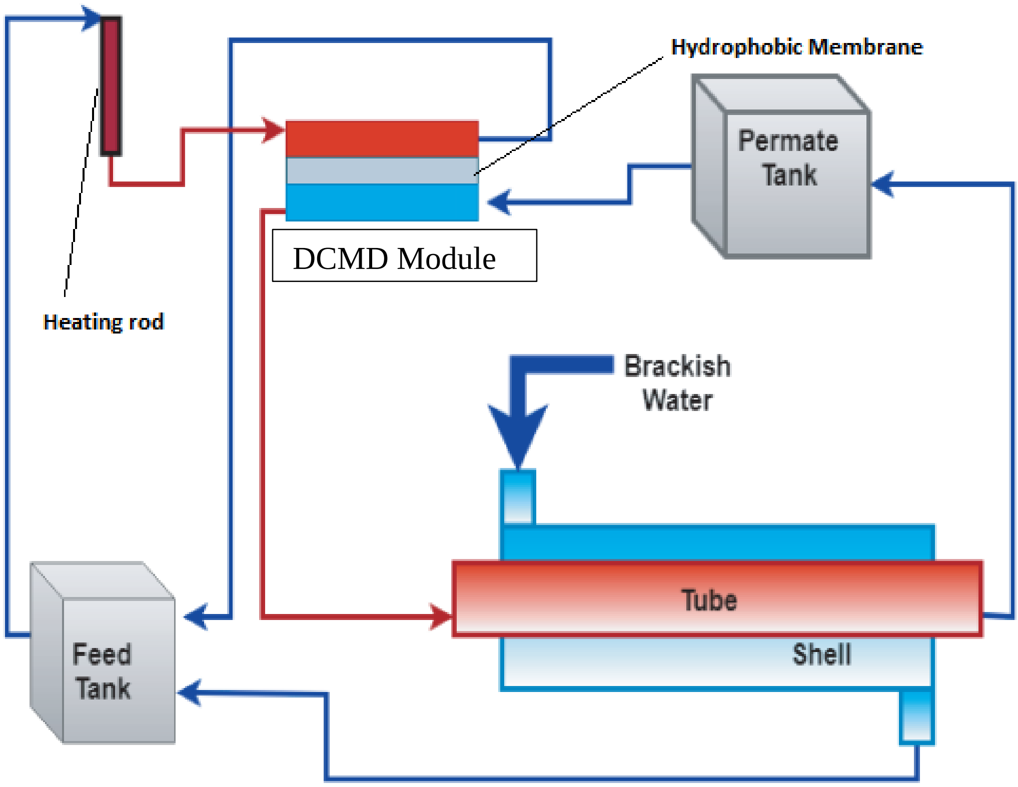

Figure 3: Schematic Diagram

3.1.1 Working Cycle:

- The main working component in the cycle of membrane desalination is porous hydrophobic membrane.
- Fresh water (to be purified) is initially stored in fresh feed water tank having tubes hence it also acts as shell and tube heat exchanger.
- Hot feed water tank is connected with F.W.T to maintain water level in H.F.W.T.
- Water is heated to 50-60 Degree Celsius through heating rod and pumped to the feed side of membrane which allows only vapors to pass through it.
- Concentrated water (brine) is pumped back to H.F.W.T which also decreases pressure in it (helps in formation of vapors).

- Condenser on the permeate side of membrane condenses the pure vapors using cold water from permeate water tank (purified) and exchanges heat. This heated water (because of condensation) is also used to pre heat the fresh water in F.W.T (Heat Recovery).
- The process is a closed loop as well as standalone process. All the above steps are repeated as described above.

3.2 CAD Model:

To use membranes practically, large membrane area is needed. The smallest section into which a membrane area is packed is called a module. A module typically consists of membrane, feed inlet, and permeate outlet and a supporting structure which provides the necessary support to the whole unit. There are different configurations present in the literature for a membrane module. Some of these configurations include; hollow fiber module, spiral wound module, plat and frame module and tubular module.

We will be using plat and frame (cross-flow) module configuration. A 3D model of the proposed model is shown in **Figure 3**. In this configuration, two rectangular plates are present on both sides to provide necessary support to the module during the operation. Spacers are also used on either sides and the membrane is enclosed in between the two spacers. In membrane distillation, thermal polarization is one of the important factors which limit the performance of the distillation process by reducing the thermal driving force. Spacer helps to decrease the temperature polarization by increasing the heat transfer which results in higher permeate flux. The whole geometry will be assembled together tightly with the help of nuts and bolts to prevent any leakage and disturbing of membrane sheet during the operation.

The parts labeled in the figure are as:

1) Supporting plate

2) Spacer

3) Membrane Sheet

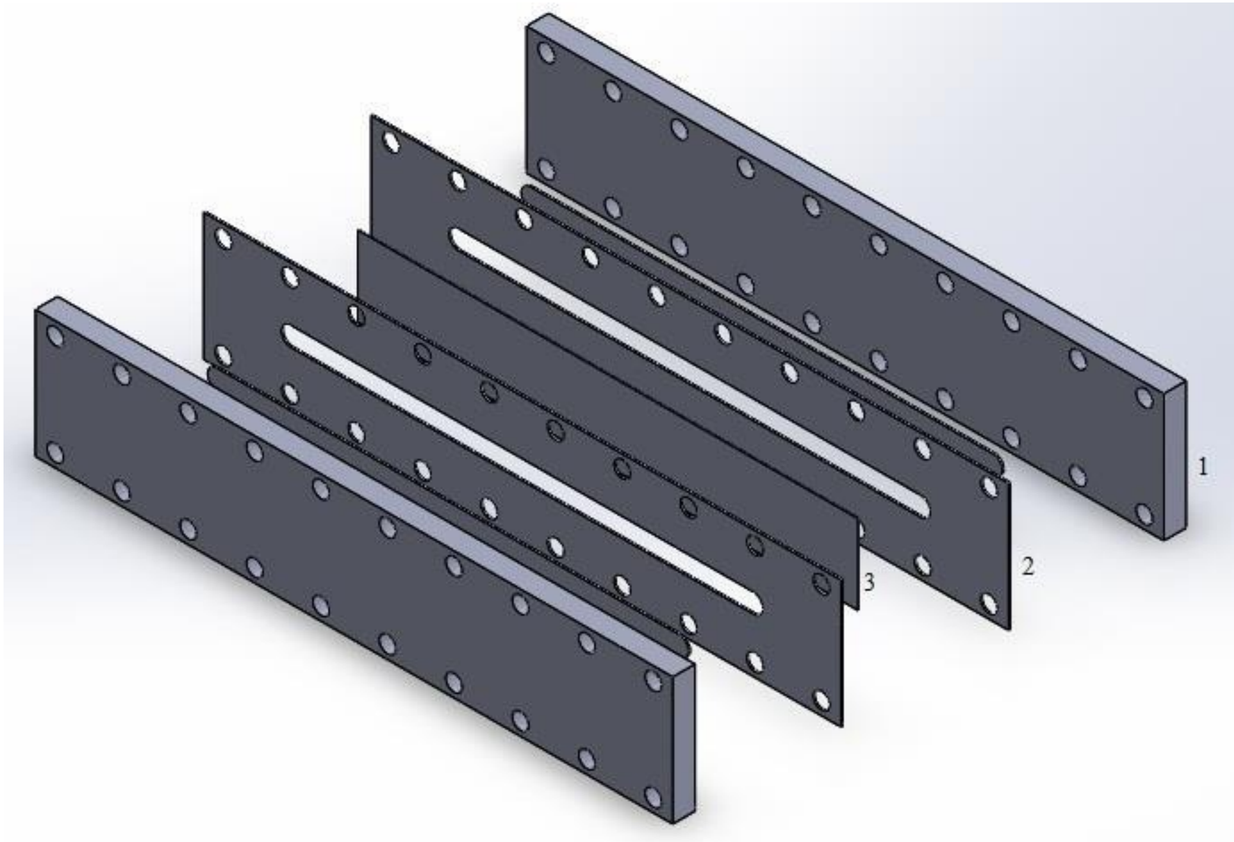

Figure 4: CAD Model

3.3 Mathematical Modelling:

3.3.1 Mathematical Modelling of DCMD:

As Membrane desalination is a process that occurs due to the pressure difference created due to the temperature difference across feed and permeate side so analysis can be split into three different regions. **(1)** Feed side Heat transfer (includes heat transfer through convection $Q_{f,conv.}$ as well as it incorporates mass transfer which governs the second type of heat transfer$Q_{f,M.T.}$); **(2)** Heat transfer in membrane (includes heat transfer through conduction $Q_{m,cond.}$ and transfer of heat due to the passage of water vapors through pores of membrane $Q_{m,M.T.}$); **(3)** Transfer of heat in permeate side (includes convectional heat transfer $Q_{p,conv.}$ as well as transfer of mass governs the second type of heat transfer across permeate boundary $Q_{p,M.T.}$) [14].

Ours and previous years' researches of our seniors resulted in the following equations;

- Feed side

$$Q_f = Q_{f,conv.} + Q_{f,M.T.} = h_f\left(\left(T_{bf} - T_{mf}\right)\right) + J_w H_{L,f}\left\{\frac{T_{bf} + T_{mf}}{2}\right\} \quad (1)$$

- Membrane:

$$Q_m = Q_{m,cond.} + Q_{m,M.T.} = h_m\left(\left(T_{mf} - T_{mp}\right)\right) + J_w H_v \quad (2)$$

- Permeate Side:

$$Q_p = Q_{p,conv.} + Q_{p,M.T.} = h_p\left(\left(T_{bp} - T_{mp}\right)\right) + J_w H_{L,p}\left\{\frac{T_{mf} + T_{bf}}{2}\right\} \quad (3)$$

In literature, it has been determined that the type of heat transfer that dominates is the convection heat transfer on both sides of membrane [35]. Hence we can eradicate the terms of mass transfer for both sides.

