Physico-Chemical Processes for Wastewater Treatment
Professor – V.C. Srivastava
Department of Chemical Engineering
Indian Institute of Technology – Roorkee
Lecture – 45
Wastewater Treatment by Membrane Processes – V

Good day everyone and welcome to these lectures on Physico-Chemical Processes for Wastewater Treatment. So, will be continuing our discussion or knowledge sharing with respect to reverse osmosis. So, in the previous lecture we started understanding the reverse osmosis process which is used a lot in for water treatment in different industries as well as in the households.

So, we try to find out the basic equations of reverse osmosis, understood osmosis as well as reverse osmosis in the previous lecture. Continuing further, today we are going to learn regarding the properties of RO membranes as well as we will try to see that what are the different variables which affect he RO process in detail.

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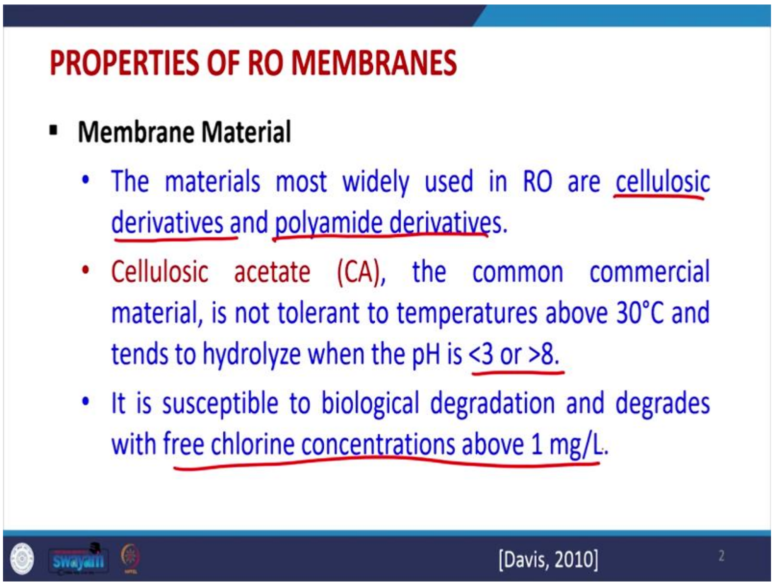

So, membrane materials, the materials most widely used in the RO like cellulosic derivatives are polyamide derivatives. So, these are very very common materials which are used as RO membrane material and cellulose acetate the most common commercial material which is used in the membranes for RO is not tolerant to temperatures above 30 degree centigrade and tends to hydrolyze for the pH range which is beyond three and eight.

So, this is the common issues which are there with respect to cellulose acetate. Also it is susceptible to biological degradation and degrades when free chlorine concentration above one milligram per litre is there. So, this is another problem with respect to cellulose acetate.

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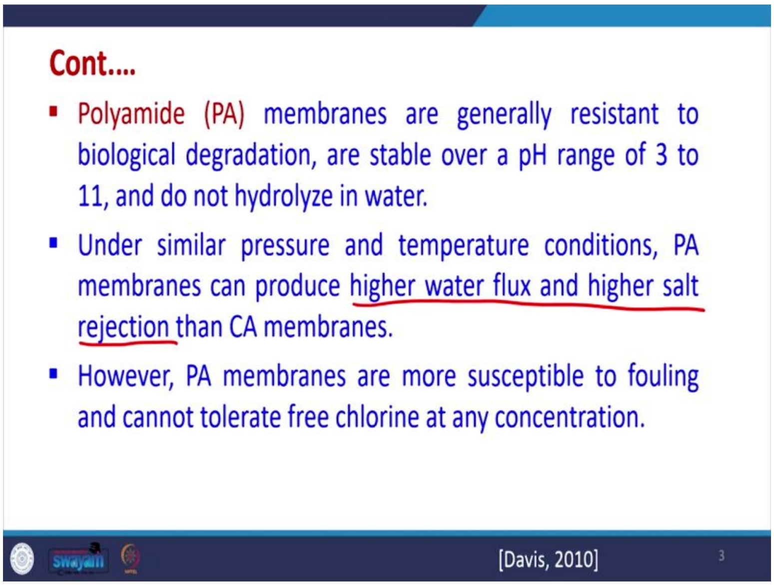

Now polyamide membranes are more resistance to biological degradation and also they are stable beyond the pH range of 3 to 11 and they do not hydrolyze in water as well. So, in this way polyamides are better as compared to cellulose acetate. Under similar pressure and temperature conditions polyamide membranes can reduce higher water flux and higher salt rejection than the CA membranes.

