

Lec 30: Reverse Osmosis

. Hello everybody, welcome to this massive open online course on solid fluid operations. We are discussing about the filtration process in a module of that filtration and in the previous lectures we have discussed about that the special type of filtration where that particulate materials can be separated from the slurry. Those type of filtration is called plate and frame filter phase and also rotary drum filter. In that case, we have discussed something about how that particulate materials can be separated, what is the basic mechanism and what is the governing equation and based on that governing equation how we can assess that filtration process, what are the basic components of those filtration process like there are some factors like cake deposition, even specific cake resistance, even filter medium resistance, those will be actually affecting the filtration efficiency there. Also, we have discussed that rotary drum filter, also some components like rotational speed, even filter medium resistance, cake resistance, also the submerged area of that filter which will affect that efficiency of the filtration process.

There you have calculated how to, there we have discussed how to estimate that filter medium resistance as well as specific cake resistance from the experimental data just by taking that volume of filtrate with respect to time. Also, there it is discussed that what are the basic modes of that operation, either it will be constant rate filtration or constant pressure filtration or not. So, there we have discussed both the modes there. Today's lecture will be including also that regarding the filtration, but it will be a different mechanism.

It is called that reverse osmosis process. Here also the filtration process will be governed by the driving force of pressure. And in this case, some terms will be there that will be discussed and also what will be the mechanism and how to assess this reverse osmosis process where it can be applied and also what is the basic mass transfer equation for assessing this reverse osmosis to be discussed here. So, before going to that reverse osmosis, you have to know what is osmosis. So, what is osmosis? Basically, it is the movement of solvent across a semi permeable membrane towards a higher concentration of solute.

Suppose there is a solute here in this picture, it is shown that if suppose there is a solution of having some solute and there will be a certain concentration of that solute here in this solution. Whereas in the opposite side of a membrane which is placed here between these two solution, here other side of this membrane there will be no solute. So, here pure solvent you can say. So, you will see that there will be a movement of solvent across the semi permeable membrane towards the higher concentration of the solute. So, where that concentration here, you will see that the concentration of that solute will be higher relative to the concentration of the solute here.

If here there is no solute, then it will be concentration 0 whereas there will be certain amount of solute in the solution. So, we can say that this will be higher concentrated solution and here this is the pure solvent, there will be no solute. So, there will be a

movement of this solvent from this lower concentration to the higher concentration solution. So, this mechanism of movement or this transport of this solvent from its lower concentration to the higher concentration will be regarded as that osmosis. In biological systems, you will see that solvent is typically water, but osmosis can occur in other liquids like supercritical liquids and even gases also there you can say that means gases will be moving from lower concentration to the higher concentration.

So, this is called osmosis. This is the basic concept of this osmosis osmotic pressure by which that solvent will be moving from the lower concentration to the higher concentration. So, here the osmotic pressure is the driving force. So, this is called osmosis. Whereas you will see that reverse osmosis what they are the direction of the movement of that solvent to be opposite because of that applying some pressure externally.

So, that will be reverse osmosis. So, that will come later. So, let us discuss about this osmosis again here. So, osmosis will occur when there is a concentration gradient of solute within a solution. But if the membrane does not allow diffusion of the solute, the solvent moves to the higher concentration till the solution reaches equilibrium.

So, here the solvent will move up to when the solvent will be moving till this concentration of this higher concentration that till the solution reaches its equilibrium. That means in the both the cases you will see that there will be equilibrium condition. So, in this case, that there will be a concentration gradient of a solute within a solution, but if the membrane does not allow diffusion of that solute, the solvent moves to the higher concentration till the solution reaches its equilibrium. Now, the minimum pressure which needs to be applied to a solution to prevent the inward flow of its pure solvent across this semi permeable membrane is called that osmotic pressure. So, by osmotic pressure, this pure solvent will be moving to that higher concentration.

So, it is denoted by ϕ . So, ϕ is called osmotic pressure. In earlier lecture, we have also shown that there will be a net pressure based on which that filtration happens, that net pressure is the total pressure minus that osmotic pressure. But when we are talking or we are actually doing the operation with the pure solvent in that case, this osmotic pressure will be very negligible compared to the total pressure. So, in that case ϕ is considered as a negligible amount.

