Novel Separation Processes
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Lecture No. # 05
Membrane separation processes

Good morning everyone so, in the last class we have seen the application of irreversible thermodynamics to quantify the solvent flux in during the reverse osmosis process. So, we started with the basic equation and kept on deriving things you know depending on several assumptions, you know and simplification and ultimately, we arrived at the osmotic pressure model for quantification of the solvent flux through the porous membrane. Now, in today is class we will derive the left over portion, if it that is the solute flux to the porous membrane.

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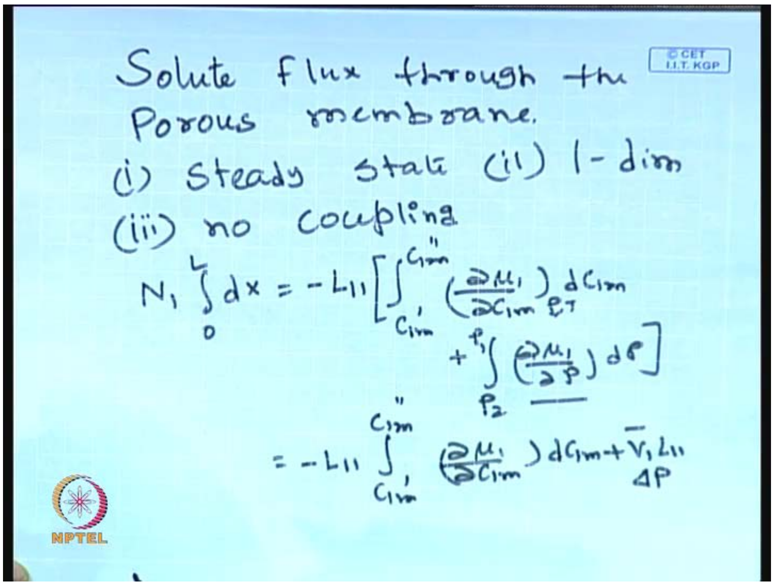

Solute flux through the Porous membrane.

(i) Steady state (ii) 1-dim

(iii) no coupling

$$N_1 \int_0^L dx = -L_{11}\left[\int_{C_{1m}'}^{C_{1m}''} \left(\frac{\partial \mu_1}{\partial C_{1m}}\right)_{P,T} dC_{1m} + \int_{P_2}^{P_1} \left(\frac{\partial \mu_1}{\partial P}\right) dP\right]$$

$$= -L_{11} \int_{C_{1m}'}^{C_{1m}''} \left(\frac{\partial \mu_1}{\partial C_{1m}}\right) dC_{1m} + \bar{V}_1 L_{11} \Delta P$$

So, let us develop Solute Flux through the porous membrane again the assumptions in word that one is steady state, second one is one dimensional flow field that will be talking about and third one will be no coupling.

So, we indicate the solute balance equation at the steady state so, N 1 0 to L l is the thickness of the membrane minus L 1 1 integral C 1 m prime to C 1 m double prime dell mu 1 dell C 1 m d C 1 m at constant pressure temperature plus P 2 to P 1 dell mu 1 dell P d p. So if we so now, substitute will invoke the definition of partial molar volume and put it here so, will be getting minus L 1 1 C 1 m prime to C 1 m double prime dell mu 1 dell C 1 m d C 1 m plus V 1 bar L 1 1 delta P is the pressure drop across the membrane and for the dilute solution, you know the activity will be almost equal to concentration.

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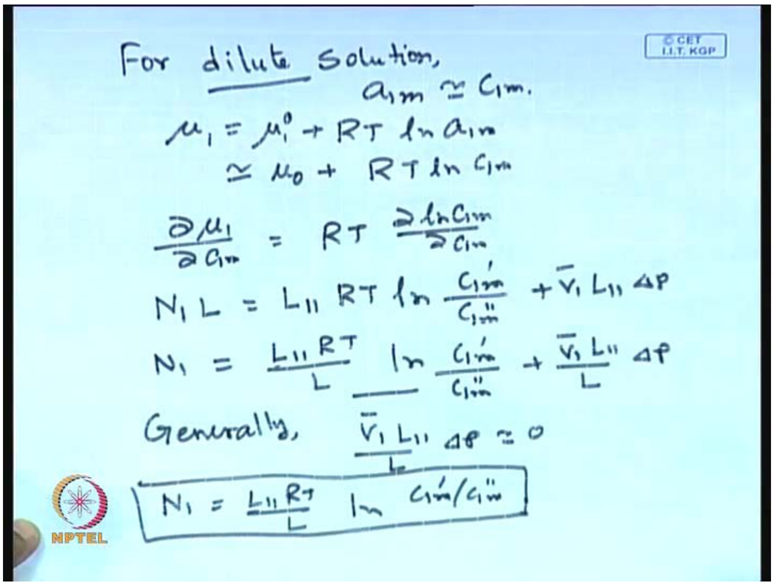

For dilute solution,

$$a_{1m} \simeq C_{1m}.$$

$$\mu_1 = \mu_1^0 + RT \ln a_{1m}$$

$$\simeq \mu_0 + RT \ln C_{1m}$$

$$\frac{\partial \mu_1}{\partial C_{1m}} = RT \frac{\partial \ln C_{1m}}{\partial C_{1m}}$$

$$N_1 L = L_{11} RT \ln \frac{C_{1m}'}{C_{1m}''} + \bar{V}_1 L_{11} \Delta P$$

$$N_1 = \frac{L_{11} RT}{L} \ln \frac{C_{1m}'}{C_{1m}''} + \frac{\bar{V}_1 L_{11}}{L} \Delta P$$

Generally, $\frac{\bar{V}_1 L_{11}}{L} \Delta P \simeq 0$

$$\boxed{N_1 = \frac{L_{11} RT}{L} \ln C_{1m}'/C_{1m}''}$$

So, will be utilizing the in the concept of dilute solution for dilute solution act activity will be almost equal to concentration and let us, look into the expression of chemical potential mu is equal to mu naught plus R T l n a 1 m that will be at in dilute limit, it will be mu 0 plus R T l n C 1 m .Now, let us look into the derivative del mu 1 del C 1 m it will be nothing, but R T del l n C 1 m by del C 1 m so, just putting the mu 1 0 .

Now, you can combine the equation the integrated form this becomes L 1 1 R T l n C 1 m prime C 1 m double prime plus V 1 bar L 1 1 delta P so, the expression of Solute Flux. This is the molar flux these become L 1 1 R T by length thickness of the membrane C 1 m prime C 1 m double prime plus V 1 bar L 1 1 divided by L delta P. Now, again there are certain approximation one can has in most of the case is the second term of this expression becomes very small.

So, generally the second term V 1 bar L 1 1 divided by L times del P are negligibly small compare to these term therefore, you can get an expression of Solute Flux as L 1 1 R T by L l n C 1 m prime divided by C 1 1 m double prime. So, these give a logarithmic distribution of the solute in the downstream and upstream of the membrane surface. Now, again since we are already assuming a dilute solution.