Moreover, the enthalpy of vapor H_v is regarded as approximately equal to latent heat of vaporization (ΔH_v). Based on this approximation, the Eq. [(1-3)] can be rewritten as follows:

$$Q_f = h_f\left(\left(T_{bf} - T_{mf}\right)\right) \quad (4)$$

$$Q_p = h_p\left(\left(T_{bp} - T_{mp}\right)\right) \quad (5)$$

$$Q_m = h_m\left(\left(T_{mf} - T_{mp}\right)\right) + J_w \Delta H_v \quad (6)$$

In correspondence to the above equations, the average bulk feed temperature T_{bf} is the average of bulk inlet and bulk outlet flow temperatures:

$$T_{bf} = \frac{T_{bf,in} + T_{bf,out}}{2} \tag{7}$$

Similarly, for average bulk permeate temperatureT_{bp}:

$$T_{bp} = \frac{T_{bp,in} + T_{bp,out}}{2} \tag{8}$$

Coefficient of heat transfer plays a very pivot role in heat transfer across the membrane and controls the flux through the membrane. Its evaluation is done with the help of thermal conductivity of the material k_m from which membrane is made as well as the air which is trapped inside the membrane k_g. Its equation is given as follows:

$$h_m = \frac{k_g \varepsilon + k_m (1 - \varepsilon)}{\delta} \tag{9}$$

For finding the shell and lumen side heat transfer coefficients (h_f h_p), we would take help of various dimensionless numbers [36] like Nusselt Number, Prandtl Number etc.

Reynolds Number (i=feed, permeate):

$$Re_i = \frac{\rho_i v_i d_i}{\mu_i} \tag{10}$$

Prandtl Number (i=feed, permeate):

$$Pr_i = \frac{\mu_i c_{p,i}}{k_i} \tag{11}$$

Nusselt Number –laminar flow (i=feed, permeate):

$$Nu_i = 1.86 \left(\frac{Re_i Pr_i d_i}{l_i} \right)^{0.33} \tag{12}$$

Nusselt Number –turbulent flow (i=feed, permeate):

$$Nu_i = 0.023(Re_i)^{0.8}(Pr_i)^{0.33}\left(\frac{\mu_i}{\mu s_i}\right)^{0.14} \quad (13)$$

Heat transfer coefficients (i=feed, permeate):

$$h_i = \frac{Nu_i k_i}{d_i} \quad (14)$$

Heat of vaporization of water ΔH_v is an experimental factor but certain relations exists which operate only in the certain temperature range. The following relation operates in the 273K-373K temperature range. Its evaluation is done on the average temperature between feed and permeate side as follows [35, 37]:

$$\Delta H_v = 1.7535T + 2024.3 \quad (15)$$

Where mean temperature between bulk feed and permeate side is represented by T as:

$$T = \frac{T_{bf} + T_{bp}}{2} \quad (16)$$

At steady state:

$$Q_f = Q_m = Q_p = Q \quad (17)$$

Combining equations [Eq. (4-6)] in Eq. 17 the heat becomes:

$$Q = h_f\left(\left(T_{bf} - T_{mf}\right)\right) = h_p\left(\left(T_{bp} - T_{mp}\right)\right) = h_m\left(\left(T_{mf} - T_{mp}\right)\right) + J_w \Delta H_v \quad (18)$$

Solving for Q, we get the following equation:

$$Q = \left(\frac{1}{h_f} + \frac{1}{h_m + \frac{J_w \Delta H_v}{T_{mf} - T_{mp}}} + \frac{1}{h_p}\right)^{-1} \left(T_{bf} - T_{bp}\right) \quad (19)$$

Also one factor that is interconnected to heat flux is overall heat transfer coefficient U which is a very critical factor as indicated below:

$$U = \left(\frac{1}{h_f} + \frac{1}{h_m + \frac{J_w \Delta H_v}{T_{mf} - T_{mp}}} + \frac{1}{h_p} \right)^{-1} \tag{20}$$

The mass flux J_w is dependent on two very important factors in this process i.e. first is mass transfer coefficient (Viscous model, Knudsen model, ordinary-diffusion model or their pair) and second is pressure difference across membrane. It is calculated by [35, 38]:

$$J_w = B_m \left(\left(P_{mf} - P_{mp} \right) \right) \tag{21}$$

Evaluation of partial pressure is governed by Antoine equation which converts the temperature of any side into partial pressure of that side as shown below:

$$P^v = \exp\left(23.328 - \frac{3841}{T - 45} \right) \tag{22}$$

There exist many different types of governing mechanisms to represent mass transfer through a porous media: Viscous model, Knudsen model, ordinary-diffusion model and may be a combination as well. Knudsen number K_n is responsible for calculating which type of mechanism governs the mass transfer. It is dependent on two things i.e. mean free path of molecules λ and membrane pore size diameter d:

$$K_n = \frac{\lambda}{d} \tag{23}$$

In our model, we are using a combination of Knudsen model and ordinary diffusion model. So membrane permeability B_m for combined Knudsen-ordinary diffusion is given by the following equation:

$$B_m^c = \left[\frac{3}{2}\frac{\tau\delta}{\varepsilon r}\left(\frac{\pi RT}{8M}\right)^{\frac{1}{2}} + \frac{\tau\delta}{\varepsilon}\frac{P_a}{PD}\frac{RT}{M}\right]^{-1} \tag{24}$$

Where P_a represents the air which is trapped inside the membrane pores and D is the water diffusion coefficient. Water-air PD value is given as [16] which will then be substituted in the above equation:

$$PD = (1.895 \times 10^{-5})T^{2.072} \tag{25}$$

Membrane tortuosity τ is primarily dependent on porosity of membrane and it can be calculated by using the following correlation:

$$\tau = \frac{(2-\varepsilon)^2}{\varepsilon} \tag{26}$$

As coefficient of heat transfer is dependent on conductivity of the material from which membrane is composed k_m as well as the air which is trapped inside the membrane k_g. Similarly, membrane's ability to conduct heat k_m is also dependent on these factors. Hence

$$k_m = \varepsilon k_g + (1-\varepsilon)k_p \tag{27}$$

So by putting all the values of parameters in Knudsen- ordinary diffusion model and then replacing its values in mass flux equation along with the result of Antoine equation for feed and permeate side, we could obtain the mass flux J_w at desired temperatures. Also, evaluation of other parameters is dependent primarily on membrane interfaces temperatures and the mass flux.

One of the most critical and pivot element that influences the effectiveness and efficiency of this system is the Temperature Polarization Coefficient (TPC) which heavily affects and decreases the permeate flux passing across hydrophobic membrane. Heat losses that occur during the process are responsible for the bulk temperatures to be not equal to the membrane interfaces temperatures. This phenomenon is actually known as TPC which is a factor responsible for the effectiveness of process. It is dependent on membrane interface temperatures and bulk temperatures on both sides. It is stated as follows:

$$TPC = \frac{T_{mf} - T_{mp}}{T_{bf} - T_{bp}} \tag{28}$$

The evaporation efficiency EE can be delineated as portion of heat that is migrated due to water vapors passing across the membrane out of total heat transferred [39]:

$$EE = \frac{Q_{m,M.T.}}{Q_{m,cond.} + Q_{m,M.T.}} = \frac{J_w H_v}{h_m\left(\left(T_{mf} - T_{mp}\right)\right) + J_w H_v} \tag{29}$$

For finding the rate of total heat transferred through hydrophobic membrane, we will use the following equation:

$$Q_t = U\left(\left(T_{bf} - T_{bp}\right)\right) \tag{30}$$

Where U is the overall heat transferred coefficient which is determined with the help of Eq. (20).

To solve these equations in MATLAB it requires an iterative scheme of many equations and combination of many variables. To make it easy in solving in this software, following pivot equations are derived from the above equations. The extensive iterative process is used to evaluate these temperatures of both sides of the hydrophobic membrane. The code used in MATLAB is given in Appendix 2.

On feed Side:

$$T_1 = \frac{h_m\left(T_p + \left(h_f/h_p\right)T_f\right) + h_f T_f - JH_v}{h_m + h_f\left(1 + h_m/h_p\right)} \tag{31}$$

On Permeate Side:

$$T_2 = \frac{h_m\left(T_f + \left(h_p/h_f\right)T_p\right) + h_p T_p - JH_v}{h_m + h_p\left(1 + h_m/h_f\right)} \tag{32}$$

3.3.1.1 Overview of Modeling of DCMD in Matlab:

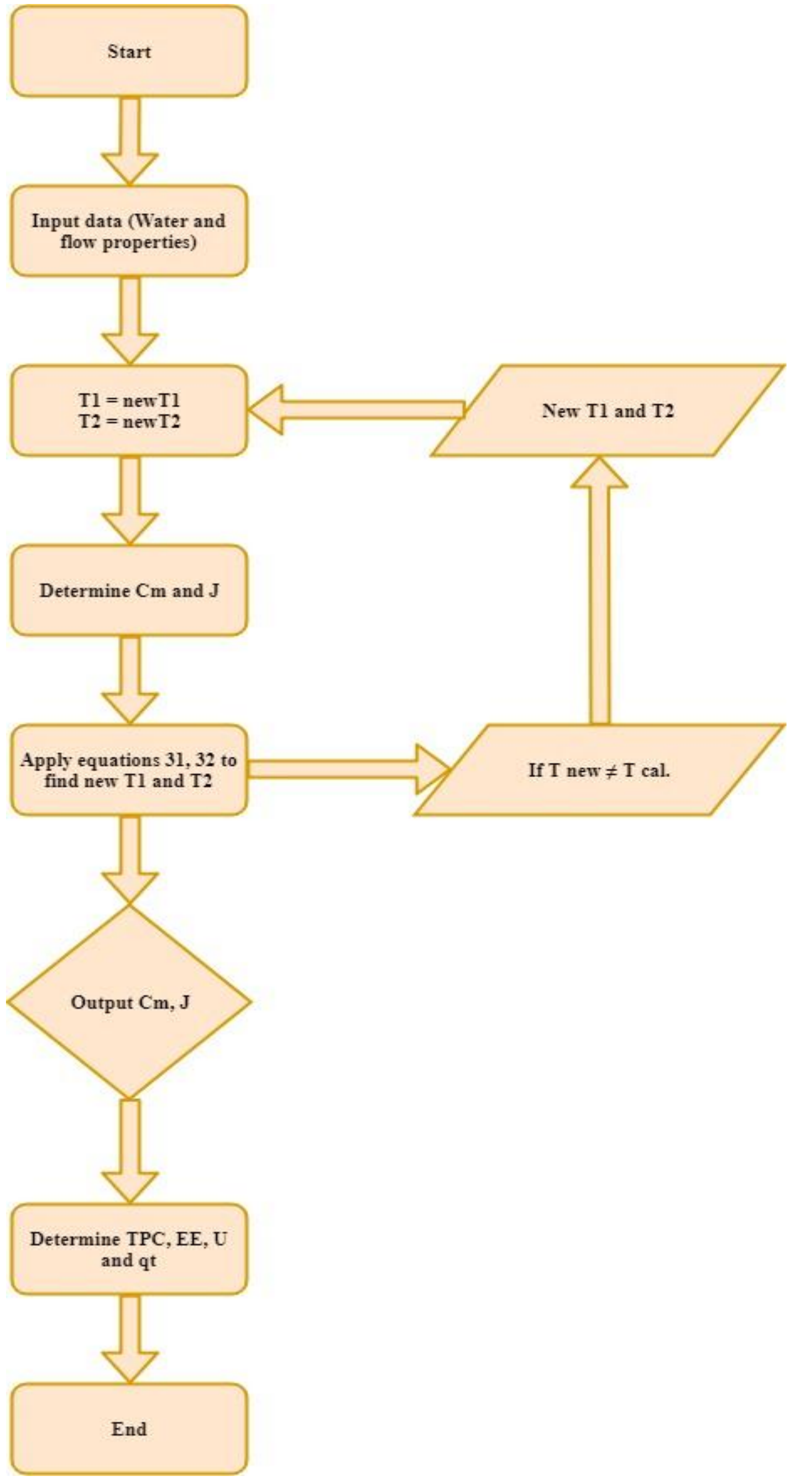

Figure 5: Flow Chart of DCMD Module

An iterative scheme has been used to find the flux over a vast range of temperatures.

