Novel Separation Processes
Dr. Sirshendu De
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture No. # 27
Gas Separation

Good morning everyone. So, you are looking into the gas separation by membrane base process is; in case of gas separation of the membrane the first characteristic are the first difference of this membrane compare to the other membrane, where we until the liquid materials is that the (( )) is very small in this membrane. So, these are very dense membranes.

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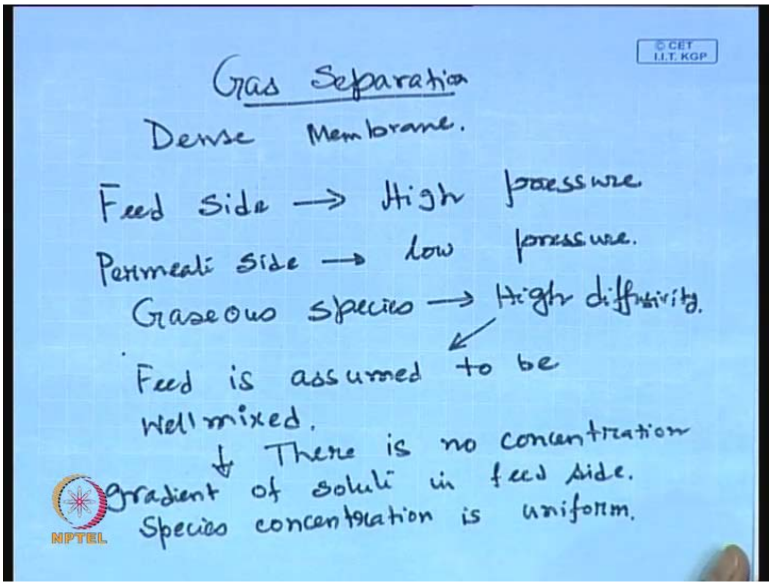

So, the first characteristic in gas separation by the membranes is that; the membrane that we are going to use this say very very dense membrane. So, that the gas species is gaseous species is only will diffuse to the membrane phase through the membranes. Now, typically the feed side pressure is very high that mean you are injecting a gas at high pressure the feed side and the permeate side is of low pressure. In sometimes the permeate sides is kept under vacuum so, there will be tremendous pressure gradient are delta p will be occurring at the across the membrane and the species that will be permeated through the membrane it will be (( )) transported from feed side to the permeate side.

Now, the another characteristic is that the gaseous material, gaseous species will be having definitely a high diffusivity compared to the liquid solute; the solute diffusivity in a liquid stream. So, gaseous species is having high diffusivity. And because of the high diffusivity they are well mixed in the stream that means, because of the diffusivity there is less probability that there will be formulation of boundary area or (( )) thing in the feed side or in the permeate side. Therefore, because of the high diffusivity of the species is the feed is assumed to be well mixed that means there is no concentration gradient of solute in feed side.

So, it is that means that the concentration is uniform, that means concentration solute concentration or species concentration is uniform, so that is an assumption and it is say valid assumption simply, because of the fact that the gas diffusivity of the gas species is extremely high.

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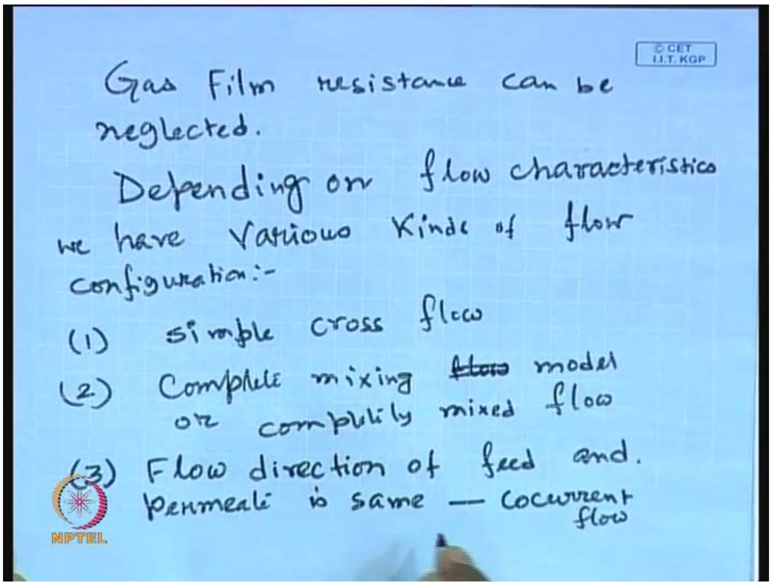

Therefore, you can neglect the gas film resistance, gas film resistance can be neglected. So, there are; this are silent some of the salient features of the gas permeation through the for the gas separation for the membrane. Now, depending on the flow configuration the system can be categorised into several categories there are characteristic, we can have various kinds of flow configurations, what are this? Number one is that simple cross flow, in simple cross flow configuration the gas will be (( )) in the feed side and the permeate will be coming normal to the direction of the membrane in the permeate solute.

So, it is called a cross flow, that means the direction of the feed flow and the permeation detection of the species will be a 90 degree, so that is the cross flow configuration, simple cross flow configuration. If the feed side in the permeate side of both whole mixed that means there are whole star that means quite after (( )) the concentration gradient if there is that all (( )) exist it will be whole mixed. So, this is known as the complete mixing flow, complete mixing flow mixing module or configuration or completely mixed flow.

