جامعة الملك فهد للبترول والمعادن
King Fahd University of Petroleum & Minerals

Water Arabia 2015

Water Desalination Using Membrane Distillation "KFUPM Experience"

Atia Khalifa

Assistant Professor
Mechanical Engineering Department
King Fahd University of Petroleum & Minerals (KFUPM)
Dhahran city, Kingdom of Saudi Arabia

18 Feb., 2015

Objectives

1. Introduce the MD technique
2. Show the KFUPM activities
3. Share some results
4. Future plans

Energy Water Nexus

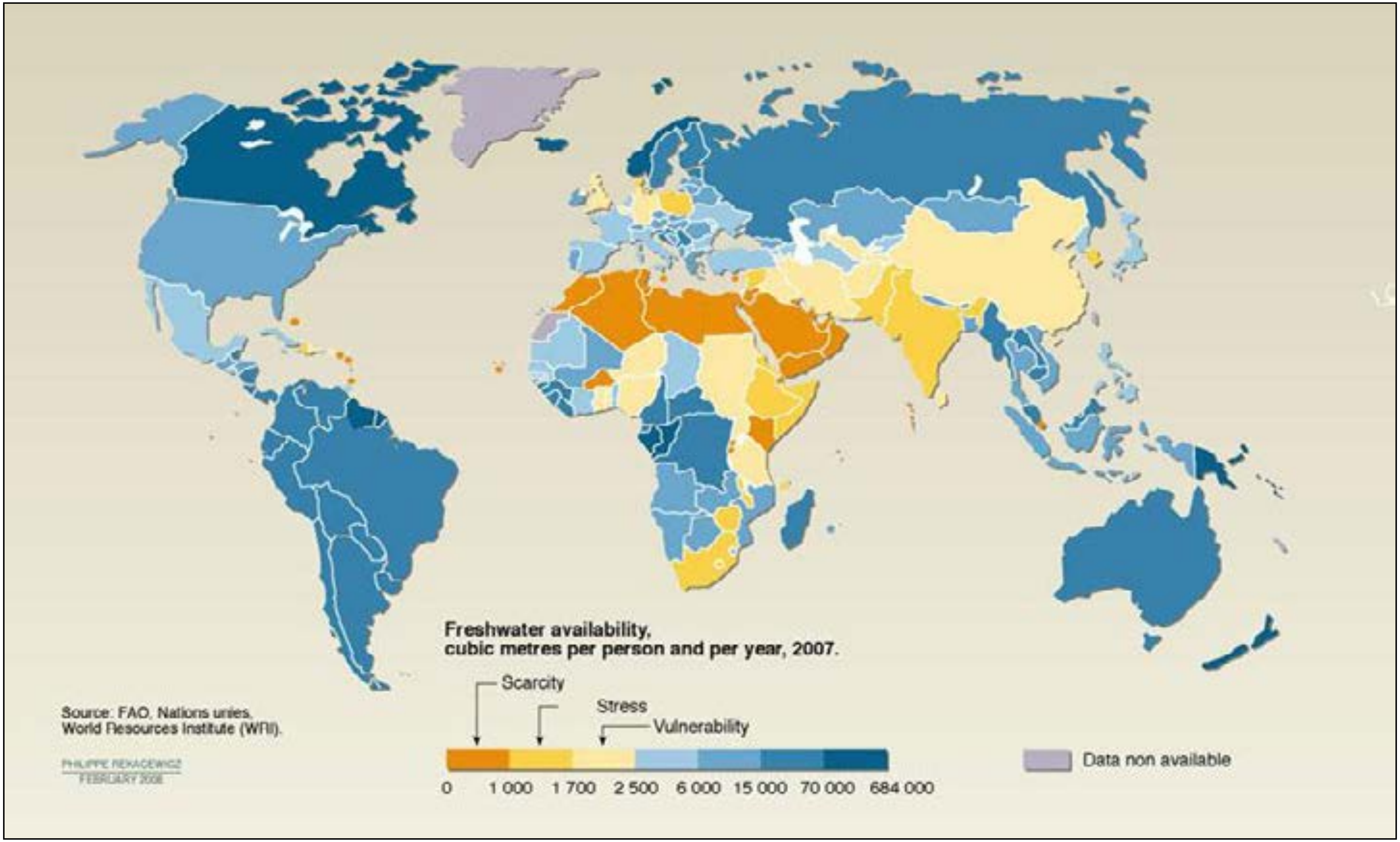
Energy & Water: Basic Ingredients of Modern Society.

Population ↑ Conventional Energy & Water Resources ↓

Alternative Sources for Energy (Solar, Wind, Geothermal, Nuclear, etc.)

Alternative Sources of fresh Water ==➔ Desalination

Water Scarcity

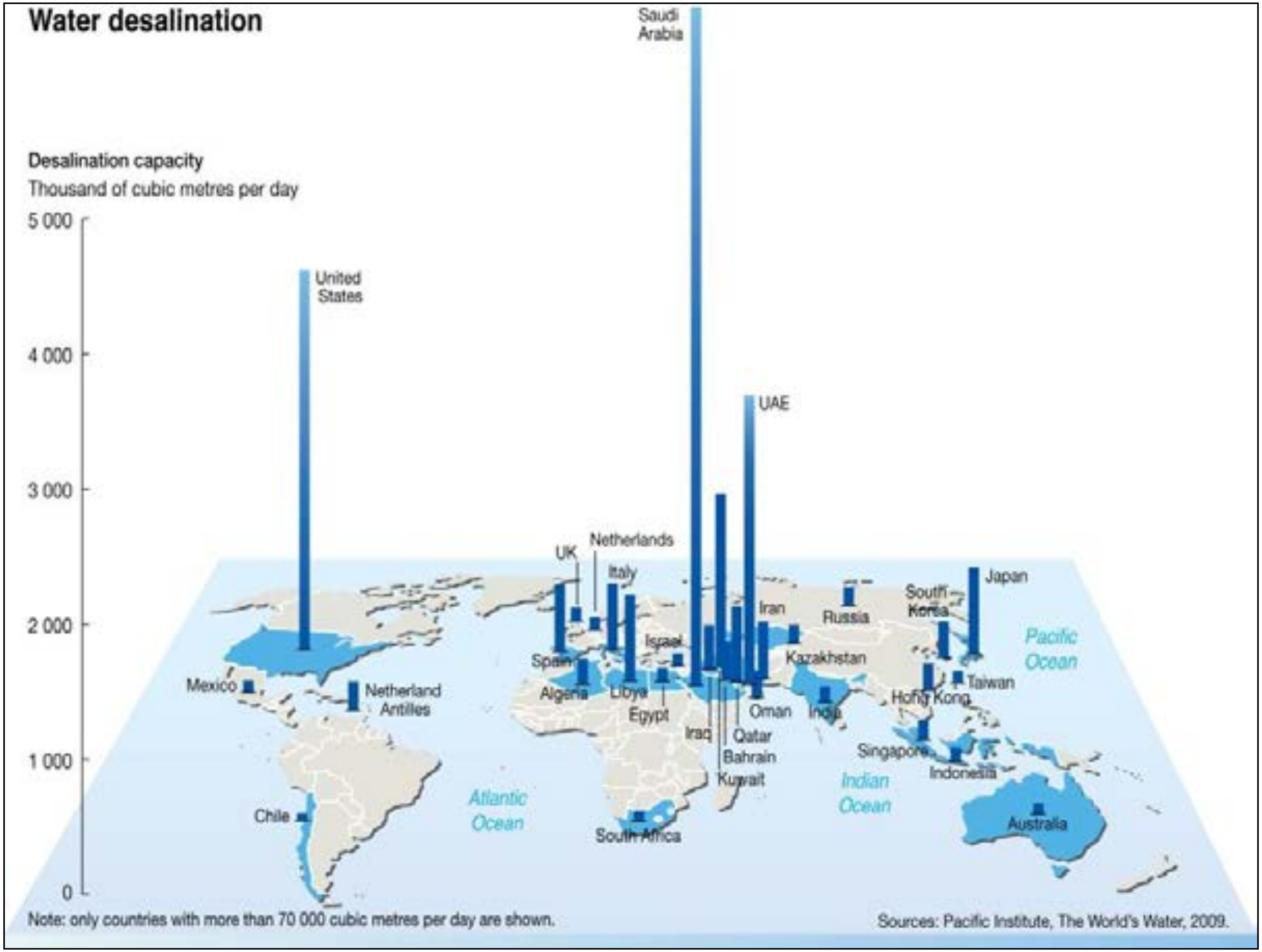


Freshwater availability,
cubic metres per person and per year, 2007.

Source: FAO, Nations unies,
World Resources Institute (WRI).

PHILIPPE REKACEWICZ
FEBRUARY 2008

Production of desalinated water



Note: only countries with more than 70 000 cubic metres per day are shown.

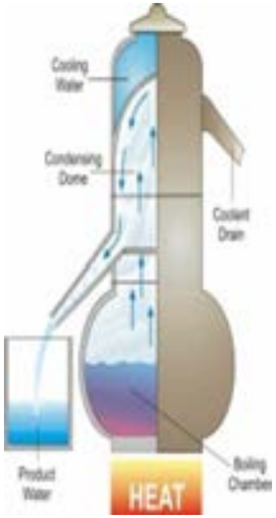
Sources: Pacific Institute, The World's Water, 2009.

DESALINATION

refers to any processes that remove some amount of salt and other minerals from saline water to obtain clean water, suitable for human consumption, irrigation and industrial uses.

- **Thermal Desalination**
- **Membrane Desalination**

1. Thermal Desalination Processes



It is the most widely used desalination techniques in the world.

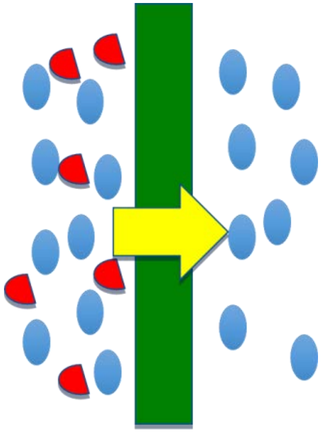
In thermal desalination, the specific amount of heat is provided to boil the water.

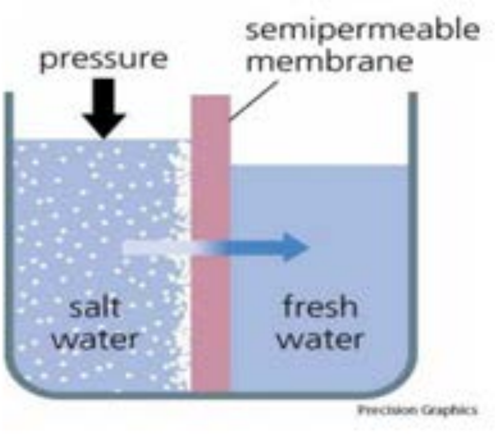
Examples:

- Multi-Stage Flash (MSF) Desalination
- Multi Effect Distillation (MED)

2. Membrane Desalination: **Reverse Osmosis**

Forcing a solvent from a region of high solute concentration through a semipermeable membrane to a region of low solute concentration by applying a pressure in excess of the osmotic pressure.





Reasons of Change

- **High consumption of non-renewable energy:**

we are looking for new techniques or processes with lower energy consumptions.

- **High cost**

Capitals and running cost (maintenance and operations) are very high. New designs and/or technologies may be cheaper and more compact.

- **Pollution**

Environmental concerns

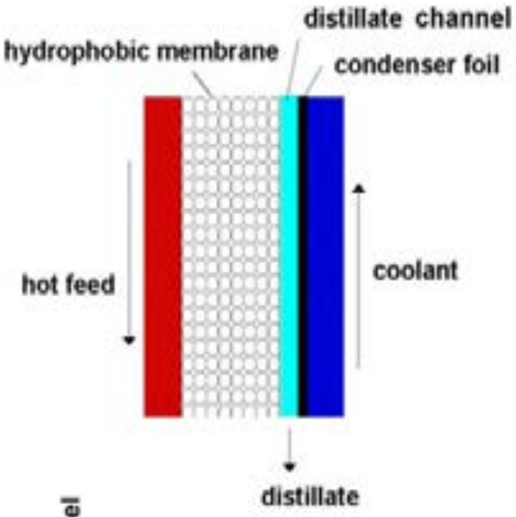
Emerging Desalination Technologies

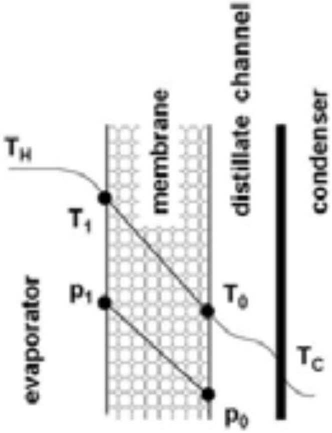
- Membrane Distillation
- Forward Osmosis
- Dew Evaporation
- Nano-Desalination
- Thermo-Ionic Desalination Process
- Low Temperature Thermal Desalination
- Capacitive Deionization (CDI)
- Solar Desalination
- Geothermal Desalination

Membrane Distillation (MD)

MD is a thermally driven membrane technique for separating water vapor from a saline solution using a micro-porous hydrophobic membrane.

- A hot, saline feed stream is passed over a micro-porous hydrophobic membrane.
- The temperature difference between the two sides of the membrane leads to a vapor pressure difference.
- This causes water vapor in the hot feed side to pass through the membrane pores, and condense either on the cold side of the membrane, directly or in an external condenser.
- The hydrophobicity of the membrane keeps the liquid from passing through the pores.

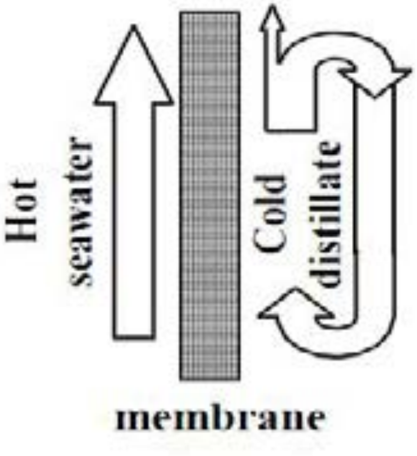




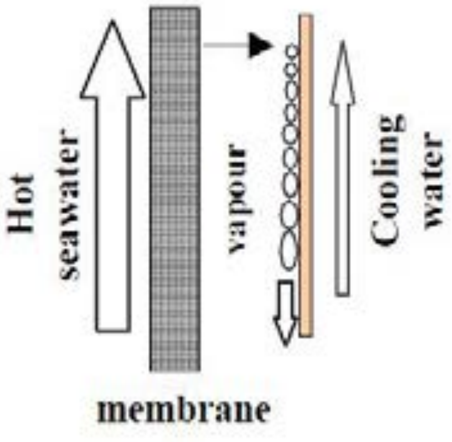
Why MD?