- All the water properties and flow characteristics are inputted in the beginning.
- As an initial guess, values of T_{mf}, T_{mp} are inputted after this.
- These Temperatures and water parameters contribute to determine Knudsen – Ordinary diffusion coefficient as well as Mass flux.
- Mass flux value will lead us to new membrane interfaces temperature.
- Then it is checked whether the new temperatures calculated are equal or close to (within tolerance of 1e-04) to the previous membrane temperatures.
- If the condition is not satisfied, then steps (2-5) are repeated again in such a manner that the new temperatures are set equal to the old temperatures.
- The above steps will continue until and unless the difference between the old and new temperatures gets less than or equals to 1e-04 (tolerance).
- If the condition is satisfied then these temperatures are the true or close to true membrane interfaces temperatures. These temperatures are proceeded further to calculate the actual amount of flux pass across the membrane.
- These temperatures are then further engaged to find other valuable parameters like Evaporator Efficiency (EE), Thermal Polarization coefficient (TPC) etc.

3.4 Experimental Setup:

On the basis of the theoretical model, we developed a physical model which looks like the one in the figure below. First of all, brackish water comes in to the shell side of a Shell and tube heat exchanger. After initial preheating, this water goes to the feed water tank. The feed water tank consists of a heating rod which heats the water to about 80 to 90 degree Celsius. This liquid-vapor mixture goes to the upper compartment of the membrane which allows only vapor to pass through it while moving the liquid back to the feed water tank. Now coming on to the second stream of water, where the distilled water from the permeate tank condenses the vapors that passes through the membrane. The distilled water flows between the tube side of Shell and Tube heat exchanger and permeate tank.

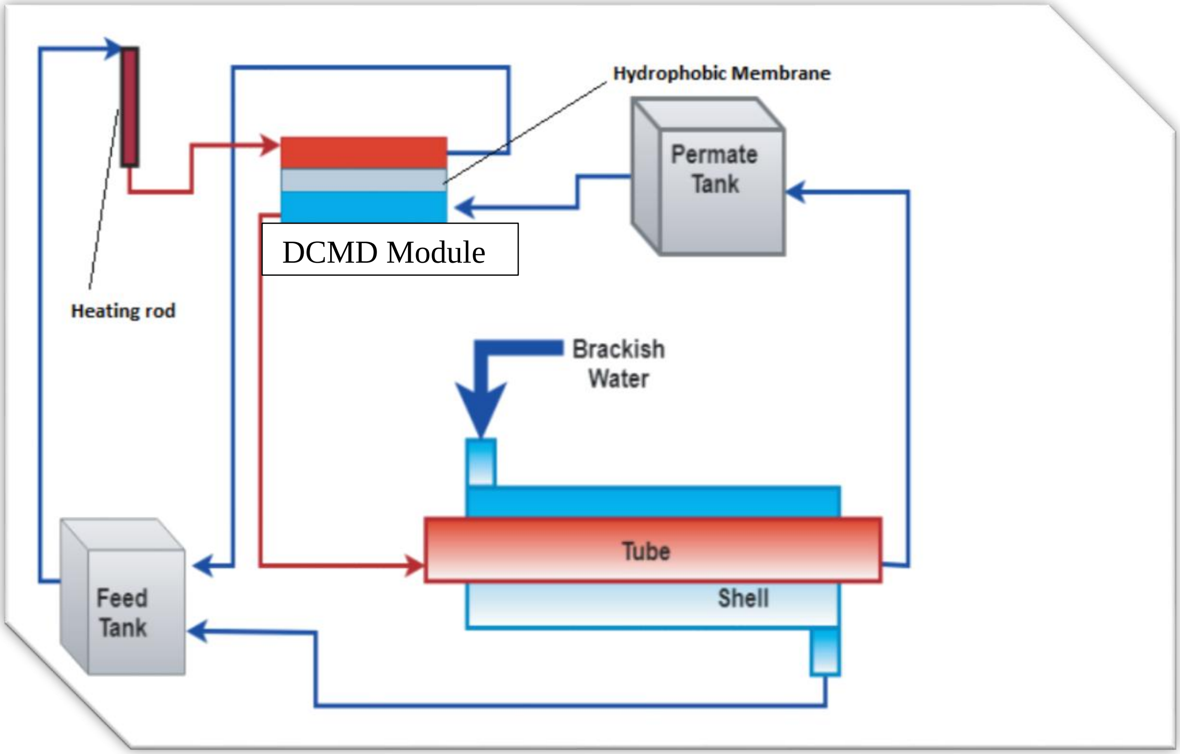

Figure 6: Experimental Setup

The DCMD module consists of a flat-sheet membrane and a channeled MD module. The module is made up of two Plexiglas flow compartments. The module assembly consists of the membrane, sandwiched between the two flow compartments. One compartment is used for hot feed water; while the other compartment is used for permeate cold water.

In our system, we have used K-type temperature sensors and flow meters to obtain temperatures at feed and permeate sides of the membrane and the flow rates of the two streams of liquids flowing. These parameters help in finding the permeate flux through the membrane. We have also made an Arduino Interface of the whole system in order to digitalize our system and obtain the continuous results of temperatures and flow rates on the LEDs.

A conductivity meter is used to find out the concentrations of the feed and the permeate side. We have also used flow meters to measure the feed flow rate and permeate flow rates. Arduino Mega is used for data acquisition. We have used K-type thermocouples to calculate the inlet and outlet temperature of feed and permeate sides. The figure below shows a photograph of our hydrophobic membrane module and of the whole system.

Figure 7: Prototype

The effects of parameters that affects the permeate flux are measured. The different parameters that were experimentally varied were feed temperature, permeate temperature and the concentrations of feed water.

CHAPTER 4: RESULTS AND DISCUSSIONS

The Direct Contact Membrane Distillation Unit (DCMD) present a comprehensive experimental and analytical study on the parameters that affect the performance of the DCMD system. These variables that were experimentally or theoretically varied were feed temperature, permeate temperature, the concentrations of feed water, feed velocity, membrane thickness.

4.1 Effect of feed temperatures

4.1.1 Experimental Result of the effect of feed temperatures

The effects of feed temperature on the permeate flux are studied over a range of temperatures from 313K to 363 K with every 10 K increase in temperature. The permeate flux change with feed temperature was observed at constant cold permeate temperatures of 283 K, 288 K and 293 K; respectively. Experimental results are shown as separate figures.

At 283 K Permeate Temperature:

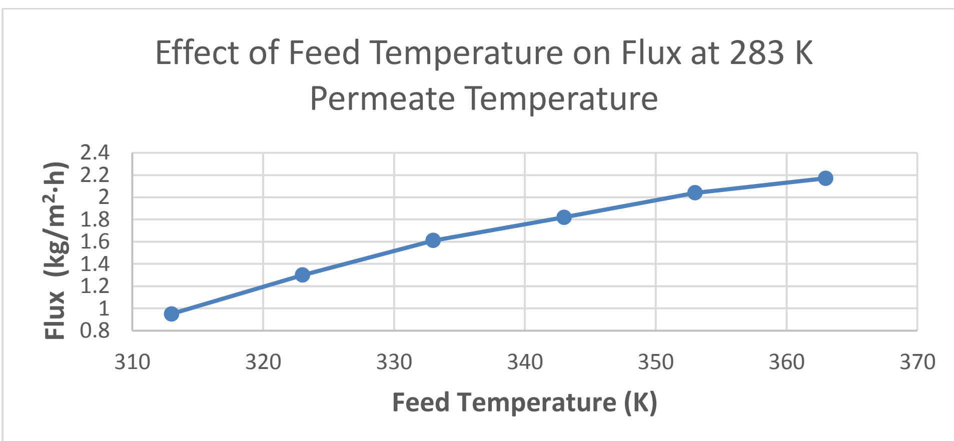

Figure 8: ***Effect of Feed Temperature on Flux at 283 K Permeate Temperature***

At 288 K Permeate Temperature:

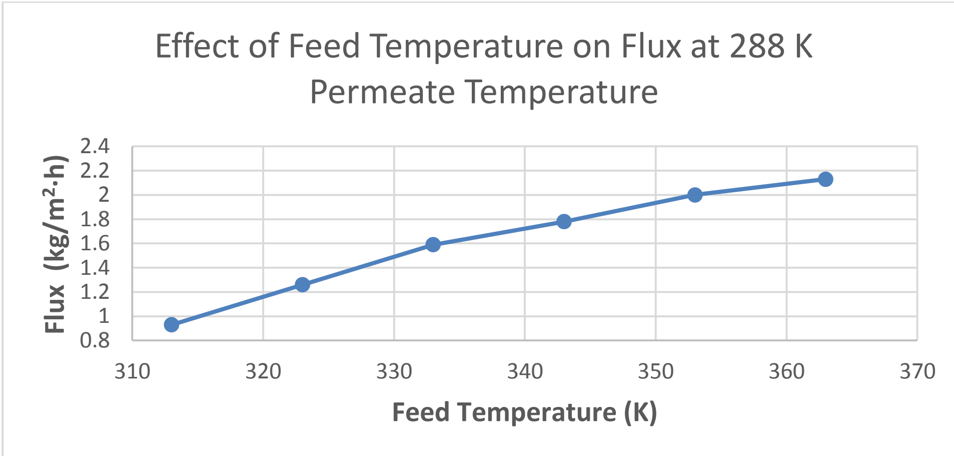

Figure 9*:* Effect of Feed Temperature on Flux at 288 K Permeate Temperature

At 293 K Permeate Temperature:

