CH 3522: Unit Operations Lab

Reverse Osmosis

Batch - R, Group - 05
Date of Experiment: 26th Feb 2025
Date of Submission: 4th March 2025

Roll Numbers	Group Members
CH22B019	N. Pranavi
CH22B020	Deepanjhan Das
CH22B021	Siddhartha R
CH22B022	P. Ganesh

1. Objective

- To estimate the recovery & the reject ratio of the osmosis membrane using aqueous KCl solution.
- To find the mass transfer coefficient of the solvent & solute across the semipermeable membrane.

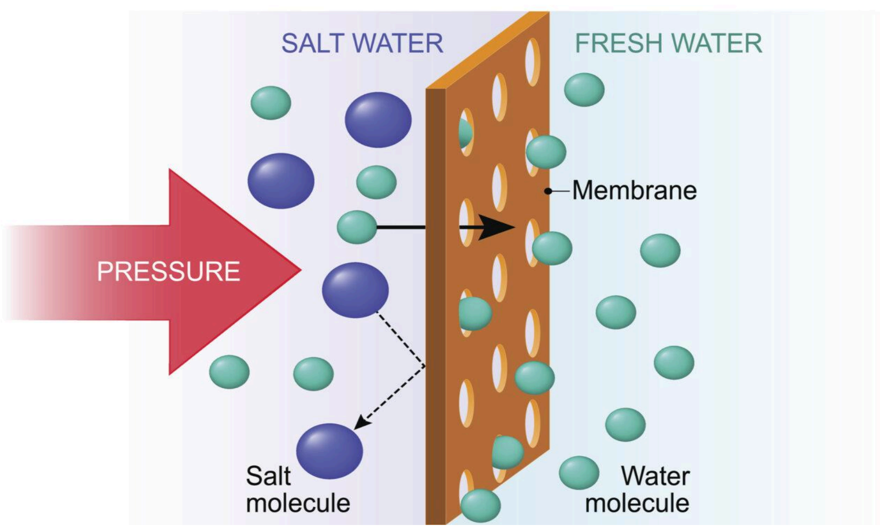


Figure 1: Reverse Osmosis Process

2. Introduction

Reverse osmosis (RO) is an advanced water purification process that removes ions, unwanted molecules, and larger particles from water by applying pressure to force it through a semipermeable membrane. This process is widely used for desalination, wastewater treatment, and producing high-purity drinking water. The fundamental principle of RO is overcoming natural osmotic pressure to separate purified water from contaminants. The efficiency of the process is quantified using the recovery and rejection rates, ensuring optimal operation for applications such as drinking water purification, desalination, and wastewater treatment.

3. Theory

Reverse osmosis primarily operates through molecular diffusion rather than convection. The core component of the system is a semi-permeable membrane with microscopic pores that allow only water molecules to pass through while blocking larger dissolved substances such as salts, minerals, bacteria, and viruses. The process occurs as follows:

- **Feed Water:** Untreated water, known as "feed water," is introduced into the system under high pressure. This water contains various contaminants, including dissolved solids and organic impurities.
- **Semi-permeable Membrane:** The membrane selectively permits water molecules to pass while preventing the passage of dissolved salts and other impurities, ensuring the production of purified water.