- Lower operating temperatures (40^0C – 90^0C).
- Possibility to use waste heat and renewable energy like solar energy (Solar heating can be easily applied in Saudi Arabia).
- Lower operating hydrostatic pressures.
- High salt rejection factors (we got 99.99%)
- Less demanding membrane characteristics.
- Membrane fouling in MD is less of a problem.
- No Extensive pretreatment is necessary.
- Compactness of Design

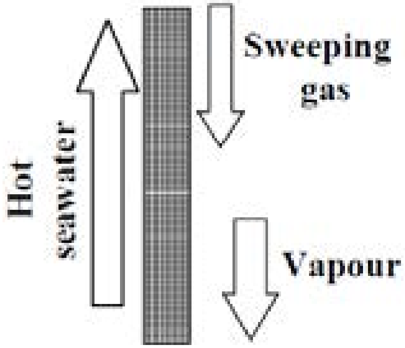
Basic Configuration of MD modules



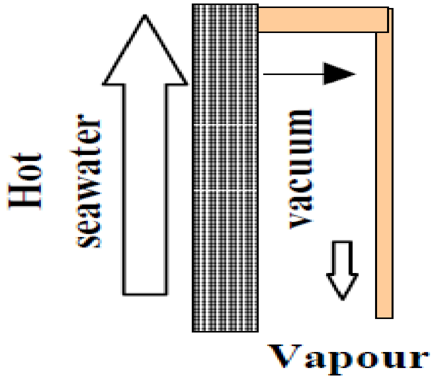
Direct Contact MD



Air Gap MD



Seeping Gas MD

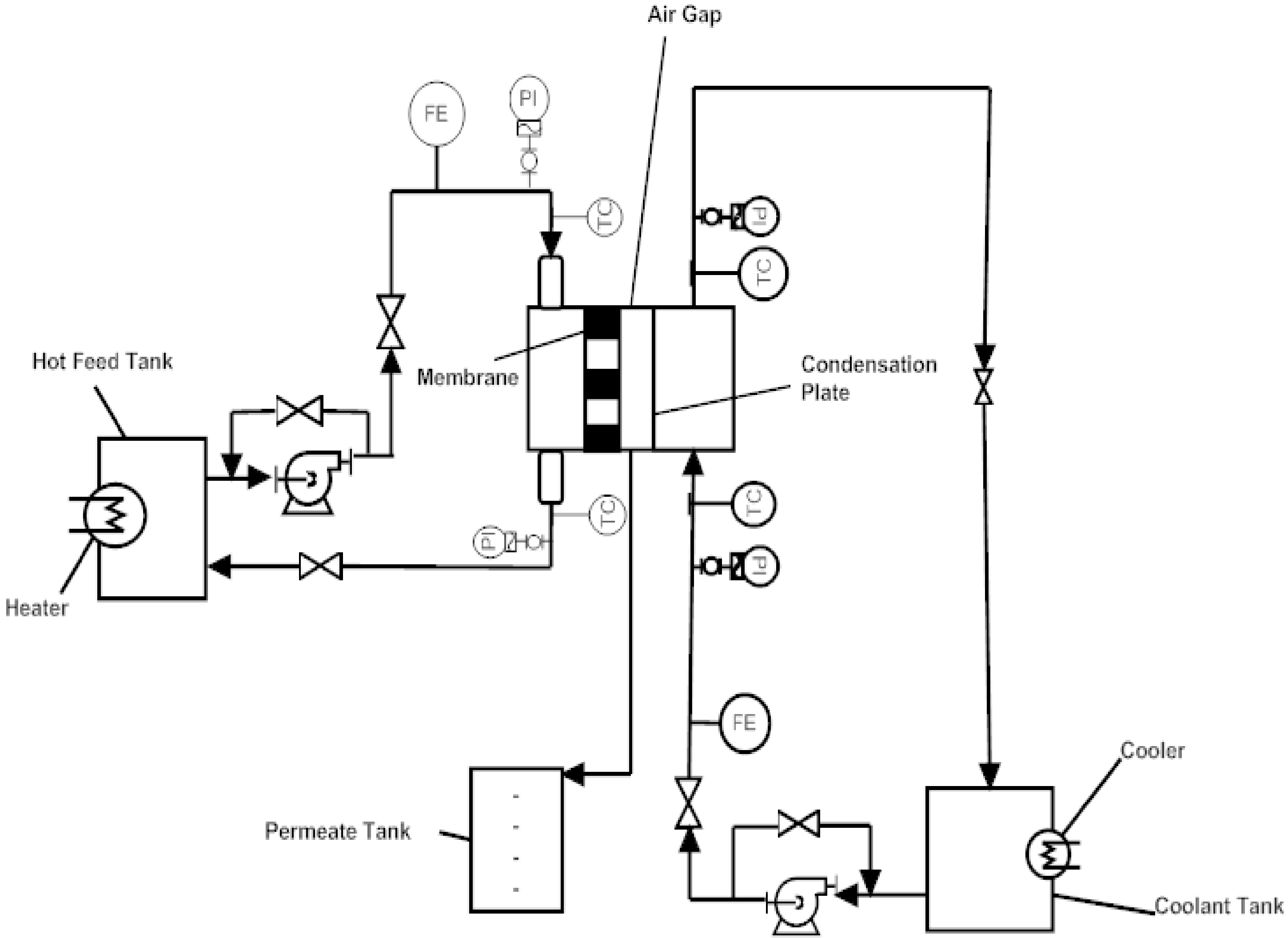


Vacuum MD

MD Research Activities at KFUPM

Undergraduate Students Work

Sep.2012 to Sep. 2013

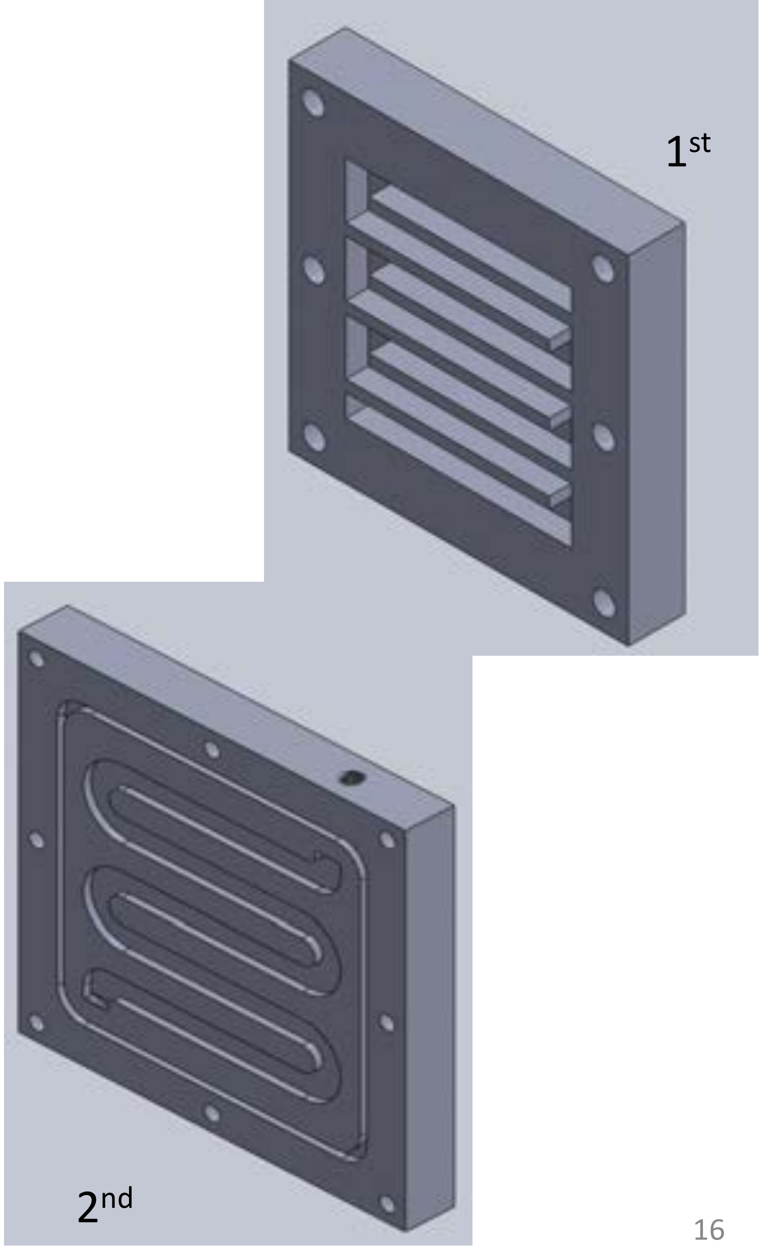


Design of Module

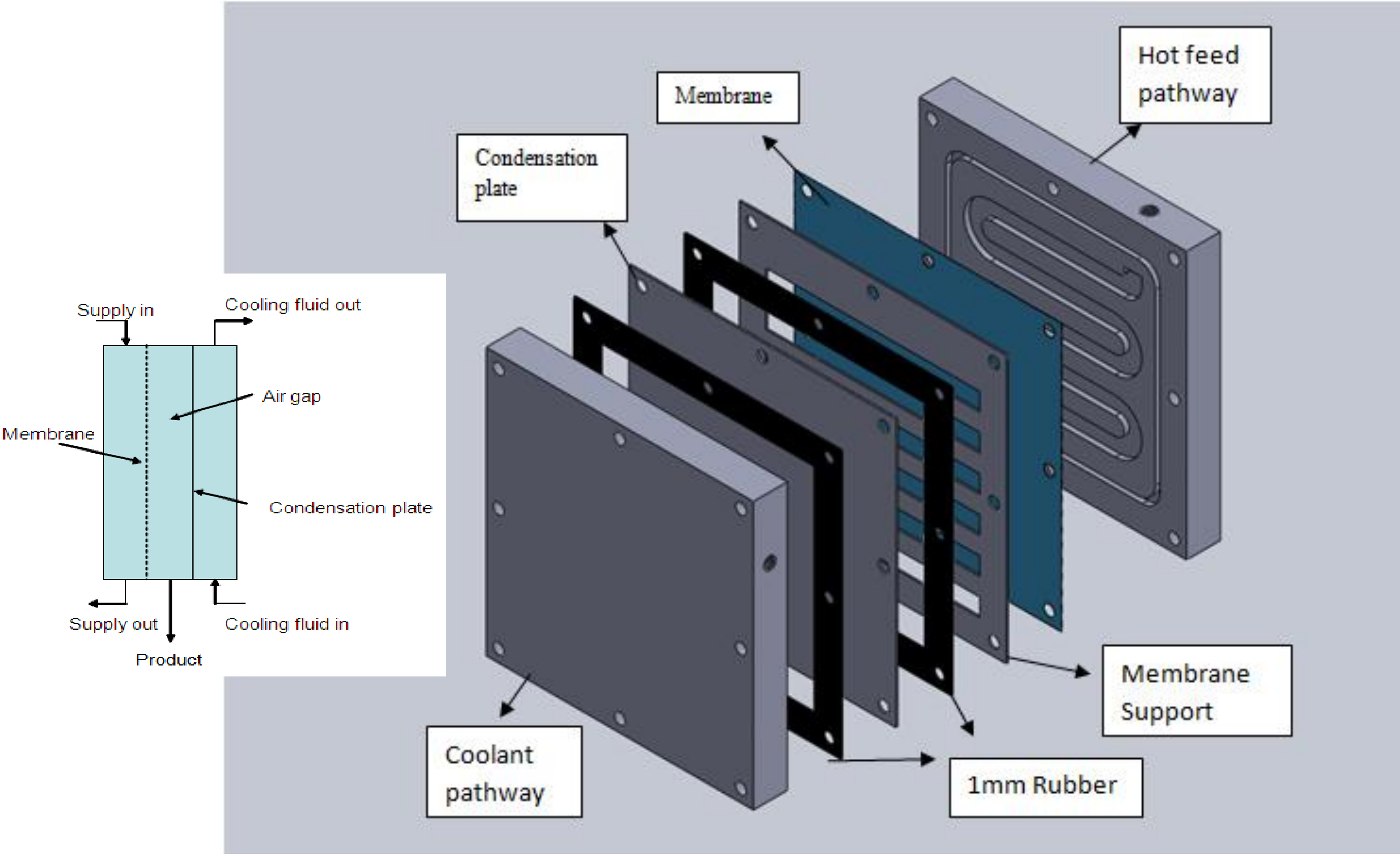
Criteria considered

- Pressure losses
- Good level of turbulence

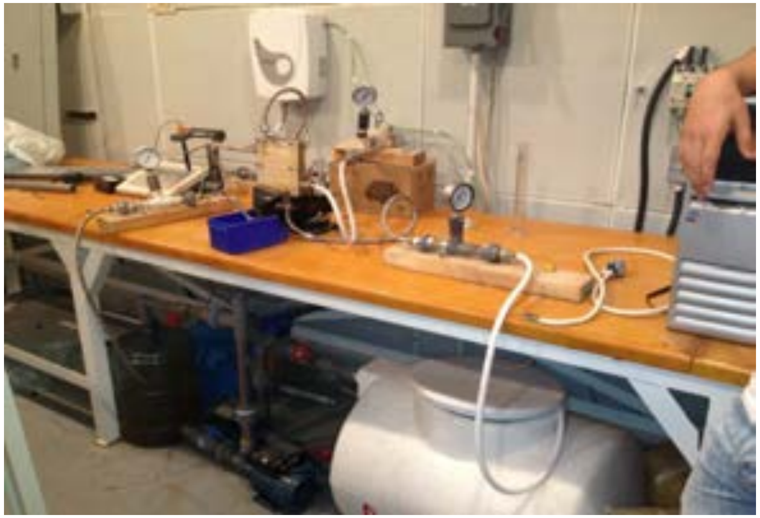
channel width 10 mm		dimensions in m	Temperature	20	
width =	1.00E-02	depth =	3.00E-03	length =	3.00E-01
Perimeter =	0.026	friction factor =	0.00425	D-hydrulic=	0.00461538
density=	998.2	viscosity=	1.002E-03	Area=	0.0000300
#	V (m/s)	flow Q (l/min)	Renolds No#	pressure drop (pa)	
1	0.55556	1	2,554.378	42.554	
2	1.11111	2	5,108.757	170.218	
3	1.66667	3	7,663.135	382.990	
4	2.22222	4	10,217.514	680.871	
5	2.77778	5	12,771.892	1,063.861	
6	3.33333	6	15,326.271	1,531.960	
7	3.88889	7	17,880.649	2,085.167	
8	4.44444	8	20,435.027	2,723.484	
9	5.00000	9	22,989.406	3,446.909	
10	5.55556	10	25,543.784	4,255.444	
11	6.11111	11	28,098.163	5,149.087	
12	6.66667	12	30,652.541	6,127.839	
13	7.22222	13	33,206.920	7,191.700	
14	7.77778	14	35,761.298	8,340.670	
15	8.33333	15	38,315.676	9,574.748	

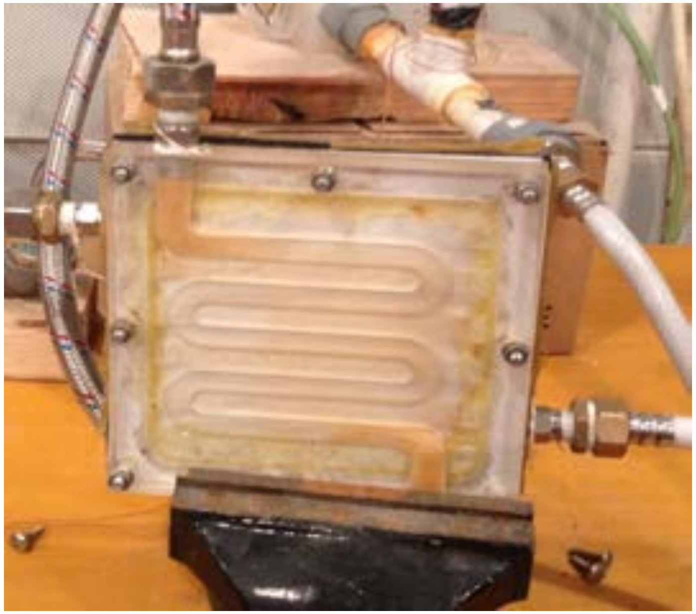


AGMD Cell

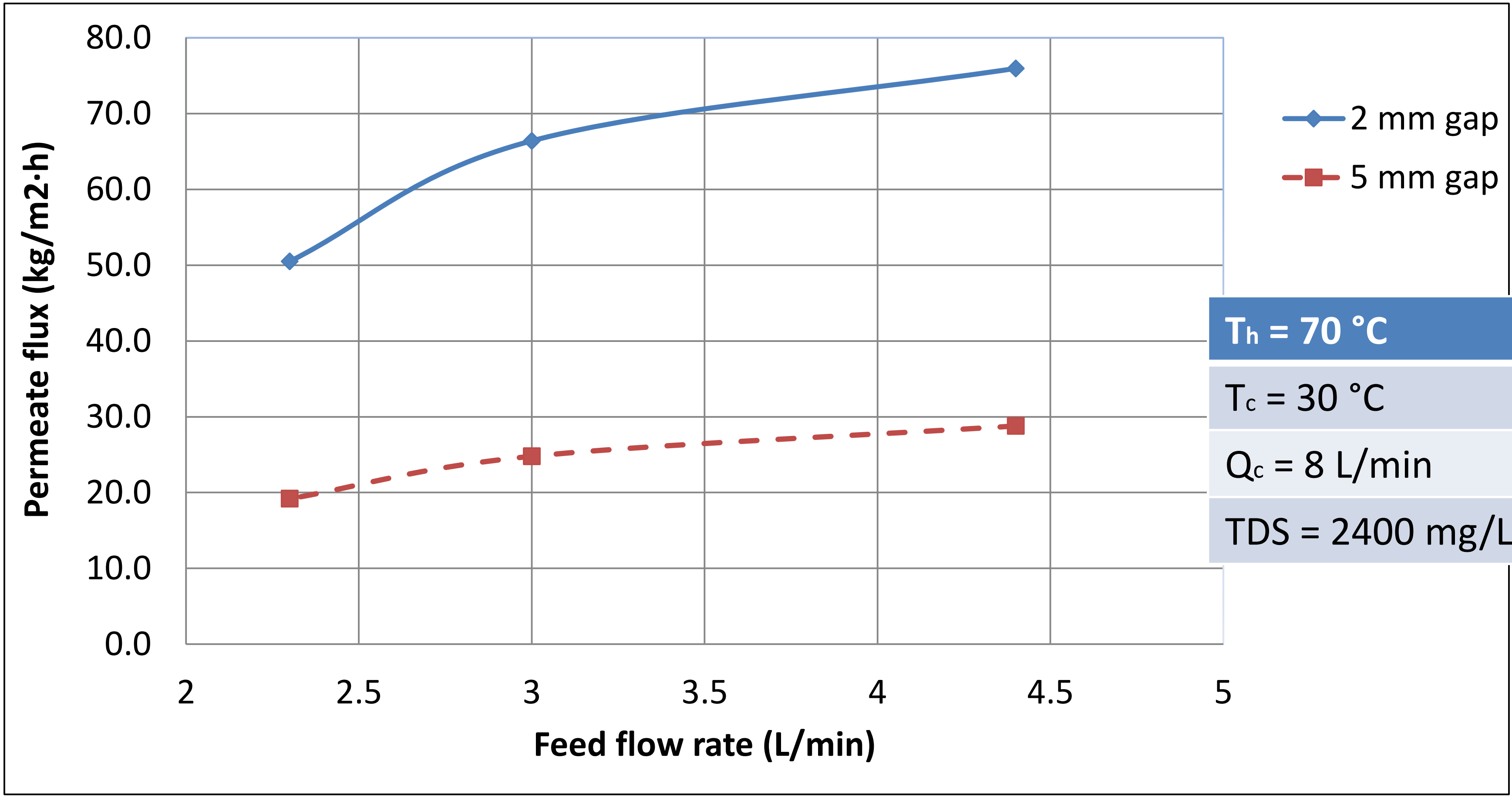

Supply in
Cooling fluid out
Air gap
Membrane
Condensation plate
Supply out
Product
Cooling fluid in
Condensation plate
Membrane
Hot feed pathway
Membrane Support
Coolant pathway
1mm Rubber