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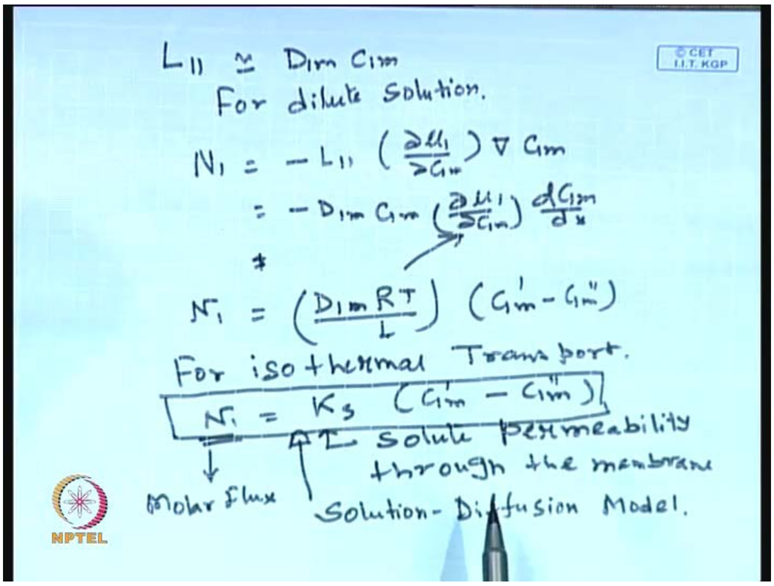

$L_{11} \simeq D_{1m} C_{1m}$

For dilute solution.

$$N_1 = -L_{11} \left(\frac{\partial \mu_1}{\partial C_{1m}}\right) \nabla C_{1m}$$

$$= -D_{1m} C_{1m} \left(\frac{\partial \mu_1}{\partial C_{1m}}\right) \frac{dC_{1m}}{dx}$$

*

$$N_1 = \left(\frac{D_{1m} RT}{L}\right) \left(C_{1m}' - C_{1m}''\right)$$

For isothermal Transport.

$$\boxed{N_1 = K_s \left(C_{1m}' - C_{1m}''\right)}$$

Solute permeability through the membrane

Molar flux

Solution-Diffusion Model.

It is L 1 that coefficient L 1 1 will be roughly proportional to D 1 m multiply by C 1 m. These for dilute solution D 1 m is the solute diffusivity through the polymeric membrane phase and C 1 is the concentration of the membrane. Now, if you put the expression here the final expression of N 1 it becomes L 1 1, we just start it couple of steps earlier del C 1 m gradient of C 1 m and now, we put L 1 1 has minus D 1 m C 1 m del mu 1 del C 1 m, this is d cone m by dX. So, if you integrate these equation out and del put the expression of del mu 1 del C 1.

If put the expression of del mu 1 del C 1 in from the derivation and integrate it out it will give you the expression of Solute for Flux as D 1 in R T divided by L C 1 m prime minus C 1 m double prime. Now, if D 1 m is treated as constant membrane thickness is constants R is inversely constant t is the temperature for isothermal case for isothermal transport N 1 the Solute Flux becomes some constant multiplied by C 1 m prime minus C 1 m double prime. This is known as the solute permeability through the membrane now, these solute permeability will be related to the solute, this Solute Flux; this is Solute Molar Flux of the solute will be related to the Molar Flux of the Solute and will be coming to the, but these relationship is known as the Solution Diffusion Model.

So for the Solvent Flux we have the osmotic pressure relationship or drays law for the Solute Flux to the Porous Membrane, we have derive the Solution Diffusion Model what Solution Diffusion Model presence, it presence relationship of Solute Flux to the Porous

Membrane with respect to feed concentration upstream side and in downstream side membrane phase.

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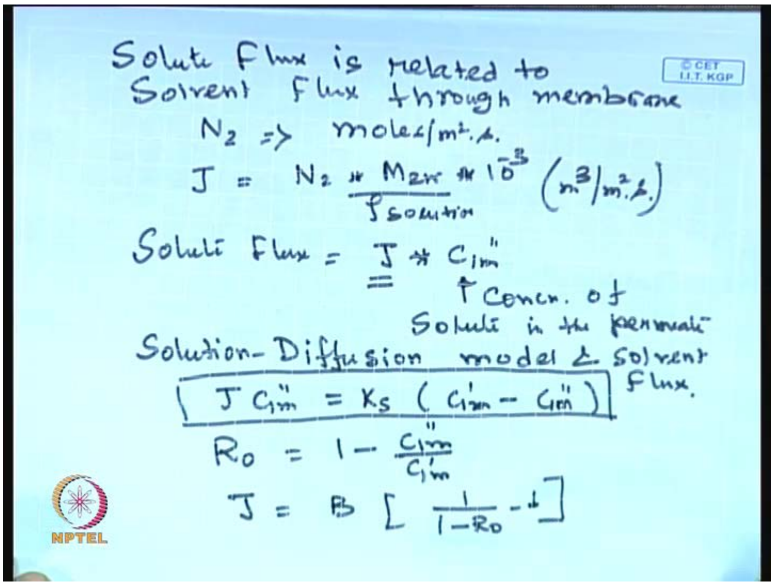

Solute Flux is related to Solvent flux through membrane

$N_2 \Rightarrow$ moles/m^2.s.

$$J = \frac{N_2 * M_{2w}}{\rho_{solution}} * 10^{-3} \quad (m^3/m^2.s.)$$

$$\text{Solute Flux} = \underline{\underline{J * C''_{1m}}}$$

↑ Concn. of Solute in the permeate

Solution-Diffusion model & solvent flux.

$$\boxed{J\, C''_{1m} = K_s\,(C'_{1m} - C''_{1m})}$$

$$R_0 = 1 - \frac{C''_{1m}}{C'_{1m}}$$

$$J = B\left[\frac{1}{1-R_0} - 1\right]$$

Now, this Solute Flux is related to solvent flux through the membrane. Now, if you look into the expression of the solvent flux it has the unit of molar unit moles per meter square per unit time. So, volumetric flux J becomes N 2 times molecular weight of the solute multiplied by 10 to the power minus 3 dived by roe of the solution that gives you the unit of meter cube per meter square second. So, there is a relationship of Molar Flux to the volumetric flux J is having a unit meter cube per meter square second and N 2 having the unit molar moles per meter square per unit time now, what is solute flux? Solute flux is nothing, but J times C 1 m double prime.