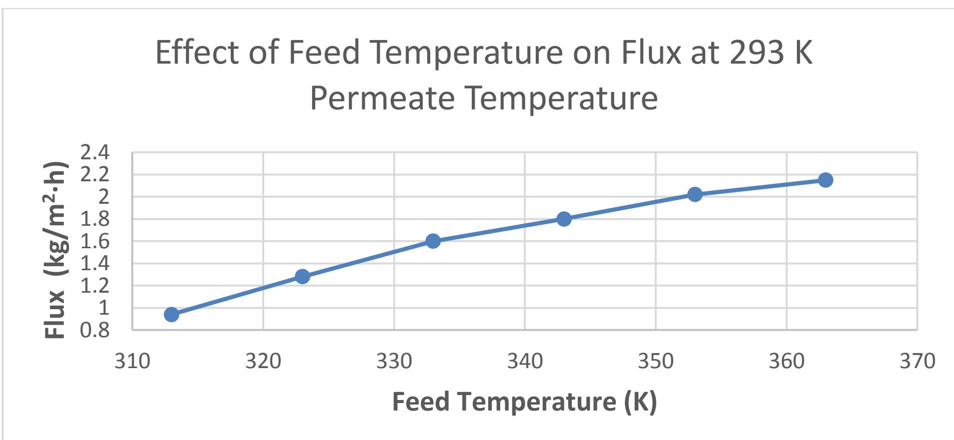

Figure 10***: Effect of Feed Temperature on Flux at 293 K Permeate Temperature***

The feed temperature increases the permeate flux exponentially in agreement with the Antoine Equation. According to the Antoine equation, the impact of temperature on vapor pressure is little at low feed temperature, and turns out to be huge at high feed temperature. The high estimate of permeate flux is credited to the high temperature difference across the membrane. Increasing the temperature difference across the membrane increases the vapor pressure difference between the membrane sides.

4.1.2 Theoretical Result of the effect of feed temperatures

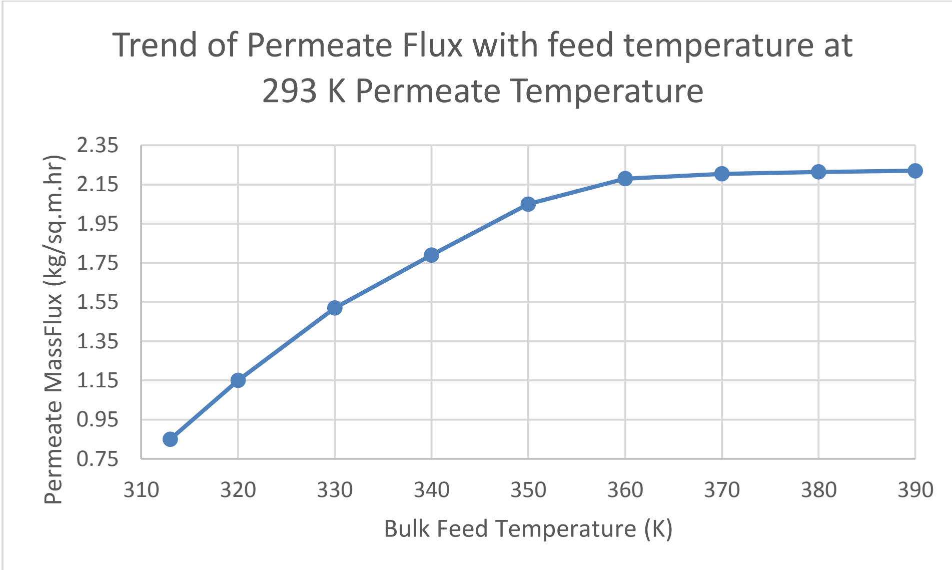

Figure 11***: Effect of Feed Bulk Temperature on Mass Flux***

The effect of feed temperature on the flux is determined using MATLAB iterative scheme. Bulk feed temperature is the temperature of the water on the feed side and is monitored by heating rod in our DCMD unit. As deduced from the chart above, raise in feed temperature augmented the permeate flux. The reason being greater temperature difference across the membrane with the escalated Bulk feed temperature and hence greater pressure difference across both sides of the membrane. According to Antoine equation,

$$J_w = B_m\left(P_{mf} - P_{mp}\right)$$

Additionally, when the feed temperature is raised, the temperature of the vapors moving across permeate side is also high which gives it more proportion to be condensed in a proper way as compared to low temperature. Its MATLAB code is given in Appendix.

4.2 Effect of feed concentration

The impact of feed concentration on the flux of the DCMD unit is also studied by taking different levels of feed concentrations in the DCMD module unit. The results show that the permeate flux is consistently diminishing as the feed saltiness increments. The flux reduction with increasing the feed concentration is mainly due to the increasing effect of the salt concentration polarization. Moreover, scaling and fouling on the membrane surface due to salts and impurities tend to cover some effective area of membrane that slow down the evaporation process and reduces the vapor pressure difference across the membrane, so as a result the flux decreases. The decrease in flux pursues direct or linear diminishing pattern with increasing the feed concentration.

4.3 Effect of feed velocity on Mass flux

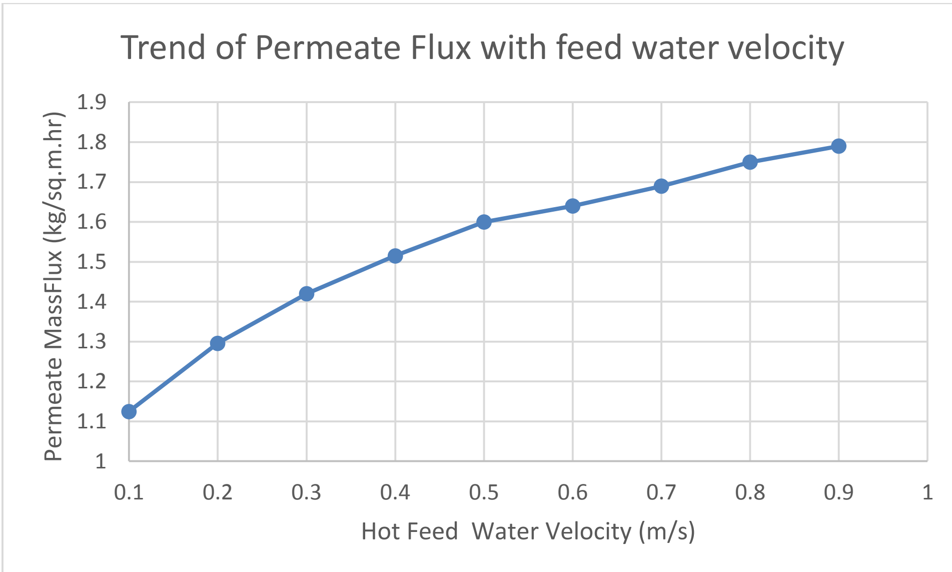

Figure 12*:* Effect of Feed velocity on Mass Flux

The effect of the feed velocity on the flux is determined theoretically using MATLAB. Its MATLAB code is given in Appendix. It is the mean velocity of the water entering the feed side and exiting it. Raising the velocity of feed water from 0.1m/s to 1m/s augments the flux from 1.079 kg/m^2hr to 1.78 kg/m^2hr. Reynolds number gets closer to the turbulent nature of water which causes high rate of mixing and effective heat transfer.

$$\mathrm{Re} = \rho v d / \mu$$

4.4 Effect of Porosity of membrane on Mass flux

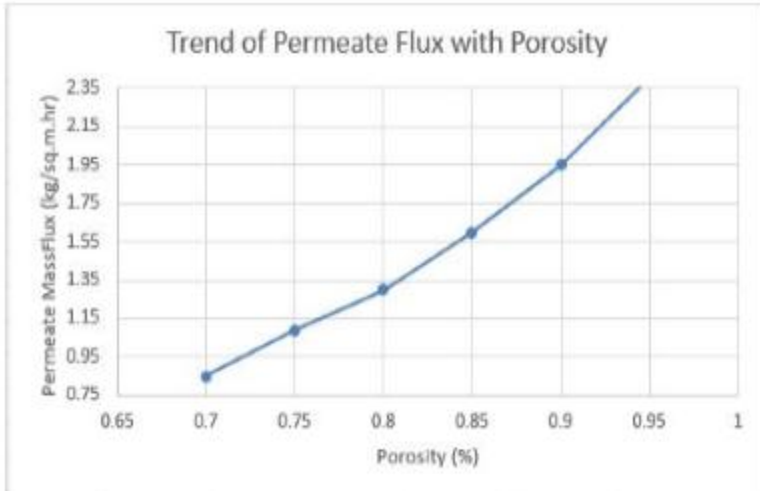

Figure 13***: Effect of porosity on Mass Flux***

This factor is only studied theoretically and its effect is also seen through MATLAB. Results of Matlab conclusively indicate that increasing the porosity of membrane from 0.7 to 0.94 directly enhances the value of Permeate flux from 0.87 kg/m^2hr to 2.27 kg/m^2hr. Essentially, porosity is the fraction of voids present in the material. So if the porosity is 75%, it implies that 3 fourth of the material has spaces inside it out of 4 quarters and just 1 quarter has solid material. Its MATLAB code is given in Appendix.

As the porosity is increased, percentage of voids in membranes increases which results in extra measure of vapors passing through it. This enhanced vapors then condenses on the permeate side to yield more mass flux in terms of consumable water. It is essential to mention that pore diameter too affects the porosity yet it can't be greater than the size of water molecule as then it won't be able to obstruct the water atom and surface tension forces will fall short of it.

4.5 Effect of thickness on Mass flux

This factor is only studied theoretically and its effect is also seen through MATLAB. Effect of thickness on flux has been shown in the above graph. Its MATLAB code is given in Appendix. It is evident that flux is quite sensitive to thickness and are related inversely i.e. increase in the thickness of membrane decreases the water flux.