It will be like CSTR continuous start the director, that means it is wholes star and the concentration is uniform throughout. If the flow of the flow direction of the feed and the permeate alone the same direction then it is a cocurrent flow. Flow direction of feed and permeate is same them is a cocurrent flow and is the flow direction of the feed and permeate are in the opposite direction when it is called a counter current flow and you know the counter current configuration is much more efficient compare to the co-current configuration. That we have already seen in the fit transfer case is for the deduct (( )) change is you are already seen in the mass transfer case is (( )) in dialysis

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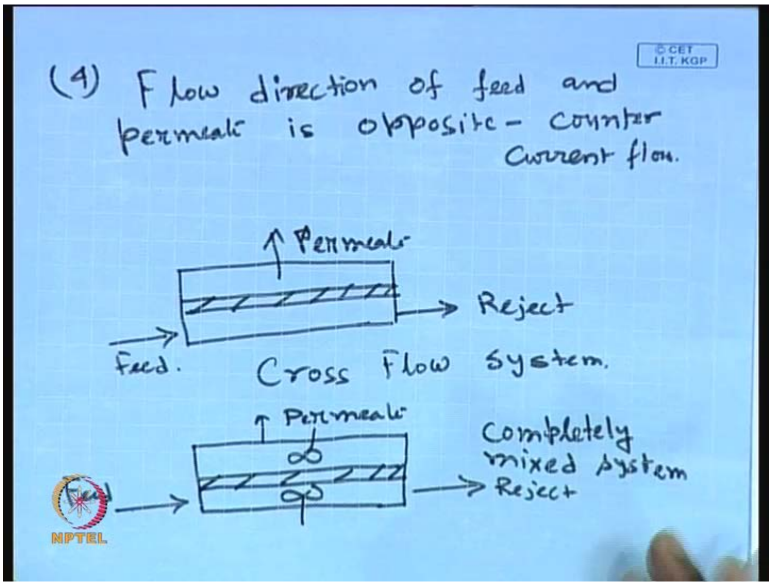

Flow direction of feed and permeate is opposite then it is known as the counter current flow. So, if you have a system something like this, suppose you place the membrane in between dividing the whole Chambal into two parts, this is the feed going in and you are collecting the permeate feed is going into the system then the reject stream is coming out of feed. And the permeate we are going to get almost of 90 degree to the direction of the feed flow, this is the simple cross flow system. On the other hand if you to have almost the same thing that the both the chambers are whole star then it is a completely mixed the system, is the second configuration we have discussed.

So, this is the feed, this is the reject and we going to get permeate out of it and the both the chambers are whole star, this configuration is known as completely mixed configuration completely mixed system. On the other hand next will be; if you do not have the star of the something like that if you use a carrier gas or a neutral or non reactive gas, so that the permeate will be taken out in a flowing stream then it is called co-current or counter current depending on the direction of the flow of the permeate and the detection of the flow of the feed

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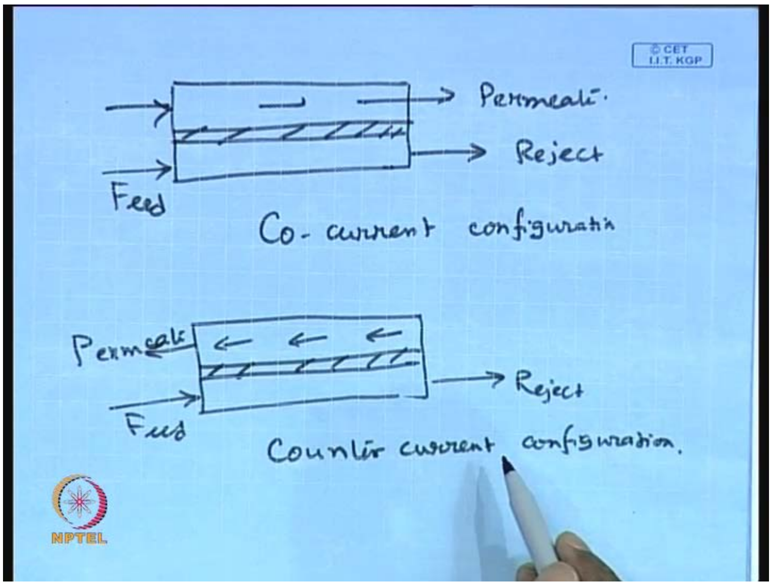

For example, if you have the system something like this where the both the Chambal is are separated by a semi permeable period are the membrane. And will be having a feed here, feed is going to the system on the reject stream is coming out of feed. And the similarly, the permeate is flowing by carrier gas the permeates is flowing in the same direction, this is a co-current configuration. On the other hand, if you have the opposite the direction of the flow are just opposite will be having the counter current configuration is the permeate, so it is a counter current configuration.

Now, there are two different approach is we are you already know what is approach is when we like to analyse this two system. For example, if you like to talk about the completely mixed system it is exactly what is like a CSTR that we are already done the modelling of completely start in reacting in react the analysis course (( )) as well as flux to reacted. So, we have two types of reactive that is the CSTR and the flux flow reacted in this case the analysis will be like a CSTR analysis. For example, the concentration is uniform, it is assume to uniform so the whole length are the region of the permeate and the feed.

On the other hand if you have a co-current or counter current configuration then it is basically like a flux flow type of analysis, you are going to do. So, we remember the fundamentals of flux flow reacted the every location, so concentration varies the every point of length. So, why we are talking about concurrent, counter current configuration? The analysis that we are going to adapt is the flux flow reaction analysis. On the other hand whenever the talking about the completely mixed reactor will be we taking request to the CSTR types of analysis.

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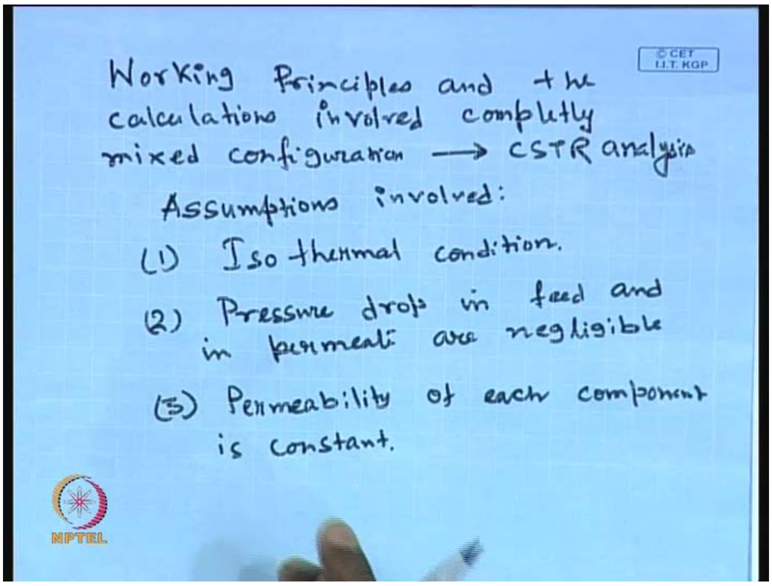

Now, what we are going to do next? Is that you are going to do calculate the walking looking into the working principle and the calculations those are involved in the configuration that we have to discussed. The first configuration you are talking about is the completely mixed configuration, is like a CSTR type of analysis. Now, let us (( )) in the assumption involved in the analysis are number one is the isothermal condition. There is no change in temperature during the operation, secondly negligible pressure drop is in feed and permeate flux the pressure drop in feed and in permeate or negligible. And the permeability of each component is constant, there means will be having a stream containing two components A and B.