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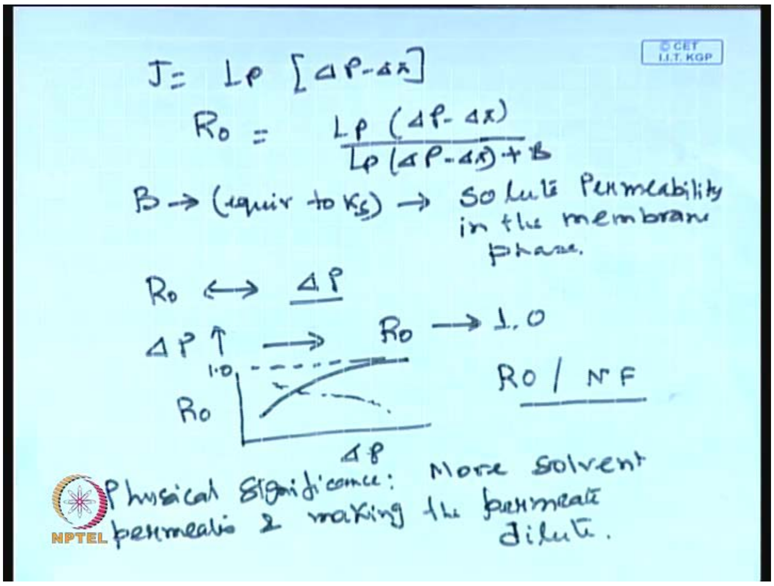

$J = L_p [\Delta P - \Delta \pi]$

$R_0 = \frac{L_p (\Delta P - \Delta \pi)}{L_p (\Delta P - \Delta \pi) + B}$

$B \rightarrow$ (equiv to K_s) $\rightarrow$ Solute Permeability in the membrane phase.

$R_0 \longleftrightarrow \underline{\Delta P}$

$\Delta P \uparrow \longrightarrow R_0 \rightarrow 1.0$

RO / NF

Physical Significance: More solvent permeation & making the permeate dilute.

So, that is the concentration of solute in the permeate, this is the solvent flux multiplied by concentration of the solute that will give you the Solute Flux moles of solute are unit per meter square per unit time. Now therefore, the Solution Diffusion Modeling can be written as J C 1 m double prime a constant K s multiply by C 1 m prime minus C 1 m double prime. So, this is the relationship of the Solution Diffusion Modeling and solvent flux.

Now, if you can these in fact these constant case will be having a different unit compare to the constant that appear in the Solution Diffusion Model, because of the volumetric flux that we are talking about now, J will be let say, if you write down the expression observed retention observed, retention is 1 minus concentration of solute in the permeate divided by concentration of the solute in the feed that means, C 1 m double prime divided by c 1 prime. Now, whenever writing this expression that means, you are assuming the concentration of the solute and the membrane surface is send as the bulk concentration that means, we are not considering the in C in the absence of polarization mass transfer boundary layer on the feed side, if that is not present when whatever the concentration is in the bulk that will be same and the membrane surface that can be realized, if an only if you can have a very high study the feed side, that is know polarization of the solute on the feed side.

What are the concentrations appear in the membrane surface? that will be appear on the bulk, but in an actual case, it is not happening you have to couple these equation if the concentration polarization model that will see later on so, if you write down this expression if you just eliminate this concentration in favor of the observed retention the expression of J trans out to be some constant divided by 1 minus multiply by 1 minus R not minus 1 and you know the expression of J are the Solvent Flux from the osmotic pressure model that is nothing, but J is equal L P into delta P minus delta pi .

We just divide their relationship so, utilizing these relationships in earlier one can write the expression or R naught L P delta P minus delta pi divided by L P delta P minus delta pi plus B what is B? B is nothing, but equivalent to K s and this is the solute permeability is the membrane phase now, it is look into the implication of variation of observed retention, how it varies as an operating condition? Which is almost critical in the case of reverse osmosis that is delta P if you increase delta P what happens?

The B becomes very insignificant will be getting R naught tends to 1 so, that means the higher pressure if you plot observed retention versus delta P in case of reverse osmosis. We are going to expect a curve something like this and this value will be equal close to one and the other hand in case of ultra filtration. So this is the case of reverse osmosis and nano filtration membrane that means, observed retention increases as you increase the operating pressure drop in case of ultra filtration and micro filtration in that case is simply reverse, because at the because the pore size is very hight, the more solute will be permeating through the membrane in that case observed retention will be going down as you increase the pressure the in case of ultra filtration, and micro filtration the will be just reverse, now physically what it means physically it means that the membrane becomes non porous, it has a capability of it has certain capability to retain the solute so, the solute will be retain to the maximum possible extent, but if you increase the pressure the solvent being smaller in size more solvent will be permeating through the membrane therefore, the extent of since the extent of retention by these reverse osmosis and nano filtration membrane is almost constant.

The concentration of permeate of the solute in the permeate stream will be more or less constant, it has a particular capability, it cannot retain extend beyond the particular point. So, the concentration you cannot by changing the operating pressure and operation condition at is very difficult to increase the decrease the capacity so, the concentration of the solute in the permeate stream will be more or less constant, but if you still increase the operating pressure more solvent will be coming through that coming through the membrane therefore, the permeate stream will be diluted the concentration of the permeate concentrate solute in the permeate will be less, because the total once amount will be same.

You are adding more water to it so it will be diluted therefore, observed retention will be tend to the 1 so, physical significant is that more solvent permeates and in making the permeate dilute. So one can expect and increase the retention in case of reverse osmosis and nano filtration as increase the operating pressure drop.

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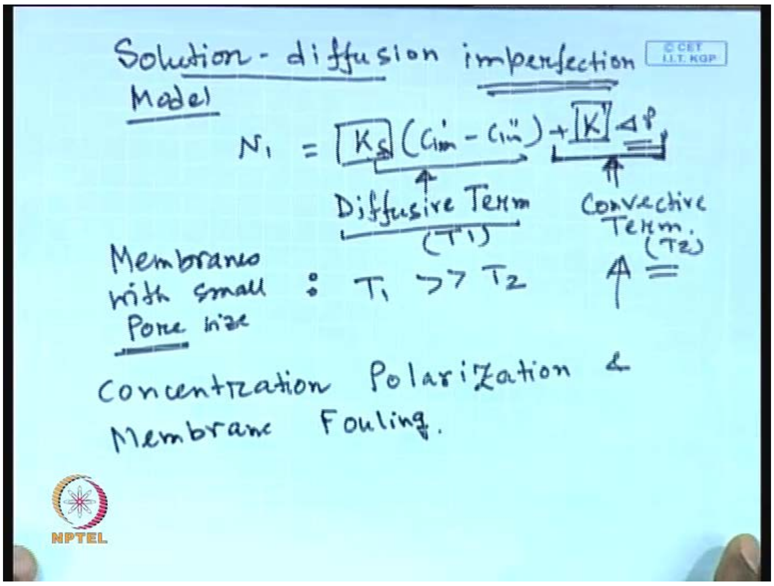

Solution - diffusion imperfection Model

$$N_1 = \underbrace{\boxed{K_s}(C_{1m}' - C_{1m}'')}_{\substack{\text{Diffusive Term} \\ (T1)}} + \underbrace{\boxed{K'}\Delta P}_{\substack{\text{Convective Term.} \\ (T2)}}$$

Membranes with small Pore size : $T_1 >> T_2$

Concentration Polarization & Membrane Fouling.

Now, there is another variation of solution diffusion model is solution diffusion imperfection model, why is the model? If you remember in the derivation of solute, solution diffusion model will omitted one term that is the delta P term pressure drop term. We have a term of let say K s times C 1 m double prime C 1 m prime minus C 1 m double prime plus another term that is, some constant let say K prime times delta P.