So, again the PA membranes are better but PA membranes are more susceptible to fouling and cannot tolerate free chlorine at any concentration. So, this is the harmful or disadvantage with respect to PA membrane.

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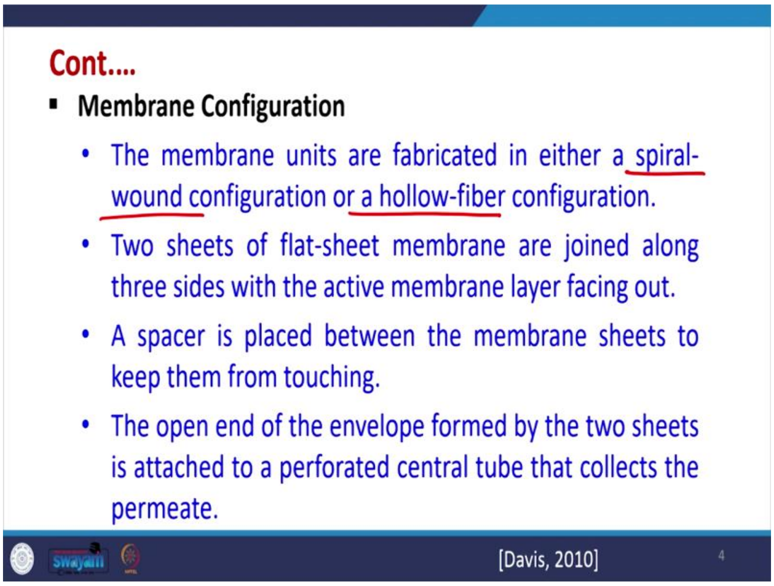

Now there are many configurations which are possible and previously also for overall membrane, nanofiltration ultra-filtration, microfiltration also we have studied these membrane configurations. So, again for RO membrane configuration the units are fabricated in either spiral wound configuration or hollow fiber configuration, so both of these are common.

Now two sheets of flat sheet membranes are joined along with the three sides with the active membrane layer facing out. So, this is also there, the spacer is placed between the membrane sheets to keep them from touching. So, this spacer is used here, now open end of the envelope formed by the two seeds is attached to the perforated central tube that collects the permeate. So, this is how the membrane configuration is there.

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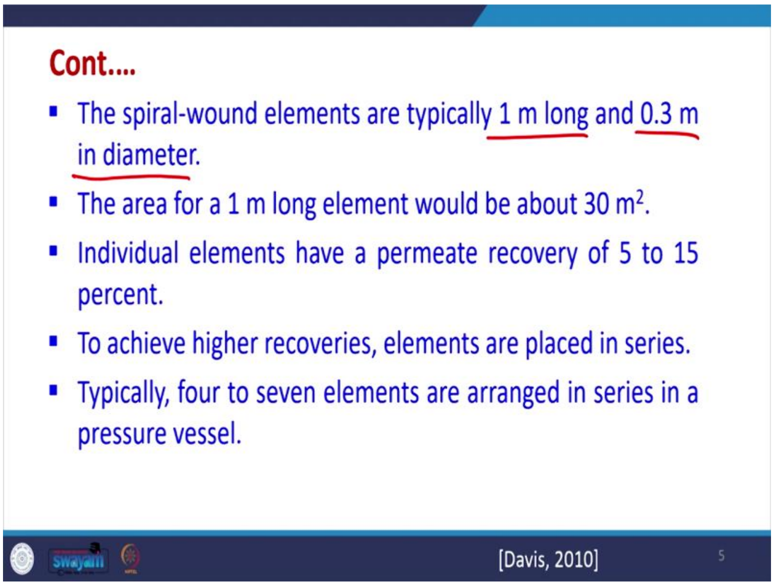

Now the spiral wound elements are typically one meter long and 0.3 meter in diameter. So, this is there. This is a typical configuration of spiral wound element. Now the area for one meter long element will be typically 30 meter square. Individual elements may have permeate recovery of 5 to 15 percent. To achieve higher recoveries these maybe placed in series also and typically 4 to 7 elements are arranged in a series in a pressure vessel. This is how the recovery rates are increased.