So, there it is neglected. But here osmosis in that case, it is the natural process you can say that solvent will be passing from this lower concentration to the higher concentration by this pressure. This is called osmotic pressure. And then reverse osmosis coming. Now, in this case, you will see that in this figure, the higher concentrated solute will be that tend to be applied to this high pressure.

Because of this high pressure, you will see that the solute particles will not be passed through that membrane, whereas the liquid or solvent will be passed through that

membrane because of that high applied pressure. So, in this case, movement of that solvent will be in the reverse direction. In this case, the solvent from the higher concentration to the lower concentration will be moving. So, it will be basically under a pressure which will be greater than that osmotic pressure. So, the RO process involves, RO means reverse osmosis, this is a short form.

So, RO process involves the forced passage of water or solvent through a membrane against the natural osmotic pressure to separate water and some solute, solute may be ions or other things. In these high pressures, greater than that osmotic pressure, the water molecules can pass through the membranes and the salt are left behind as a briny concentrate. So, that means here, we will see that in this amination process, you will see that from this higher concentrated solution of that solute, the solvent will be passing through that membrane whereas solute remains or it will be separated by this that membrane there. That means solute will not be passing through that membrane. So, this technique is mostly used for desalination of water, especially you will see that when we are actually making drinking water from the seawater.

So, in that case, this reverse osmosis is very important and in large scale industrial operation it is being done that reverse osmosis whereas in our domestic use also there are some systems that is called reverse osmosis systems also available and there are also some solid particles to be separated by this reverse osmosis mechanism. So, in that case, there will be certain membrane, those membrane through which that solute will be retained under this high pressure just by allowing the clean water there. So, if ΔP that means applied pressure is less than $\Delta \pi$ that means osmotic pressure, then water flows from the dilute to the concentrated salt solution side by normal osmosis. And if ΔP is equal to $\Delta \pi$ that way there will be no occurs, there will be no flow occurs that means equilibrium condition will be there. If ΔP is greater than $\Delta \pi$, then water flows from the concentrated solution to the dilute salt solution side of the membrane.

Here in this picture also it is shown that under this osmotic pressure, this solvent is flowing from this lower concentration to the higher concentration where in the reverse osmosis, the solvent will be flowing from the higher concentrated solution to the lower concentrated solution to the semi permeable membrane. Then in industrial scale, you will see that Crist water technology group, they are producing drinking water commercially in a large scale that is capacity is very high. In that case, they are separating different solute by this reverse osmosis technique. And they are producing this portable water that is desalted drinkable water around that 7 lakhs gallon per day from this that salting water by this reverse osmosis technique. Now, we will assess this reverse osmosis technique which is actually governed by that driving force of pressure drop and how to assess this reverse osmosis separation process.

There will be a certain mass transfer happens mainly in the feed boundary layer and the inside the membrane. What is that feed boundary layer and also the whatever mass

transfer, mass transfer means here solute transfer here from one concentrated solution to the another diluted solution. So, there will be transport of that solute it is called mass transfer. So, here some boundary layer of the solid particles near about that membrane you will see that that will affect that mass transfer and also you will see that some operational process variables also will affect that mass transport of solute from high concentrated solution to the dilute solution to the membrane under that pressure. And now in that case that mass transfer model to be used to assess that reverse osmosis separation process.

For that you have to know some concept of concentration polarization. What is that concentration polarization? Here you will see that some particulate materials or solute you can say here. The concentration layer will be different along the distance in bulk region of that solution, highly concentrated solution. Suppose this solution is the concentrated solution and this is the membrane and in this side of this membrane, the concentrated solution is there and the other side of the membrane will be you the dilute solution that means the concentration of that solute will be very low whereas clear liquid you can say that it will be passed through that membrane. So, in this side where concentration of that solution you will see that particle concentration it will be different at different location.

Where that feed solution is entering the entry zone you will see that the concentration of the particles or solute will be very low compared to the region which is adjacent to that membrane. So, in that case where that solute concentration will be relatively higher at that adjacent layer of that adjacent side of that membrane. There the concentration will be higher. So, this will be regarded as a concentration polarization layer that means solute will be polarized to be coming to this side of this membrane and when with respect to time it will be coming and depositing in this side of this membrane it will be deposited as a layer. So, that is why concentration of the particles will be higher in this side.