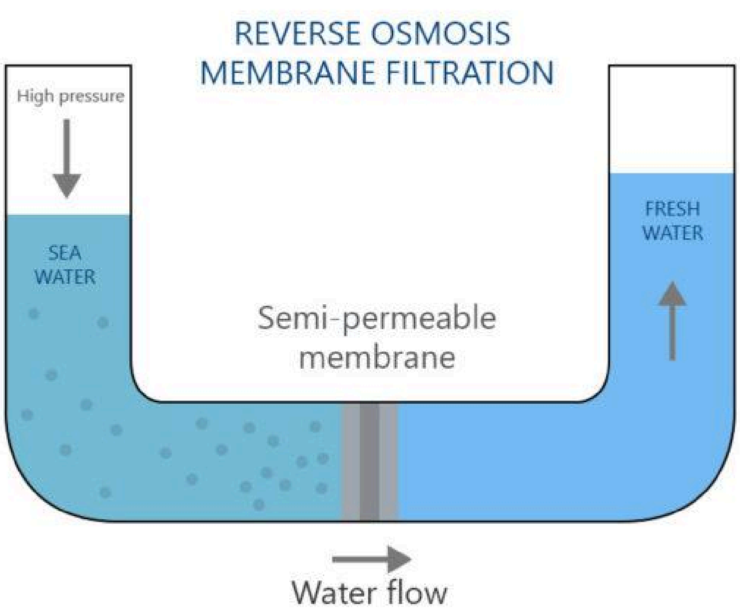


Figure 2: Schematic of Reverse Osmotic Filtration

- **Permeate:** The purified water that successfully passes through the membrane is known as the permeate. This water is largely free from dissolved solids and contaminants.

- **Reject Stream:** The impurities retained by the membrane are expelled as the reject or concentrate stream. This waste stream contains the concentrated contaminants removed from the feed water. It may be discharged or further treated, depending on the application.
- **Osmotic Pressure:** Osmotic pressure plays a crucial role in the RO process. In natural osmosis, water moves from a region of lower solute concentration to a region of higher solute concentration through a semipermeable membrane. However, in reverse osmosis, external pressure is applied to overcome the osmotic pressure, forcing water molecules to move in the opposite direction and enabling purification. For effective RO operation, the applied feed pressure must exceed the osmotic pressure to allow the permeation of purified water.

The equations and the terms involved in this phenomenon are described below:

Symbol	Term
Rej	Rejection
C_P	Permeate Concentration
C_R	Reject Concentration
C_F	Feed Concentration
π	Osmotic pressure
R	Universal Gas Constant
T	Temperature
P	External Pressure
r	Recovery
J_w	Flux of Water across membrane
J_s	Flux of Solute across membrane
k_w	Mass Transfer coefficient for water
k_s	Mass Transfer coefficient for solute
ϕ	Non-ideality factor in π (=2) for KCl as it dissociates into two ions.

The osmotic pressure (π) is determined using the equation:

$$\pi = \phi CRT \tag{1}$$

The performance of a reverse osmosis system is evaluated using two key metrics:

- **Recovery Rate (r):** The fraction of feed water converted into purified water.

$$r = \frac{C_P}{C_F} = \frac{Q_P}{Q_P + Q_R} \tag{2}$$

- **Rejection Rate (Rej):** The effectiveness of the membrane in removing contaminants, defined as:

$$Rej = 1 - \frac{C_P}{C_F} \tag{3}$$

Equations and balances involved:

At entrance : $$\Delta P = \Delta P_{FR} - \Delta\pi_{FR} = (P_{FR} - P_P) - (\pi_{FR} - \pi_p) \tag{4}$$

where:

$P_{FR} = \frac{(P_F + P_R)}{2}$ and $\pi_{FR} = \frac{\pi_F + \pi_R}{2}$

Now coming to the fluxes, we define:

$$J_w = k_w \times \Delta P_{Net} \tag{5}$$

$$J_s = k_s \times (C_F - C_P) \tag{6}$$

Now since we don't have data about the area of the RO membrane used, we will multiply both sides of the above two equations by $A_{membrane}$ and report the values of $(k_w * A_{membrane})$ and $(k_s * A_{membrane})$ respectively.

We define :

$r = \frac{Q_p}{Q_F}$ and $C_P = \frac{J_s}{J_w}$

So, Mass Balance : $$Q_F = Q_R + Q_P \tag{7}$$

Species balance over salt: $$Q_F C_F = Q_R C_R + Q_P C_P \tag{8}$$

Solving all these equations, we have:

$$C_R = C_F \times \frac{1-(1-Rej)r}{1-r} \tag{9}$$

This is the predicted values of C_R from the theoretical assumptions. We will compare this to what we actually got from the experiment at the end of the report.

4. Apparatus Required

The apparatus and the chemicals used in this experiment are as follows,

- RO water filter, Pump
- Feed tank, Reject tank, Permeate tank
- KCl, Distilled Water
- TDS meter to measure concentration

5. Schematic of Experimental Setup

Experimental setup includes the following components and we have also provided the setup used during the experiment in figure 3.