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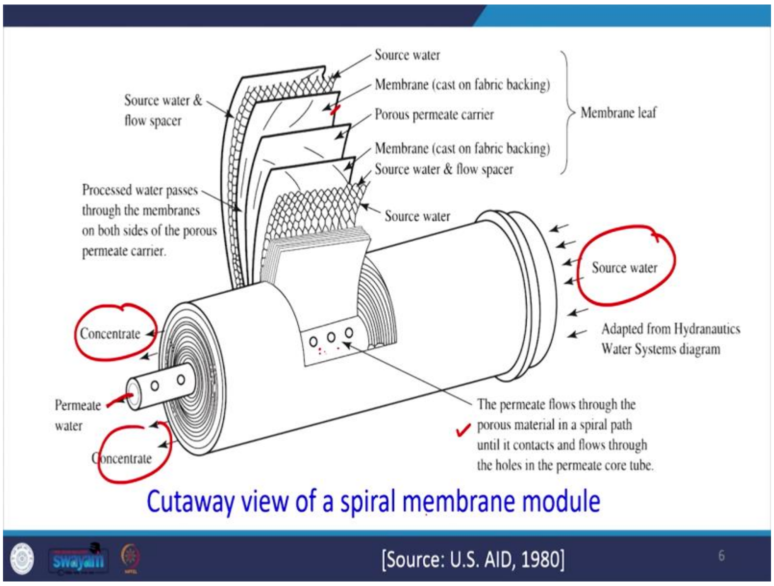

Now this is a cut away view of spiral membrane module you can see here. These are the different, so source water we can see here the permeate will be coming out from here. The concentrate will be coming out from here and the permeate flows through the through the porous material in the spiral path which is there and you can see here these pores which are shown here, the source water entry will certainly from this side and from the this way and within these membranes the separation will happen.

There are different sections, you can see here. The source water, the membrane caused on the fabric backing then porous permeate carrier also. There are different sections within the spiral membrane module which are shown here. So, we can understand little bit, better if we can actually see the any membrane module nearby to our place where we are living. So, we can go in the industry also these are very very common modules which are used.

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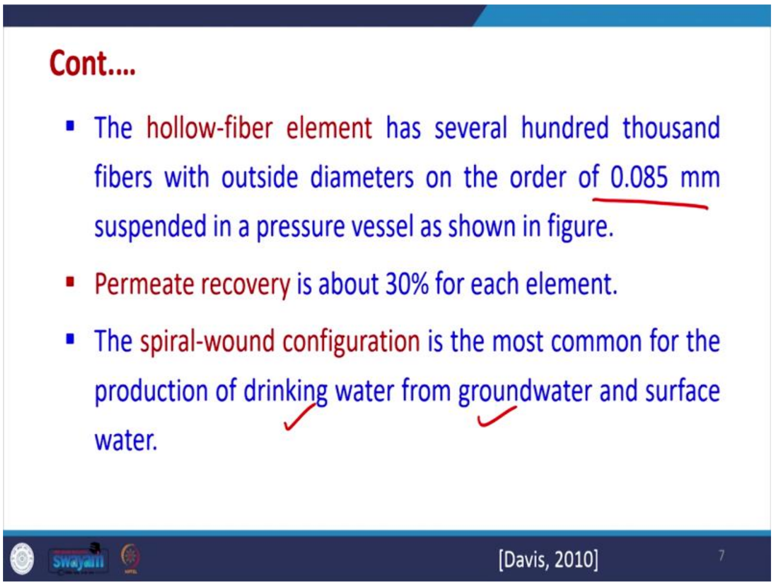

Hollow fiber element has several thousand fibers with outside diameter on the, of the order of 0.085 millimetre suspended in a pressure vessel. The permeate recovery is about 30 percent for each element and the spiral wound configuration is most common for production of drinking water from groundwater. So, if the groundwater contains lot of TDS and other things. Then spiral wound configuration is most commonly used. Also from groundwater, for surface water also we use this configuration in detail.