You are going to separate A and B by the membrane. So, it is basically in the gas stream so, the permeability of the both the components will be present that means both the component permeable one will be less permeable another will be higher permeable. So, the component that will be highly permeable the permeate stream will be rich in the particular component so, that is the idea. Now, we are assuming the permeability of the both component will be constant, because you maintaining the temperature constant since diffusivity is the strong function of temperature since the maintain the temperature constant the permeability is also suppose to constant in this.

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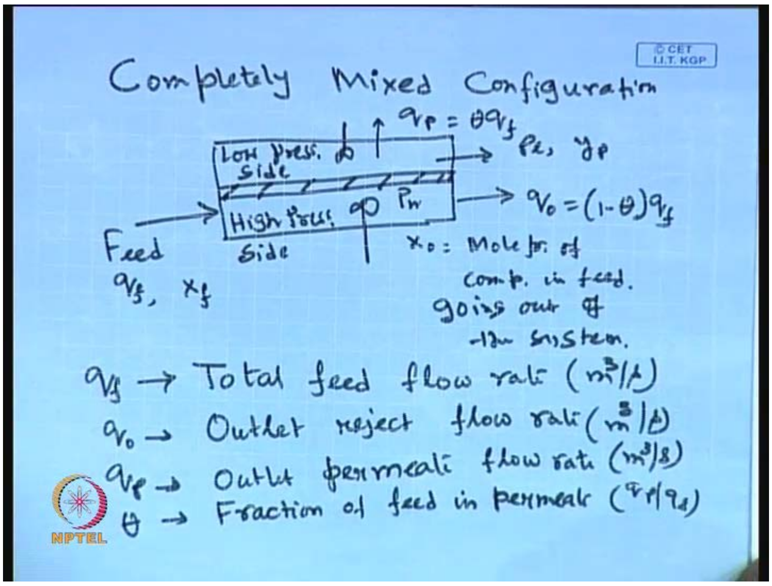

So, let us do the analysis for the completely mixed configuration.

This is the high pressure side, that means fix side fix side high pressure side this is the low pressure side or the permeate side. So, will be having the feed that is going into the system, you they flow rate q f and the mole fraction of the component that we are talking about separated X f. And there it is completely mixed up and these also completely mixed up. And we have a flow rate that is going out is nothing but 1 minus theta tomes q f, what is theta? Theta is the volume fraction of the fraction of the flow that is going into the permeate.

So, the permeate stream will be having q p, q p is nothing but theta times q f, what is theta? Theta is basically the fraction of the feed that is going in to the permeate. So, 1 minus theta of q f will be coming to the q not. And the pressure in the feed side the assume to the constant so that is p X and X not is the mole fraction of component in feed and this is P l y p and P l is the pressure in the permeate side the low pressure side and y p is an mole fraction of the component in the permeate. So, y indicate the permeate stream X indicate the feed stream. And the mole fraction of the component that is in the feed that is going out, mole fraction of component in feed going out of the system.

And we just see observe that the mole the quality of the permeate that is going out of the step is assumed to be same here, it is an assumption regarding to the CSTR analysis, that mean whatever, the concentration that is going out of the system will be having in the same concentration within the reactor, because is the short term reactor, it is completely mixed reactor. So, what is let as write down? All the notation q l e, q f is total feed wall feed flow rate in meter cube per second, q not is the outlet reject flow rate in meter cube per second, q p is the outlet permeate flow rate meter cube per second. And theta is the fraction of feed in permeate, that is q p divided by q f. So, these are the notations that are going to use and write; so, let us write down the overall material balance.

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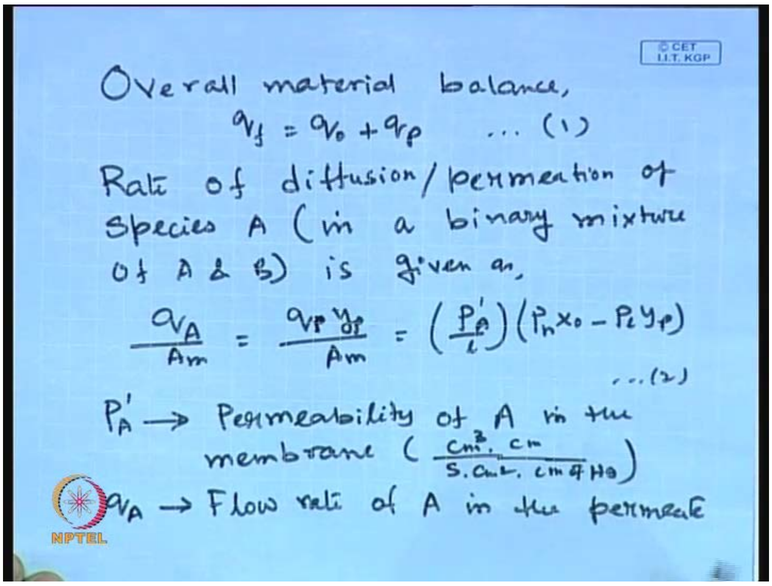

So, if you right over all material balance, you will be getting total flow rate that is going to the system will be total floe rate plus going out of the system q not plus q p. So, this is basically should be multiplied with the density of which stream, so there is it becomes k g per unit time. But you are assuming the density of all the stream will be more only constant so, it will be q f is equal to q not plus q p. Now, rate of diffusion or permeation of species a in a binary mixture of A and B is given as q A divided by A m is equal to q p y p multiplied by; divided by A m is equal to P A prime by l P h X not minus P l y p, this is number two equation.