- **Feed Water Tank** – Upper transparent container covered with aluminum foil.
- **High-Pressure Pump** – Likely located near the tubing to provide pressure for RO.
- **Pressure Gauge** – Measures pressure in the system.
- **Reverse Osmosis Membrane Housing** – White cylindrical component where separation occurs.
- **Tubing & Valves** – Used to transport water and control flow.
- **Permeate (Purified Water) Collection Tank** – Lower transparent container.
- **Reject Water Outlet** – Disposal pathway for concentrated brine.
- **Support Frame** – Metal structure holding the components in place.

6. Procedure

- Prepare a feed solution and measure the concentration using TDS meter.
- Utilise a pump to push the feed solution through the Reverse Osmosis (RO) unit.
- Measure the back pressure, which is represented by the transmembrane pressure, using a pressure gauge (P).
- Start the pump and observe a certain flow rate of permeate and reject.
- Measure the flow rates of permeate (QP), reject (QC), and feed (QF) using a measuring cylinder and stopwatch.
- Measure the concentrations of all streams (feed, reject, and permeate) using the TDS meter.
- Repeat the experiment for different back pressures.

Figure 3: The Experimental Setup & Weighing Machine used

7. Experimental Observations

The following table (refer to table 1) contains the data collected while performing the experiment, corresponding to which the datasheet is also provided at the end of this report.

One thing to note is that the feed concentrations provided in the brackets were expected to come based on the amount of KCl that was mixed in the water. But due to an unmeasured off-set in the TDS meter the values of the concentration obtained are provided along with the expected values, whereas while performing the calculations we have used the actual values of feed concentrations and the obtained values of reject & permeate concentrations.

The tabulated values are as follows,

Feed Conc (ppm)	Pressure (kgf/cm²)	Reject			Permeate		
		Conc (ppm)	Time Taken (s)	Flow rate (mL/s)	Conc (ppm)	Time taken(s)	Flow rate (mL/s)
(300) 255	40	508	5.65	7.08	6	6.05	6.61
	50	523	5.84	6.85	5	7.07	5.66
	60	554	5.91	6.77	3	6.99	5.73
(400) 358	40	653	5.80	6.89	5	5.77	6.93
	50	680	6.12	6.54	4	5.87	6.81
	70	794	8.46	4.73	6	5.54	7.22
(500) 440	45	805	6.74	5.93	5	6.28	6.37
	55	885	7.46	5.36	6	5.55	7.21
	75	1030	9.63	4.15	8	6.10	9.64

Table 1: Experimentally Obtained Data

8. Sample Calculations

For the first tabulation, we have

$P_F = 40\ kgf/cm^2 = 40\ atm,\ \&\ P_R = 10\ atm.$

Now using equation 1 for feed, reject & permeate we get,

$\pi_F = \frac{2\times300\times0.0821\times303.15}{74.55\times10^3} = 0.2003\ atm,\ MW_{KCl} = 74.55\times10^3 mg/mol.$

Similarly we get, $\pi_R = 0.3392\ atm,\ \ \pi_P = 0.004\ atm.$

Following the definition from the "*Theory*" section, we obtain,

$\pi_{FR} = \frac{\pi_F+\pi_R}{2} = 0.2698\ atm,\ \ P_{FR} = \frac{P_F+P_R}{2} = 25\ atm.$

$\Delta P_{net} = (P_{FR} - P_P) - (\pi_{FR} - \pi_P) = 14.7343\ atm.$

This follows the flux values multiplied with the area which are gives as,

$J_W A = Q_P = 0.00661\ L/s.$

$J_S A = C_P \times Q_P \times (10^3/(74.55\times10^3)) = 0.000532\ mmol/s.$

And the values of the mass transfer coefficients are as follows,

$$k_W A = \frac{J_W A}{\Delta P_{net}} = 0.0004486\ L/s.atm$$

$$k_S A = \frac{J_S A}{\Delta C} = \frac{J_S A}{(C_F - C_P)/(74.55\times 10^3)} = 0.0001349\ mL/s.$$