What is it generally this term becomes very small, what is these term? These terms signifies a diffusive term, because this is driven by the concentration difference. So this is the diffusive term, what is these term? this team is a convective term because it depends on the delta P so, this is the convective term for a pure reverse osmosis and nano filtration membrane this diffusive term will be dominate, because we are talking about non porous.

Almost non porous membranes with small pore size this is term one this term two term, one will be much greater than term two, so you can neglect the convective term that we real it the is some case is when you will be having some, because you know in a membrane there is no fixed pore size. You do not have or you can not have a membrane of uniform pore size there is there will be a distribution of the pore size in the membrane, so there will be some proves which will be larger in size, some pores which will be smaller in size and there will be distribution existing in the system and you can find out the average distribution or average pore size, so there may be some pore size when the pore size larger in the convective term of the solute flux becomes predominant in that case these term will be constant.

So this is the so it is termed as the imperfection to the membrane, because for a reverse osmosis and nano filtration membrane, we are assume to have we are suppose to have in small pore size is, because if there are some pore size are there, because of the know problems in casting or operating condition in the casting that in that is basically nothing, but on imperfection to the membrane casting. So this is known as the solution diffusion imperfection model in these cases, these particular terms will be included.

Now, what that what this mean is that when you depend increasing the terms like these, what we do you really? Do not know how to get these value how to get there value. Now, these are the parameters of the model, so what we are going to do, you are basically do some calculation using N assigned values of these parameter and get the value of the permeate concentration in the permeate flux, and measure and compare their value in the measure experimentally measure values of the permeates concentration or permeate flux likewise, if the differ and see the difference error involved in it.

If error is large then you have another guess it of the parameters likewise you can know keep on iterating and being an optimization study you can fix the you can convict set of values of parameters, but the is when you keep or increasing the you know complication in your model, the number of parameters will be increasing in your system a and in if a system will be having large number of and determined coefficients the less flexible in the system is.

So it is always not it is always and desirable having large number of adjustable parameter in your system, so that is the so these parameter physically becomes physically consistent that there may be imperfection in the matrix. So these pressure driven on their bit it includes another complication in the calculation as per the calculation is there physically more robust, but as per as the calculation is constant. This is very this become very weak, because the number of adjustable parameter is increasing. So, we have to keep always thing in your mind during over calculation modeling of the system, then we look into the two terms concentration polarization and membrane fouling before going into the concentration polarization membrane fouling.

I would like just like to elaborate one thing that whenever we are talking about the calculation cut the prediction of the permeate flux permeate concentration, you have to understand that there are two distinct regents in that transport.

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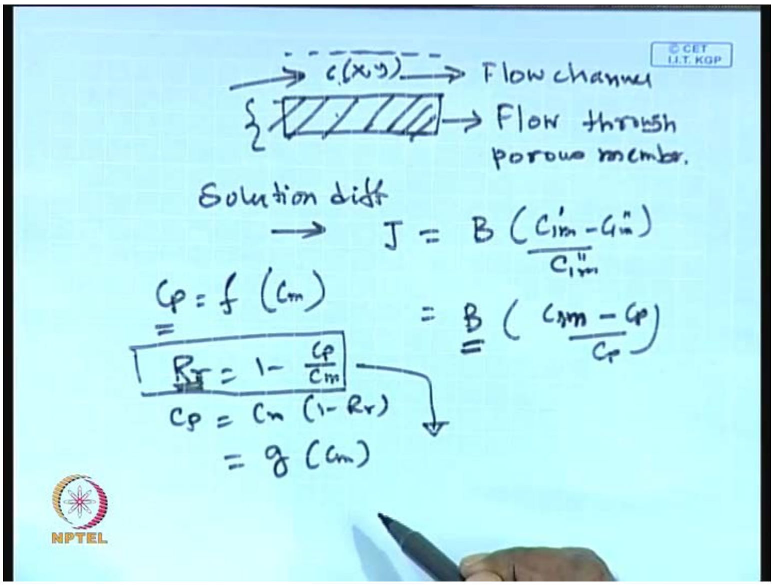

$$J = B\left(\frac{C'_{1m} - C''_{1m}}{C''_{1m}}\right)$$

$$= \underline{\underline{B}}\left(\frac{C_{1m} - C_p}{C_p}\right)$$

$$\underline{\underline{C_p = f(C_m)}}$$

$$\boxed{R_r = 1 - \frac{C_p}{C_m}}$$

$$C_p = C_m(1 - R_r) = g(C_m)$$

What are the two distinct regents? One is the transport to the porous membrane another is the flow outside the membrane in the flow channel, so this is the flow in the channel and this is the flow through porous membrane. Now how will be modeling the flow outside in the flow channel we will do a (()) study, you write down the equation of continuity you have to write down the species balance equation solute balance equation. So you will be getting the and after solvent that C will be getting as function of X and y and that has to be so, there will be a transport phenomena outside the flow channel outside the membrane and there will be a transport phenomena inside the porous medium. Now what will be the solute flux and these will be coupled these two will be coupled at the interface than combining these two transport, you will getting the full prediction of the system.

Now whatever you have seen till now we are seen till now so, the flow through the flow through the porous membrane, so you have got the solution diffusion model to quantify the solvent flux, we got the we got the solution diffusion model to quantify the solute flux, and we got the osmotic pressure model to quantify the solvent flux to the porous medium. Now that has to be if the transport phenomenon that is occurring outside the membrane in the flow channel now, these is very complicated flow through the porous medium is very complicate.

The simplest version in the simplest version I just presented in the form of darsys law and solution diffusion model, if you remember what it does? What it gives solution diffusing model? it says that permeate flux volumetric permeate flux or solvent flux is nothing, but B times C 1 double prime C 1 m minus C 1 m double prime divided by C 1 m double prime. Now actually this will be B times C 1 m C m minus C p divided by C p C m is the concentration of the solute in the mem concentration solute is the membrane feed interface and C 1 double m C 1 m double prime nothing, but permeate concentration right.

Now, these gives a relationship between a functional relationship between C m and C p what is C p solute concentration in the permeate and C m is the solute concentration in the feed membrane interface. This gives the relationship between and if you remember the real retention the definition of real retention is 1 minus C p by C m and what is C p C P is simple C m into 1 minus R r. These also give relationship between C p and C m a different relationship, so what is the difference between the two.

if you talk about the real retention, then we cannot talk about the solution diffusion model they are mutually exclusive both are almost equal say equal to same, because real retention is nothing, but as I discussed earlier nothing, but is but a partial coefficient of the solute in the in the permeate phase, and in the feed phase and the other hand solution diffusion model becomes. So what is real retention? real retention basically a parameter huge dumps all the flow characteristics of the solute to the porous membrane. So this is this is own adjustable parameter, this is not an adjustable parameter. We have discussed earlier classes, how to determine it experimentally from different set of experiment, you conduct the experiment at high turbulence so, the observed retention will become almost real retention on the other hand, experimental determination of these coefficient will be extremely difficult in this almost impossible.