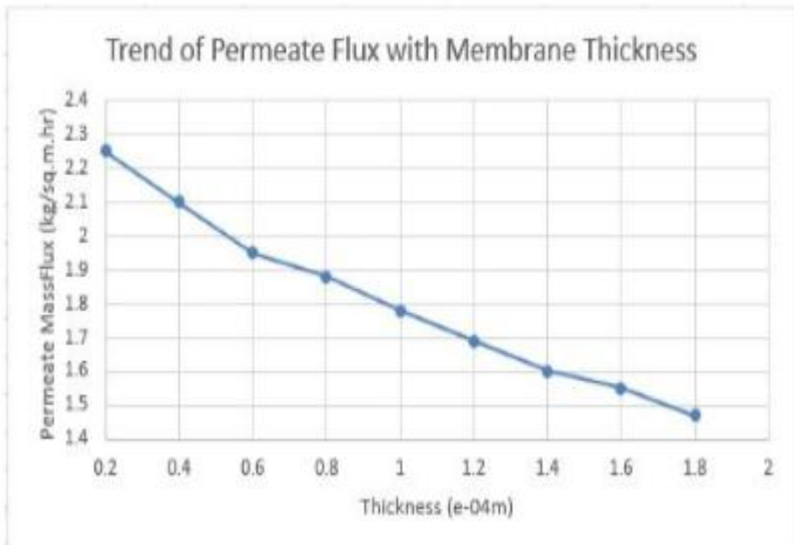

Figure 14*:* Effect of thickness on Mass Flux

When the membrane is thin, heat that will be transferred by conduction will be excessive that's leads to low heat efficiency of this process. But it is very important to mention here that optimum conditions are very important to have greater mass flux and compromise should be made between heat and mass transfer by adjusting its thickness. It is formulated by:

$$N \propto \varepsilon r^{a} / \tau\delta$$

Where N is the molar flux passing through membrane and δ is thickness of hydrophobic membrane. The equation written above indicates that membrane thickness is inversely proportional to the Permeate flux and it increases as thickness decreases.

4.6 Flux Comparison

The experimental and theoretical values of the flux at increasing feed temperatures are compared and histogram is drawn below that shows the difference in the values. There is slight difference in both the values. The difference between the results for all temperature is quite less and error is less than 10%.It also infers that as the feed temperature is increased, flux continuous to increase till it reaches the steady value.

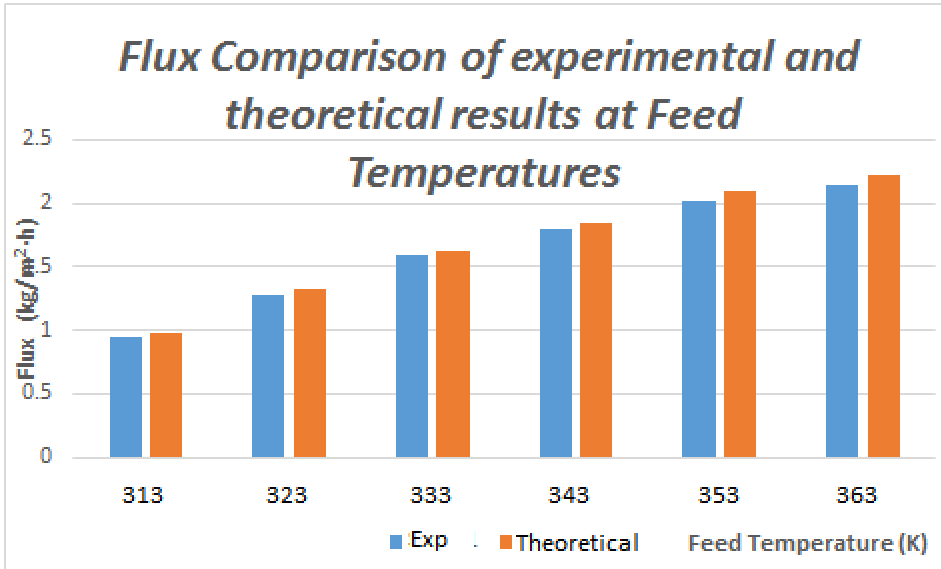

Figure 15*:* Flux Comparison

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

A study was carried out on the distillation process by using a heating rod and is compatible and perfectly ready to use solar collector as its main source of energy to power the distillation system in future applications. The different parameters that affected the performance of the distillation system were studied deeply. A mathematical model was developed on the basis of heat and mass transfer in the distillation system. This mathematical model was solved on EXCEL® and MATLAB® by the iterative technique to get useful results. The same results were then also obtained using a finite element analysis of the membrane module using COMSOL®. On the basis of the results obtained, following conclusions could be drawn:

- As the membrane distillation process occurs due to change in vapor pressure, vapor pressure is dependent on the temperature of water. With the increase in temperature, the vapor pressure also increases. So by increasing the feed water temperature, the permeate flux also increases. So this means the performance enhances with the rise in temperature of water.
- Porosity also affects the performance of membrane distillation system. With the increase in the porosity, the membrane flux also increases.
- The performance of membrane distillation system is also affected by the feed velocity. Increasing the feed water velocity results in the increase in membrane flux because the flow moves towards the turbulent flow which reduces thermal polarization.
- Membrane thickness also affects the performance of our distillation system. The flux decreases with the increase in the membrane thickness.
- Permeate water temperature also affects the flux variation of the distillation system. As the permeate water is used for condensation in our system for condensing the vapors that passes through the membrane, therefore higher temperature of permeate water results in lesser membrane flux due to lesser

temperature difference between the hot and cold fluids during condensation. Due to this, condenser efficiency is reduced.

- There is a tradeoff between the flux obtained and conduction losses if the thickness is reduced. By the use of a thicker membrane, conduction losses in the membrane module can be lowered but this would results in lower flux. Therefore a tradeoff is required between the two parameters.
- The finite element analysis on COMSOL® shows that the accuracy of the simulation results increases by increasing the quality of mesh used to discretize the membrane module. But this will require greater time to process. So a compromise must be made between accuracy and processing time.

5.2 Recommendations

Direct Contact membrane distillation is a great source of providing pure and clean water. As membrane distillation needs lower operating temperature and can be achieved at lower cost as compared to some other distillation processes. For future work, following points are recommended:

- In order to increase the performance of the membrane distillation, the flux through the membrane needs to be increased. To increase the flux, the ways to increase feed water temperature, feed velocity and porosity must be needed.
- For increasing feed water temperature, higher absorber plate temperature in solar collector must be used. This can be done by using a parabolic trough.
- Fouling and wetting is another parameter that must be reduced to increase the performance of the distillation system. Research is required to find out the exact causes and solutions of fouling and wetting because they limit the performance of the distillation system and result in an increase in the associated cost of a distillation process.
- It can easily be integrated with solar energy or other renewable sources of energies in future.
- To make solar powered membrane distillation, research is required to improve the thermal efficiency and the performance of the system. This can be done by making better membranes and improving the design of the overall modules.
- The material for the membrane can be changed in order to compare the performance of both types of materials in a membrane.
- Certain modifications can be induced to use the membrane distillation process for the treatment of sea water as well as waste water. For this purpose, further study and research is required.
- MD is proposed as very challenging technology for concentration of fruit juice allowing to overcome the drawbacks of conventional methods.

The world is facing the problem of water shortage and it is expected that the fresh water availability in the world will be scarce in a short time. Nearly 70 percent of the world is covered by water, only 2.5 percent of it is fresh. The rest is saline and ocean-based. A lot of diseases occur due to shortage of pure and fresh water. In this scenario, membrane distillation provides an easy and simple way to produce clean and pure water. By integrating the MD process with some renewable energy resources like solar power, the problem for the energy crisis can be resolved. Solar energy resources are present in abundance and it will also decrease the harmful effects of traditional energy consumption on the environment. With further research and proper development of membrane and renewable technologies, direct contact membrane distillation could become a valid course of action for future distillation plants.

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APPENDIX 1: PROPERTIES OF PTFE MEMBRANE

PROPERTIES	**VALUES**
MELTING POINT	600 K
DENSITY	2200 kg/m^3
COEFFICIENT OF FRICTION	0.049-0.10
GLASS TEMPERATURE	327 K
YIELD STRENGTH	22.9 MPa
YOUNG MODULUS	0.498 GPa
THERMAL CONDUCTIVITY	0.25 W/(m.K)
TYPE	Thermoplaster polymer
SPECIFIC GRAVITY	2.16