The MD setup and module





Effect of feed flow rate



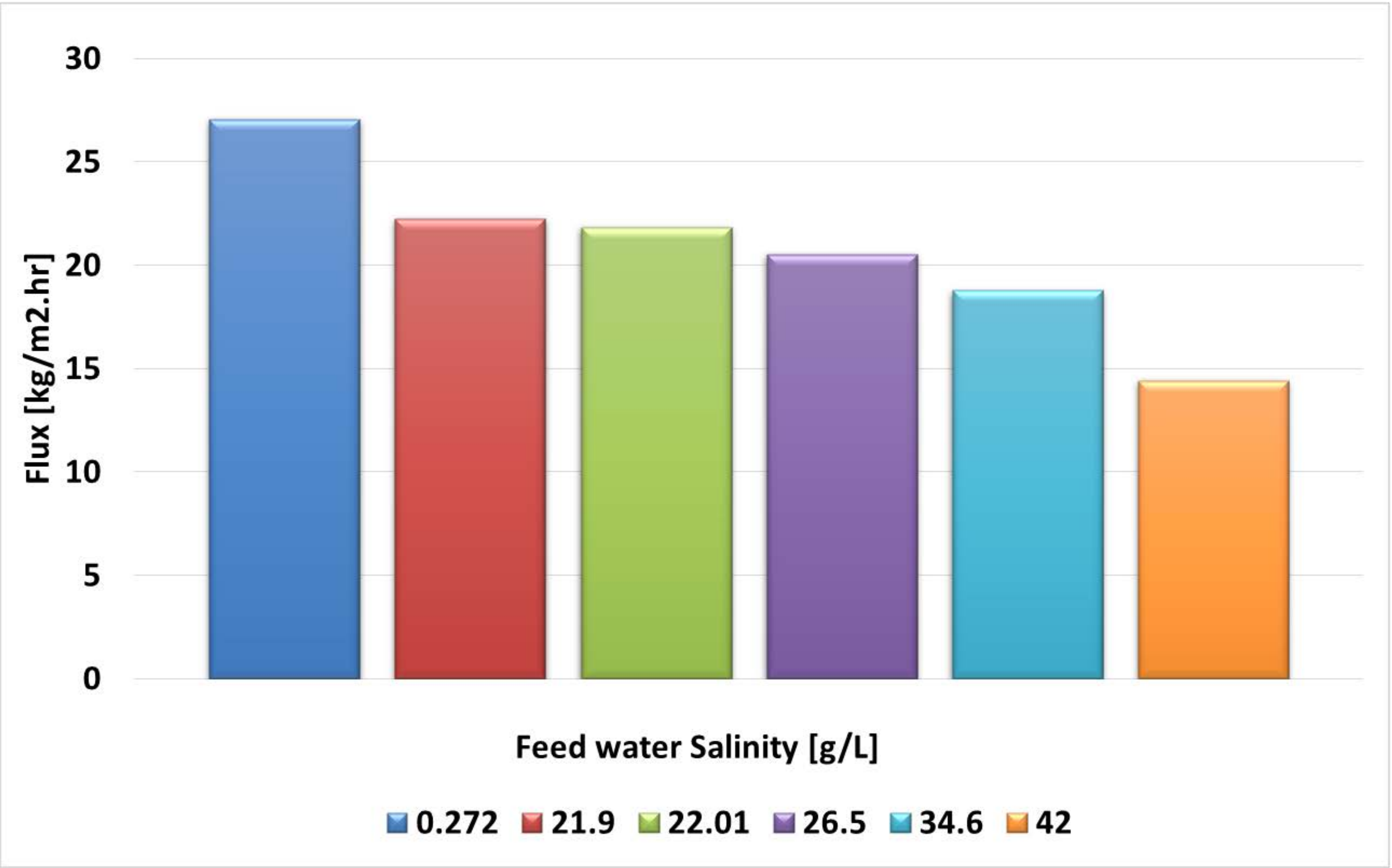
T_h = 70 °C

T_c = 30 °C

Q_c = 8 L/min

TDS = 2400 mg/L

Effect of Feed Water Salinity [g/L] on permeate flux



Academic year 2013-2014

Objective: get into details

- University funded project
- Theoretical analysis to predict the flux
- Design of the MD module and System
- Benchmark experimental data

Theoretical Analysis: DCMD

Mass Transfer

$$J_W \propto \Delta P_m$$

$$J_W = B_w \Delta P_m$$

$$J_W = B_w \left(P^{\circ}{}_{mf} - P^{\circ}{}_{mp}\right)$$

$$p^{0}{}_{wf} = exp\left(\left(23.1964\right) - \frac{3816.44}{T_{mf} - 46.13}\right)$$

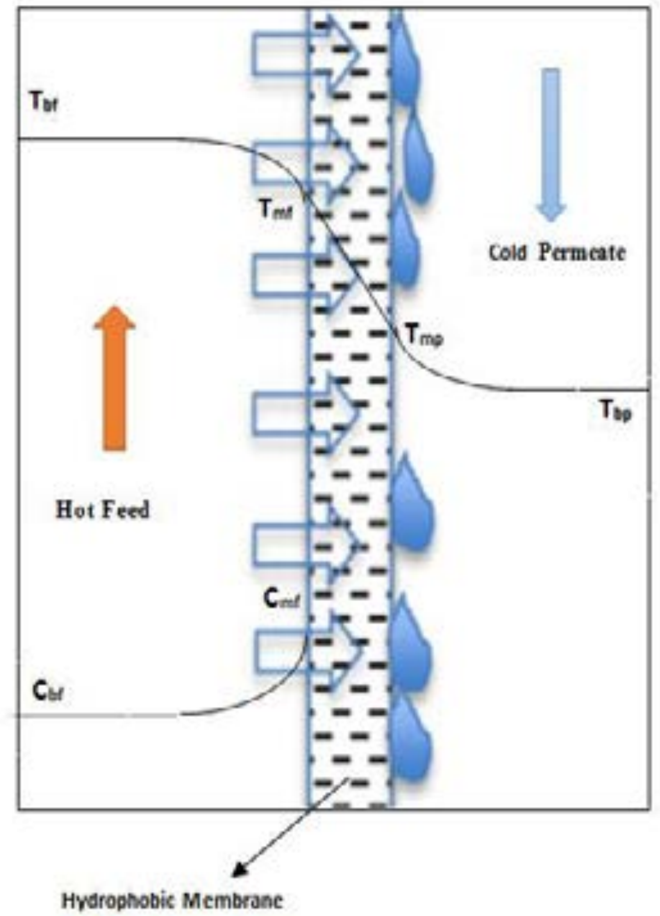
Antoine equation

$$p^{0}{}_{wp} = exp\left(\left(23.1964\right) - \frac{3816.44}{T_{mp} - 46.13}\right)$$

OR

$$P^{\circ}{}_{mf} - P^{\circ}{}_{mp} = \left(\frac{dP}{dT}\right)_{T_m} \left(T_{mf} - T_{mp}\right)$$

$$J_W = B_W \left(\frac{dP}{dT}\right)_{T_m} \left(T_{mf} - T_{mp}\right)$$



B_w is based on Knudsen and molecular diffusion

Heat Transfer

Feed side

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

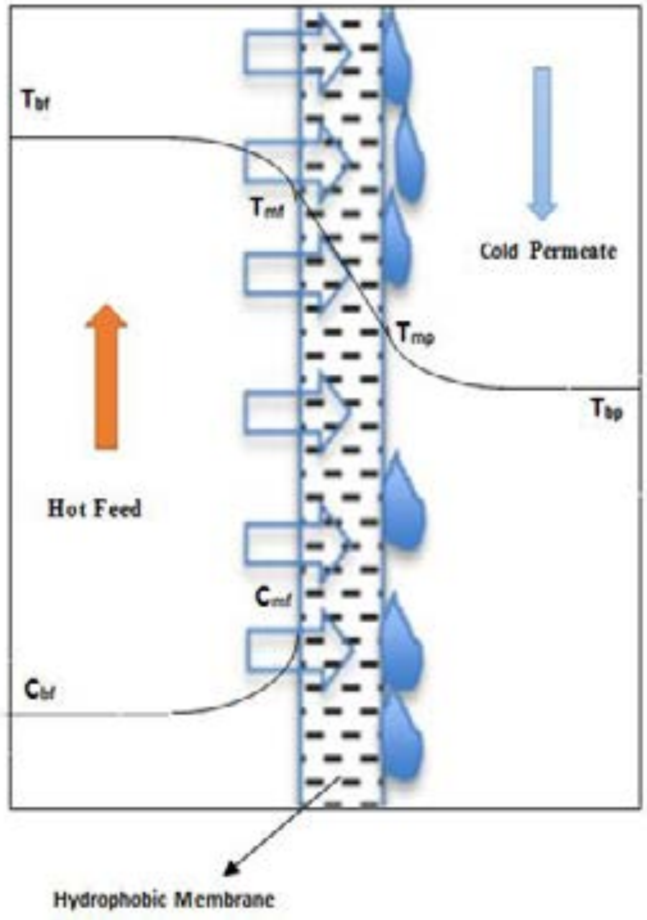
Through ***Membrane***

$$Q_v = J_W \, \Delta H_{vw}$$

$$Q_C = -K_m \frac{dT}{dX} = \frac{K_m}{\delta} \left(T_{mf} - T_{mp}\right)$$

Coolant ***side***

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



Heat & Mass Transfer in DCMD..

$$T_{mf} = \frac{\frac{K_m}{\delta}\left(T_{bp} + \frac{h_f}{h_p}T_{bf}\right) + h_f T_{bf} - J_w \Delta H_{vw}}{\frac{K_m}{\delta} + h_f\left(1 + \frac{K_m}{\delta h_p}\right)}$$

$$T_{mp} = \frac{\frac{K_m}{\delta}\left(T_{bf} + \frac{h_p}{h_f}T_{bp}\right) + h_p T_{bp} - J_w \Delta H_{vw}}{\frac{K_m}{\delta} + h_p\left(1 + \frac{K_m}{\delta h_f}\right)}$$

$J_W =$ Permeate flux

$P^{O}_{wf} =$ water vapour pressure at feed side

$P^{O}_{wp} =$ water vapour pressure at feed side

ΔHvw = heat of vaporization of water

$T_{mf} =$ temperature at the feed side of membrane Surface

$T_{mp} =$ temperature at the permeate side of membrane . surface

$T_{bf} =$ bulk temperature at the feed side of membrane

$T_{bp} =$ bulk temperature at the feed side of membrane

$K_m =$ Thermal conductivity of the membrane material

R = membrane radius

$\varepsilon =$ membrane porosity

$M_w =$ molecular weight of water

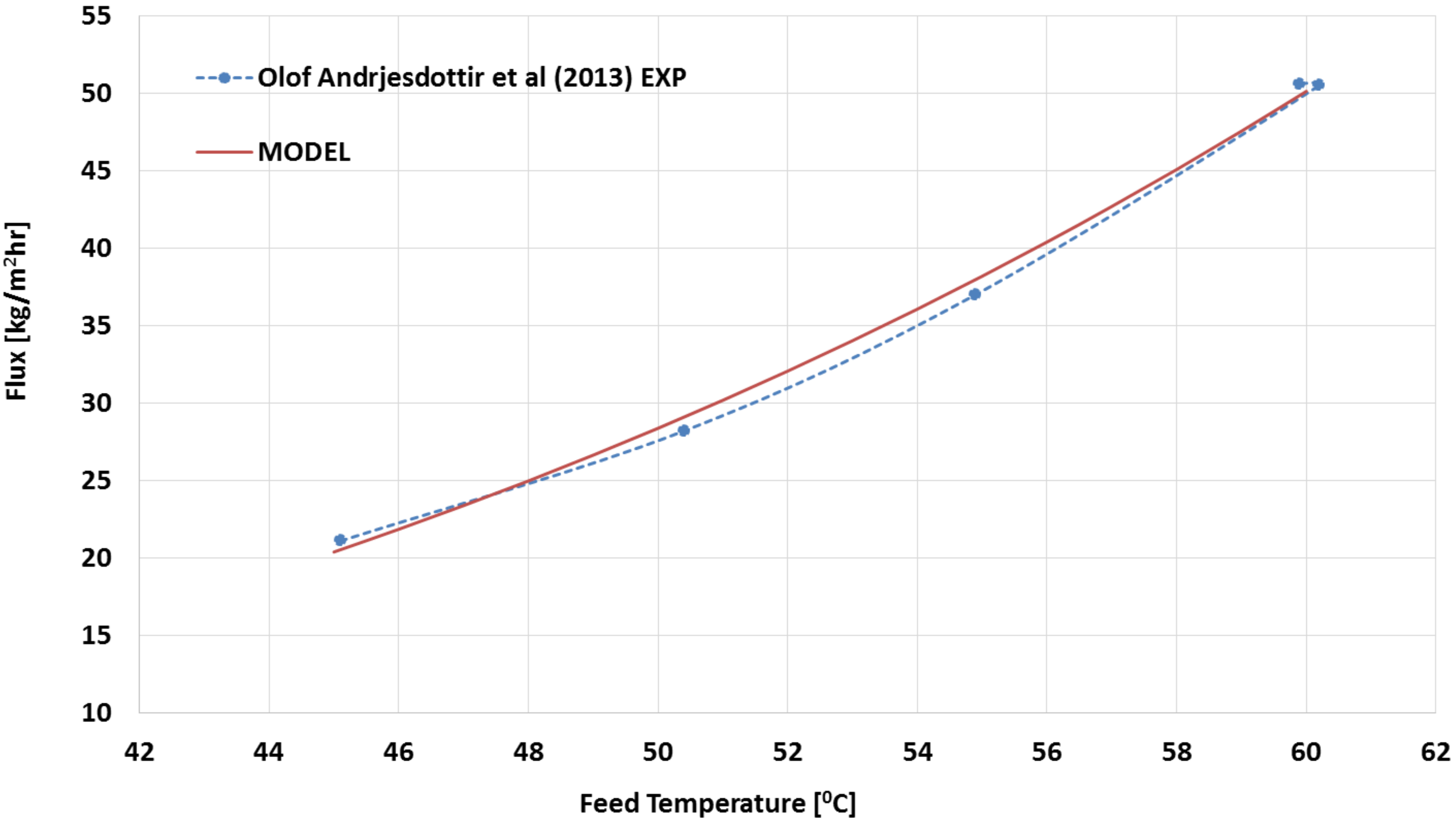
$\tau =$ membrane tortuosity

$\delta =$ Membrane thickness

$h_p =$ Heat transfer coefficient for permeate side of membrane

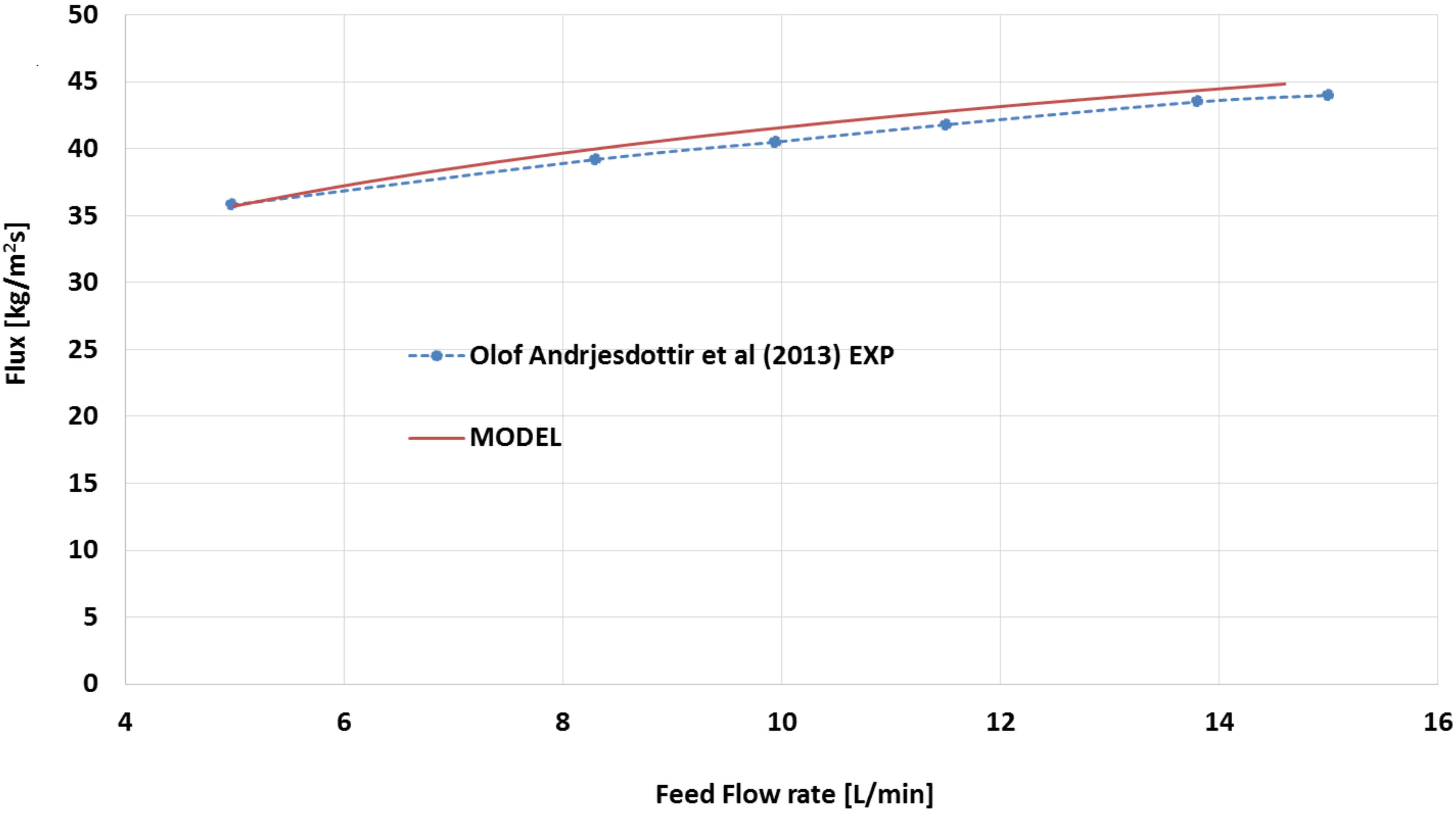
$h_f =$ Heat transfer coefficient for feed side of membrane