So it has to be again it has to be determined again by the against the experimental values by doing optimization study the measure, I just discussed we have to guise value of the and permeate concentration permeate flux and compare with the experimental result, and doing optimization study therefore, sometimes the these formulation becomes very handy because real retention can be experimentally determined separately, and can be incorporated in your model.

So the whole model can run in a predictive mode on the other hand if you adopt the solution diffusion model to quantify the solute flux membrane surface to the porous membrane, you do not know the value of the in that case what you have to do the is to in order to determine the value of the method. I just mention you have to use experimental value so the modeling cannot be a predictive made it, you use the solution diffusion model what you can do maximum suppose, you can have 20 experiment are 27 experiments.

You can take half of the experimental set up using different operating condition and use those experimental values data to optimize the value of B ,once you optimize these values of the B then the further the rest of the data you can run in it predictive mode. So in that case solution diffusion model of the short coming the advantage of solution diffusion model is it, it is physically correct compare to the real retention formulation on the other hand, it creates the complication or know and in accuracy during the experimental detect during the modeling calculation stage because for half of the you have to use the experimental values to determine value of B in other hand, you can use the real retention formula formulation for a completely predictive calculation that is the difference between the solution diffusion modeling and the real retention formulation.

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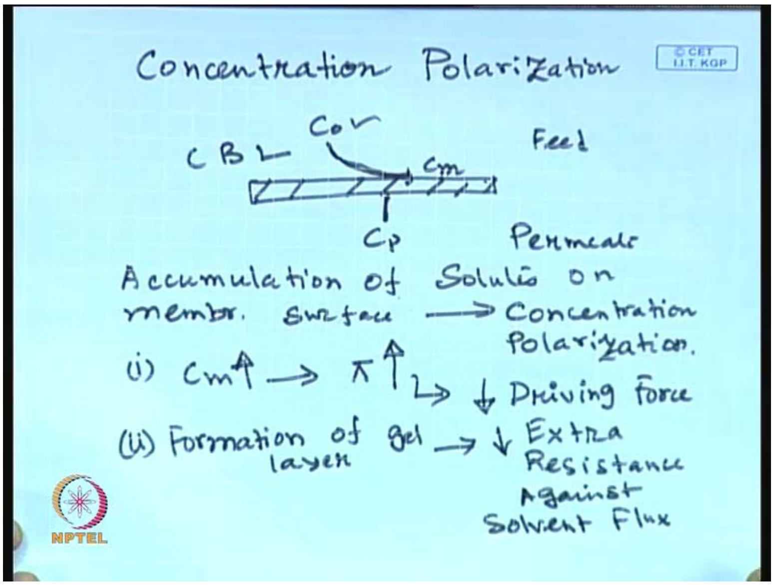

Concentration Polarization

Accumulation of Solutes on membr. surface ⟶ Concentration Polarization.

(i) $C_m \uparrow \rightarrow \pi \uparrow \rightarrow \downarrow$ Driving force

(ii) Formation of gel layer → ↓ Extra Resistance Against Solvent Flux

Now, let us come to the concept of concentration polarization now, suppose this is a membrane system and you are having a feed at concentration C naught, and you are getting conducting experiment and getting concentration in the permeate as the as C p permeate concentration now, it is not that simple that you are going to get a concentration C not feed stream, you are going to get permeate concentration C p.

There is something that is that is a deposition of solute in the membrane surface which provides a concentration boundary layer not in the membrane surface, that you have discussed in the earlier lectures. Now, the these concentration becomes C m so, the membrane as per the membrane is concerned the membrane does not realize or does not experience or does not recognize the presence of the bulk concentration membrane experiences, only the surface concentration over it and the permeate concentration on the downstream.

So there will be accumulation of solutes over the membrane surface is this is known as concentration polarization that is polarization of the solute particles over the membrane surface. Now, there are several implication of this concentration polarization, one is first one is more concentration polarization means more solutes will be over the membrane surface, why there will be solute concentration on the membrane surface? because this is the pressurized system as you remember in case of reverse osmosis we are talking about pressure of 25 atmosphere in case of nano filtration, talking about pressure about fifteen atmosphere ultra filtration six atmosphere micro filtration two atmosphere.

So, it is pressurized system so because of the convection more solutes will be coming and depositing over the membrane surface so, concentration polarization is more that means membrane surface concentration is more as so, if membrane surface concentration is more than osmotic pressure across the membrane will be more because osmotic pressure is an increasing function of concentration, and that we have discussed earlier.

So, concentration polarization high means, your osmotic pressure of the membrane surface will be high if the osmotic pressure of the membrane surface will be high in order to get at higher flux your operating pressure has to be more. So if osmotic pressure is high then it gives a reduction of the driving force delta P minus delta pi ,so delta pi will be if you if you delta P is same delta pi will be more and you will reduction in driving force thermally formation of gel layer over the membrane surface.

What is formation of gel layer? so basically if in a in a actual system the membrane channel will be in long is the tune of 1 meter 2 meter like that 1 meter means 3 feet, it may be several meters now, initially that we have discussed earlier that at the at the intense of the channel the concentration polarization will be less the concentration boundary, thickness will be less and it will be increasing slowly over the channel length and these growth of concentration boundary layer will be extremely slow, because the intense length will be pretty high in case of the solute like this, that we are discussed intense length require will be 0.0 5 into Renaults number and smite number and we are talking about solute of very low diffusivity that means very high smite number.

Therefore, the intense length will be extremely high therefore, as you go down in the membrane channel the surface concentration will keep on increasing the surface concentration will keep on increasing and beyond the particular point, it may exist the solubility limit of the solute in the particular solvent at the particular temperature. So what happen at the point? if it exists the solubility limit the whole solute will be towards the membrane surface as a solid in that case it is terms it forms the gel some case is like polymers protein gel is not that distinct in that case, gel will be basically very highly viscous thick solution, so what formation of gel gives? it gives extra resistance against gel means, it is a very thick it viscosity is will be extremely high.

So, the porosity will be extremely low so, it acts as a dynamic membrane in and additional membrane in presence of the actual membrane the physical membrane. So, it is called as formation of dynamic membrane therefore, it offers an extra resistance of formation of gel layer means, extra resistance against the solvent flux therefore, the operator should very careful the gel formation you should operate under the condition because that gel formation is avoided.