So, it will be this particular zone it will be regarded as or will be defined as a concentration polarization layer or concentration polarization zone. So, in order to build a mass transfer model you will see that a one-dimensional flow to be assumed which is to be valid for the transport of this solvent and solute through the membrane. So, for that you have to know the concentration of that solute in this concentration polarization region. So, whenever you are going to assess that mass transfer of that solute to this membrane you have to know that concentration difference of this solute either in this concentration polarization region or in the permeate region in the permeate solution. Now on the basis of that concentration polarization the mass transfer equation can be written based on the mass balance equation by this equation 1.

Here the Equation

$$J_w \cdot C_p = J_w C - D \frac{dC}{dx}$$

Where you will see that $J_w C_p$ that will be equal to $J_w C$ minus D into DC by DX where J_w is the solvent flux. Flux that that means the rate of volumetric flow of that solvent per unit

cross sectional area of the membrane that is called flux and here C_p , C_p is basically the permeate solution concentration and C is called the solute concentration in the concentration polarization layer. Here C_p as shown in the picture here what is the C_p concentration. Here C_p is C is the solute concentration in the C_p layer here in this region C and D is the diffusion coefficient. So, here in this case we can say that there will be a certain concentration gradient with respect to x in this concentration polarization region and this concentration gradient with respect to x in this direction of flow this will give you the diffusion what amount of diffusion will be there rate of diffusion you can say.

So, this will be basically minus $D \frac{dC}{dx}$ where D is a diffusion coefficient as per Fick's law of diffusion and then what will be the other flow of that solute that will depend on that solvent flux. So, in that case what will be the solute will be transported by that solvent flux this will be $J_w C$ whereas by diffusion how that solute also to be transported that will be minus $D \frac{dC}{dx}$. So, what is the effective that transport of that solute that will be regarded by this $J_w C$ minus $D \frac{dC}{dx}$. So, that will be basically what is the J_w into C_p this is what is that the amount of solute which is actually transported through the membrane at that particular solvent flux. And in this representation of this schematic diagram you will see that there it is written C_f , C_f is basically the feed solution concentration $C_{\delta,1}$ is term this is basically the solute concentration at the membrane surface this is $C_{\delta,1}$ and $C_{\delta,2}$ you will see that it is the solute concentration at the membrane surface that is in the permeate side.

And another terms you will see that there will be J_s , J_s is basically the solute flux and δ_{cp} is called the length of that C_p layer or thickness of that C_p layer concentration polarization layer. So, we are having that mass balance equation that is represented by equation number 1 that is $J_w C_p$ that will be $J_w C$ minus $D \frac{dC}{dx}$. Now if you do the integration within a certain boundary condition that means x is ranges from 0 to δ_{cp} and concentration will be ranging from C_1 to $C_{\delta,1}$ within that you know x ranges.

Here the Equation

$$-\int_{C_{\delta,1}}^{C_f} \frac{dC}{C - C_p} = \frac{J_w}{D} \int_0^{\delta_{cp}} dx$$

So, based on this boundary condition we can integrate this equation number 1 and then we can get this equation number 3 as $C_{\delta,1} - C_p$ by $C_f - C_p$ that will be equal to exponent of $J_w \delta_{cp}$ by D is equal to exponent of J_w by k .

Here the Equation

$$\frac{C_{\delta,1} - C_p}{C_f - C_p} = \exp\left(\frac{J_w \delta_{cp}}{D}\right) = \exp\left(\frac{J_w}{k}\right)$$

So, this equation number 3 will give after integration of this equation number 1 with that boundary condition and this equation will be called as that governing equation for this reverse osmosis filtration process.

In this case one term you will get this K, K is basically the mass transfer coefficient in the concentration polarization layer and is defined as K will be is equal to D by delta Cp.

Here the Equation

$$k = \frac{D}{\delta_{cp}}$$

So, D is called diffusion coefficient and delta Cp is called that thickness of that boundary layer of that concentration polarization. Now according to this figure you will see that the solute flux J_s is expressed by the following equation this is fine because it is coming from that concentration differences. So, it will be basically J_s into Cp that will be is equal to B_s into C delta 1 minus C delta 2.