Modelling Results for DCMD



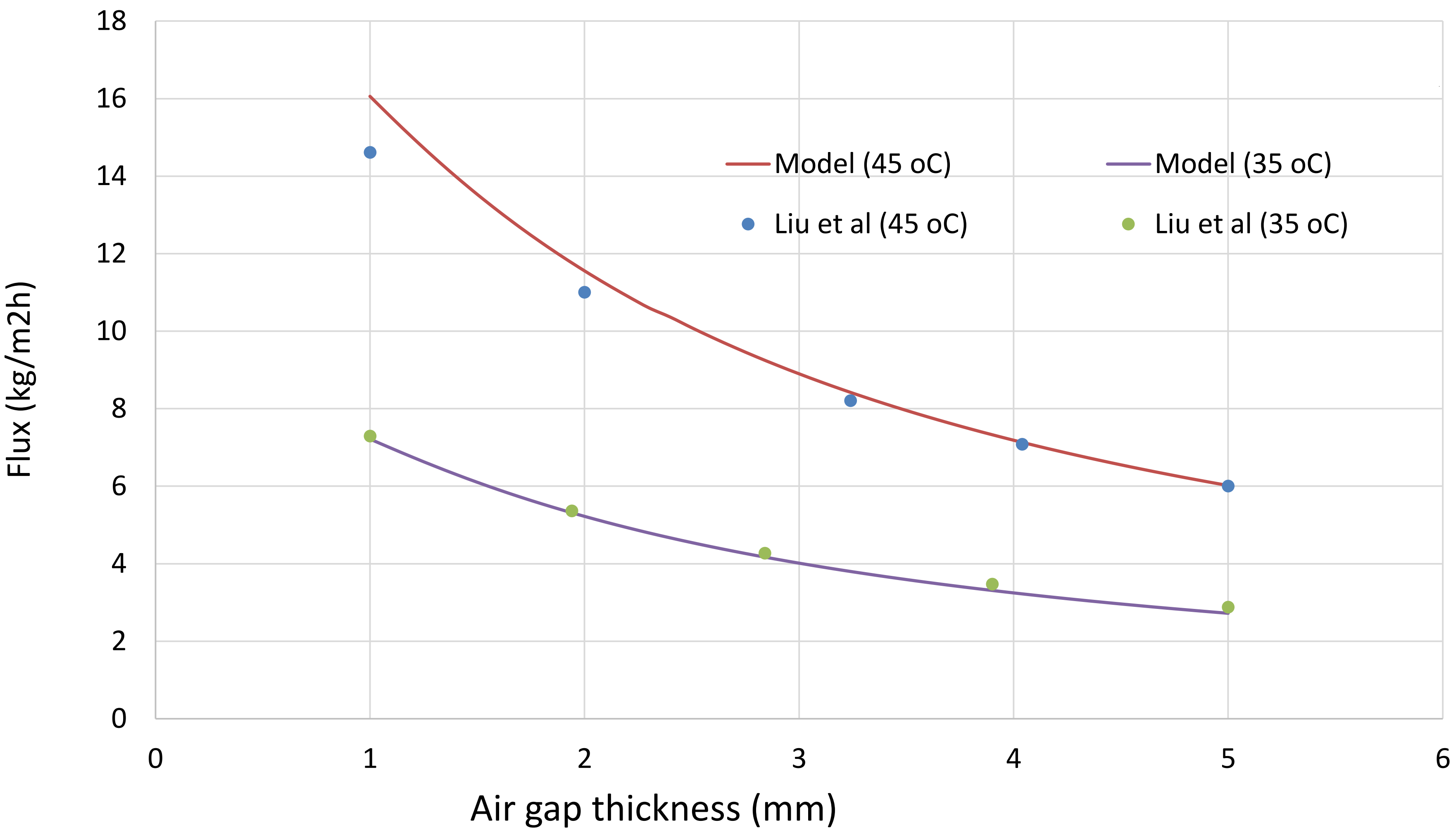
Flux vs. **feed temperature** in DCMD. Permeate temperature is 21^0C; feed flow rate is 12 L/min and permeate flow rate is 4 L/min. **No salt concentration.**

Modelling Results for DCMD



permeate flow rate is 3 L/min, feed temperature is 60°C, permeate temperature is 21°C.

Modelling Results for AGMD

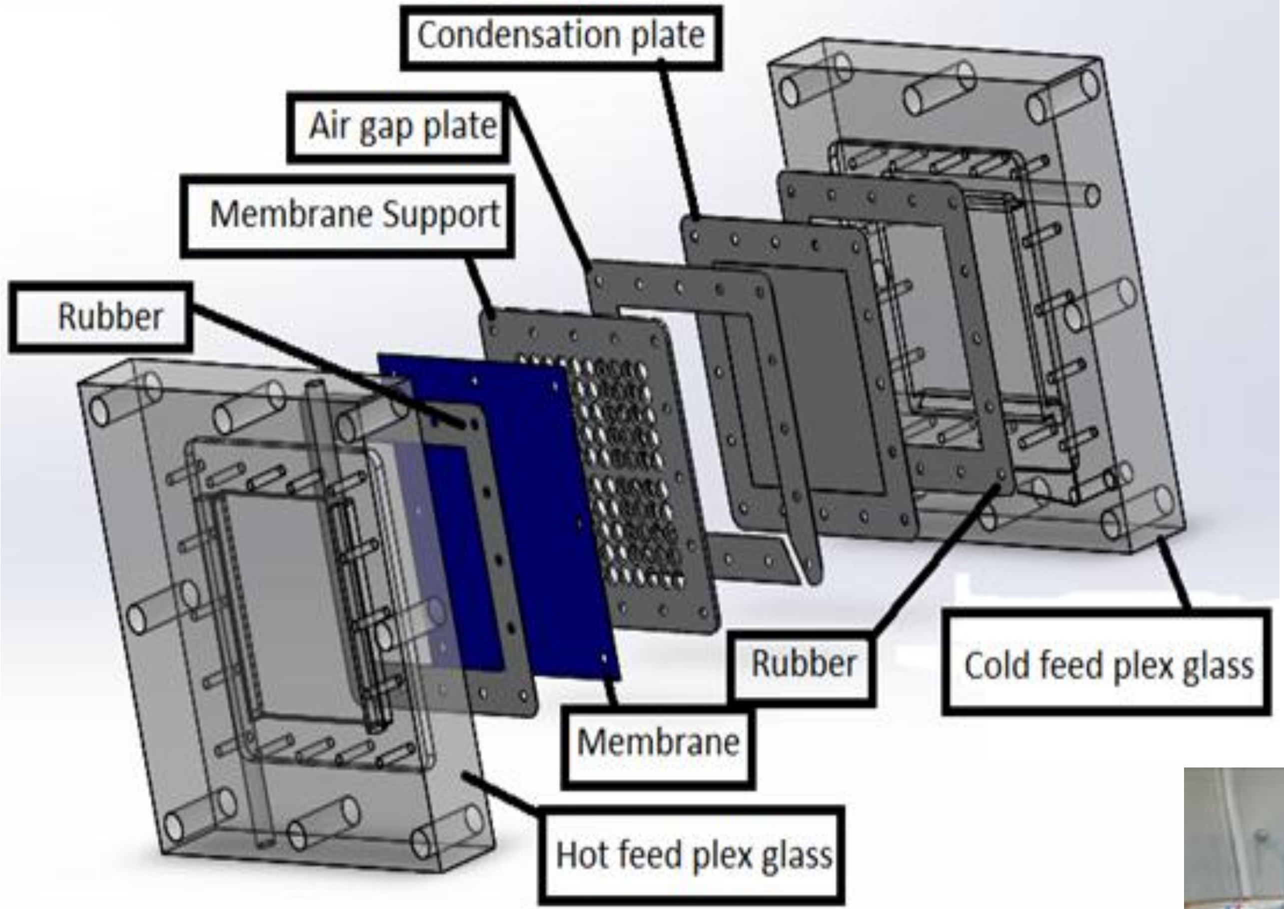


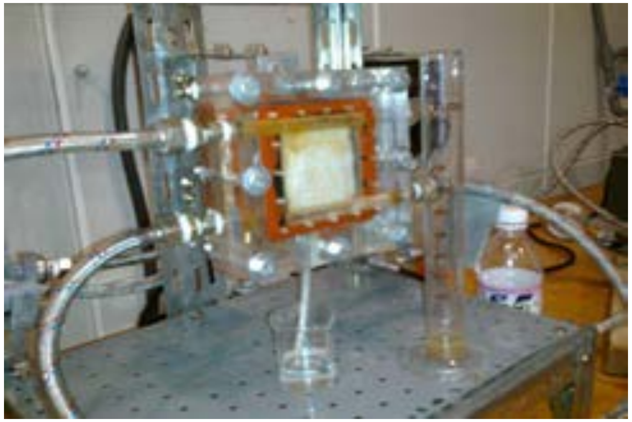
Effect of the **air gap thickness** at feed flow rate (16 L/min), coolant flow rate (16 L/min) at different feed temperature (45 and 35) ˚C, and coolant temperature (20 ˚C).

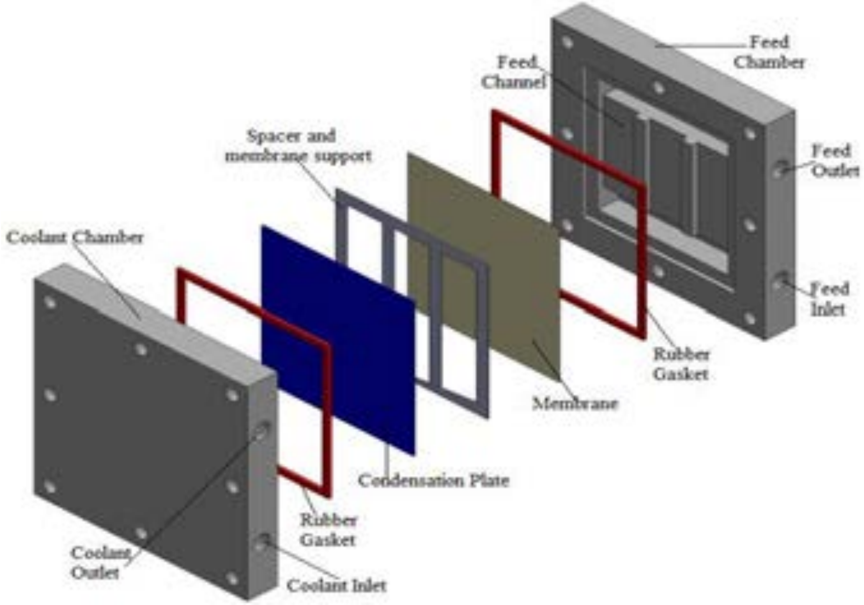
Improving the Design of MD system:

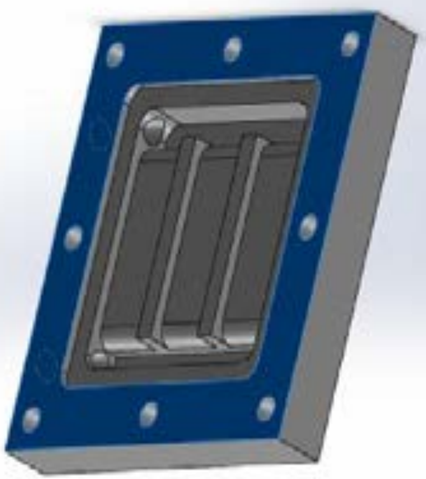
- Prevent internal leakage
- Easy to assemble
- Easy to control (flow, temp., pressure,….)
- Use different material
- Structural support to hold the system
- Sensors (flow, temperature, pressure, power, E. conductivity, etc.)
- Data Acquisition System with labview software.
- Optimization of the operating conditions

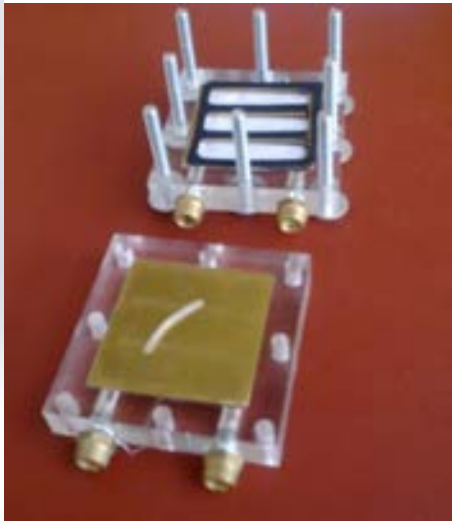
Other designs

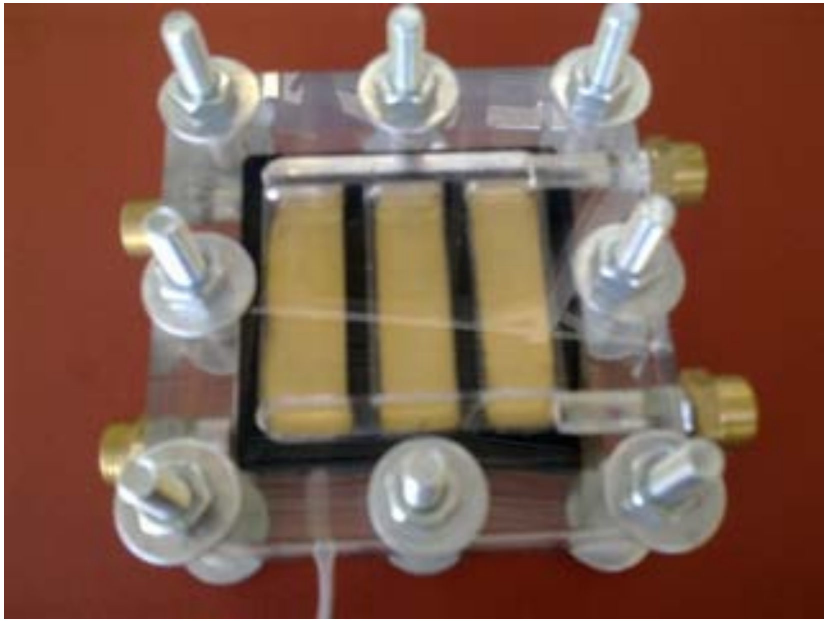


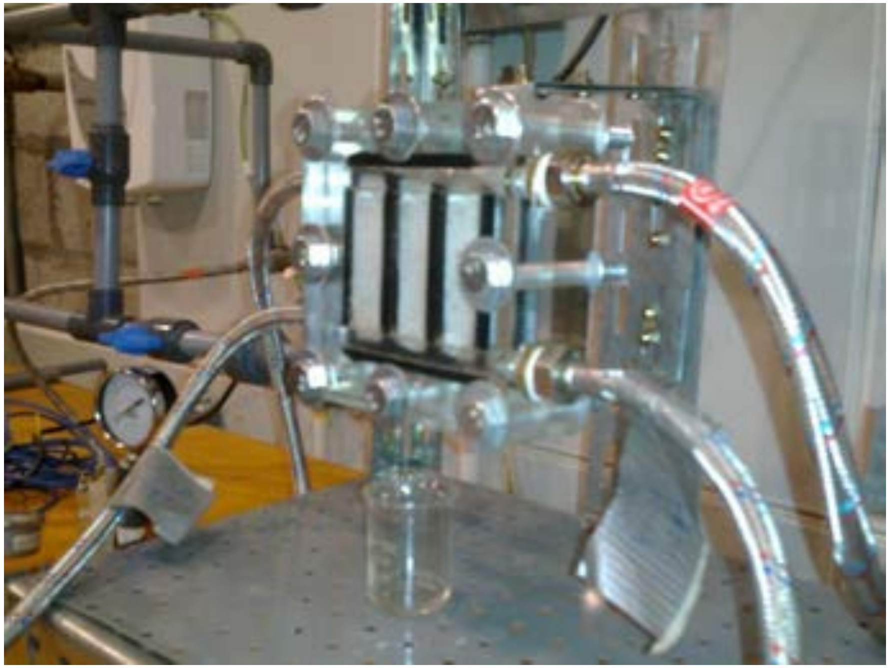



Feed Chamber
Feed Channel
Spacer and membrane support
Feed Outlet
Coolant Chamber
Feed Inlet
Rubber Gasket
Membrane
Condensation Plate
Rubber Gasket
Coolant Outlet
Coolant Inlet