Table 2:Properties of PTFE Membrane

APPENDIX 2: CODE FOR MEMBRANE DISTILLATION

```
T_bf=input('enter first feed temperature guess:');
%Enter first guess of Bulk feed temperature
T_bp=input('enter first permeate temperature guess:');
%Enter first guess of Bulk permeate temperature
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
T=(T_bf+T_bp)/2; %Average of bulk feed and bulk permeate
temperature
i=1;
k_m=0.259; %Thermal conductivity of Membrane(PTFE)
A=0.0300; %Surface Area of Membrane
LEP=100; %Liquid Entry pressure in KPa
CA=132; %Contact Angle in degree
P_bf=exp(23.328-3841/(T_bf-45)); %Bulk feed vapour pressure
P_bp=exp(23.328-3841/(T_bp-45)); %Bulk permeate vapour
pressure
tck=145e-06; %Thickness of Membrane in metres
d=0.22e-06; %Pore size in meters
M=18.02e-03; %Mass of water in kg/mole
e=0.85; %Porosity
uf=1.0; %Feed water velocity
up=0.5; %Permeate water velocity
d_h=3.4e-03; %Hydraulic diameter
mew_f=0.5470e-03; %Dynamic Viscosity of feed water at 50
degree
celsius(60 and 40)
```

```
mew_p=0.8900e-03; %Dynamic Viscosity of permeate water at
25 degree
celsius(30 and 20)
Cp_f=4182; %Specific heat of feed water at 50 degree
Celsius
Cp_p=4182; %Specific heat of permeate water at 25 degree
celcius
k_f=0.64; %Thermal conductivity of feed water at 50 degree
celcius
k_p=0.59; %Thermal conductivity of permeate water at 25
degree celcius
den_f=988; %Density of feed water at 50 degree celcius
den_p=997.1; %Density of permeate water at 25 degree
celcius
tur=((2-e)^2)/e; %Tortuisity of membrane
L=200e-03; %Length of membrane
R=461.5; %Gas constant in J/(kg.K)
h_m=k_m/tck; %Membrane heat transfer coeffecient
Hv=(1.7535*(T)+2024.3)*1000; %Latent heat of vaporization
P_a=(P_bf+P_bp)/2; %Based on absolute pressure at
temeprature of 20 and 60
P_d=(1.895e-05)*((T^(2.072)));
while ( abs(T5-T3)>1e-04 && abs(T6-T4)>1e-04)
T3=T5;
T4=T6;
fprintf('ITERATION NO');
disp(i); %No of iterations
i=i+1;
Re_Nof=(den_f*uf*d_h)/mew_f; %Reynolds no at feed side
Re_Nop=(den_p*up*d_h)/mew_p; %Reynolds no at permeate side
Pr_Nof=(mew_f*Cp_f)/k_f; %Prandl no at feed side
```

```
Pr_Nop=(mew_p*Cp_p)/k_p; %Prandl no at permeate side
Nu_f=1.86*(Re_Nof*Pr_Nof*d_h/L)^0.33; %Nusselt no at feed
side
Nu_p=1.86*(Re_Nop*Pr_Nop*d_h/L)^0.33; %Nusslet no at
permeate side
h_f=Nu_f*k_f/d_h; %Heat transfer coefficent at
feed side
h_p=Nu_p*k_p/d_h; %Heat transfer coefficent at
permeate side
C= [((3*tur*tck)/(2*e*d))*(((3.14*R*T)/(8*M))^0.5)+
((tur*tck)/(e))*((P_a/P_d))*((R*T)/M)]^(-1);
P_mf= exp(23.238-3841/(T3-45)); %vapour pressure at
membrane
feed side
P_mp= exp(23.238-3841/(T4-45)); %Vapour pressure at
membrane
permeate side
J= C*(P_mf-P_mp); %Permeate flux
T5=(h_m*(T_bp+(h_f/h_p)*T_bf)+h_f*T_bf-
J*Hv)/(h_m+h_f*(1+h_m/h_p));
%Membrane feed side temperature
T6=(h_m*(T_bf+(h_p/h_f)*T_bp)+h_p*T_bp+J*Hv)/(h_m+h_p*(1+h_
m/h_f));
%Membrane permeate side temperature
fprintf('Value of C = ')
disp(C);
fprintf('Value of P_mf in Pascals = ')
disp(P_mf);
fprintf('Value of P_mp in Pascals= ')
disp(P_mp);
fprintf('Value of J in (kg/m^2*s) = ')
```

```
disp(J);
fprintf('Value of heat transfer coefficient at feed side =
')
disp(h_f);
fprintf('Value of heat transfer coefficient at permeate
side = ')
disp(h_p);
fprintf('Value of feed Membrane Temperature in Kelvin = ')
disp(T5);
fprintf('Value of permeate Membrane Temperature in Kelvin =
')
disp(T6);
fprintf('--------------------------------------------------
-----------
----');
fprintf('\n');
end
J_w=J*3600;
fprintf('Value of Permeate flux in (kg/m^2*hr) = ')
disp(J_w);
U=[(1/h_f)+(1/((k_m/tck)+(J*Hv/(T5-T6))))+(1/h_p)]^-1;
fprintf('Value of Overall heat transfer coeffecient = ')
disp(U);
qt=U*(T_bf-T_bp);
fprintf('Value of Rate of total heat transfer = ')
disp(qt);
EE=((J*Hv)*A/(qt*A))*100;
fprintf('Value of Evaporator Effeciency in percentage = ')
disp(EE);
TPC=(T5-T6)/(T_bf-T_bp);
fprintf('Value of Thermal Polarization = ')
```

```
disp(TPC);
GOR=(J*Hv*A/(EE+ET));
fprintf('Value of Gain Output Ratio = ')
disp(GOR);
```

APPENDIX 3: CODE FOR POROSITY VARIATION

```
% POROSITY VARIATION
T_bp=input('enter first permeate temperature guess:');
%Enter first
guess of Bulk permeate temperature
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
T=(T_bf+T_bp)/2; %Average of bulk feed and bulk permeate
temperature
i=1;
k_m=0.259; %Thermal conductivity of Membrane(PTFE)
A=0.0300; %Surface Area of Membrane
LEP=100; %Liquid Entry pressure in KPa
CA=132; %Contact Angle in degree
P_bf=exp(23.328-3841/(T_bf-45)); %Bulk feed vapour pressure
P_bp=exp(23.328-3841/(T_bp-45)); %Bulk permeate vapour
pressure
tck=145e-06; %Thickness of Membrane in metres
d=0.22e-06; %Pore size in meters
M=18.02e-03; %Mass of water in kg/mole
uf=0.5; %Feed water velocity
up=0.5; %Permeate water velocity
d_h=3.4e-03; %Hydraulic diameter
mew_f=0.5470e-03; %Dynamic Viscocity of feed water at 50
degree
celcius(60 and 40)
mew_p=0.8900e-03; %Dynamic Viscocity of permeate water at
25 degree
```

```
celcius(30 and 20)
Cp_f=4182; %Specific heat of feed water at 50 degree
celcius
Cp_p=4182; %Specific heat of permeate water at 25 degree
celcius
k_f=0.64; %Thermal conductivity of feed water at 50 degree
celcius
k_p=0.59; %Thermal conductivity of permeate water at 25
degree celcius
den_f=988; %Density of feed water at 50 degree celcius
den_p=997.1; %Density of permeate water at 25 degree
celcius
L=200e-03; %Length of membrane
e=0.70;
R=461.5; %Gas constant in J/(kg.K)
h_m=k_m/tck; %Membrane heat transfer coeffecient
Hv=(1.7535*(T)+2024.3)*1000; %Latent heat of vaporization
P_a=(P_bf+P_bp)/2; %Based on absolute pressure at
temperature of 20 and 60
P_d=(1.895e-05)*((T^(2.072)));
i=1;
while e<0.95;
tur=((2-e)^2)/e; %Tortuisity of membrane
while ( abs(T5-T3)>1e-04 && abs(T6-T4)>1e-04)
T3=T5;
T4=T6;
Re_Nof=(den_f*uf*d_h)/mew_f; %Reynolds no at feed side
Re_Nop=(den_p*up*d_h)/mew_p; %Reynolds no at permeate side
Pr_Nof=(mew_f*Cp_f)/k_f; %Prandl no at feed side
Pr_Nop=(mew_p*Cp_p)/k_p; %Prandl no at permeate side
Nu_f=1.86*(Re_Nof*Pr_Nof*d_h/L)^0.33; %Nusselt no at feed
```

```
side
Nu_p=1.86*(Re_Nop*Pr_Nop*d_h/L)^0.33; %Nusslet no at
permeate side
h_f=Nu_f*k_f/d_h; %Heat transfer coefficent at
feed side
h_p=Nu_p*k_p/d_h; %Heat transfer coefficent at
permeate side
C= [((3*tur*tck)/(2*e*d))*(((3.14*R*T)/(8*M))^0.5)+
((tur*tck)/(e))*((P_a/P_d))*((R*T)/M)]^(-1);
P_mf= exp(23.238-3841/(T3-45)); %vapour pressure at
membrane
feed side
P_mp= exp(23.238-3841/(T4-45)); %Vapour pressure at
membrane
permeate side
J(i)= C*(P_mf-P_mp); %Permeate flux
T5=(h_m*(T_bp+(h_f/h_p)*T_bf)+h_f*T_bf-
J(i)*Hv)/(h_m+h_f*(1+h_m/h_p));
%Membrane feed side temperature
T6=(h_m*(T_bf+(h_p/h_f)*T_bp)+h_p*T_bp+J(i)*Hv)/(h_m+h_p*(1
+h_m/h_f));
%Membrane permeate side temperature
end
J(i)= C*(P_mf-P_mp);
fprintf('Value of porosity = ')
disp (e);
fprintf('Value of C = ')
disp(C);
fprintf('Value of P_mf in Pascals = ')
disp(P_mf);
fprintf('Value of P_mp in Pascals= ')
```

```
disp(P_mp);
fprintf('Value of J in (kg/m^2*s) = ')
disp(J(i));
J_w(i)=J(i)*3600;
fprintf('Value of Permeate flux in (kg/m^2*hr) = ')
disp(J_w(i));
fprintf('Value of heat transfer coefficient at feed side =
')
disp(h_f);
fprintf('Value of heat transfer coefficient at permeate
side = ')
disp(h_p);
fprintf('Value of feed Membrane Temperature in Kelvin = ')
disp(T5);
fprintf('Value of permeate Membrane Temperature in Kelvin =
')
disp(T6);
fprintf('---------------------------------------------------
-----------
---------');
fprintf('\n');
E(i)=e;
i=i+1;
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
e=e+0.01;
end
plot(E,J_w,'--','linewidth',1.5,'color','b');
hold all
```

```
title('Effect of Porosity on Mass flux');
xlabel('Porosity');
ylabel('Mass flux in (kg/m^2*hr)');
grid on;
box on;
print -dmeta
clc
```