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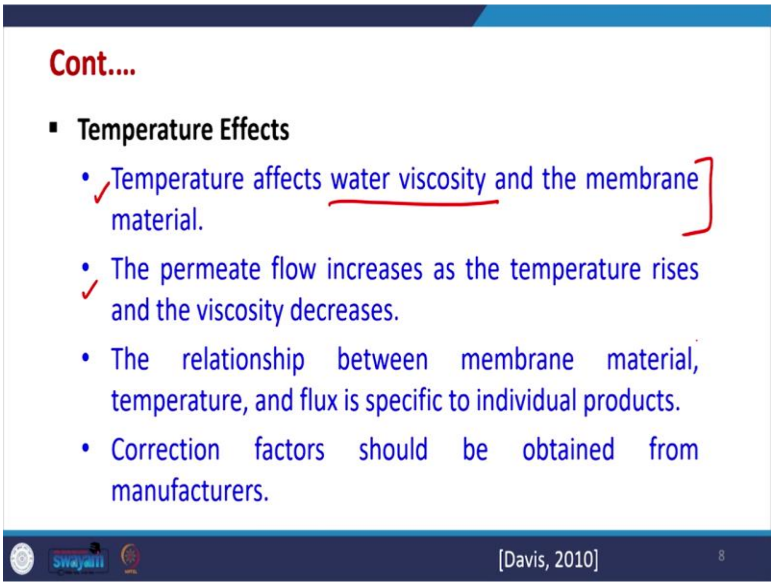

Now there are different effects which are there. So, earlier we have seen that the temperature affects the membrane performance of ultrafiltration, nano-filtration and microfiltration. For reverse osmosis case also it is the same because the temperature affects the water viscosity and as well as the membrane material also. So, we have seen with respect to cellulose acetate that temperature there is the effect of temperature on the cellulose acetate material.

So, similarly for different membrane materials let us, there is lot of effect of temperature which affects the water viscosity also. So, if water viscosity gets changed the flux also gets changed, so the permeate flow increases as the temperature rises because the viscosity decreases with increase in temperature. The relationship between membrane materials temperature flux is specific to different types of individual products.

A correction factor should be obtained from the manufacturers, so that means the manufacturers have to provide the correction factor. So, we can always help the manufacturers, if we can understand the problem and let them find the correction factor in detail. Now and that will be there with respect to temperature. So, these correction factors, a manufacturer have to report with respect to different temperatures.

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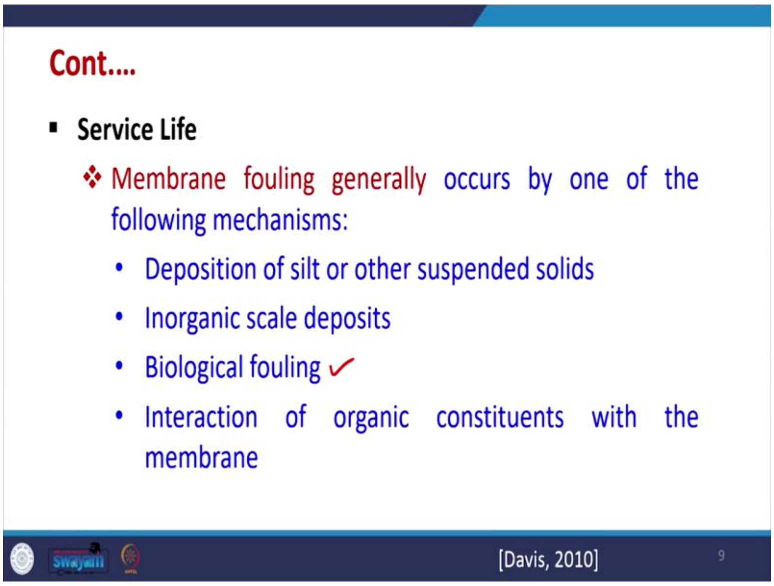

Now what, the service life of these membranes. The membranes fouling will be one of the major reasons for decrease in the service life of the RO membrane. So, any of these things may happen like deposition of silt or other suspended solids on the membrane.

