

DELFT UNIVERSITY OF TECHNOLOGY

EQUIPMENT FOR HEAT AND MASS TRANSFER
ME45165

Equipment for Mass Transfer - Assignment 2

Authors

Group - EHMT 12

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June 22, 2020



Question 1

Did you wash your hands before starting this assignment?

Solution. Yes!

Question 2

Let's say you are an engineer at International Space Station (ISS). You have decided to prank your fellow team mates by replacing the available fresh drinking water with salt water. To prepare the concentrated salt solution, you place fine-ground salt on the bottom of a square vessel (volume = 1 m³) and add distilled water on top of it until full. While cooking, you have observed that salt dissolves faster in hot water and therefore, you decide to place this vessel over a hot plate stove. Meanwhile, you decide to watch a movie and wait for the salt to dissolve. (Assume water loss over surface is negligible and there are no bubbles formed while heating in all the below cases).

- (a) After some time you touch the surface of the water and you feel warmth. To check the saltiness, you taste the water from surface. But unfortunately, you don't sense the salt. Now you are wondering why you feel the heat but not the salt. Can you explain why? What is the dimensionless number that characterises this? (tip: neglect gravity)

Solution. As there is no gravity, convective heat transfer or convective mass transfer does not take place and hence, the hot water at the bottom of the vessel stays at the bottom. As a result, the salt at the bottom of the vessel can only be transported all over the vessel through molecular diffusion. The diffusion rate for such a process is very small compared to convective mass transfer and hence, the water at the top of the tank does not feel salty. The dimensionless number that characterises this is the **Sherwood number** (Sh) which is mathematically expressed as follows.

$$Sh = \frac{\text{Total Mass Transfer Rate}}{\text{Rate of Diffusion}} = \frac{kL}{D} \quad (1)$$

where k is the mass transfer coefficient in [mol/(s m²)/(mol/m³)], L is the characteristic length [m] and the D is the diffusion coefficient [m²/s].

Additionally, it is to be noted that the thermal conductivity of water [1] is higher than the mass diffusivity of salt in water [2] by three orders of magnitude which signifies that the heat transfer in liquid is much faster than the mass transport. Hence, the water at the top of the vessel feels warm due to thermal conduction whereas the salt concentration at the top remains very less. The dimensionless number related to this is the **Lewis number** (Le) which is mathematically expressed as follows.

$$Le = \frac{\text{Thermal Diffusivity}}{\text{Mass Diffusivity}} = \frac{\alpha}{D} \quad (2)$$

where α is the thermal diffusivity in [m²/s] and D is the diffusion coefficient as previously defined.

- (b) Later after returning to earth you decided to redo the prank on your family members using the same vessel size. This time what difference would you expect? Why?

Solution. In this case, the gravity will come into effect. As the water is heated at the bottom, the hot water starts to rise due to the difference in density (free convection) and hence, there is a bulk motion which increases the transport of species along with molecular diffusion. Hence, this causes convective heat and mass transfer which is more prominent than conductive heat transfer and molecular diffusion. As a result, the water at the top of the vessel will be **salty and warm**.

This can also be interpreted from the Sherwood number. For the previous case where gravity was negligible, the mass transfer rate k will be proportional to the molecular diffusion rate D/L and hence, $Sh = 1$. However, for this case, the mass transfer rate will be higher than the molecular diffusion rate and hence, $Sh > 1$.

- (c) While you are busy analysing the solution, your curious cat tries to have a peek into the vessel. Accidentally, it slips into it and swims across, thereby introducing a flow at the top portion. This time what additional dimensionless numbers characterises your setup? What concentration change at the top would you expect now and why? (tip: lid driven cavity).

Solution. In this case, assuming the cat creates a near-uniform flow at the top of the vessel, re-circulation of water is formed in the vessel causing forced convection. Hence, the presence of both forced and free convective heat transfer is significant enough that the flow in the vessel depends on the balance of these two heat transfer phenomena. The dimensionless numbers relating to natural convection and forced convection are respectively the **Grashof number** (Gr) and the **Reynolds number** (Re).

$$Gr = \frac{g\beta\Delta TL^3}{\nu^2}, \quad Re = \frac{vL}{\nu} \quad (3)$$

where g is the acceleration due to gravity in $[m/s^2]$, β is the thermal expansion coefficient in $[1/K]$, ΔT is the difference in temperature between the heated surface and the ambient fluid in $[K]$, L is the characteristic length scale in $[m]$, ν is the kinematic viscosity in $[m^2/s]$ and v is the velocity scale in $[m/s]$.