Predicted reject concentration, $C_{R,pred} = C_F \times \frac{1-(1-Rej)r}{1-r} = 574.4831\ atm.$

The % error on the experimentally obtained value $= |\frac{C_R - C_{R,pred}}{C_R}| \times 100\% = 13.087\%.$

9. Results & Discussions

The complete results for all the tabulated data are provided in the following table,

P_F	P_{FR}	π_F	π_R	π_{FR}	π_P	ΔP_{net}	$J_w A$	$J_s A$	$k_w A$	$k_s A$	r	Rej
40	25	0.20	0.34	0.26	40	14.7	66	5.32	4.49	134.9	0.4828	0.980
50	30	0.20	0.35	0.27	33	19.7	57	3.79	2.87	95.93	0.4524	0.983
60	35	0.20	0.37	0.29	20	24.7	57	2.31	2.32	57.88	0.4584	0.990
40	25	0.27	0.44	0.35	33	14.6	69	4.65	4.73	87.72	0.5014	0.987
50	30	0.27	0.45	0.36	27	19.6	68	3.65	3.47	68.79	0.5101	0.990
70	40	0.27	0.53	0.39	40	29.6	72	5.81	2.44	109.9	0.6042	0.985
45	27.5	0.33	0.54	0.44	33	17.1	64	4.27	3.73	64.34	0.5179	0.990
55	32.5	0.33	0.59	0.46	40	22.0	72	5.80	3.27	87.57	0.5736	0.988
75	42.5	0.33	0.69	0.51	53	31.9	96	10.3	3.01	156.7	0.6991	0.984

Table 2: Various Important Results

We also compare the estimated reject concentration values, provided in the following table,

C_R	508	523	554	653	680	794	805	885	1030
$C_{R,pred}$	574.48	543.75	551.38	797.29	812.35	1001.4	1031.7	1164.5	1642.9
%Err	13.09	3.97	0.47	22.09	19.46	26.12	28.17	31.58	59.50