Now, what is this q A? Is the total flow rate of a in the permeate stream, suppose we are talking about in the separation of species. Now, what is the total flow rat a in the permeate stream? It will be total permeate flow rate total permeate flow rate that is q p multiplied by the mole fraction of the of the species a that is the y divided by membrane area. A m is nothing but the membrane area that is flow rate of a per unit membrane area will be what will we nothing but the permeability this is p f time the permeability co efficient divided by l, l is the thickness of the membrane multiplied by the driving force.

Now, what is the driving force? Driving force it will be the partial pressure of a in the feed side minus a partial pressure of a in the permeate side. What is the partial pressure of a in the feed side? The feed side the mole fraction is X not. X not is the mole fraction that is going out of the system, since it the CSTR is the completely mixed system. So, what will the called mole fraction in the and going is out of the system will be same as that is existing inside the system. So, P h is the total pressure the feed side multiplied the mole fraction of a in the permeate in the feed side.

So, there is the partial pressure of a in the feed side minus p l is the total pressure in the permeate side multiplied by the mole fraction of k in the permeate side. So, you write down the different notation, P A prime is nothing but permeability of a in the membrane. That is centimetre cube divided by per second centimetre square times centimetre of Marcel, that is the pressure, indict q A is the flow rate of A in the permeate.

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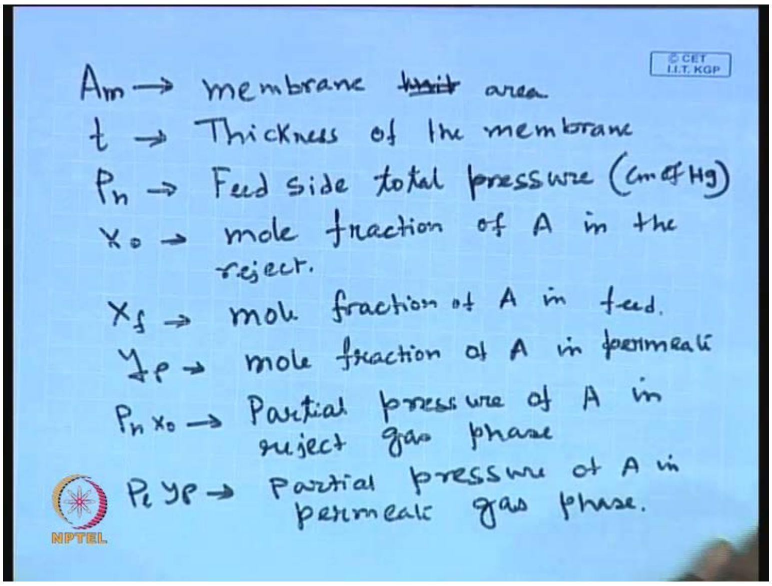

In the permeate, A m is the membrane area with a suitable unit, that will discussed later honour (()) will be solving the some the problems membrane area, t is the thickness of the membrane, P h is feed side total pressure that is centimetre of Marcel. X not is the mole fraction of a in the reject X f is the mole fraction of A in feed, y p is mole fraction of a in permeate, P h X not as a; it is a partial pressure of A in the reject gas phase.

And P l X not P l y p is nothing but the partial pressure of A in permeate gas phase. Now, once you identified in the parameters.

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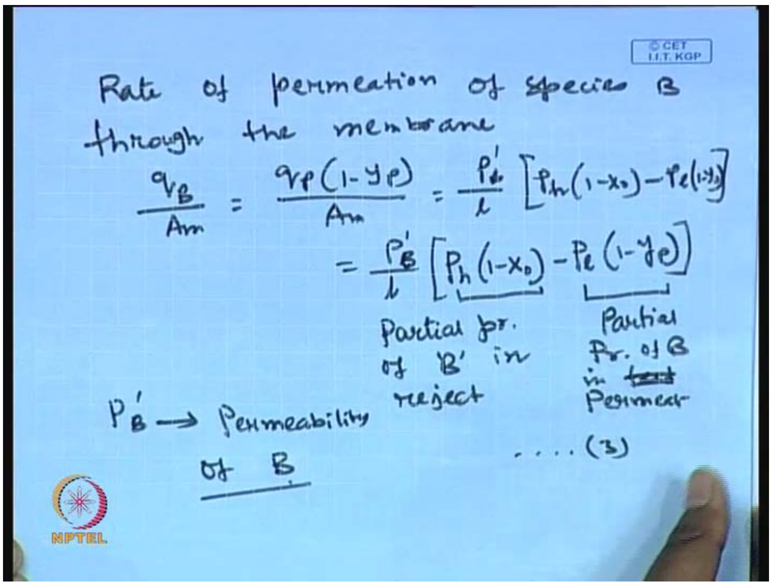

Now, let us write down the rate of permeation of species B through the membrane.

That will be nothing but q B divided by A m membrane area and what is q B? q B will be nothing but q p multiplied the 1 minus y p, you are considering it is a binary mixed. Since the y p is mole fraction a then 1 minus y p should be the mole fraction of B divided by A m should be equal to P B prime P h 1 minus X not minus p i 1 minus y not. So, this will be equal to let us me let me right it more clearly P B prime divided by l P h 1 minus X not minus P l 1 minus y p. So, this is nothing but the partial pressure of species B in the feed for the reject strength of component B in reject and this is the partial pressure of B in permeate, this is the third equation are talking about. And P B prime is permeability of species B through the same membrane. Now, what we can do? You can divide equation number 2 equation number 3 and will be getting as this q p, q p is cancelling out A m a m will be cancelling out.