The Grashof number, indicating natural convection, and the Reynolds number, indicating forced convection, can be combined into a single dimensionless number, *viz.*, the **Richardson number** (Ri). The Richardson number is mathematically expressed as

$$Ri = \frac{\text{Heat flux through natural convection}}{\text{Heat flux through forced convection}} = \frac{Gr}{Re^2} \quad (4)$$

The Richardson number can be interpreted as the ratio between heat flux through natural convection and forced convection [3]. Based on the value of Ri , the following inferences can be made:

- If $Ri \gg 1$, natural convection dominates and hence, there would be minimal consequences of the flow induced by the cat. The level of saltiness at the top of the vessel is more or less similar to what it was before the cat swam across.
- However, if $Ri \ll 1$, forced convection dominates and hence, mass transfer through eddy diffusion might be seen in the vessel. This implies that the mixing of salt becomes faster through eddy diffusion and hence, the saltiness at the top of the vessel would be more than the previous case where the vessel was undisturbed.
- When $Ri \approx 1$, a mixed convection phenomena occurs and the level of saltiness at the top would still be greater than the previous case but not as high as the case where forced convection entirely dominates.

It is to be noted that molecular diffusion is assumed to be very weak compared to natural convection and does not play a role in this case. If one were to compare advective mass flux and diffusive mass flux, the **Péclet number**, which is the ratio between advective mass flux and diffusive mass flux, would be useful.

- (d) Being an engineer now you want to measure and quantify the concentration gradient in the absence of stove/heat input. Therefore you insert a probe at half the depth and try to measure the concentration. How long will it take for the probe to sense the concentration of C and what is the degree of supersaturation. Assume that at the bottom the salt is always saturated (sat) - degree of supersaturation equals 1. Use table 1 for C and C_{sat} specific for your group - the units are in kg of salt to kg of water.

C_{sat} [kg/kg]	C [kg/kg]	Amount [kg]
0.43	0.162	41.071

Table 1: Given values for saturation concentration, actual concentration and amount of salt in solution

Solution. In the absence of heat input, the transport of species occurs only by molecular diffusion. The time taken for the probe to sense the concentration change can be determined from the equation given below.

$$\frac{C - C_0}{C_s - C_0} = \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right) \quad (5)$$

where C is the concentration at a certain depth, C_0 is the initial concentration at $t = 0$ and C_s is the concentration at the surface. By computing the fractional concentration change from the given values, we get,

$$\operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right) = 0.3767$$

From the tables of error function [4],

$$\frac{z}{2\sqrt{Dt}} = 0.625 \quad (6)$$

It is given that the probe is located at a distance of 0.5 m from the bottom of the vessel where the liquid is supersaturated. Hence, we have the value for $z = 0.5$ m. Also, a typical value for the diffusion coefficient D for salt (considering NaCl) in water is found to be $D = 1.5 \times 10^{-9} \text{ m}^2/\text{s}$ [2]. The time taken can be determined by solving the equation (6) for t as computed below.

$t \approx 3.38 \text{ years}$

The degree of supersaturation or supersaturation ratio is determined by the ratio of solute concentration to the equilibrium/saturation concentration. From the values given in table 1, **the degree of saturation** is found to be **0.3767**.

- (e) If heat of dissolution of your salt is considered, how will your concentration penetration be affected? Assume the total heat released is instantaneous once after the salt is added. Using the data from table 1, can you compare it with a solution at ambient conditions? Take $\Delta H = -82.9 \text{ kJ mole}^{-1}$, heat capacity of water as $C_p = 4.2 \text{ kJ kg}^{-1} \text{ K}^{-1}$ and molecular weight of the salt to be 20 g mole^{-1} . (tip: for water, $\mu = 2.414 \times 10^{\left(\frac{247.8}{T-140} - 5\right)} \text{ Pa s}$, where T is in [K]).

Solution. When the heat of dissolution of the salt is taken into account, the concentration of salt penetrates faster in water when compared to the case of absence of heat. This is due to the presence of convective mass flux from the bottom of the vessel to the top owing to the exothermic reaction which occurs when the salt mixes with the water.