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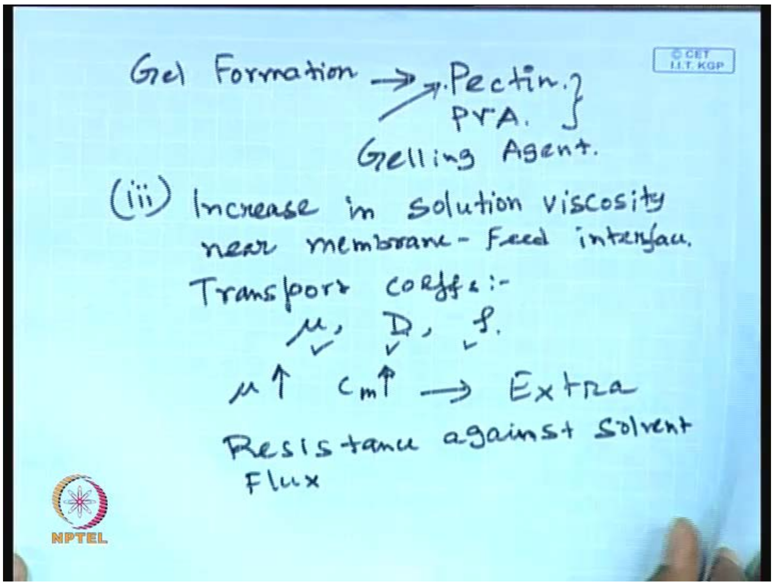

Gel Formation → Pectin. PVA. } Gelling Agent.

(iii) Increase in solution viscosity near membrane - Feed interface.

Transport coeff.:- μ, D, ρ.

$\mu \uparrow$ $C_m \uparrow$ → Extra Resistance against Solvent Flux

Now, in solute gel formation (()) for example, solute like pectin is while known gel forming agent PVA poly venial alcohol, this a polymer this is a polysaccharide this pectin is a polysaccharide on it is you know it occurs in high quantity in the fruit juice in fruit juice, so these are all gel form gel forming agent these are while known gelling agent for filtration of such gelling agent gel formation is there, it is an accordable and it occurs from the very beginning of the operation third implication of concentration polarization is that increase in solution viscosity increase in solution viscosity near membrane feed interface.

So, it becomes very concentration increases and you know what the various parameters are? You know kind parameters transport coefficient in the solute balance equation the transport coefficients, those are involves in the solute balance equation, one is viscosity and diffusivity another is density. Now, you know that viscosity diffusivity density all that 3 parameters are function of concentration.

Now, out of these three parameters viscosity is the strongest function of concentration and diffusivity and density at the weaker function, because between diffusivity and density is the weakest function of concentration. So, once the for the high concentration polarization membrane surface concentrate increases means here, viscosity increases very high that means, viscosity solution is there present near the membrane surface again it offers an extra resistance against the solvent flux.

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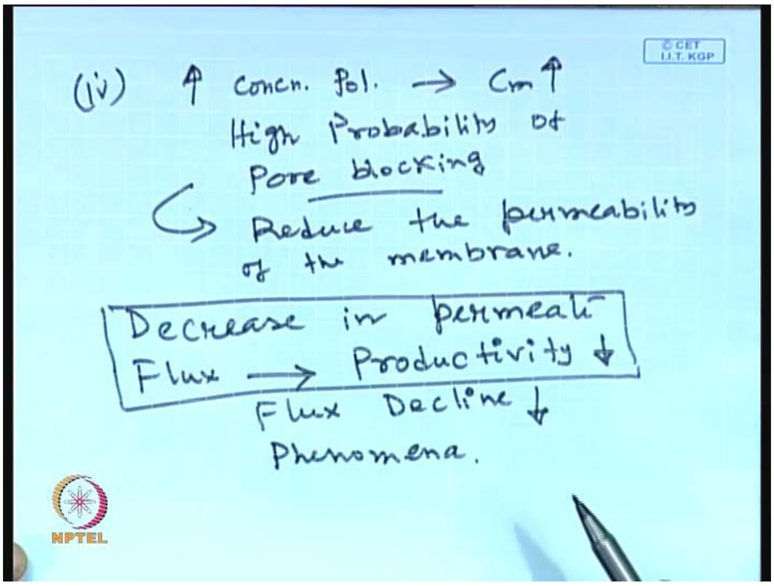

(iv) ↑ Concn. Pol. → C_m ↑

High Probability of

Pore blocking

↳ Reduce the permeability of the membrane.

Decrease in permeate Flux → Productivity ↓

Flux Decline ↓

Phenomena.

The fourth implication is that increase in concentration polarization means a membrane surface concentration increases therefore; the concentration difference across the membrane will be more, if concentrate difference across the membrane will be more solute will be getting try transport to the membrane. So, there will be chance high probability of pore blocking, so more solute will be transported through the membrane and since he pores are not always straight cylindrical pores.

They are all inter connected zigzag force some of the pores will be may be blocked some of the pores may be completed may be partially blocked partially blocking always things can occur. So, these pore blocking what it does this pore blocking will reduce the permeability of the membrane always look into the implication of these four phenomena.

First one increasing osmotic pressure increasing osmotic pressure means here, driving force will be less if the driving force will be less the productivity of the process will be less the solvent flux that means, you have the productivity of the process will be less formation of gel layer over the membrane surface, you they it offers extra resistance against the solvent flux, if the solvent flux will be decreasing permeate flux will be decreasing, third one increasing the viscosity of the solution if the solution viscosity increase it offers again and again extra resistance solvent flux solvent flux will decrease, fourth one is pore blocking it reduces the membrane permeability L p will be decreasing if L p decreasing against solvent flux decreasing.

So, all these problem all these four phenomena will point to common result the decrease in the solvent, in the permeate flux solvent flux in the permeate stream decreasing permeate flux that means, it decrease in productivity of the of the process these phenomena is known as flux decline in a trans in a actual process diff because of these phenomena.

Now, all these phenomena can occur one at a time or more than one at a time all of the at a time, because of that the flux decline over the over the period of time, and this is known as the flux decline phenomena in membrane process, there are considerable research going on now, it is to avoid the to minimize the flux decline. Now, concentration polarization cannot be avoided it is all is there, but it can be minimized the several techniques, there for minimizing these concentration polarization and we looking into some technique later on in our course.

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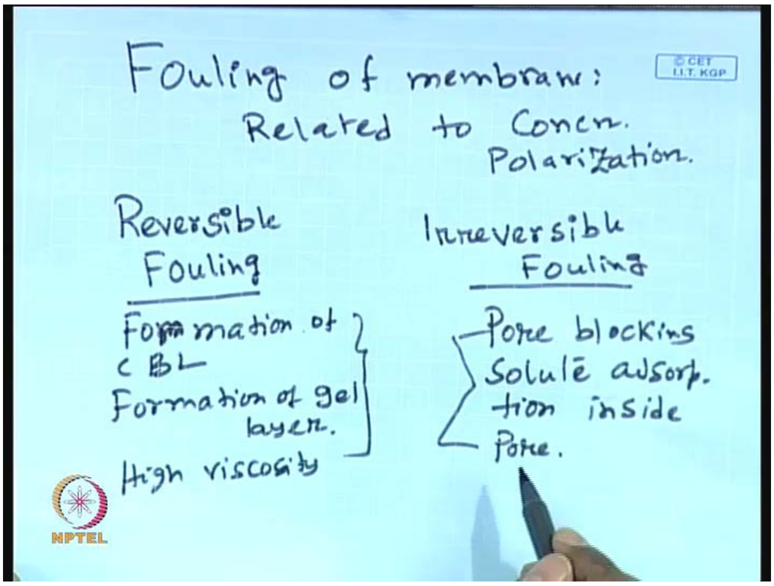

Fouling of membran:
Related to Concn. Polarization.