Then inorganic scale deposition may also happen. Biological fouling because the pathogens bacterial species viruses etc may get screened out and also because organic material also there so biological growth may also happen. Interaction of organic constituents with the membrane may also follow the membrane itself. So, this is there.

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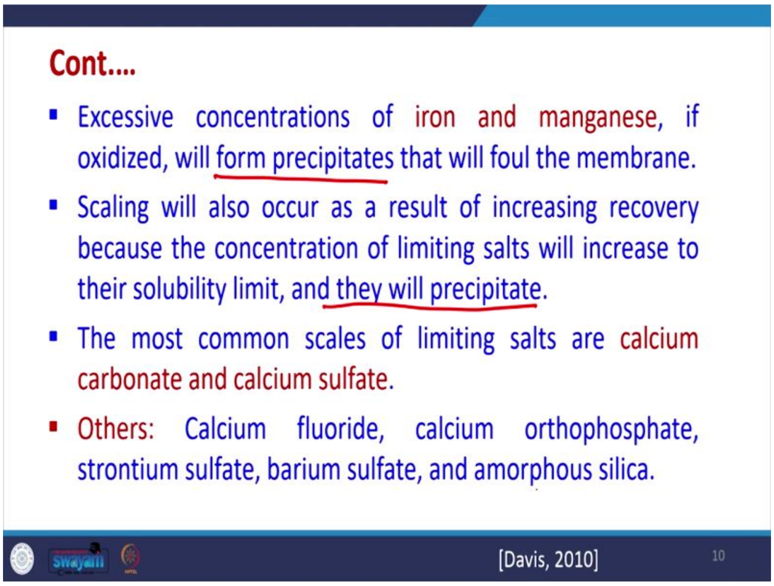

Excessive concentrations of iron and manganese, if they are present in the water and if they are oxidized. So, what will they do is that, they will form precipitate and that will follow the membrane. So, this is there. Scaling will also occur as a result of increasing recovery because the concentration of the limiting salts will increase to their solubility limit and after that they will start precipitating. So, this is another reason for fouling or scaling.

The most common scales of limiting salts are like calcium carbonate calcium sulphate. Other types are also possible, scales may be formed because of the calcium fluoride, calcium orthophosphate, strontium sulphate, barium sulphate, amorphous silica etc. So, any of these things present beyond the limiting conditions they may form scales. Within limiting scales or limiting salt concentration under certain conditions, they will also follow the RO membrane.

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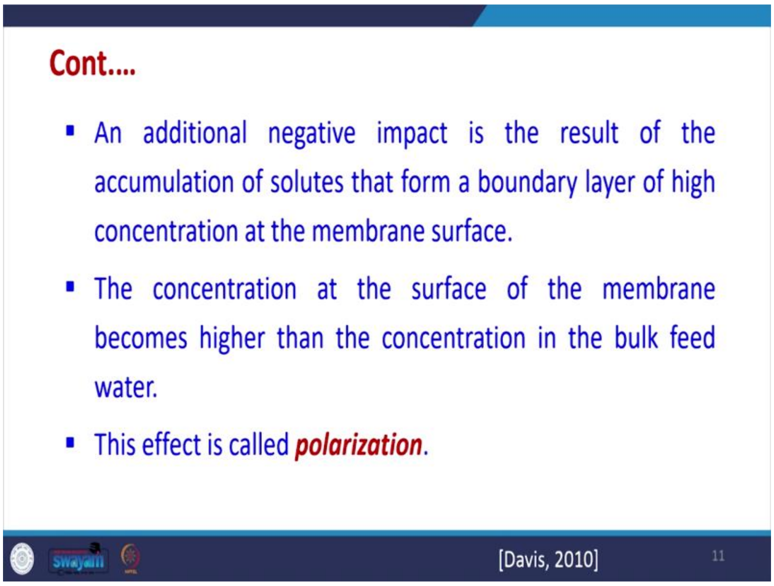

Now, an additional negative impact will be because of the accumulation of solute that will form a boundary layer of high concentration at the membrane surface. So, this is additional negative impact which will always occur at the higher concentration level. The concentration at the surface of the membrane becomes higher than the concentration in the bulk feed and this effect is called as polarization.