Table 3: Comparing the reject concentrations

The units followed in the result tables are listed below,

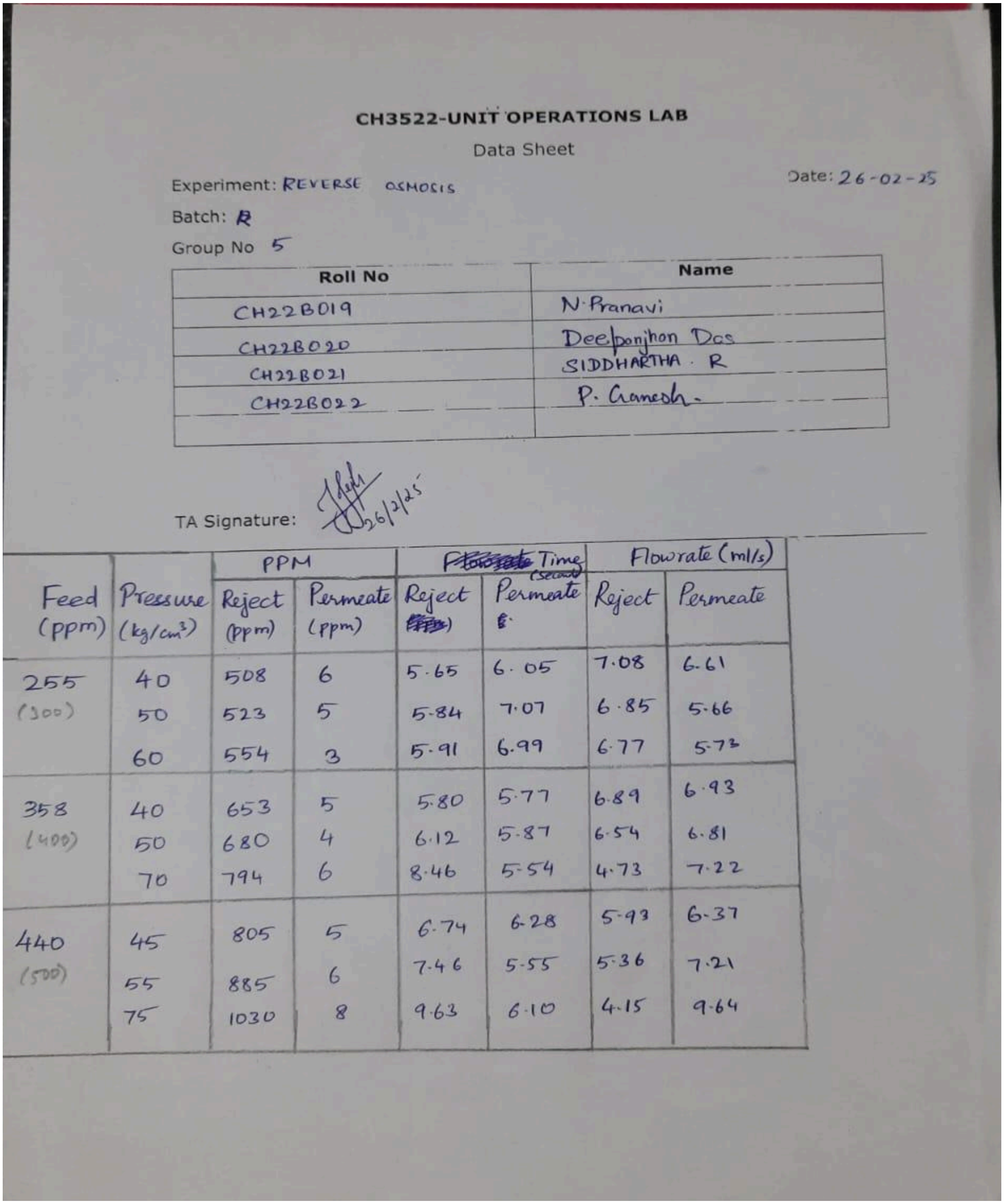
Term	Units
P_F	atm
P_{FR}	atm
π_F	atm
π_R	atm
π_{FR}	atm
π_P	atm ($\times\ 10^{-4}$ for each record in table)
ΔP_{Net}	atm
$J_W A$	L/s ($\times\ 10^{-4}$ for each record in table)
$J_S A$	mmol/s ($\times\ 10^{-4}$ for each record in table)
$k_W A$	L/s.atm ($\times\ 10^{-4}$ for each record in table)
$k_S A$	mL/s ($\times\ 10^{-6}$ for each record in table)
$C_{R,\,pred}$	ppm

10. Conclusions

- k_w is constant for increasing pressure at constant concentrations.
- Reject ratio comes down for increasing pressure at constant feed concentration.
- For rise in feed concentration at constant pressure, J_s increases.
- Except for a few outliers, k_W & k_S are fairly constant over conc. & pressures. This is probably because we expect mass transfer coefficients to be independent of feed concentration & pressure.

11. References

I. Resource from Moodle.
II. The GitHub repository contains all the related data & coded scripts used for calculations.



CH3522-UNIT OPERATIONS LAB

Data Sheet

Experiment: REVERSE OSMOSIS

Date: 26-02-25

Batch: B

Group No 5

Roll No	Name
CH22B019	N. Pranavi
CH22B020	Deepanjhon Das
CH22B021	SIDDHARTHA . R
CH22B022	P. Ganesh.

TA Signature: 26/2/25

Feed (ppm)	Pressure (kg/cm³)	PPM		~~Flowrate~~ Time (seconds)		Flowrate (ml/s)	
		Reject (ppm)	Permeate (ppm)	Reject	Permeate	Reject	Permeate
255 (300)	40	508	6	5.65	6.05	7.08	6.61
	50	523	5	5.84	7.07	6.85	5.66
	60	554	3	5.91	6.99	6.77	5.73
358 (400)	40	653	5	5.80	5.77	6.89	6.93
	50	680	4	6.12	5.87	6.54	6.81
	70	794	6	8.46	5.54	4.73	7.22
440 (500)	45	805	5	6.74	6.28	5.93	6.37
	55	885	6	7.46	5.55	5.36	7.21
	75	1030	8	9.63	6.10	4.15	9.64

Figure 4: Datasheet containing Lab-Data.