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Reversible Fouling
Formation of CBL
Formation of gel layer.
High viscosity

Irreversibl Fouling
Pore blocking
Solute adsorption inside Pore.

Now, let us look into the fouling of membrane fouling is related to concentration polarization must be realizing related to concentration polarization depending on is of removal of fouling the fouling can be categorized into two types. One is reversible fouling, another is irreversible fouling while reversible fouling in case of, reversible fouling the deposition over the membrane surface for example, the formation of boundary layer concentration, boundary layer formation of gel layer formation of a very thick high viscous solution over the membrane surface.

If the Polari if the flux decline occurs because of these now, if you stop the operation and open up the system and towards the membrane all these depositions will be washed away, if you reuse the membrane or if you is the appropriate washing protocol all the these will be removed.

So, you get that original permeability of the membrane, these are this is known as these are known as reverse fouling. So, fouling can be reversed you can get that original permeability of the membrane and the other hand now, pore blocking are solute absorption inside the pore. Now, some of these things most of these case is pore blocking extra you cannot get that the original permeability of the membrane, so these loss of the loss permeability in these case becomes irreversible, so you cannot get that original permeability in these case becomes irreversible. So you cannot get that original permeability is always lost so, this is known as the irreversible fouling irreversible fouling generally occurs because of the pore blocking partial or complete absorption of the solutes inside the pores and reversible fouling are they occur, because if there is the formation of the concentrate solute layer over the membrane surface reversible fouling can be the fouling layer can be remove by adopting a suitable washing protocols in the care of irreversible fouling some amount of permeability of the membrane is (()) lost.

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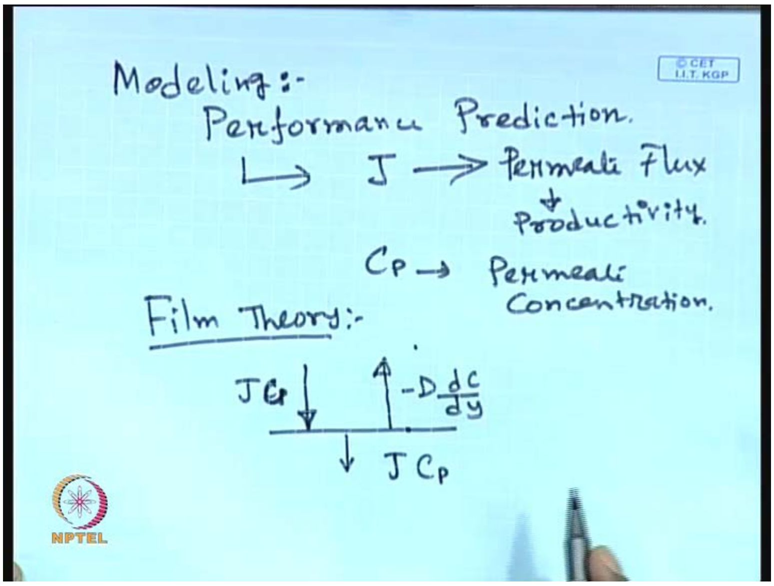

Modeling:-

Performance Prediction.

↳ J → Permeate Flux

↓

Productivity.

C_P → Permeate Concentration.

Film Theory:-

Now, let us look into the modeling aspect in fact we have drive the simplest modeling earlier modeling means, prediction of system performance prediction, what is performance prediction of calculation of it gives the operating condition geometric excreta you should know what is the value of permeate flux? Why permeate flux, this is nothing, but the productivity of the process and permeate concentration the simplest model. We just think of about one dimensional steady state model that is known as the film theory, there a discussed an derived earlier probably couple of classes back and I will just give the highlight of these then there are several assumption in the film theory.

It is assumed that the solute layer in solute forms a concentration boundary layer towards the membrane surface of constant thickness that obviously that assumption is not very correct, because most of the channel near the entrance, there will be an entry length existing towards the thickness is growing, but it is not constant number 1 number 2 is that in this case, are we are assume that there will be a convective flux towards the solute existing this is by the delta P J C p J C and there will be a diffusive flux higher from membrane surface, because of the concentration gradient membrane surface concentration is more compare to the bulk concentration.

So, that will be diffusive flux doing because of the concentration difference fix law and there will be convective flux higher from the membrane surface at the steady states times C p. Now, at the steady state all the summation of all the flux is will be equal to 0 and will be getting, it differential equation by solving that will be getting the expression of film theory that we have earlier.

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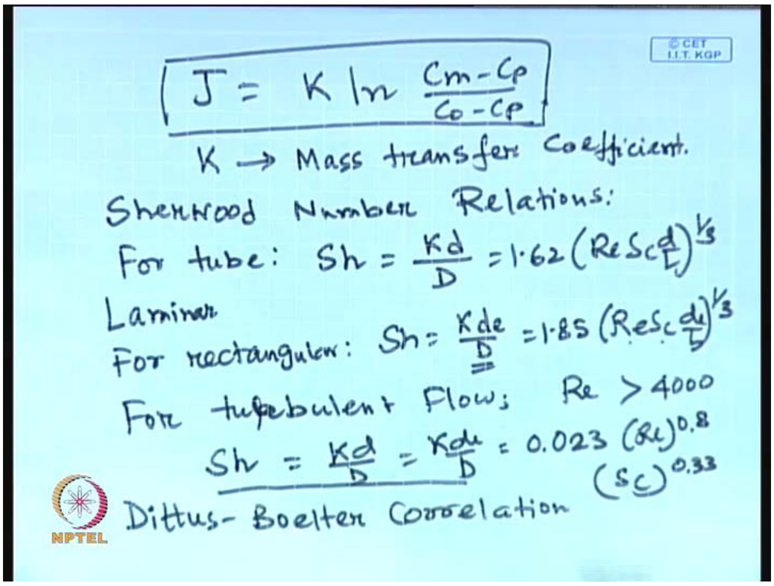

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$$\boxed{J = K \ln \frac{C_m - C_p}{C_o - C_p}}$$

K → Mass transfer Coefficient.

Sherwood Number Relations:

For tube: $Sh = \frac{Kd}{D} = 1.62 \left(Re\,Sc\,\frac{d}{L}\right)^{1/3}$

Laminar

For rectangular: $Sh = \frac{Kde}{D} = 1.85 \left(Re\,Sc\,\frac{de}{L}\right)^{1/3}$

For turbulent Flow; $Re > 4000$

$Sh = \frac{Kd}{D} = \frac{Kde}{D} = 0.023\,(Re)^{0.8}\,(Sc)^{0.33}$

Dittus- Boelter Correlation

The expression of film theory is J is equal to K l n C m minus C p divided by C not minus C p there, we have always drive earlier J am not drive one second. What is K? is the mass transfer coefficient now, mass transfer coefficient is very important parameter in this case and it can be obtain from the Sherwood number relation in fact, we have first upon some the Sherwood number relations for flow through a tube that tube geometric will be something like this.