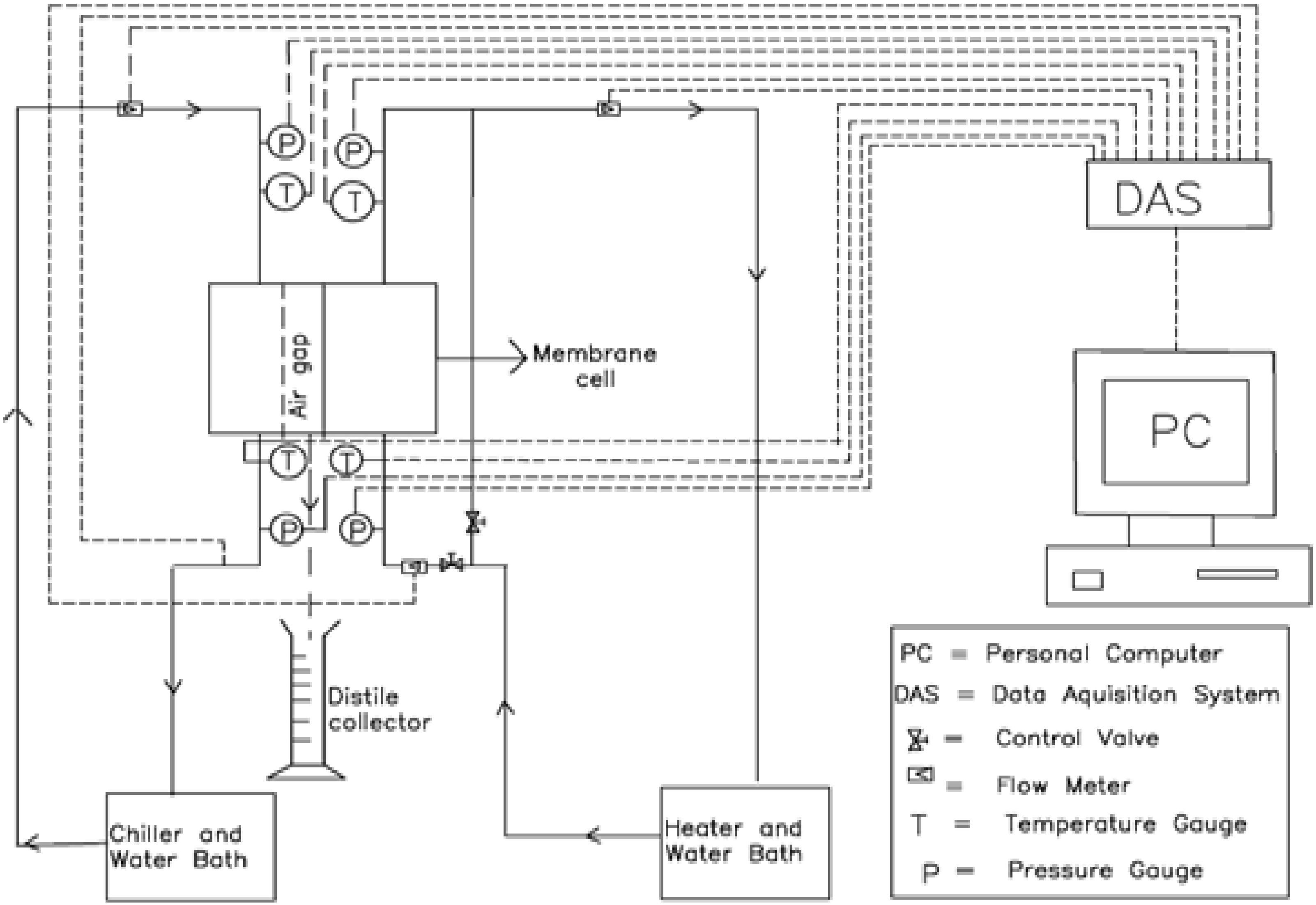




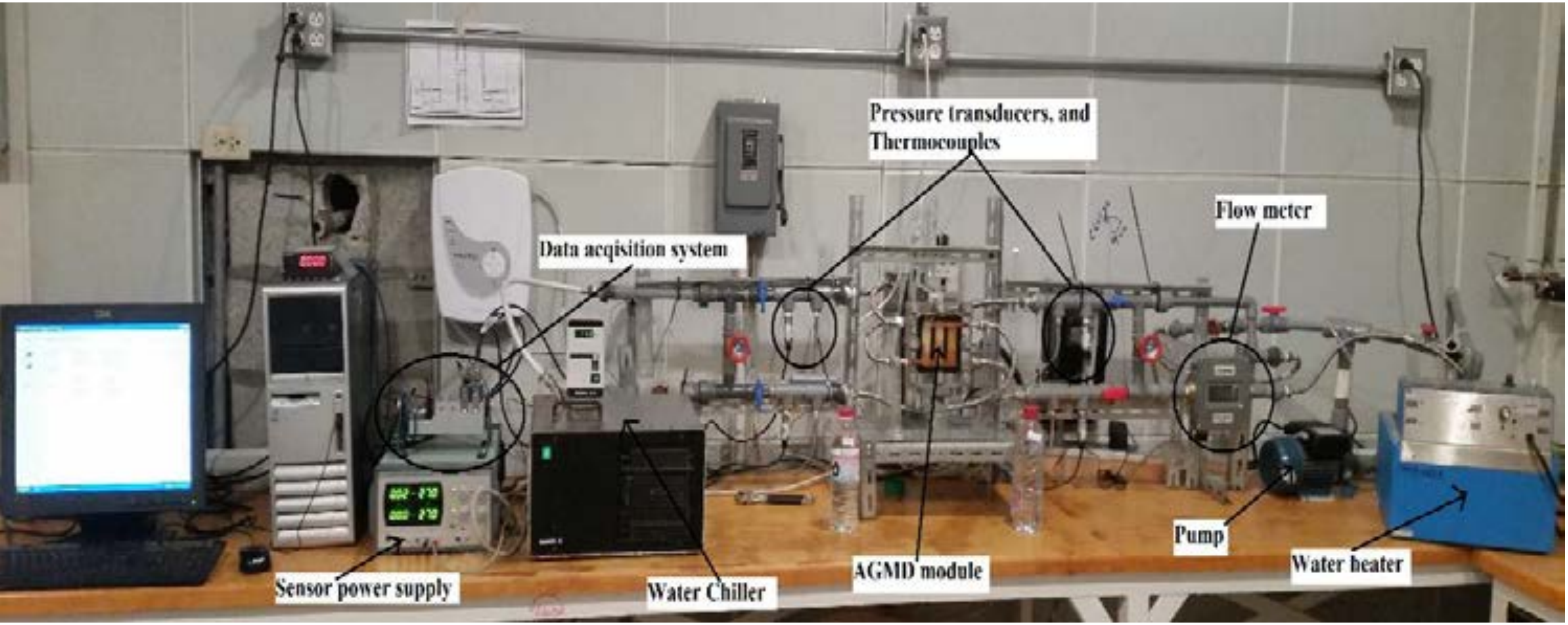




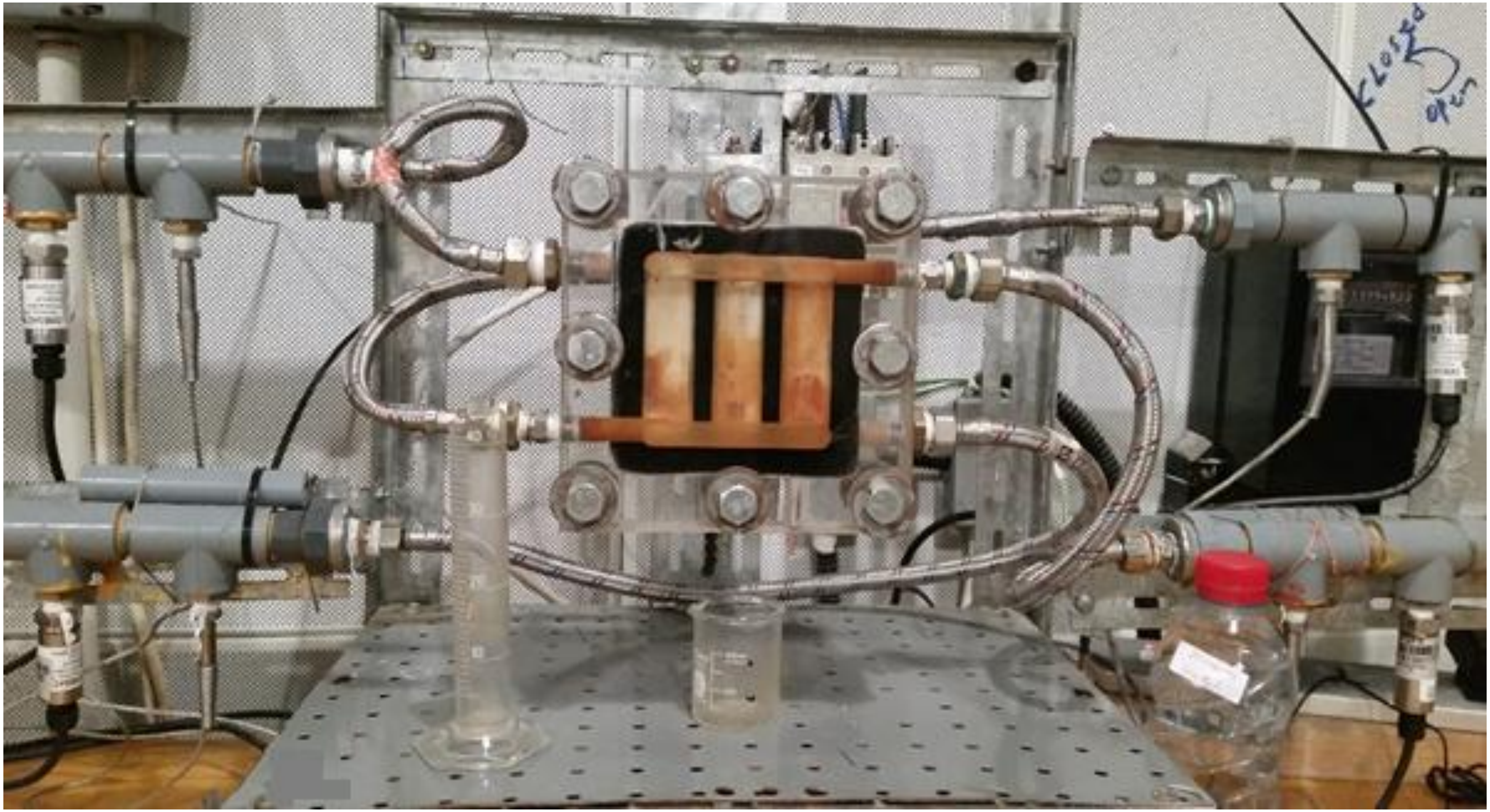
Schematic Diagram Of The Experimental Setup