Here the Equation

$$\begin{aligned} J_s \cdot C_p &= B_s (C_{\delta,1} - C_{\delta,2}) \\ &= B_s (C_{\delta,1} - C_p) = J_w \cdot C_p \end{aligned}$$

Here this is C delta 1 the concentration of the solute in the what is that retentate side of the membrane whereas C delta 2 is the concentration of solute in the permeate side of that membrane.

So, this concentration difference will give you the expression for the mass transfer of that solute which can be represented by this equation number 5. Also it can be expressed by the concentration difference of this C delta 1 and this Cp. Cp is basically what is that concentration of solute in the permeate solution which will be exactly the same concentration in the near region of that membrane at this permeate side. So, we can write this equation number 5 according to this figure based on the concentration difference for this mass transfer equation where B_s is called solute transport coefficient. Now for the reverse osmosis the total flux of the solvent and solute which represents the volumetric flux on the permeate side of the reverse osmosis membrane and can reflect the concentration capacity of the reverse osmosis membrane which can be expressed by the following equation here.

Equation number 6 here JV is basically the total flux of the solvent and solute which is basically J_w plus J_s

Here the equation

$$J_v = J_w + J_s \approx J_w$$

and since J_s is very negligible compared to that J_w then J_v can be regarded as J_w here itself. Where J_v can be defined by this volumetric flow rate divided by the surface area of that membrane through which that feed will be flowing or solute will be retentate or solvent will be transporting.

Here the equation

$$J_v = \frac{Q_p}{S}$$

Now according to that principle of mass conservation we get the following equation here. We can write that mass conservation equation what will that total solute that is in feed that will be is equal to what $Q_b C_b$ plus $Q_p C_p$ that will be is equal to $Q_f C_f$ means what that means here the you can say that feed no here it is basically that retentate flow rate retentate flow rate you can say and C_b is the concentration at that retentate flow that means at the bulk flow you can say and C_p is the concentration of solute in the permeation solution or permeate solution and Q_p is the permeate flow rate. So, $Q_f C_f$, $Q_b C_b$ and $Q_p C_p$ these are actually feed solution flow retentate flow and permeate flow respectively and C_f , C_b and C_p are the solute concentration respectively.

Also the total balance of that solute can be regarded as $Q_f C_f$ that will be is equal to $Q_b C_b$ plus $Q_p C_p$.

Here the equation(s)

$$Q_f C_f = Q_b C_b + Q_p C_p$$

$$Q_f = Q_b + Q_p$$

o, here Q_f is basically solute and solvent Q_b also solute and solvent Q_p also solute and solvent in the feed bulks or retentate you can say and also permeate side of that membrane. And so this is actually the governing equation to assess this membrane separation process by this reverse osmosis. Now let us do an example based on this theory suppose 100% pure water is if permitted by a reverse osmosis membrane at a rate of 1000 cc per second what should be the concentration that is per gram per cc at a distance 1 millimeter from the membrane surface. If the concentration gradient of a solute at a distance from the membrane surface follows the relation as C will be is equal to 0.

$1 \times \text{square} + 0.2 \times \text{plus} + 0.1 \text{ per unit}$ is given in gram per cc per millimeter. The diffusion coefficient of the solute in the solution is given 1000 millimeter square per second. So, here what you have to find out you have to find out what will be the concentration at a distance 1 millimeter from the membrane surface. You have to find out what is the C value. The

governing equation for expressing the mass transfer in a concentration polarization region of the RO membrane which can be written by this equation here $J_w C_p$ that is equal to $J_w C$ minus $D \frac{dc}{dx}$.

For 100% pure water in the permeate in that case we can write that C_p will be is equal to 0 since 100% pure water there will be no solute there. So, C_p will be is equal to 0. So, we can write $J_w C$ that will be is equal to $D \frac{dc}{dx}$ from this equation. Which implies that J_w is given 1000 C we have to find out D again 1000 into $\frac{dc}{dx}$ it is given as per 0.1 what is that after in after derivative $\frac{dc}{dx}$ from this equation where concentration with respect to x is given here.

So, from this $\frac{dc}{dx}$ that will be coming as $0.2x + 0.2$. So, at 1 millimeter that means x is equal to 1 millimeter. So, C will be coming as 0.