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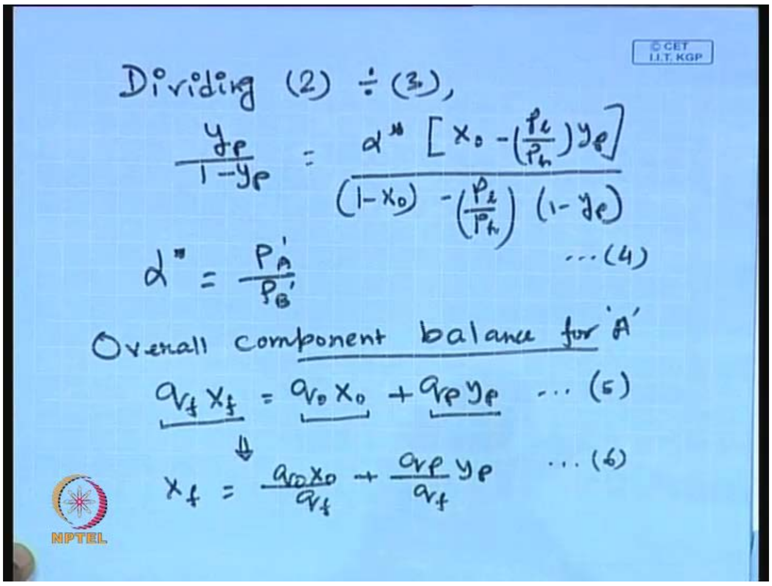

And what will be getting as y p dividing equation 2 by 3, will be getting y p divided by 1 minus y p is equal to alpha star X not minus P i over P h multiplied by y p divided by 1 minus X not minus P l by p h 1 minus y p, this is equation number 4. What is the alpha star? Alpha star is nothing but P B prime divided by P B prime, it is a non dimensional constant and this is ratio of permeability of species a in the membrane permeability of species B in the membrane. Now, if you do as overall component balance for A earlier

(()) do as overall component A, so that will give the following relation q f X f equal to total mole that is going into the system per unit time.

So, q f X f is equal to q not X not plus q p y p, total moles of a that is going in to the system per unit, total moles of the system that is going out of the good. Total moles of the a that is going out of the system through the reject stream q not X not and that is going through the permeate. So, you can rearranging the equation and this rearranging we let to they be you X f is equal to q not X not divided by q f plus q p divided by q f times y p this is equation number 6, that means you are dividing both side by q f. And now, to defined the fraction theta, theta is nothing but the q p divided by q f the fraction of feed that is going in to the permeate.

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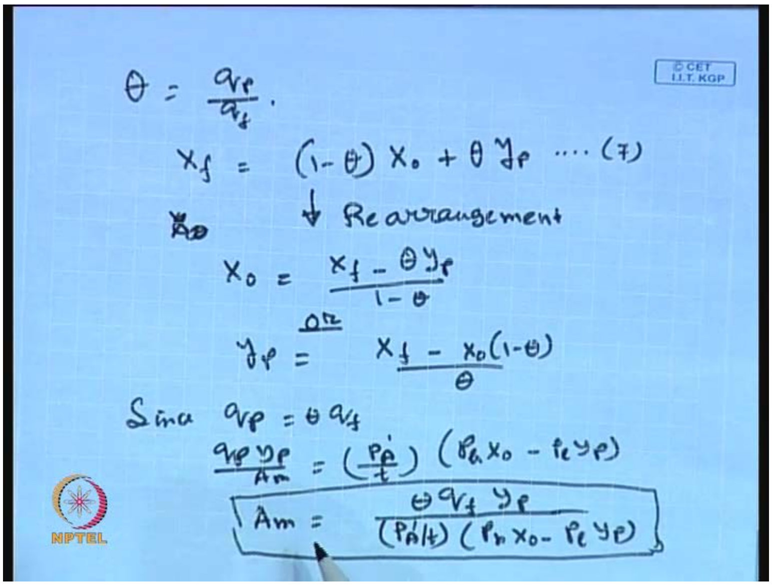

Now, if you divide; it defined a theta that is q p divided by q f so, this becomes X f is equal to 1 minus theta times X not plus theta times y p this equation number 7. Now, this equation can be reorganised to estimate the feed mole fraction are that is there in the permeate, that means you can find out the mole fraction of the feed from this that means rearrangement of the equation can give a two things. Suppose, X not is equal to X f minus theta y p divided 1 minus theta, that means if you know the fit concentration mole fraction, if you know p the cu that means how much; what is the; how much the fraction of the feed going in to the permeate? If you know that for let say (()) 0.3, 30 percent of that.

And if you know the permeate concentration and then X not that is the concentration of the mole fraction of the reject stream can be calculated from these equation. Or if you know the other thing calculate the mole fraction of the a in the permeate stream that means this or this X f minus X not into 1 minus theta divided by theta. If you measured the permeate mole reject mole fraction and if you know the what is the cut off feed fraction the that is going to the permeate. And if you know the feed composition will be able to calculate, what is the y p? The concentration mole fraction of a in the permeate stream q p is theta into q f.

So, you can get an idea since q p is theta times q f by the definition the fraction theta from the equation q p y p divided by A m is equal to P A prime by t equal to P h X not minus P l y p, there is this equation have return earlier that is the total flux of the permeate of the species a that is going into the permeate stream, so that the membrane from this 1 can calculate the value of membrane surface area, is will be theta times q f times y p multiplied; divided by P A prime divided by t that is P h X not minus P l y p. From this equation, if you know all the other parameter, that means if you know the some of the parameter are any calculates.

Some of the other parameters then whole right hand side will be known to you that is will be able to calculate, what is the membrane area? That will be required for such a purpose for this is the design. So, if you know the feed condition, if you know the some of other condition you will be able to calculate, what is the permeate mole fraction? And the amount of permeate that is going out in the system that is the design parameter let say you set it the 0.3 or 0.5 or 0.7 then, you will be you will be able to calculate. The value of membrane area that is required that means if you set a caught of the permeate that means what is the fraction of the feed that is going in to permeate.