To describe the type of mixing, we can use the dimensional numbers mentioned previously. To start, the total heat transfer through dissolution has to be estimated. The heat of dissolution to the solvent is provided as $\Delta H = -82.9 \text{ kJ mol}^{-1}$. The number of moles of solute (N_s) can be estimated from the mass of the solute ($M_s = 41.071 \text{ kg}$) and the molecular weight ($m_w = 20 \text{ g mole}^{-1}$) as

$$N_s = \frac{M_s}{m_w} = 2053.55 \text{ mol}$$

Hence, the total heat dissipated to the solvent (Q) can be computed as

$$Q = \Delta H \times N_s = 170.29 \text{ MJ}$$

This heat energy is responsible for the heating up of the solution. The total temperature rise can be determined from a simple energy balance with the solution as

$$Q = mC_p \Delta T$$

$$\Delta T = \frac{Q}{mC_p}$$

The mass of the solution m has been computed assuming that the density of the solution, in this case, water, is 998.2 kg/m^3 . Hence, the estimated temperature rise of the solution is determined as

$$\therefore \Delta T = 40.6 \text{ K}$$

Assuming an initial temperature of 20°C , the final temperature of the system after dissolution will be 60.6°C . The diffusion coefficient is a function of temperature and is subject to changes. It can be determined [5] by the following equation.

$$D = \frac{RT[(1/n_+) + (1/n_-)]}{F^2[(1/\lambda_+) + (1/\lambda_-)]}$$

where R is the gas constant, F is the Faraday's constant, n_+ and n_- are the valencies of the cation and the anion, in this case, 1, and the values of λ_+ and λ_- are determined with the temperature correction as prescribed. Therefore, the new value for the diffusion coefficient will be

$$D = 3.924 \times 10^{-9} \text{ m}^2/\text{s}$$

Therefore, substituting the new value for the diffusion coefficient in equation (6) gives a diffusion time of

$$t \approx 1.293 \text{ years}$$

Hence, it can be seen that the diffusion is faster if the heat of dissolution is considered. However, in many practical cases, dissolution of the salt is localised and creates heat plumes which result in a small advective mass transport which increases the mixing orders of magnitude higher than pure diffusion.

- (f) Overall mention what design parameters can be changed to make the process faster? List at least 3 options.

Solution. The design and operating parameters that can be modified to make the dissolution process faster are listed below.

- Reduce the depth of the container and increase the cross sectional area.
- Increase the temperature of water through external heating or increasing the heat absorption of water by insulating the vessel.
- Enhance mixing by increasing stirring speed or through novel techniques to induce eddy diffusion.

Question 3

- (a) Later, after the solution cooled down and has uniform concentration, your mother decides to cook rice using the water you left at the kitchen without knowing the history of the liquid. Would she see a difference in the cooking time than usual. If yes/no then why? Consider the vessel to be open to atmosphere. (pro tip: always add salt while you cook though it can be added even after preparing the meal for taste).

Solution. There certainly would be a difference in the cooking time when using salt water than when using normal tap water. This is due to two reasons namely the **dissolution of an additional species** in a solvent reduces the vapor pressure and the fact that **salt water has a lower specific heat** at constant pressure compared to the specific heat of normal water.

The former can be mathematically expressed through the Raoult's law which states that the total pressure of a mixture can be expressed as the product of mole fraction of the solvent in the liquid phase and the saturation pressure of the solvent as a pure substance. In the absence of dissolved salt, the mole fraction of water would be 1 or close to 1. However, in the presence of a second component, the mole fraction decreases, reducing the

vapor pressure. This reduction results in an increase in the boiling point of the mixture which leads to the mixture staying in the liquid phase for higher temperatures, resulting in better and faster cooking.

The latter can be verified mathematically by determining the exact value of the specific heat of the salt solution. We first determine the molality of the uniformly dispersed salt solution from the given weight of the salt ($M_s = 41.071$ kg) and the volume of the tank ($V = 1$ m³) as

$$m = 0.704 \text{ mol/kg}$$

Now, the specific heat at constant pressure of the solution is determined from the molality [6] as

$$C_{p,s} \approx 3979 \text{ J/kg/K}$$

The specific heat capacity of normal water at NTP is found to be $C_{p,w} = 4184.1$ J/kg/K which is higher than $C_{p,s}$. Hence, the **salt solution requires less heat input than normal water** to get hot. As a result, the cooking process is generally faster upon using salt water.