The flow is very flowing across the tube and in a surface of the tube and in a surface of the tube will be rape by the membrane so, membrane surface call be pi d L and the other hand, if it is a fair geometric that means, if there is a channel that is channel like this and if you put membrane on the top surface and the bottom surface.

Top surface the membrane area will be length times width twice of that one surface will be available at the bottom one surface will be available cut the top dyes for the flow through rectangular channel, flow tube flow through tube the Sherwood number relationship will be K d by d 1 .62 Renault smite d by L rest to the power 1 upon 3 for laminar flow, laminar flow means Renaults number lass than twenty to hundred for rectangular geometric Sherwood equal to K d by d equal to 1 point 85 Renault smite d by L rest to the power 1 upon 3 d is the is the equivalent diameter, and it will be equal to 4 into half weight of the channel that we have derived in the earlier classes d is the diffusivity of the solutes, and this d is the diameter of the tube and equivalent diameter Renault smite excreta can be applied from flow condition.

The properties and the geometric now one can calculate the mass transfer coefficient using these relation, these are relation and they are not correction and in fact one of the earlier classes, we discussed about the difference between the correction, and relation these relations are theoretical obtain from very first principle on the other hand, in most of the industrial application the flow condition and not laminar their turbulent for turbulent flow that means, your Renaults number greater than 4000.

We can use the detespolter relation K d by d or K d e by d this will be in case of tube and this will be in case of rectangular geometric. This is nothing but 0 point 0 2 3 Renaults rest to the power point of smite rest to the power 0 point 3 3 so, this is Renaults number based on parameter, if it is a flow through tube and it is based an equivalent diameter.

If it is flow through rectangular channel now, this is a correction this is if you learn, but detespolter relation for the heat transfer case this is indeed a correlation and formula heat and mass transfer analogy, you know there are similar non dimensional term mass for the heat transfer Sherwood number mass transfer smite number for the mass transfer number from the heat transfer therefore, from the heat and mass transfer analogy we use detespolter correlation to calculate the mass transfer coefficient.

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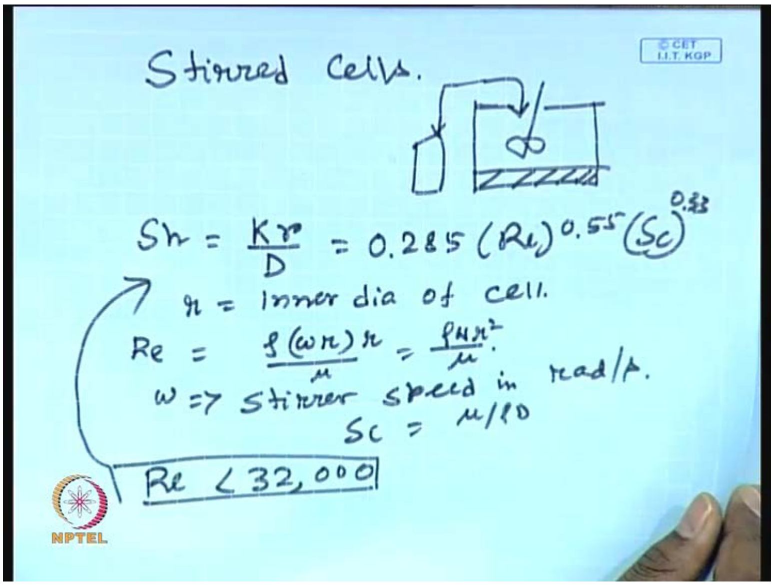

Stirred Cells.

$$Sh = \frac{Kr}{D} = 0.285\,(Re)^{0.55}\,(Sc)^{0.33}$$

r = Inner dia of cell.

$$Re = \frac{\rho(\omega r)r}{\mu} = \frac{\rho\omega r^2}{\mu}$$

$\omega \Rightarrow$ stirrer speed in rad/s.

$$Sc = \mu/\rho D$$

$$\boxed{Re < 32,000}$$

If you have now, in some in some industrial application there are stirred cells so, basically this is big vessel if you have very important item which will be the feed is very small and very costly then you can use the stirred cell. So, there is a there you put the membrane in the bottom of the well and you put a stirred their fill the top, and there will be a tap which will be pressurized from the outside for using nitrogen cylinder something like that.

So this is called stirred cell all in stirred cell the mass trans mass transfer coefficient the Sherwood number correction is obtained as given as K r by D is equal to 0.285 Renaults rest to the power 0.5 5 smite rest to the power 0.3 3. So, r is basically the inner diameter of cylindrical cell stirred cell and Renaults number is defined as roe omega or is the linear velocity multiply by r mu so, omega roe omega it square by mu why omega is basically stirred speed is radiant per second so, s this is not R P m rpm can be convert in to radiant per second and all of you know about it and smith number is basically mu by roe d, and this is for Renaults number less than 32,000. This relationship is valid for Renault number less than 32,000 in fact this is a correction for it the Renaults number greater than 32,000 another correlation is available

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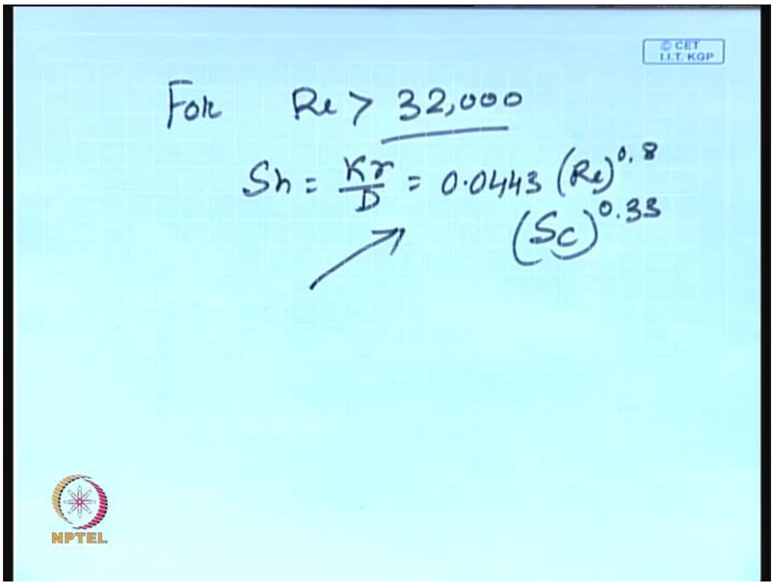

For $Re > \underline{32{,}000}$

$$Sh = \frac{Kr}{D} = 0.0443\,(Re)^{0.8}\,(Sc)^{0.33}$$

For Renaults number greater than 32,000, we have Sherwood equal to K r by D is equal to 0.043 Renaults rest to the power 0.8 smite rest to the power 0.8 smite rest to the power

0.33. Now, for Renaults number greater than 32,000 you can use these correlations for estimation of mass transfer coefficient.

So, we can we can use several mass transfer appropriate mass transfer coefficient mass transfer coefficient relationship under the turbulence flow conditions depending on the geometric and using those mass transfer coefficient one can have you know you can calculate the you can have a system prediction, how to do that? That will see in detail in the next class in tomorrow class.