You can have that means theta will be feed fixing a theta, under the that condition will be calculate will be able to calculate what is the membrane area that is required for the for such a system, to decide such a system. Now, what we can do? You can select several values of theta and calculate, what is the value corresponding values of A m? That means typically, if you do that then you required you can plot the value of the membrane area is required verse theta. From the plot one can get that is if you have a; if you fixed fraction of the feed that is going in to the permeate then what is the corresponding value of the membrane area that is required for the system. Now, if you closely look into various equations, you can find out that.

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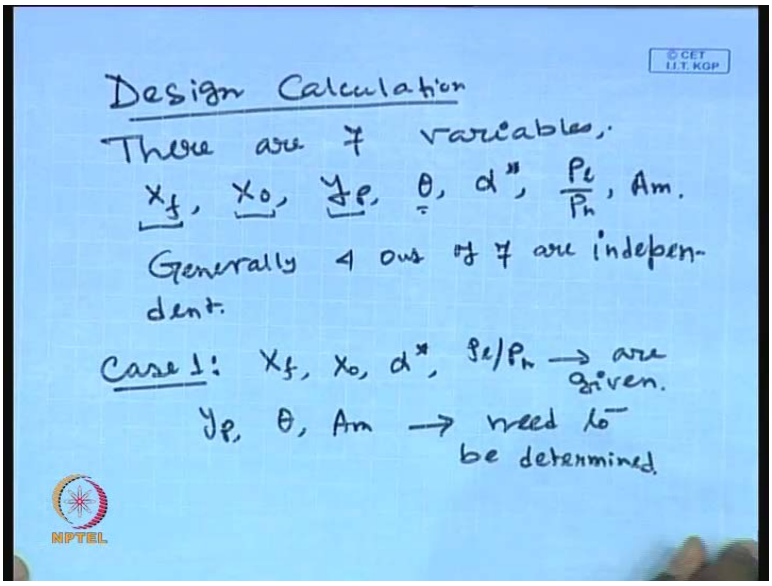

Let us do some design calculations, if you know; if you closely look at all the equation will be will be seeing that there are 7 variables in all. What are the 7 variables? There will be X f the X not y p theta alpha star P l by P h A m. X f is the mole fraction of the of the species a in the feed, X not is the mole fraction of the species there is going the rejects stream, y p is the mole fraction from the species in the permeate stream, theta is the ratio of feed permeate divided by the feed flow rate are you first there is the ratio of permeability of species e n b through same time (()) P l by P h is the pressure ratio in the permeate side to the fixed side and A m is the surface area on the membrane.

Now, generally four of them are independent, generally out of 7, 4 out of 7 are independent. Now, we sub divides this problem and closely looking into two cases, case number 1 is that X f X not alpha star P l by P h are given so, this are basically operating condition. Now, alpha star is the property that is the permeability of the ratio permeability of species A and species B. P l by P h the operating condition pressure that maintaining in the permeate side the feed side, X f is the quality at the mole fraction of the in the feed and the reject quality set by u.

Let us say it the reject quality that is going to have, once you have that then you are going to estimate what are the permeate quality y p and what is the theta? The mole fraction if you set the X not the permeate that the reject quality then what will be required by theta that we are going to get, theta and A m need to be determined. So, we are going to get; you are having the four parameters and three parameters going to estimate. So, that you can really designed the whole system.

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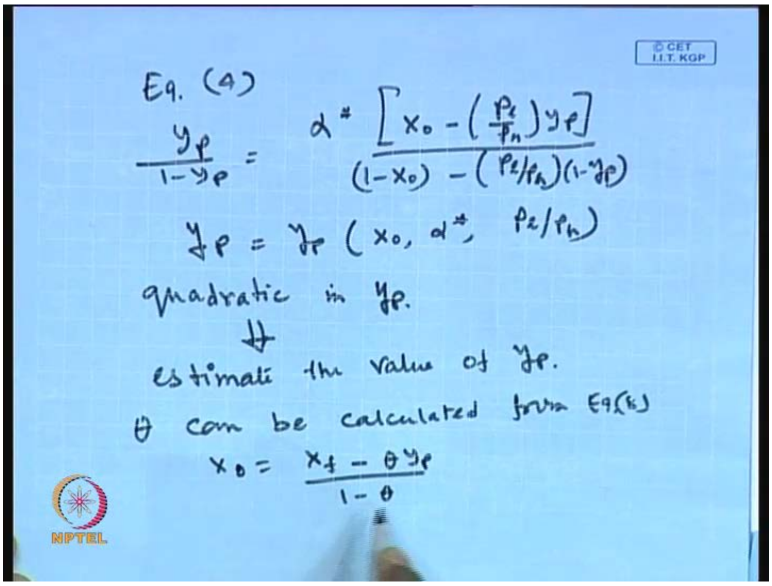

So, first of all will be we are going looking in to the equation 5 and 4, the equation 4 what we are going to have here y p divided by 1 minus y p is equal to alpha star X not minus P l by P h by p divided by 1 minus X not minus P l by P h 1 minus y p. So, these equation can be return as that y p as the function of X not alpha star and the ratio P l by P h, all this are known to you, know it is the quadratic equation. If you look in to the equation this is multiply both side will becomes one term will be y p square and another term that will be y p square.

So, it is a quadratic in y p there means X not will be known to you, alpha star to be known to you, P l by P h known to you. Because there given only one unknown is y p. So, you are going to get and quadratic in y p going to solved that and you are going to get the value of the y p estimate. The value of y p I am not solving this equation, is solving equation (()) there is nothing rate in the equation will be all the other parameters are unknown. If you simplify this equation by cross multiply, it will be a quadratic in y p bring all the coefficient y p square in 1 side y p in 1 side the everything.

So, it will be quadratic equation in, how to find out the roots of the quadratic equation? and estimate the value of y p. Now, once you know the y p, you can get the value of X not, X not is given so, you can you can get the value of theta. Theta can be calculated from equation 8, where is the equation 8? That is the X not is equal to X f minus theta y p divided by 1 minus theta. This equation you have return from this equation y p is known, X f is known. So, you can y p was estimated X f is known so, you can estimate the value of theta.