- (b) Since you are a curious person you try to cross validate your mother's observation. Therefore you close the lid of the vessel and decide to measure the pressure inside the vessel while maintaining it at 100 °C. Would you observe a deviation from an expected saturation pressure of water calculated using Antoine equation? If so what is the value of the measured and calculated pressure? (for pressure in bar and temperature in K, the component-specific constants for water are $A = 6.20963$, $B = 2354.731$, $C = 7.559$).

Solution. The saturation pressure of water can be calculated from the Antoine equation as follows.

$$\log_{10} p_s = A - \frac{B}{C + T} \quad (7)$$

For the temperature of 100°C, the **saturation pressure** is found to be **1.058 bar**.

The measured pressure can be determined from Raoult's law which states

$$\frac{y_i}{x_i} = \frac{P_i^s}{P_{\text{tot}}} \quad (8)$$

In the above equation, y_i denotes the mole fraction of component i in the vapor state, x_i the mole fraction of component i in the liquid state, P_i^s the saturation pressure of component i at the system temperature and P_{tot} the total vapor pressure.

Assuming that the vapor does not contain salt, $y_w = 1$ or the mole fraction of water in the vapor phase is 1. In order to determine the mole fraction of water in the liquid phase, we must first know the number of moles of salt and water in the liquid phase. This can be determined from the mass of the salt given in Table 1 and the volume of the tank as

$$n_s = 702.7892 \text{ mol}, \quad n_w = 55408.52 \text{ mol} \quad (9)$$

Hence, the mole fraction of water in the liquid phase has been determined to be

$$x_w = \frac{n_w}{n_w + n_s} = 0.9874$$

It is also known that the saturation pressure of water at 100 °C is $P_w^s = 1.058$ bar from equation (7). Hence, the total pressure can be determined from equation (8) as

$$P_{\text{tot}} = x_w P_w^s = \mathbf{1.0447 \text{ bar}}$$

The observed deviation is in the order of 10^{-2} bar. The deviation occurs as a result of the dissolution of salt in the water. However, the deviation is low considering that the mole fraction of salt in the dissolved liquid phase is very minimal ($x_s \approx 0.012$).

- (c) You have decided to have the rice with a liquid sauce you purchased at the supermarket. The sauce is composed of 2 liquid ingredients which is labelled on its packet. Now you decide to figure out the company's secret recipe by measuring the exact composition of the mixtures. In order to do so you decide to measure the pressure of the closed vessel containing the sauce at 100 °C. But for this experiment you are required to choose a right pressure transducer for better sensitivity. Thus, using the ingredients and their component-specific constants given in Table 2, estimate the range of pressure you can expect (pressure minimum and maximum).

Ingredient 1			Ingredient 2		
A	B	C	A	B	C
5.321	2270.601	6.688	5.48	2355.143	6.593

Table 2: Question 3 values

Solution. The saturation pressures of ingredients 1 and 2 is calculated from the Antoine equation as 0.5185 bar and 0.4858 bar respectively.

It can be shown from Raoult's Equation and Dalton's Law of Partial Pressures that

$$P_{\text{tot}} = \sum_i x_i P_i^s \quad (10)$$

It is also known that

$$\sum_i x_i = 1 \quad (11)$$

For a two component system like the current case, equations (10) and (11) give

$$\begin{aligned} x_1 P_1^s + x_2 P_2^s &= P_{\text{tot}} \\ x_1 + x_2 &= 1 \end{aligned} \quad (12)$$

Hence, substituting $x_2 = 1 - x_1$ in the equation for pressure, we get

$$x_1 P_1^s + (1 - x_1) P_2^s = P_{\text{tot}} \quad (13)$$

We know that x_1 can range from 0 to 1. Hence, the range of measured pressures will be P_1^s and P_2^s or, in this case, **between 0.5185 bar and 0.4858 bar**.

- (d) Now you have measured the total pressure inside the vessel containing the sauce as p . Using this how will you estimate the required composition. Lets say all of a sudden this mixture becomes an non-ideal mixture. If we consider both of our ingredients to have activity coefficient greater than 1 what will be the newly measured total pressure. Will it be greater or smaller than before? Why?