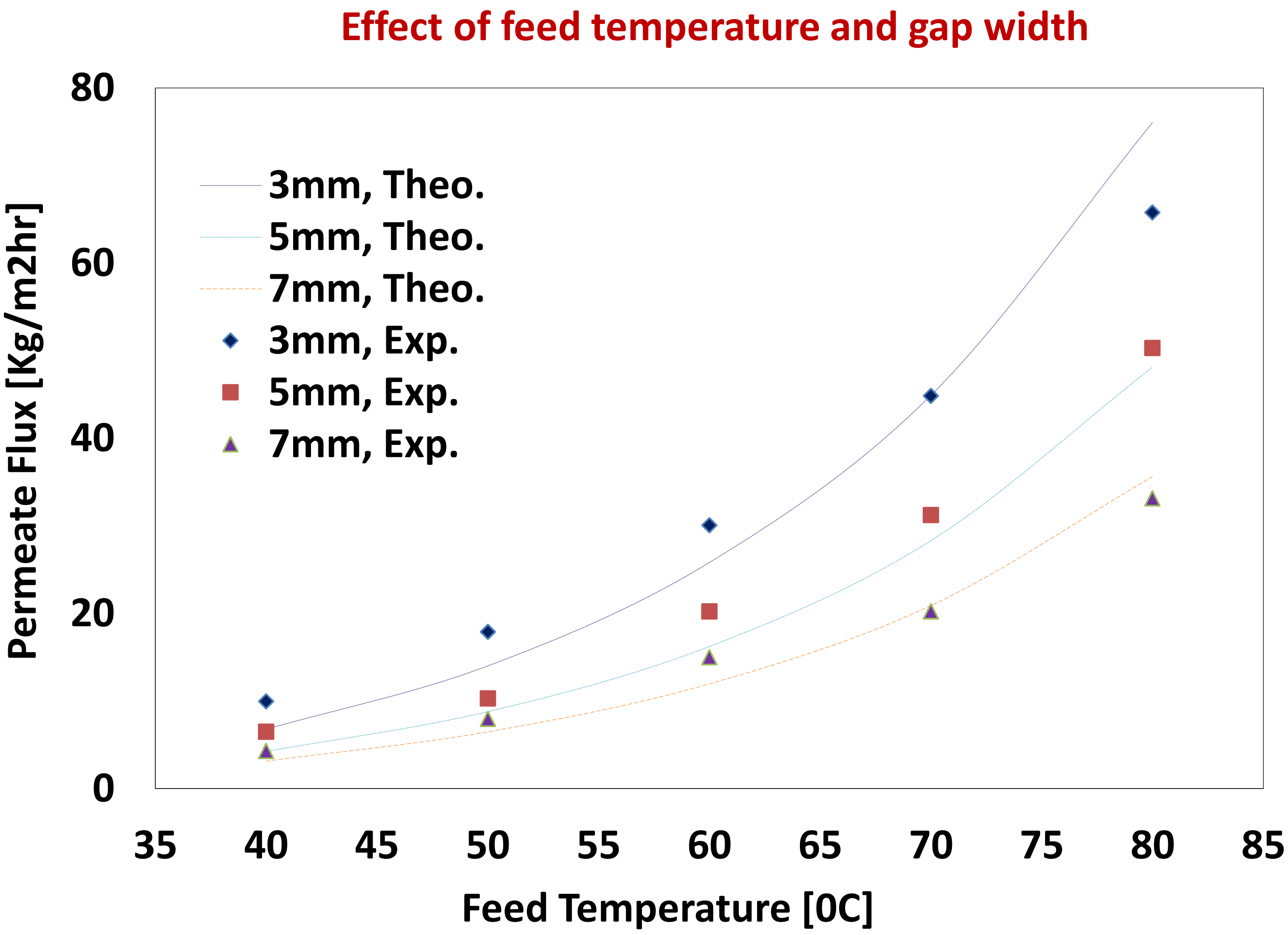
The Actual Laboratory Setup



The Connected MD Module

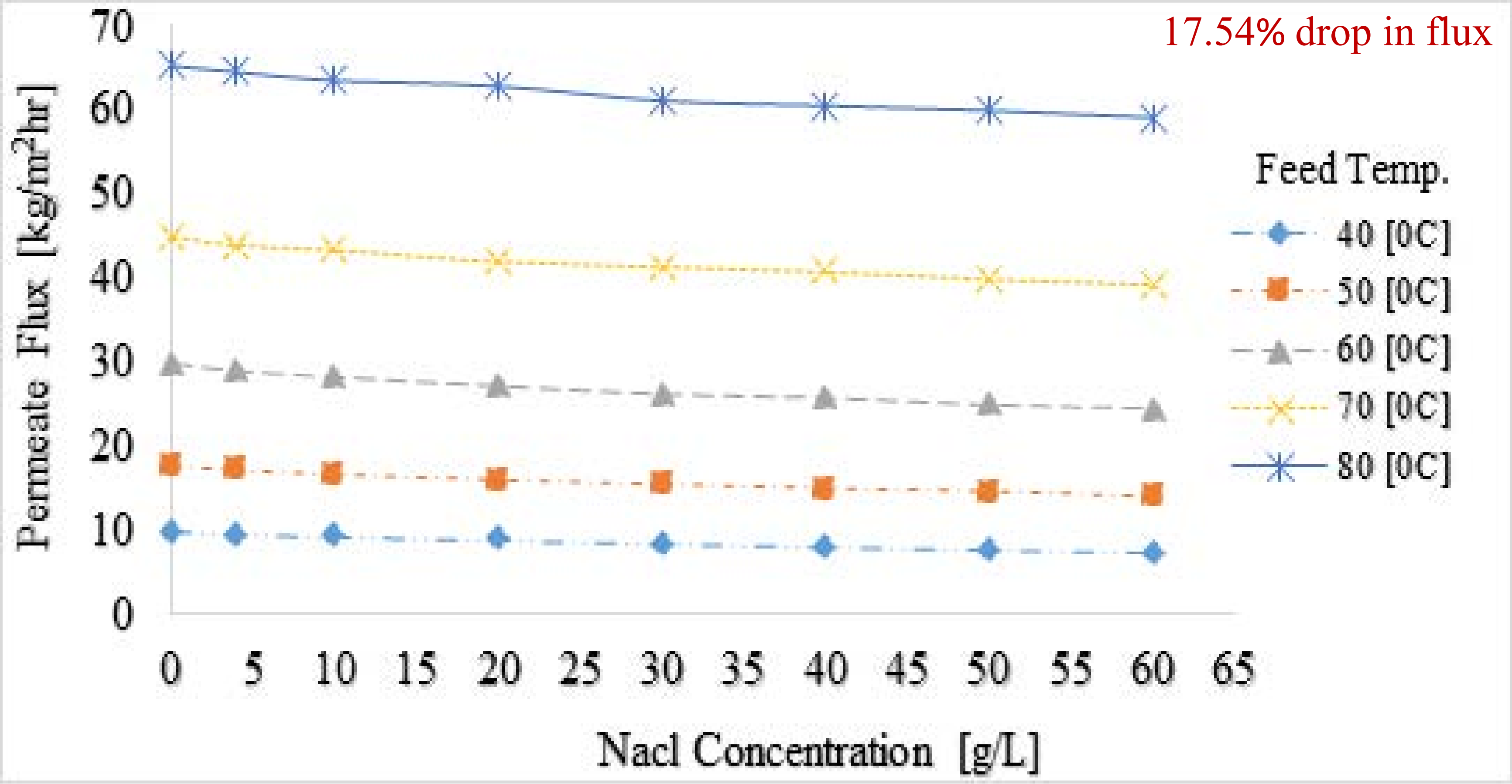


Samples of results: AGMD



coolant temperature of 30 ˚C, feed flow rate of 3L/min and coolant flow rate of 3 L/min.

Effect of Feed solution concentration

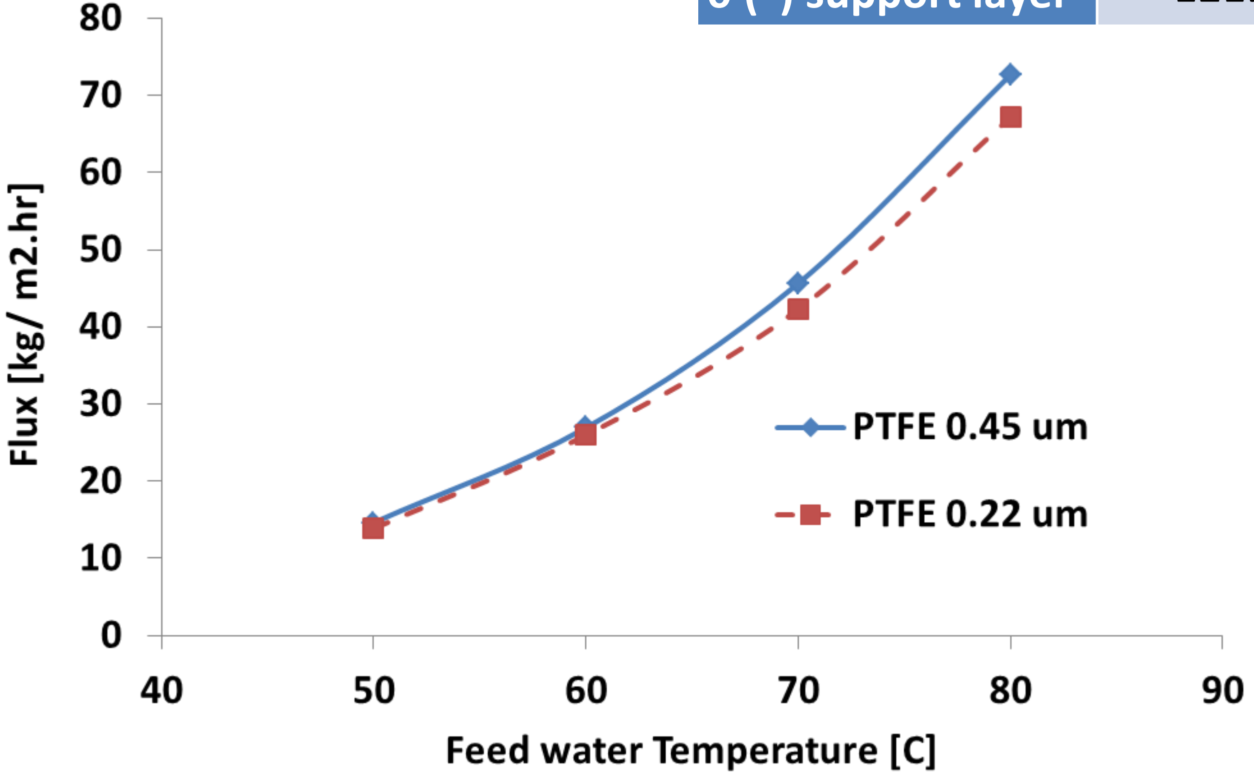


17.54% drop in flux

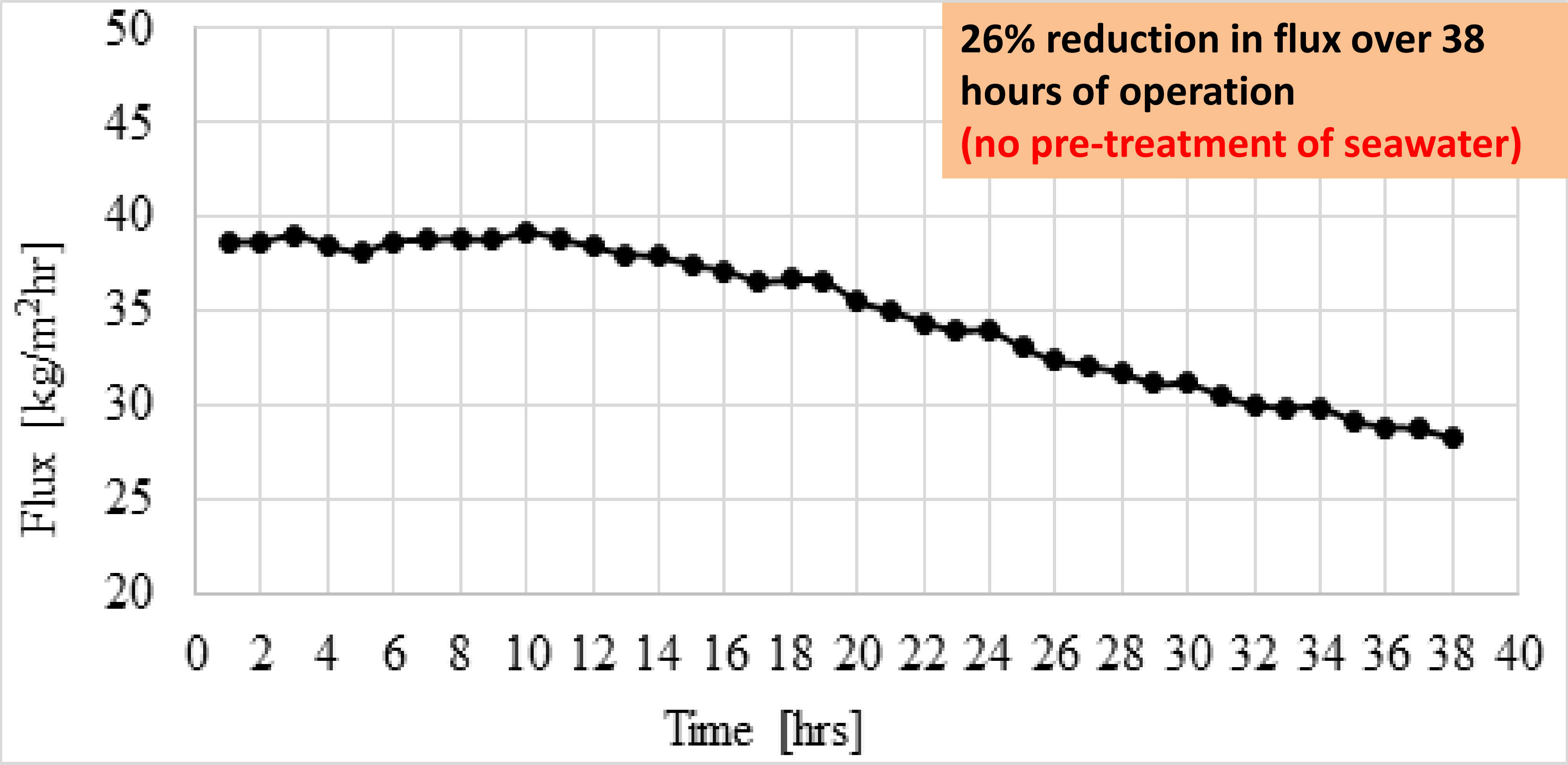
coolant temperature of 30 ˚C, feed flow rate of 3L/min, coolant flow rate of 3 L/min and air gap width of 3mm.

Membrane Pore size

Properties	PTFE 0.22 µm	PTFE 0.45 µm
$\delta_{full\ membrane}$ (µm)	159.5 ± 18.0	153.9 ± 13.6
δ_{teflon} (µm)	7.9 ± 1.8	6.9 ± 2.0
$\delta_{support}$ (µm)	143.3 ± 15.6	141.4 ± 15.8
d_p (nm)	236 ± 6	379 ± 8
ε (%)	75.9 ± 5.4	79.7 ± 8.7
θ (º) active layer	138.3 ± 2.4	139.0 ± 2.8
θ (º) support layer	121.4 ± 3.4	119.3 ± 1.0



Membrane Degradation Test



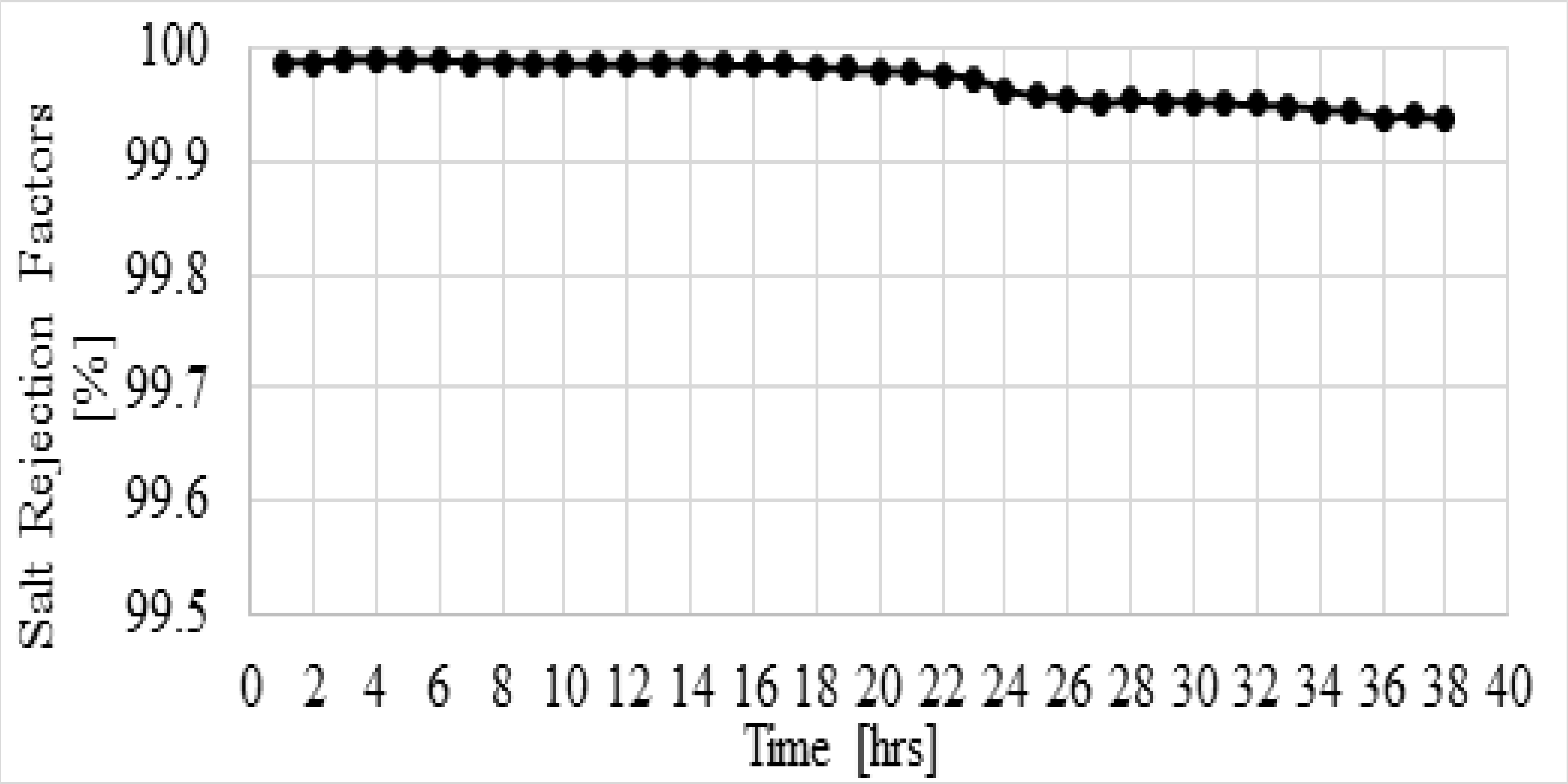
26% reduction in flux over 38 hours of operation
(no pre-treatment of seawater)

feed temperature of 70 ˚C, coolant temperature of 20 ˚C, coolant flow rate of 3 L/min, feed flow rate of 3 L/min and air gap width of 3mm.The feed solution is seawater having TDS of 60g/L.