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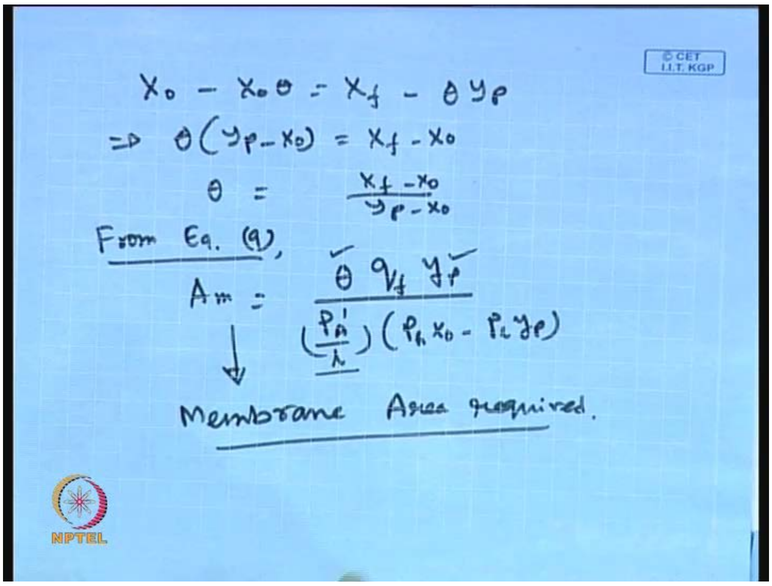

So, it will be X not minus X not theta is equal to X f minus theta y p. So, it will be theta times y p minus X not is equal to X f minus X not so, you can the value of theta. Now, from equation 9, once you know the estimate the value of theta, you can calculate the value of A m as theta q f y p divided by P A prime divided by l P h X not minus P l y p. So, you are already calculated in the value of y p now, already calculated the q of theta P h X not and so X not is known to you, y p is known to you and P l P h is known to you. So, you know the denominator in the right hand side and you know the first term denominator P A prime by l that is also given to you.

So, membrane thickness is known to you and permeability value of A to the membrane known to you, you can estimate the value of A m at the A m in the area membrane required on for this particular problem. Now, you can designed the appropriate configuration to supply the that much of membrane area so, there it can be; the whole system can be designed appropriately.

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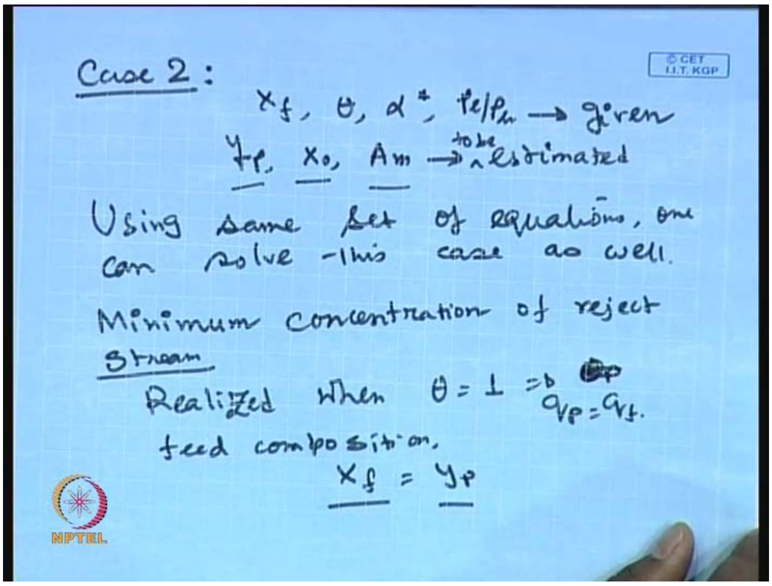

In next case that will considered case number 2 and what will be that this case X f is given X f theta out of the seven parameter X f theta alpha star P l by P h are given. This parameter have been estimate the permeate mole fraction in the reject stream and the surface area that is membrane surface area that is required to the estimated. Now, i am not going in to the retail so, using this equation exactly like that case number one, one can find out the value of y p, the value of X not and the value of A m. Exactly like the previous using the same equations that means using the same set of equation, equation one can solve this case as well.

Now, there is something called minimum concentration our reject stream, this concept is given as when all the feed is permeated, that mean when you will be getting the you will be extracting the recovering the feed complete value of feed in the permeate that means that case theta will be equal to one, q p is equal to q f. This case will be realised, when theta is equal to 1 that means q p sorry q p will be is equal to q f that is you are extracting the full value of you know feed in the permeate stream. And the feed composition becomes X f is equal to y p that means mole fraction of the feed will be equal to mole fraction of the particular species in the permeate. Now, for all values in the theta less than one there is important.

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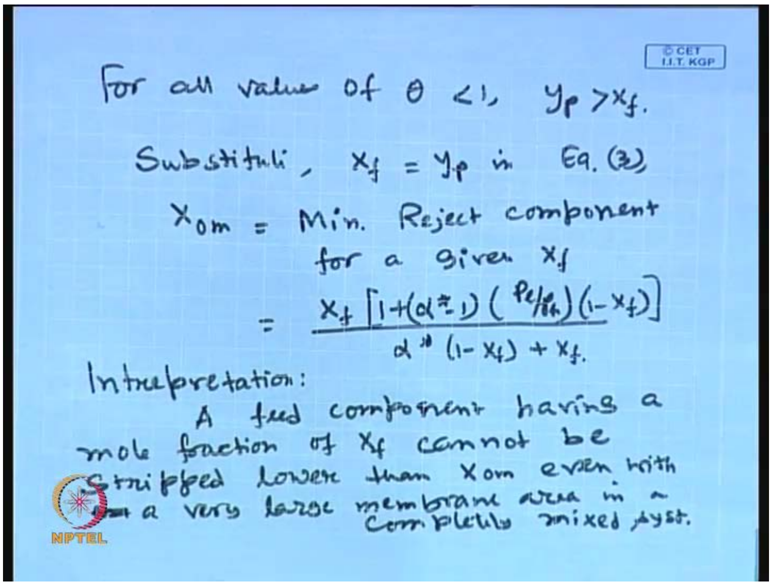

For all values of theta less than 1 y p is greater than X f. So, any way so, it is substitute X f is equal to y p in equation number 3 and will be getting the minimum reject component X o m, in this case this is minimum mole fraction of the reject component for a given X f and will be X f if you substituted the value to their it will be X f is equal to 1 plus alpha star minus 1 P l over P h 1 minus X f and it is alpha star 1 minus X f plus X f. So, that means if feed component so, this the value of minimum reject component for a given value of a X f 1 can plot X o m for X f for different value for the feed composition so, feed component X f.