Solution. The equation (13) can be modified by substituting the values of P_1^s and P_2^s as

$$0.5185 x_1 + 0.4858 (1 - x_1) = P_{\text{tot}}$$

The above equation can be simplified further to obtain

$$0.4858 + 0.0327 x_1 = P_{\text{tot}} \quad (14)$$

Hence, if P_{tot} (in bar) is known, the concentration y_1 can be determined from the equation (14) as

$$x_1 = \frac{P_{\text{tot}} - 0.4858}{0.0327} \quad (15)$$

However, if the mixture is non-ideal and the activity coefficient of both the ingredients is not 1, we can use the Modified Raoult's Law as

$$\frac{y_i}{x_i} = \frac{\gamma_i P_i^s}{P_{\text{tot}}} \quad (16)$$

Using equation (16), we have the sum relations as

$$\begin{aligned} x_1 \gamma_1 P_1^s + x_2 \gamma_2 P_2^s &= P_{\text{tot}} \\ x_1 + x_2 &= 1 \end{aligned} \quad (17)$$

From the above relations, if $\gamma_1, \gamma_2 > 1$, the measured total pressure would be greater when compared to the previous case.

Physically, a system with activity coefficients greater than 1 represents components that repel each other. Hence, minimal energy is required to separate them and the mixture can easily vaporize. Hence, the components tend to separate readily and prefer being in the vapor phase. This results in increased vapor formation and hence, an **increase in the total pressure**.

Question 4

After your meal while doing the dishes you notice that your mother hasn't utilised all of your salt solution. Your life at the ISS has taught you on how to recycle salt water. Therefore you decide use a membrane to extract the fresh water from the solution (only passage of the solvent is allowed in all the below cases). You fill 2 vessels A and B using the left over solution.

- (a) However you are not certain about the salt concentration levels of your tap water. Therefore you decide to use a container containing two compartments separated by a membrane with the solution from vessel A on one side and tap water in the other with equal levels. After sufficient time you notice that the water level in the salt solution compartment has risen. Why would that happen? Let's say that the difference in the water levels between the containers is 10 m, can you estimate the salt concentration in the tap water? (only for this case assume that the concentration in both the containers do not change due to solvent flux).

Solution. The rise of water level in the salt solution in this case is due to **osmosis**. The solvent concentration level on tap water side is higher when compared with that of the salt solution side and hence the water from tap water compartment flows into the salt solution compartment due to this concentration gradient through a semi permeable membrane that is more permeable to the solvent (water) than the solute (salt) causing dilution of dissolved salts in the salt solution side until eventually the concentrations even out on both sides.

Initially, the amount of salt was given to be 41.071 kg in a volume of 1 m³. Considering 4% salt water, the density is determined to be $\rho_s = 1026.8 \text{ kg/m}^3$ [7]. Hence, we can compute the salt concentration using the relation for osmotic pressure as shown below.

$$\pi = \rho_s g h = RT \Delta c \quad (18)$$

From equation (18), the concentration difference is found to be $\Delta c = 41.329 \text{ mol m}^{-3}$. We know that,

$$\Delta c = c_s - c_w$$

The molar concentration of salt in the solution was determined earlier in (9). Hence, we get,

$$\boxed{c_w = 661.46 \text{ mol m}^{-3}}$$

- (b) Somehow you manage to figure out the following values for the membranes, let the solvent permeability and membrane thickness be $3.5 \times 10^{-10} \text{ kg m s}^{-1} \text{ m}^{-2} \text{ bar}^{-1}$ and $2 \mu\text{m}$. In the previous question, what and when would you have the maximum flux? why?

Solution. The rate of water transport or water flux through the membrane is given by the equation as shown below.

$$N_{\text{water}} = \frac{P_{\text{M,water}}}{l_{\text{M}}}(\Delta p - \Delta\pi) \quad (19)$$

Here, $\Delta p = 0$ as there is no pressure gradient imposed in the osmosis process and $\Delta\pi$ corresponds to one osmotic pressure. The permeability of water $P_{\text{M,water}}$ and the membrane thickness l_{M} is given as $3.5 \times 10^{-10} \text{ kg m s}^{-1} \text{ m}^{-2} \text{ bar}^{-1}$ and $2 \mu\text{m}$ respectively. Hence, the flux is determined from equation (19) as follows.

$$\boxed{N_{\text{water}} = -1.763 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}} \quad (20)$$

The negative sign indicates that the ongoing process is osmotic, i.e, $\Delta p < \pi$. The computed **flux at the initial stage will be the maximum** as it corresponds to the highest osmotic pressure gradient. As the process continues, the salt solution gets diluted and hence, the concentration gradient which is the driving force reduces thereby decreasing the flux through the membrane.