Samples of results: AGMD

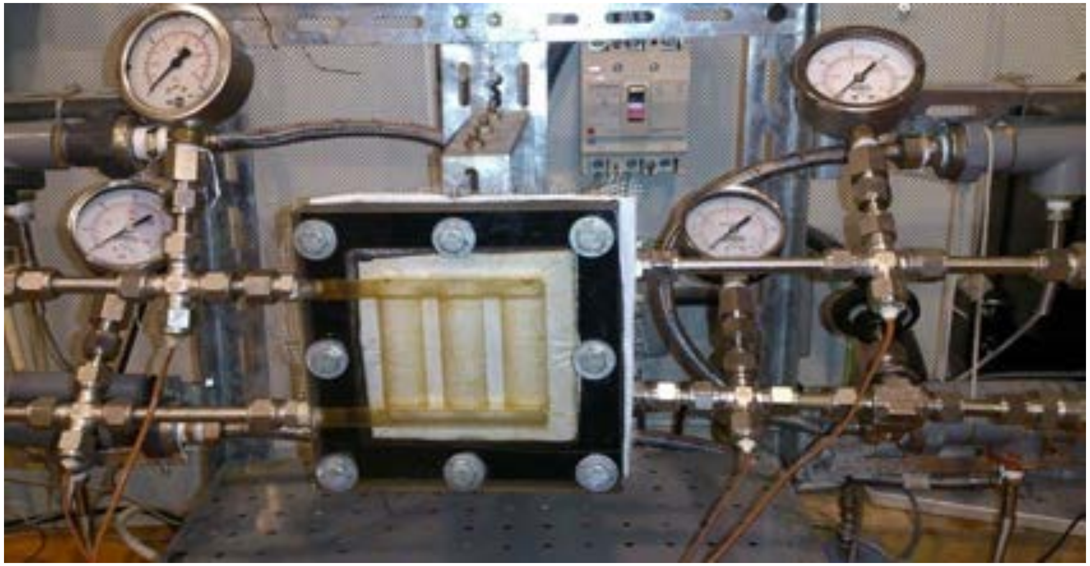
Membrane Degradation Test

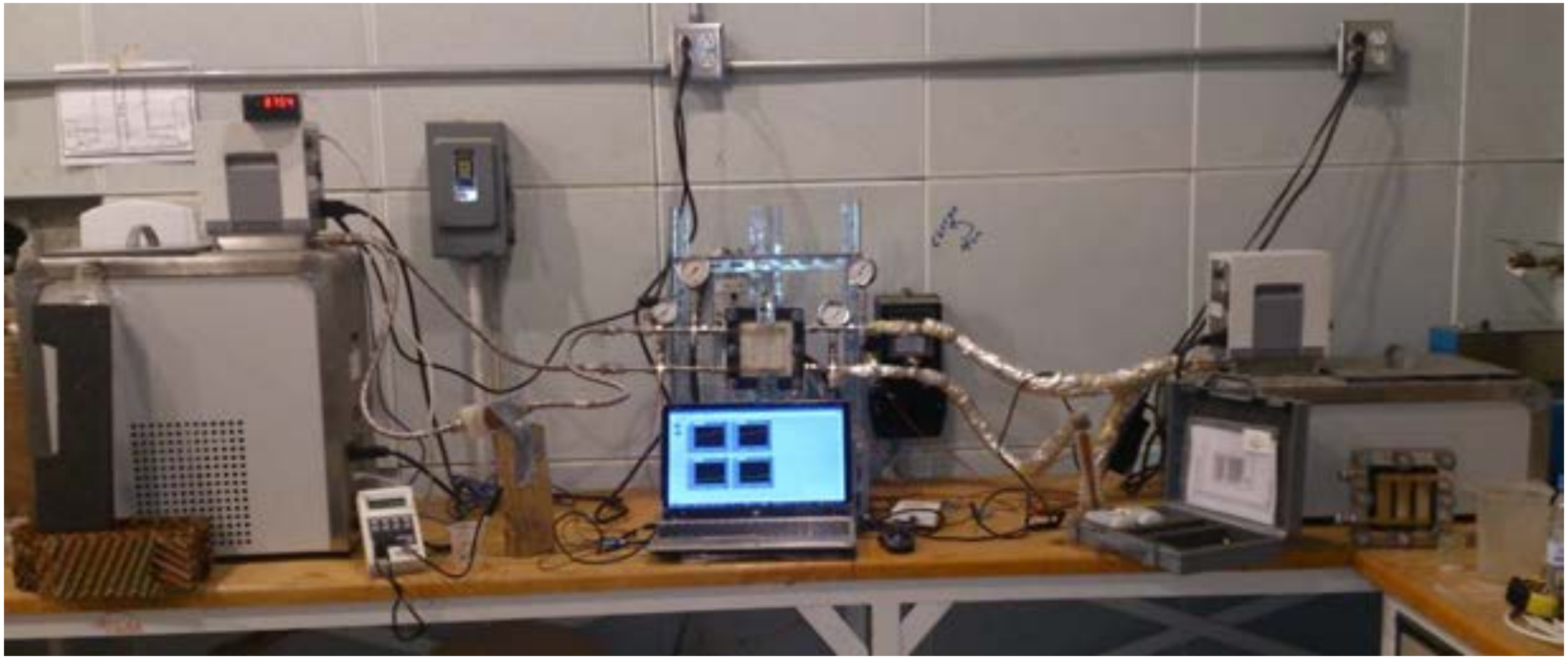
Above 99.95%



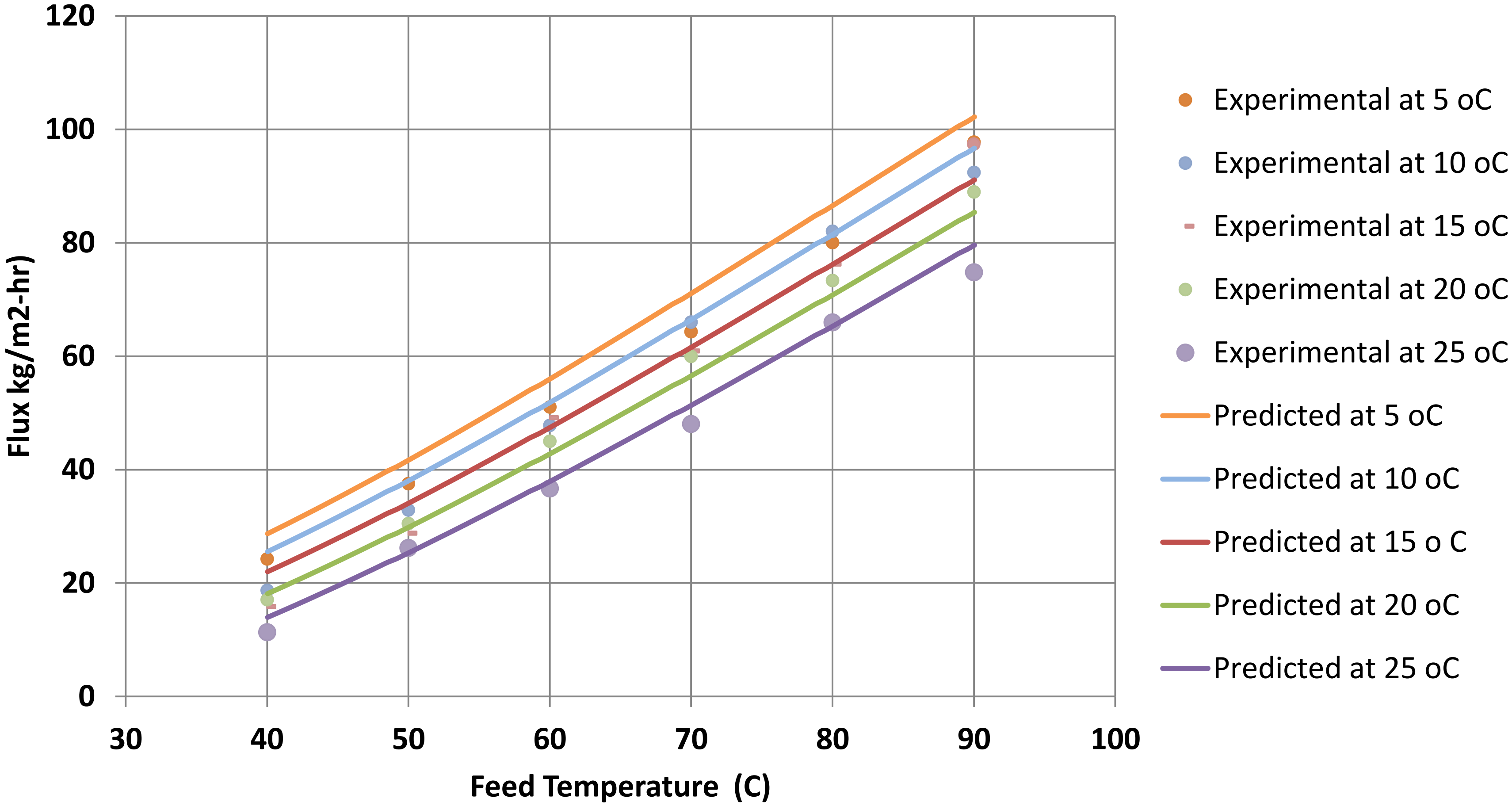
feed temperature of 70 ˚C, coolant temperature of 20 ˚C, coolant flow rate of 3 L/min, feed flow rate of 3 L/min and air gap width of 3mm.The feed solution is seawater having TDS of 60g/L.