APPENDIX 4: CODE FOR FEED TEMPERATURE VARIATION

```
% VARIATION IN FEED TEMPERATURE
T_bp=input('enter first permeate temperature guess:');
%Enter first
guess of Bulk permeate temperature
T_bf=313;
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
k_m=0.259; %Thermal conductivity of Membrane(PTFE)
A=0.0300; %Surface Area of Membrane
LEP=100; %Liquid Entry pressure in KPa
CA=132; %Contact Angle in degree
P_bf=exp(23.328-3841/(T_bf-45)); %Bulk feed vapour pressure
P_bp=exp(23.328-3841/(T_bp-45)); %Bulk permeate vapour
pressure
tck=145e-06; %Thickness of Membrane in metres
d=0.22e-06; %Pore size in meters
M=18.02e-03; %Mass of water in kg/mole
e=0.85; %Porosity
uf=0.5; %Feed water velocity
up=0.5; %Permeate water velocity
d_h=3.4e-03; %Hydraulic diameter
mew_f=0.5470e-03; %Dynamic Viscocity of feed water at 50
degree
celcius(60 and 40)
mew_p=0.8900e-03; %Dynamic Viscocity of permeate water at
25 degree
celcius(30 and 20)
```

```
Cp_f=4182; %Specific heat of feed water at 50 degree
celcius
Cp_p=4182; %Specific heat of permeate water at 25 degree
celcius
k_f=0.64; %Thermal conductivity of feed water at 50 degree
celcius
k_p=0.59; %Thermal conductivity of permeate water at 25
degree celcius
den_f=988; %Density of feed water at 50 degree celcius
den_p=997.1; %Density of permeate water at 25 degree
celcius
L=200e-03; %Length of membrane
tur=((2-e)^2)/e; %Turtuisity of membrane
R=461.5; %Gas constant in J/(kg.K)
h_m=k_m/tck; %Membrane heat transfer coeffecient
i=1;
while T_bf<393;
T=(T_bf+T_bp)/2;
P_bf=exp(23.328-3841/(T_bf-45)); %Bulk feed vapour pressure
P_bp=exp(23.328-3841/(T_bp-45)); %Bulk permeate vapour
pressure
Hv=(1.7535*(T)+2024.3)*1000; %Latent heat of vaporization
P_a=(P_bf+P_bp)/2; %Based on absolute pressure at
temeprature of 20 and 60
P_d=(1.895e-05)*((T^(2.072)));
while ( abs(T5-T3)>1e-04 && abs(T6-T4)>1e-04)
T3=T5;
T4=T6;
Re_Nof=(den_f*uf*d_h)/mew_f; %Reynolds no at feed side
Re_Nop=(den_p*up*d_h)/mew_p; %Reynolds no at permeate side
Pr_Nof=(mew_f*Cp_f)/k_f; %Prandl no at feed side
```

```
Pr_Nop=(mew_p*Cp_p)/k_p; %Prandl no at permeate side
Nu_f=1.86*(Re_Nof*Pr_Nof*d_h/L)^0.33; %Nusselt no at feed
side
Nu_p=1.86*(Re_Nop*Pr_Nop*d_h/L)^0.33; %Nusslet no at
permeate side
h_f=Nu_f*k_f/d_h; %Heat transfer coeffecent at
feed side
h_p=Nu_p*k_p/d_h; %Heat transfer coeffecent at
permeate side
C= [((3*tur*tck)/(2*e*d))*(((3.14*R*T)/(8*M))^0.5)+
((tur*tck)/(e))*((P_a/P_d))*((R*T)/M)]^(-1);
P_mf= exp(23.238-3841/(T3-45)); %vapour pressure at
membrane
feed side
P_mp= exp(23.238-3841/(T4-45)); %Vapour pressure at
membrane
permeate side
J(i)= C*(P_mf-P_mp); %Permeate flux
T5=(h_m*(T_bp+(h_f/h_p)*T_bf)+h_f*T_bf-
J(i)*Hv)/(h_m+h_f*(1+h_m/h_p));
%Membrane feed side temperature
T6=(h_m*(T_bf+(h_p/h_f)*T_bp)+h_p*T_bp+J(i)*Hv)/(h_m+h_p*(1
+h_m/h_f));
%Membrane permeate side temperature
end
J(i)= C*(P_mf-P_mp);
fprintf('Value of feed Temperature = ')
disp (T_bf);
fprintf('Value of C = ')
disp(C);
fprintf('Value of P_mf in Pascals = ')
```

```
disp(P_mf);
fprintf('Value of P_mp in Pascals= ')
disp(P_mp);
fprintf('Value of J in (kg/m^2*s) = ')
disp(J(i));
J_w(i)=J(i)*3600;
fprintf('Value of Permeate flux in (kg/m^2*hr) = ')
disp(J_w(i));
fprintf('Value of heat transfer coefficient at feed side =
')
disp(h_f);
fprintf('Value of heat transfer coefficient at permeate
side = ')
disp(h_p);
fprintf('Value of feed Membrane Temperature in Kelvin = ')
disp(T5);
fprintf('Value of permeate Membrane Temperature in Kelvin =
')
disp(T6);
fprintf('--------------------------------------------------
-----------
--------');
fprintf('\n');
T_fb(i)=T_bf;
T_bf=T_bf+5;
i=i+1;
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
end
```

```
plot(T_fb,J_w,'--','linewidth',1.5,'color','b');
hold all
title('Effect of Feed Bulk Temperature on Mass flux');
xlabel('Feed Bulk Temperature (K)');
ylabel('Mass flux (kg/m^2*hr)');
grid on;
box on;
print -dmeta
clc
```

APPENDIX 5: CODE FOR FEED VELOCITY VARIATION

```
% VARIATION IN FEED VELOCITY
T_bf=input('enter first feed temperature guess:'); %Enter
first
guess of Bulk feed temperature
T_bp=input('enter first permeate temperature guess:');
%Enter first
guess of Bulk permeate temperature
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
T=(T_bf+T_bp)/2; %Average of bulk feed and bulk permeate
temperature
i=1;
k_m=0.259; %Thermal conductivity of Membrane(PTFE)
A=0.0300; %Surface Area of Membrane
LEP=100; %Liquid Entry pressure in KPa
CA=132; %Contact Angle in degree
P_bf=exp(23.328-3841/(T_bf-45)); %Bulk feed vapour pressure
P_bp=exp(23.328-3841/(T_bp-45)); %Bulk permeate vapour
pressure
tck=145e-06; %Thickness of Membrane in metres
d=0.22e-06; %Pore size in meters
M=18.02e-03; %Mass of water in kg/mole
e=0.85; %Porosity
up=0.5; %Permeate water velocity
d_h=3.4e-03; %Hydraulic diameter
mew_f=0.5470e-03; %Dynamic Viscocity of feed water at 50
degree
```

```
celcius(60 and 40)
mew_p=0.8900e-03; %Dynamic Viscocity of permeate water at
25 degree
celcius(30 and 20)
Cp_f=4182; %Specific heat of feed water at 50 degree
celcius
Cp_p=4182; %Specific heat of permeate water at 25 degree
celcius
k_f=0.64; %Thermal conductivity of feed water at 50 degree
celcius
k_p=0.59; %Thermal conductivity of permeate water at 25
degree celcius
den_f=988; %Density of feed water at 50 degree celcius
den_p=997.1; %Density of permeate water at 25 degree
celcius
L=200e-03; %Length of membrane
uf=0.1; %Feed velocity
tur=((2-e)^2)/e; %Turtuisity of membrane
R=461.5; %Gas constant in J/(kg.K)
h_m=k_m/tck; %Membrane heat transfer coeffecient
Hv=(1.7535*(T)+2024.3)*1000; %Latent heat of vaporization
P_a=(P_bf+P_bp)/2; %Based on absolute pressure at
temeprature of 20 and 60
P_d=(1.895e-05)*((T^(2.072)));
i=1;
while uf<1;
while ( abs(T5-T3)>1e-04 && abs(T6-T4)>1e-04)
T3=T5;
T4=T6;
Re_Nof=(den_f*uf*d_h)/mew_f; %Reynolds no at feed side
Re_Nop=(den_p*up*d_h)/mew_p; %Reynolds no at permeate side
```

```
Pr_Nof=(mew_f*Cp_f)/k_f; %Prandl no at feed side
Pr_Nop=(mew_p*Cp_p)/k_p; %Prandl no at permeate side
Nu_f=1.86*(Re_Nof*Pr_Nof*d_h/L)^0.33; %Nusselt no at feed
side
Nu_p=1.86*(Re_Nop*Pr_Nop*d_h/L)^0.33; %Nusslet no at
permeate side
h_f=Nu_f*k_f/d_h; %Heat transfer coefficent at
feed side
h_p=Nu_p*k_p/d_h; %Heat transfer coefficent at
permeate side
C= [((3*tur*tck)/(2*e*d))*(((3.14*R*T)/(8*M))^0.5)+
((tur*tck)/(e))*((P_a/P_d))*((R*T)/M)]^(-1);
P_mf= exp(23.238-3841/(T3-45)); %vapour pressure at
membrane
feed side
P_mp= exp(23.238-3841/(T4-45)); %Vapour pressure at
membrane
permeate side
J(i)= C*(P_mf-P_mp); %Permeate flux
T5=(h_m*(T_bp+(h_f/h_p)*T_bf)+h_f*T_bf-
J(i)*Hv)/(h_m+h_f*(1+h_m/h_p));
%Membrane feed side temperature
T6=(h_m*(T_bf+(h_p/h_f)*T_bp)+h_p*T_bp+J(i)*Hv)/(h_m+h_p*(1
+h_m/h_f));
%Membrane permeate side temperature
end
J(i)= C*(P_mf-P_mp);
fprintf('Value of feed velocity = ')
disp (uf);
fprintf('Value of C = ')
disp(C);
```

```
fprintf('Value of P_mf in Pascals = ')
disp(P_mf);
fprintf('Value of P_mp in Pascals= ')
disp(P_mp);
fprintf('Value of J in (kg/m^2*s) = ')
disp(J(i));
J_w(i)=J(i)*3600;
fprintf('Value of Permeate flux in (kg/m^2*hr) = ')
disp(J_w(i));
fprintf('Value of heat transfer coefficient at feed side =
')
disp(h_f);
fprintf('Value of heat transfer coefficient at permeate
side = ')
disp(h_p);
fprintf('Value of feed Membrane Temperature in Kelvin = ')
disp(T5);
fprintf('Value of permeate Membrane Temperature in Kelvin =
')
disp(T6);
fprintf('--------------------------------------------------
-----------
--------');
fprintf('\n');
Uf(i)=uf;
uf=uf+0.2;
i=i+1;
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
```

```
end
plot(Uf,J_w,'--','linewidth',1.5,'color','b');
hold all
title('Effect of Feed velocity on Mass flux');
xlabel('feed velocity (m/s)');
ylabel('Mass flux in (kg/m^2*hr)');
grid on;
box on;
print -dmeta
clc
```