- (c) Lets say at the start of the question (a) you supply twice the osmotic pressure greater than the ambient on the side of salt water container at the initial state. What is the direction and maximum possible magnitude of the new flux?

Solution. When twice the osmotic pressure is supplied on the side of salt water container, reverse osmosis takes place wherein the water from the salt solution compartment is pushed to the tap water compartment through the membrane which prevents the salt particles from getting through. The magnitude of new flux can be determined in a similar way using equation (19). It is given that the applied pressure is twice the osmotic pressure and hence $\Delta p - \Delta\pi = \pi$. The **maximum possible flux** corresponds to this pressure gradient as found below.

$$\boxed{N_{\text{water}} = 1.763 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}} \quad (21)$$

As two times the osmotic pressure is applied on the salt solution side, the applied pressure gradient overcomes the osmotic pressure gradient and hence, the **direction of water flow is from the salt solution compartment to tap water compartment**.

- (d) Using the solution from vessel B, you decide to make this a continuous process. In order to do so you roll the membrane into the shape of a tube with diameter 1 m and pass the solution through it with tap water on the exterior side of the tube. The flow velocity of the solution is 1 m s^{-1} . Taking the calculated value of the flux from the previous question to be constant along the length (50 m) of the tube, can you calculate the final concentration of the solution exiting the tube?

Solution. The final concentration of the solution can be determined by performing a mass balance as shown below.

$$\dot{m}_{\text{in}} = \dot{m}_{\text{mem}} + \dot{m}_{\text{out}} \quad (22)$$

The inlet mass flow rate of salt solution through the tube can be found using the equation given below.

$$\dot{m}_{\text{in}} = \rho_{\text{s}} Q_{\text{in}} = \rho_{\text{s}} A v = \rho_{\text{s}} \left(\frac{\pi d^2}{4} \right) v \quad (23)$$

From the given values of tube diameter and velocity, the inlet mass flow rate is found to be 806.4468 kg/s .

The mass flow rate of water through the semi permeable membrane can be determined from the following equation.

$$\dot{m}_{\text{mem}} = N_{\text{water}}(\pi dL) \quad (24)$$

For the given length of the tube, the mass flow rate through the membrane is computed as 0.0277 kg/s.

From equation (22), the outlet mass flow rate is found to be 806.4191 kg/s.

The mass of the salt at the inlet can be determined from the inlet mass flow rate as follows.

$$m_s = c_s \dot{m}_{\text{in}} \quad (25)$$

The final concentration of salt solution exiting the tube can be determined using the expression given below.

$$c_{s,\text{exit}} = \frac{m_s}{\dot{m}_{\text{out}}} \quad (26)$$

The final concentration of salt at the outlet is found as

$$c_{s,\text{exit}} = 702.81 \text{ mol m}^{-3}$$

It can be noted that the concentration of the solution at the outlet is slightly greater than concentration of the solution at the inlet as expected in a reverse osmosis process.

- (e) (**bonus question**) In a real case there should be a pressure drop across the tube in order to make the solution flow. Let's say you supply twice the osmotic pressure at the inlet compared to the outlet. Can you expect the reverse osmosis to happen through the length of the tube? If yes/no, then when/why? For this question you don't need to calculate any numeric values. Just mention and balance the equations. (tip: Hagen-Poiseuille equation).

Solution. It is given that twice the osmotic pressure is supplied at the inlet of the tube. From the Hagen-Poiseuille equation [8], the pressure drop across the length of the tube can be determined as follows.

$$\Delta P = \frac{8\mu LQ}{\pi r^4}$$

Assuming the viscosity of salt solution as 1.068×10^{-3} Pa s [7], the pressure drop along the length of the tube is found as

$$\Delta P = 1.71 \text{ Pa}$$

The pressure drop across the entire length of the tube is found to be very less and hence the outlet pressure does not reduce much when compared to the inlet pressure. Therefore, reverse osmosis is expected to occur throughout the entire tube length.

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