Direct Contact MD

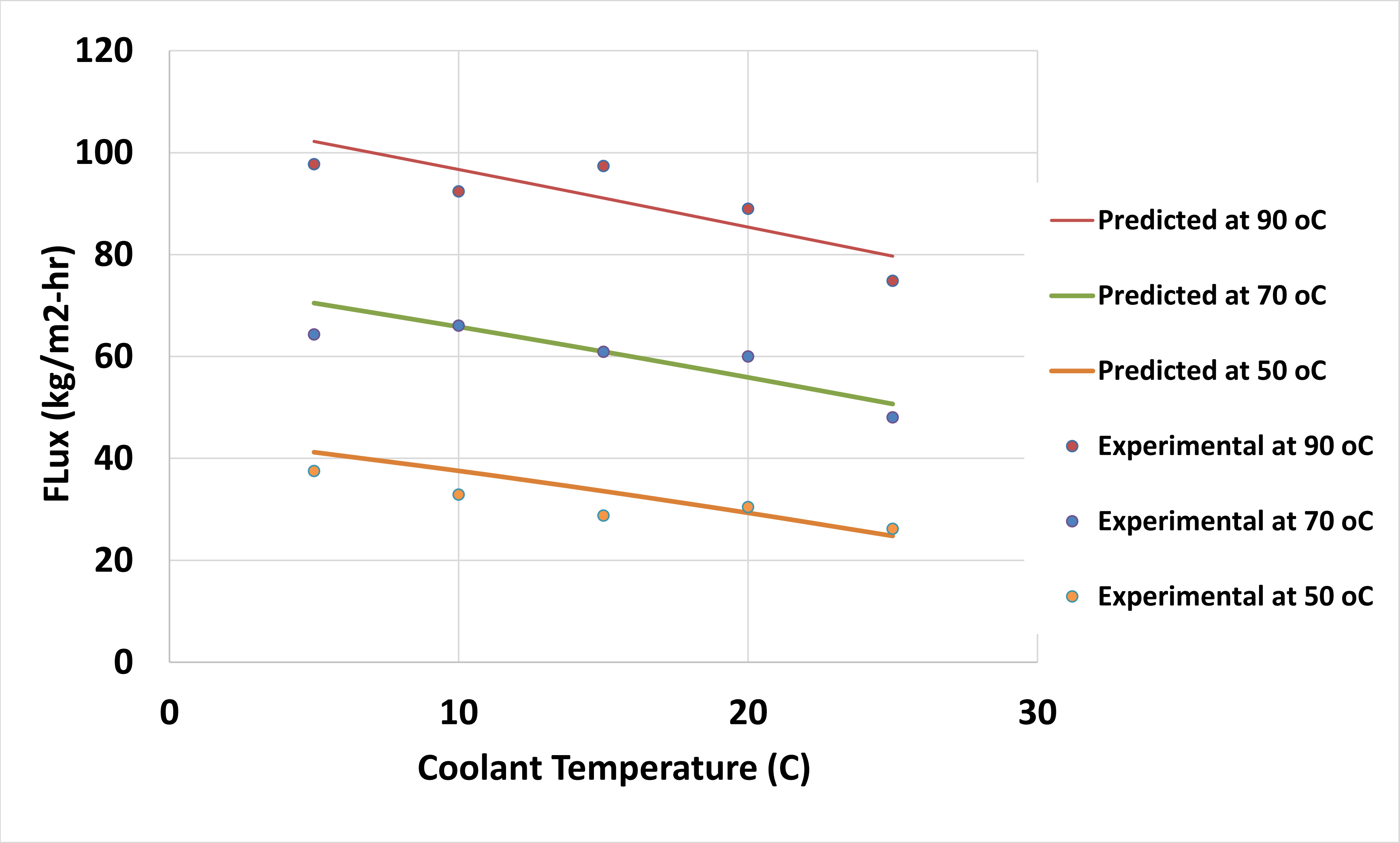




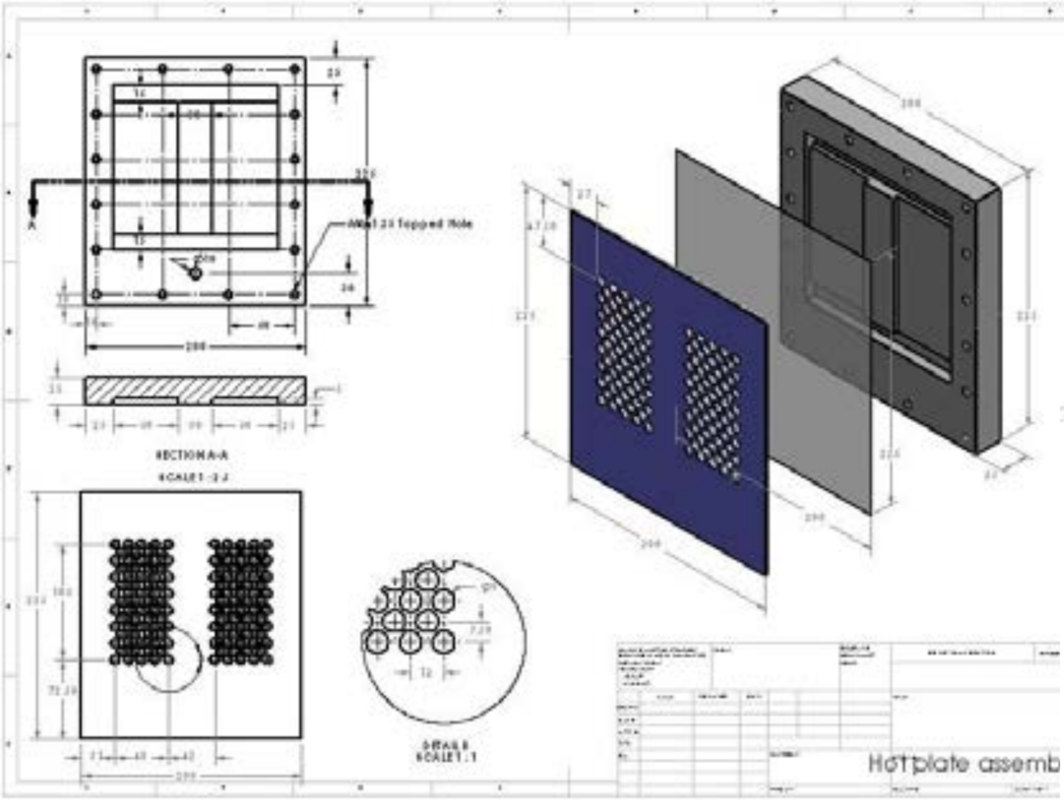
Samples of results: DCMD

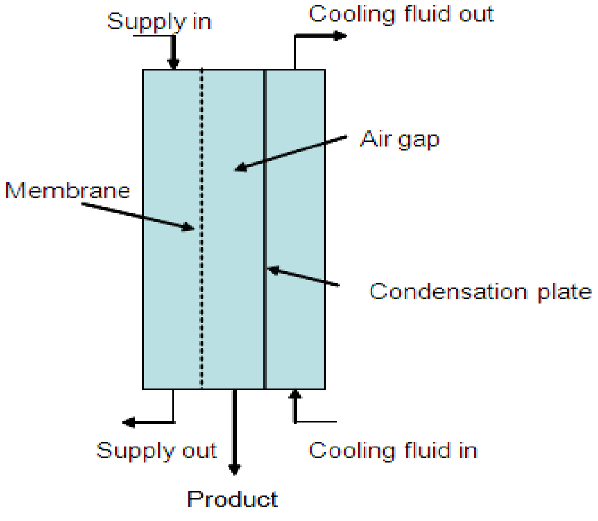


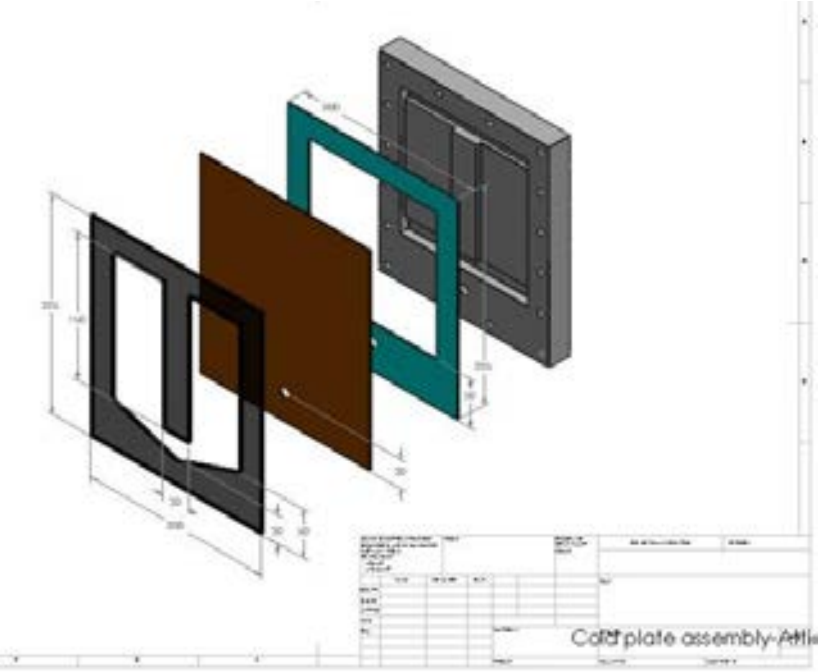
Samples of results: DCMD



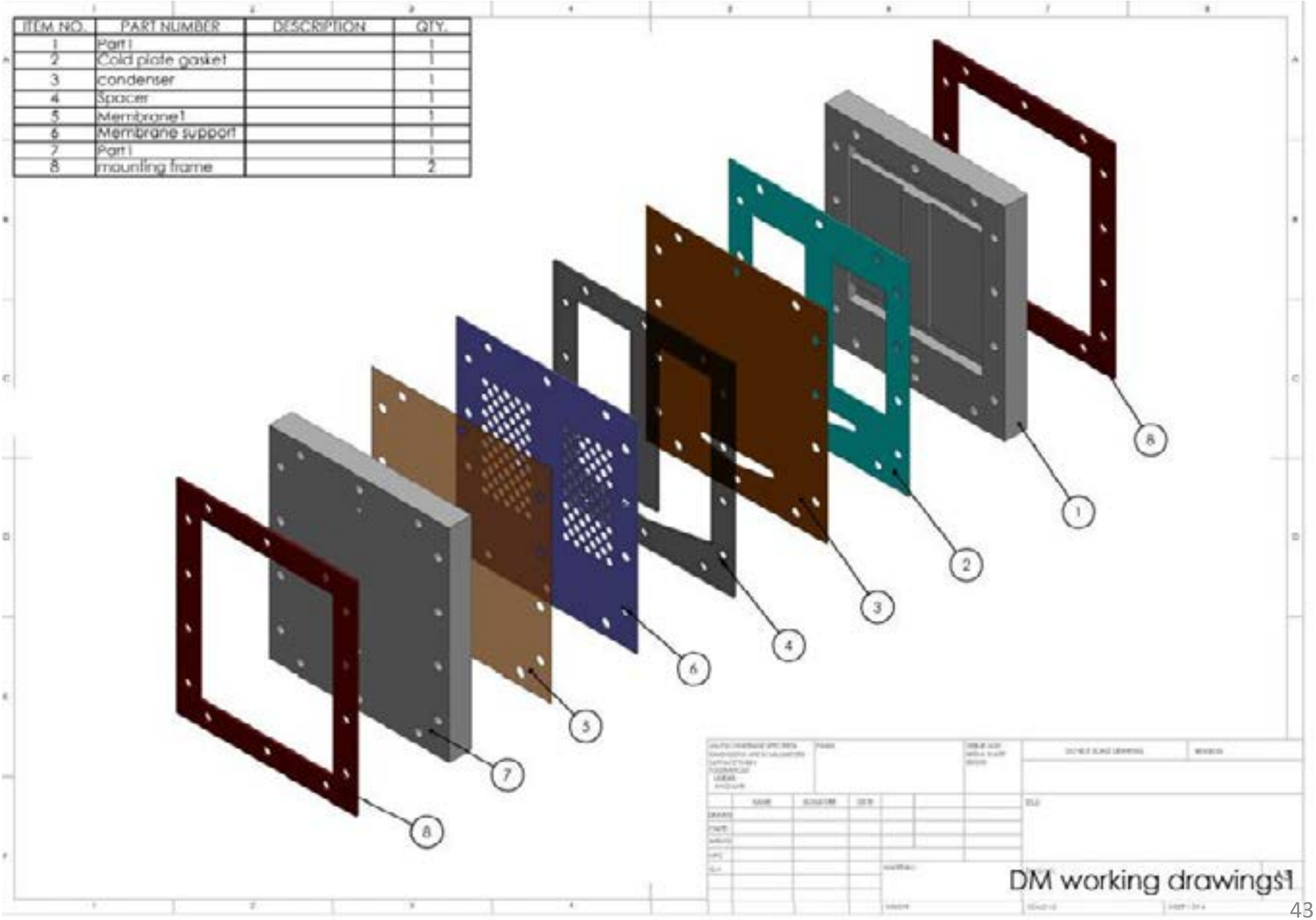
Water and Air Gap Membrane Distillation







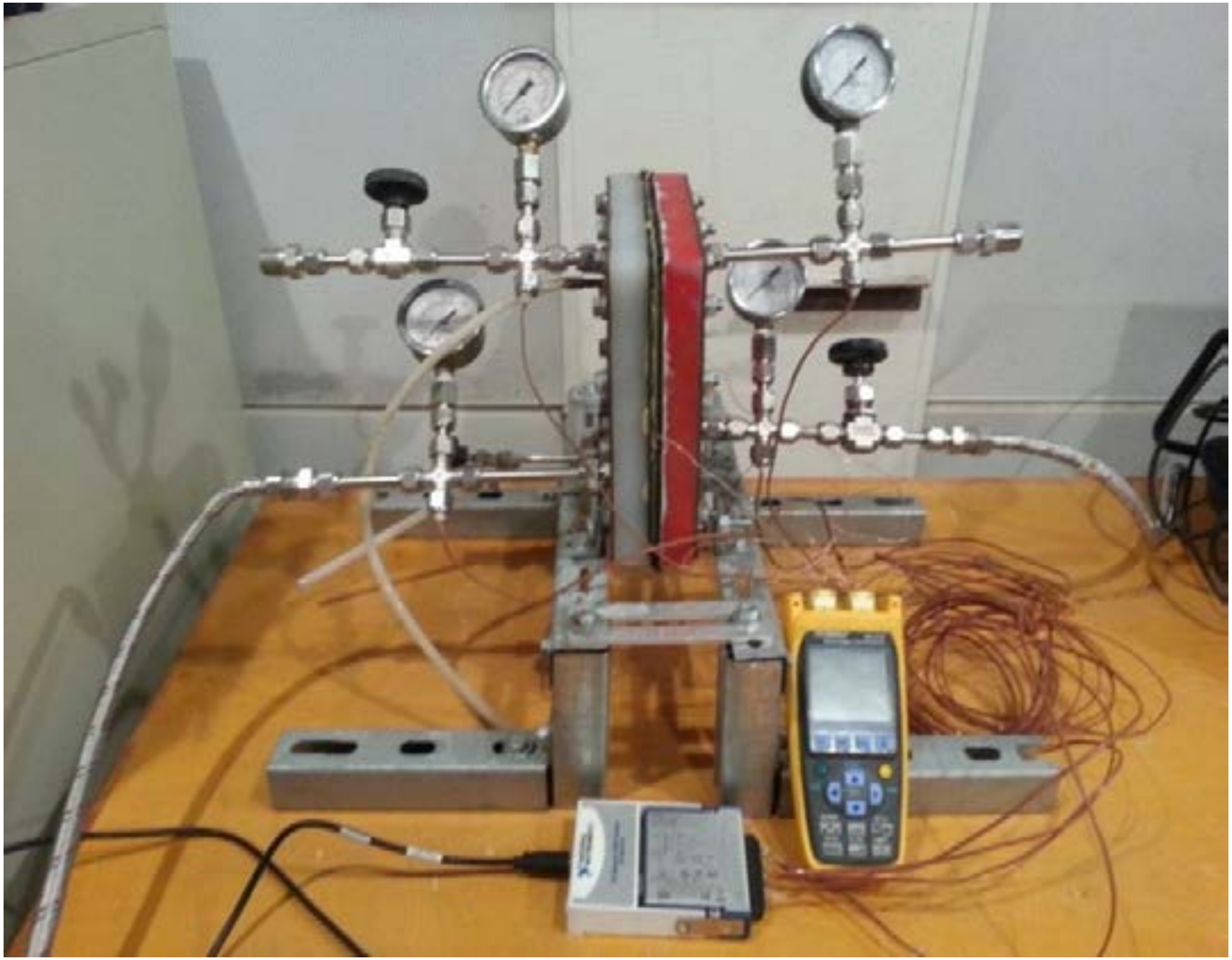
Water and Air Gap Membrane Distillation: Module Assembly



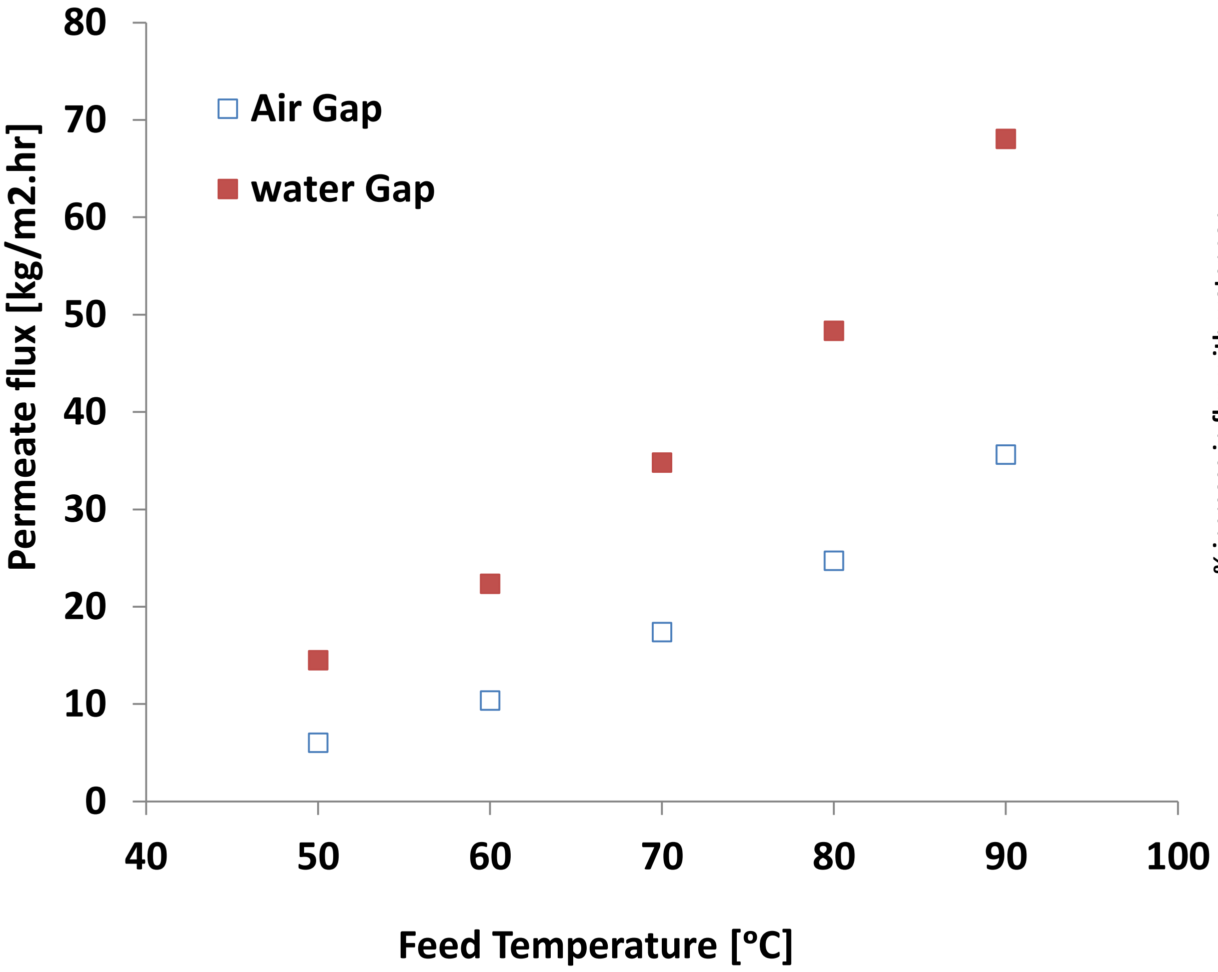
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Part1		1
2	Cold plate gasket		1
3	condenser		1
4	Spacer		1
5	Membrane1		1
6	Membrane support		1
7	Part1		1
8	mounting frame		2

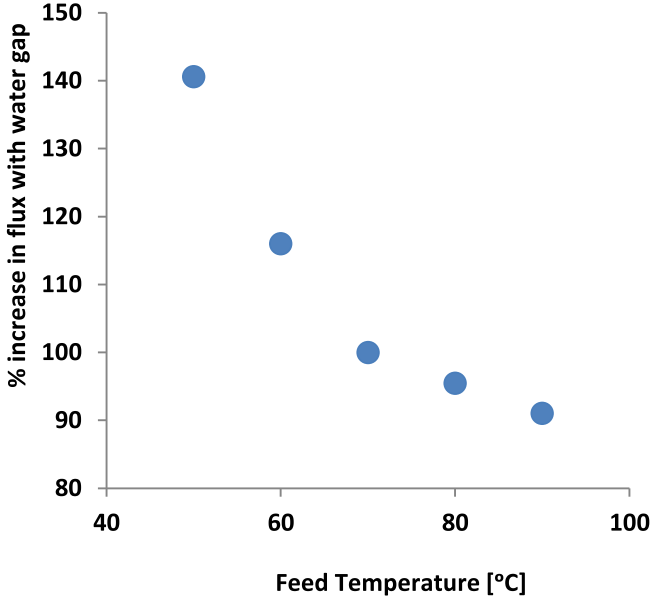
Water and Air gap Module Assembly

Instrumented Module



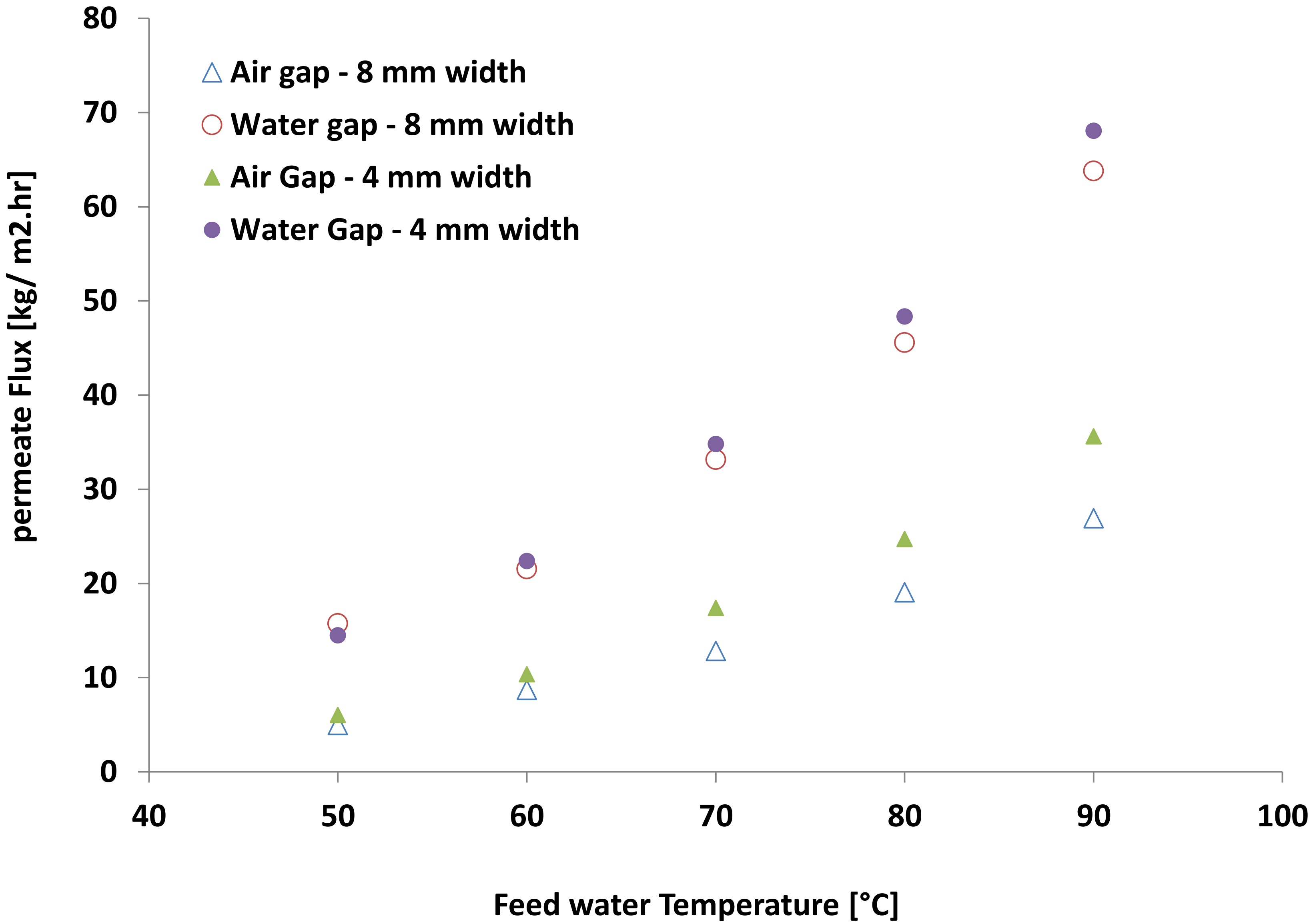
Samples of results: Water and Air Gap





Khalifa A., "Water and Air Gap Membrane Distillation for Water Desalination - An Experimental Comparative Study", Separation and Purification Technology 141 (2015) 276–284.

Samples of results: Water and Air Gap



Conclusions

- The membrane distillation (MD) technique is promising
- It is easy to apply, and with compact design.
- Low energy consumption.
- Solar energy utilization enhances its potential.
- Good flux output.
- Still there is a room for improvement.

The Future Work

Objective: To contribute in developing the MD systems

- Using the solar energy with MD
- Multi-stage module
- Energy recovery and optimization
- Advanced modeling