APPENDIX 6: CODE FOR THICKNESS VARIATION

```
% THICKNESS VARIATION
T_bf=input('enter first feed temperature guess:'); %Enter
first
guess of Bulk feed temperature
T_bp=input('enter first permeate temperature guess:');
%Enter first
guess of Bulk permeate temperature
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
T=(T_bf+T_bp)/2; %Average of bulk feed and bulk permeate
temperature
i=1;
k_m=0.259; %Thermal conductivity of Membrane(PTFE)
A=0.0300; %Surface Area of Membrane
LEP=100; %Liquid Entry pressure in KPa
CA=132; %Contact Angle in degree
P_bf=exp(23.328-3841/(T_bf-45)); %Bulk feed vapour pressure
P_bp=exp(23.328-3841/(T_bp-45)); %Bulk permeate vapour
pressure
tck=20e-06; %Thickness of Membrane in metres
d=0.22e-06; %Pore size in meters
M=18.02e-03; %Mass of water in kg/mole
uf=0.5; %Feed water velocity
up=0.5; %Permeate water velocity
d_h=3.4e-03; %Hydraulic diameter
mew_f=0.5470e-03; %Dynamic Viscocity of feed water at 50
degree
```

```
celcius(60 and 40)
mew_p=0.8900e-03; %Dynamic Viscocity of permeate water at
25 degree
celcius(30 and 20)
Cp_f=4182; %Specific heat of feed water at 50 degree
celcius
Cp_p=4182; %Specific heat of permeate water at 25 degree
celcius
k_f=0.64; %Thermal conductivity of feed water at 50 degree
celcius
k_p=0.59; %Thermal conductivity of permeate water at 25
degree celcius
den_f=988; %Density of feed water at 50 degree celcius
den_p=997.1; %Density of permeate water at 25 degree
celcius
L=200e-03; %Length of membrane
e=0.85;
R=461.5; %Gas constant in J/(kg.K)
tur=((2-e)^2)/e; %Tortuisity of membrane
Hv=(1.7535*(T)+2024.3)*1000; %Latent heat of vaporization
P_a=(P_bf+P_bp)/2; %Based on absolute pressure at
temeprature of 20 and 60
P_d=(1.895e-05)*((T^(2.072)));
i=1;
while tck<202e-06;
h_m=k_m/tck; %Membrane heat transfer coeffecient
while ( abs(T5-T3)>1e-04 && abs(T6-T4)>1e-04)
T3=T5;
T4=T6;
Re_Nof=(den_f*uf*d_h)/mew_f; %Reynolds no at feed side
Re_Nop=(den_p*up*d_h)/mew_p; %Reynolds no at permeate side
```

```
Pr_Nof=(mew_f*Cp_f)/k_f; %Prandl no at feed side
Pr_Nop=(mew_p*Cp_p)/k_p; %Prandl no at permeate side
Nu_f=1.86*(Re_Nof*Pr_Nof*d_h/L)^0.33; %Nusselt no at feed
side
Nu_p=1.86*(Re_Nop*Pr_Nop*d_h/L)^0.33; %Nusslet no at
permeate side
h_f=Nu_f*k_f/d_h; %Heat transfer coefficent at
feed side
h_p=Nu_p*k_p/d_h; %Heat transfer coefficent at
permeate side
C= [((3*tur*tck)/(2*e*d))*(((3.14*R*T)/(8*M))^0.5)+
((tur*tck)/(e))*((P_a/P_d))*((R*T)/M)]^(-1);
P_mf= exp(23.238-3841/(T3-45)); %vapour pressure at
membrane
feed side
P_mp= exp(23.238-3841/(T4-45)); %Vapour pressure at
membrane
permeate side
J(i)= C*(P_mf-P_mp); %Permeate flux
T5=(h_m*(T_bp+(h_f/h_p)*T_bf)+h_f*T_bf-
J(i)*Hv)/(h_m+h_f*(1+h_m/h_p));
%Membrane feed side temperature
T6=(h_m*(T_bf+(h_p/h_f)*T_bp)+h_p*T_bp+J(i)*Hv)/(h_m+h_p*(1
+h_m/h_f));
%Membrane permeate side temperature
end
J(i)= C*(P_mf-P_mp);
fprintf('Value of porosity = ')
disp (e);
fprintf('Value of C = ')
disp(C);
```

```
fprintf('Value of P_mf in Pascals = ')
disp(P_mf);
fprintf('Value of P_mp in Pascals= ')
disp(P_mp);
fprintf('Value of J in (kg/m^2*s) = ')
disp(J(i));
J_w(i)=J(i)*3600;
fprintf('Value of Permeate flux in (kg/m^2*hr) = ')
disp(J_w(i));
fprintf('Value of heat transfer coefficient at feed side =
')
disp(h_f);
fprintf('Value of heat transfer coefficient at permeate
side = ')
disp(h_p);
fprintf('Value of feed Membrane Temperature in Kelvin = ')
disp(T5);
fprintf('Value of permeate Membrane Temperature in Kelvin =
')
disp(T6);
fprintf('--------------------------------------------------
-----------
---------');
fprintf('\n');
TCK(i)=tck;
i=i+1;
T3=0;
T4=0;
T5=T_bf;
T6=T_bp;
tck=tck+10e-06;
```

```
end
plot(TCK,J_w,'--','linewidth',1.5,'color','b');
hold all
title('Effect of Thickness of membrane on Mass flux');
xlabel('Thickness (m)');
ylabel('Mass flux in (kg/m^2*hr)');
grid on;
box on;
print -dmeta
clc
```

APPENDIX 7: CODE FOR DAQ USING ARDUINO MEGA

```
#include <SPI.h>

#include <Wire.h>

#include <LiquidCrystal.h>

#include <max6675.h>

//==========Thermocouple1=============================

int SO = 7;

int CS = 6;

int CLK = 5;

//========Thermocouple2========================

int S1 = 8;

int CS1 = 9;

int CLK1 = 10;

//======thermocouple3===================================

int S2 = 28;

int CS2 = 30;

int CLK2 = 32;

//==========Thermocouple4============================

int S3 = 22;

int CS3 = 24;

int CLK3 = 26;


//================
```

```
MAX6675 temp(CLK,CS,SO);
MAX6675 temp1(CLK1,CS1,S1);
MAX6675 temp2(CLK2,CS2,S2);
MAX6675 temp3(CLK3,CS3,S3);
//=====temp intialize============================

LiquidCrystal lcd (8,9,10,11,12,13);
//===========Flow Rate1=============

byte statusLed    = 13;

byte sensorInterrupt = 0;  // 0 = digital pin 2
byte sensorPin       = 2;

float calibrationFactor = 4.5;

volatile byte pulseCount;

float flowRate;
unsigned int flowMilliLitres;
unsigned long totalMilliLitres;

unsigned long oldTime;
//======FlowRate1==========
```

```
byte statusLed1    = 40;


//===Flowrate2=============================

byte sensorInterrupt1 = 1;

byte sensorPin1  = 3;

//=========================================================

===========================================================

===========================

//==============

float calibrationFactor1= 4.5;


volatile byte pulseCount1;


float flowRate1;




unsigned int flowMilliLitres1;

unsigned long totalMilliLitres1;


unsigned long oldTime1;


void setup()

{
```

```
  // Initialize a serial connection for reporting values to
the host

  Serial.begin(9600);

    lcd.begin(16,2);

  delay(500);

  // Set up the status LED line as an output

  pinMode(statusLed, OUTPUT);

  digitalWrite(statusLed, HIGH);  // We have an active-low
LED attached


  pinMode(sensorPin, INPUT);

  digitalWrite(sensorPin, HIGH);

   pinMode(sensorPin1, INPUT);

  digitalWrite(sensorPin1, HIGH);


  pulseCount        = 0;

  flowRate          = 0.0;

  flowMilliLitres   = 0;

  totalMilliLitres  = 0;

  oldTime           = 0;


pulseCount1        = 0;

  flowRate1          = 0.0;

  flowMilliLitres1   = 0;
```

```
  totalMilliLitres1  = 0;
  oldTime1           = 0;

  // The Hall-effect sensor is connected to pin 2 which
uses interrupt 0.
  // Configured to trigger on a FALLING state change
(transition from HIGH
  // state to LOW state)
  attachInterrupt(sensorInterrupt, pulseCounter, FALLING);
  attachInterrupt(sensorInterrupt1, pulseCounter1,
FALLING);
}

/**
 * Main program loop
 */
void loop()
{
   if((millis() - oldTime) > 1000)
  {

    detachInterrupt(sensorInterrupt);

    flowRate = ((1000.0 / (millis() - oldTime)) *
pulseCount) / calibrationFactor;
```

```
    oldTime = millis();

    flowMilliLitres = (flowRate / 60) * 1000;



    totalMilliLitres += flowMilliLitres;

    unsigned int frac;
    pulseCount = 0;
     attachInterrupt(sensorInterrupt1, pulseCounter1,
FALLING);

    // Reset the pulse counter so we can start incrementing
again
  }
    //===flowrate2===============
    if((millis() - oldTime1) > 1000)
  {

    detachInterrupt(sensorInterrupt1);

    flowRate1 = ((1000.0 / (millis() - oldTime1)) *
pulseCount1) / calibrationFactor1;
```

```
    oldTime1 = millis();

    flowMilliLitres1 = (flowRate1 / 60) * 1000;

    totalMilliLitres1 += flowMilliLitres1;

    unsigned int frac1;

    pulseCount1 = 0;

    attachInterrupt(sensorInterrupt1, pulseCounter1,
FALLING);
  }
  Serial.print("\nThermocouple 1 readings\n");
  Serial.print("Cel.:");
  Serial.println(temp.readCelsius());
  Serial.print("Far.:");
  Serial.println((temp.readCelsius()*9/5)+32);
  delay(2000);

  Serial.print("Thermocouple 2 readings\n");
  Serial.print("Cel.:");
  Serial.println(temp1.readCelsius());
```

```
  Serial.print("Far.:");
  Serial.println((temp1.readCelsius()*9/5)+32);
  delay(1000);

  Serial.print("Thermocouple 3 readings\n");
  Serial.print("Cel.:");
  Serial.println(temp2.readCelsius());
  Serial.print("Far.:");
  Serial.println((temp2.readCelsius()*9/5)+32);
  delay(1000);

 Serial.print("Thermocouple 4 readings\n");
 Serial.print("Cel.:");
  Serial.println(temp3.readCelsius());
  Serial.print("Far.:");
  Serial.println((temp3.readCelsius()*9/5)+32);
  Serial.print("\n");
  delay(1000);
Serial.print("---------------------------------------------
-------------------------------------------------\n");
    // Print the flow rate for this second in litres /
minute
    Serial.print("Flow rate: ");
```

```
    Serial.print(int(flowRate));  // Print the integer part
of the variable
    Serial.print("L/min");
    Serial.print("\t");       // Print tab space

    // Print the cumulative total of litres flowed since
starting
    Serial.print("Output Liquid Quantity: ");
    Serial.print(totalMilliLitres);
    Serial.println("mL");
    Serial.print("\t");       // Print tab space
  Serial.print(totalMilliLitres/1000);
  Serial.print("L");
  delay(2000);
  Serial.print("\n-------------------------\n");
  // Print the flow rate for this second in litres / minute
    Serial.print("Flow rate 2: ");
    Serial.print(int(flowRate1));  // Print the integer
part of the variable
    Serial.print("L/min");
    Serial.print("\t");       // Print tab space

    // Print the cumulative total of litres flowed since
starting
    Serial.print("Output Liquid Quantity: ");
```

```
    Serial.print(totalMilliLitres1);
    Serial.println("mL");
    Serial.print("\t");       // Print tab space
  Serial.print(totalMilliLitres1/1000);
  Serial.print("L");
  delay(2000);

    Serial.print("\n----------------------------------------
--Reading again--------\n");

}
/*
Insterrupt Service Routine
 */
void pulseCounter()
{
  // Increment the pulse counter
  pulseCount++;
}
void pulseCounter1()
{
  // Increment the pulse counter
  pulseCount1++;
}
```