4 gram per cc of this equation. So, I think you understood this problem here how to solve. Then coming to that another important point here for this reverse osmosis system. How to actually calculate that recovery or permeate production capacity by that reverse osmosis system. In this case if you are considering that recovery as y which represents the water production capacity that means permeate solution capacity which would be defined as the fraction of heat flow which passes through the membrane. And in this case if we know that permeate flow rate and the feed flow rate then the value of recovery can be calculated by this equation 9.

So, y will be is equal to $\frac{Q_p}{Q_f} \times 100$ in percentage. So, this is called recovery percentage and this recovery percentage will give you the capacity of this RO. Now the higher the recovery that means the stronger the water production capacity of the RO system and the stronger the concentration capacity of the RO system. So, I think you understood this one. And then another important factor that you have to know it is called membrane rejection.

By this also this RO membrane separation process be assessed. In this case the rejection is a one term by which you can interfere that reverse osmosis filtration process. There are two actually rejection one will be observed another will be real rejection. The observed rejection is basically based on that overall concentration in the feed and permeate side. So, observed membrane rejection fraction can be expressed by this RO this is defined by this C_f minus C_p by C_f .

Here the Equation

$$R_o = \frac{C_f - C_p}{C_f}$$

C_f is the overall or average concentration in the feed solution and C_p is the average concentration of solute in the permeate solution divided by C_f . So, this what is the difference of that concentration in the feed and permeate divided by the concentration of

the feed that will be called as that observed rejection. Whereas real rejection actually will be based on the what will be the concentration of that solute in the very near a region of that membrane surface in the retentate side and also what will be the solute concentration at the nearer side of that permeate side of that membrane. So, based on those concentration it will be considered as a real rejection.

So, real rejection fraction can be defined by RR. So, it will be $C_{\delta,1} - C_{\delta,2}$ divided by $C_{\delta,1}$.

Here the Equation

$$R_r = \frac{C_{\delta,1} - C_{\delta,2}}{C_{\delta,1}} = \frac{C_{\delta,1} - C_p}{C_{\delta,1}}$$

Here $C_{\delta,1}$ that this at this concentration polarization region very adjacent to the membrane surface in the retentate side what will be the solid concentration and $C_{\delta,2}$ is the concentration of the solute at the permeate side which is very near to the membrane surface at that permeate side. So, based on these you will be able to calculate what will be the real rejection once that concentration at that side. So, very difficult to actually calculate that concentration of the solute at that surface of that membrane or at that concentration polarization region. So, for that average concentration is taking by calculating it is that in the feed solution and also in the bulk solution at that permeate side what will be the concentration it is taking as a average.

So, in that case observed rejection is to be followed for interpretation of that membrane that will be overall whereas real to be calculated based on that if that concentration at the surface of that membrane. Nowadays very sophisticated instruments are used to calculate that solid concentration at that nearer to that membrane surface and based on which you will be able to assess that membrane efficiency based on this rejection of real condition. So, I think you understood that reverse osmosis system what is the difference between osmosis and reverse osmosis. What is the driving force basically the pressure and also you have to assess that reverse osmosis based on that concentration differences and based on that concentration differences you can assess that reverse osmosis based on that one-dimensional mass transfer model and for that mass transfer model you are considering what will be the diffusion what are the net flux and based on that what are the mass balance and based on that mass balance you will be able to calculate what will be the concentration at a particular location from that membrane. So, I think you understood this saw lecture here what is the basic concept of RO membrane.

In the next lecture onward we will try to discuss the different module which will be started for the discussion of that nanoparticles. So, till now we were discussing about that micro particles and also that coarser particles conventional particle size and how to separate from that slurry by different techniques also that some hydrodynamics, frictional pressure drop,

even some material characteristics all those things. Now next module onward it will be there some introduction to that nanoparticles, nano size particles, what is the basic concept of that nanoparticles, where that nanoparticles are used, why those nanoparticles are so important nowadays, what are the different characteristics of that nanoparticles based on who is that nowadays industry look into the process intensification based on this nanoparticle systems for various application to get that enhancement of that yield of the reaction even some other separation processes all those things. So, next lecture it will be on that introduction to nanoparticles.

So, thank you for giving your kind attention. Have a nice day. Thank you.