So, what is the inter prediction? The inter prediction is a feed component having a composition, having a mole fraction of X f it cannot be stripped lower than X o m. Even with and with a very large membrane area in a completely mixed system that means we inter prediction is; if you are completely mixed system. Even if you go for a very high membrane area, you cannot get a compilation of reject lower them this well, suppose this value is 0.4 and you like to go beyond this, what we are going to do? This the maximum possible value maximum possible value, the lower most the minimum possible value that you can go at the reject stream composition, even if you supply are infinitely large membrane area.

Now, if you like to going lower than the, what you have to do? You have to do the gasket system. Why the gasket system you have to place search unit one after another in series that is in gasket. So, you so, X you go from X f you go to X o m in the first test an X o m will be now the feed composition for the next system. You can given calculate, what is the value of X o m? in carried; in equipment number two or the unit number two you can calculate that as like that. You can go down below the minimum value of this, if you have a several system in gasket. So, next thing that going to do is the cross flow model for gas permeation.

So, this is the basically a more only complete system whenever, you are talking about the completely mixed of system. So, in this completely mixed of system modules are very simplified and this module will constitute by the oral material balances number one. The balance equation for the solute A, the balance equation of solute B and the permeation rate of solute A and the permeation rate of solute B. And the driving force in this case will be the partial pressure different of component A and the partial pressure of component B. Now, using this for five basic equation one will be able to design the whole system for a completely mixed of system.

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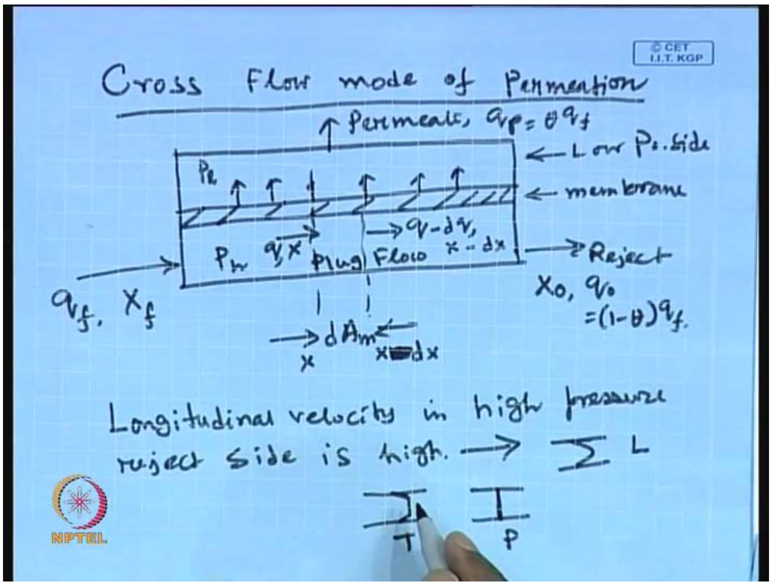

Next we go for the cross flow configuration, cross flow mode of permeation.

So, in this system will be draw s semantic first, this is the membrane and you are feed at high pressure with composition floe rate q f and X f is the composition the in the mole fraction of a in the feed. And there is the; it is a plug flow that occurs here in the earlier case it was a completely mixed flow that means concentration is uniform everywhere, in the permeate as well as the in the feed stream. But in this case it will be a flux flow and the pressure is P h at the higher side and to the lower side is P l and permeate you are going to calculate collect as q p is nothing but theta time q f. And this is the low pressure side and this is the high pressure side permeate is going to get like a cross flow 90 degree the direction of the flow.

So, will be having now, if you have a differential area, you they differential membrane area of d a n and if the cross section. So, this is d a n is located between two in the length X and X plus dx d a n is the differential membrane element area that is located between the two distance is location X an X plus delta X and the feed that is going here is q at the location X. And the other one that is going out is q minus d q at the location X minus dx so, this is X minus dx. So, we are basically calculating length and (()) from the other other side. And the reject is going to get is a X not q not and what is q not? Q not is nothing but 1 minus theta times q f that is a semantic of a cross flow system. Longitudinal velocity in a high pressure radius stream is quit high.

The longitudinal velocity in high pressure reject side or reject stream is quit high. Since the velocity will be quit high then we can assume a plot flow is prevailing their, plot flow is there is know the velocity variation that means the velocity. This a cross sectional area and if the velocity profile it is like this when it is called a it is called a laminar flow. And for a turbulent flow the velocity profile look something like this and for a plot flow the velocity profile is plot that means the whole things means like a solute plot or the solute velocity. So, it is basically velocity uniform it is not varying with a cross section. So, if you remember this is the laminar flow, this is the turbulent flow, this is the plot flow.

From the laminar flow turbulent in the velocity is very high then this curvature is molar less (()) to be loss it is becomes almost flat and add velocity increases curvature is appears the only at the wall there is the turbulent flow if you increase the velocity for further this curvature will be curvature of the velocity profile will be loss permanently. And will be having a flat profile and the uniform profile. So, it called it plot flow profile are uniform velocity profile. And it will be you are assume that, it is basically prevailing in the reject side or in the feed side. Any way will continue the discussion in the next class on the verse, will be having the full you know write down all the equation regarding in to the; this module is cross flow module, how to solve them? Also see that.

And finally, will be looking in to the design of such system in the gas permeation of the gas separation in gas. Thank you very much.