So, we always try to see that this polarization is minimized in the RO membrane. So, this we have to see and polarization if it occurs, it will have following negative impacts which are discussed here.

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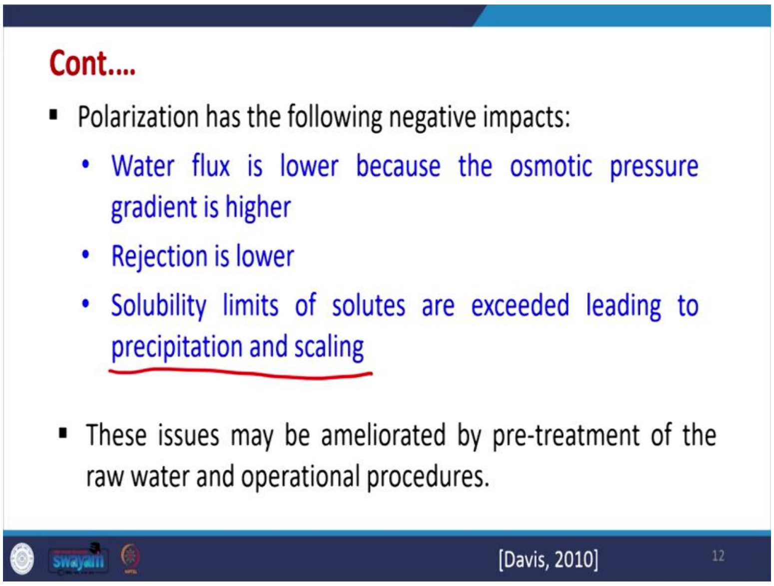

The water flux is lower because the osmotic pressure gradient is higher. So, water flux is lower here, if this polarization is occurring, rejection will also be decreased and solubility limits of solutes will exceed and that will lead to precipitation and scaling. So, already these issues we have discussed.

These issues can be taken care by pre-treatment of the raw water and some operational procedures that we can adopt to avoid these polarization and other fouling issues. So, this is possible. Now what we do is that, will further understand, what are the factors which affect the RO membrane performance. So, there are many factors which affect the RO membrane performance and we will try to analyse each of these effect.

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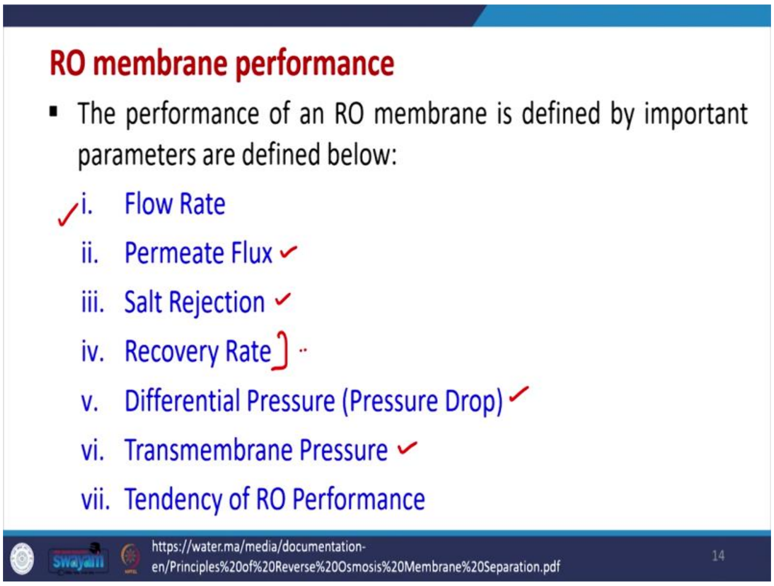

So, the typical parameters which affect the RO membrane performance include, what is the flow rate under which we are operating? What is the permeate flux that we are getting after the separation then what is the amount of salt rejection that we are performing and what is the recovery rate of water because this is very very important for industry also and for in industry in particular the differential pressure or the pressure drop for under which we are operating our RO.

So, that is also important consideration and then what is the actual trans membrane pressure which is beyond the semi permeable membrane and then the different other performance may be clubbed together in the tendency of RO performance with respect to other parameters.

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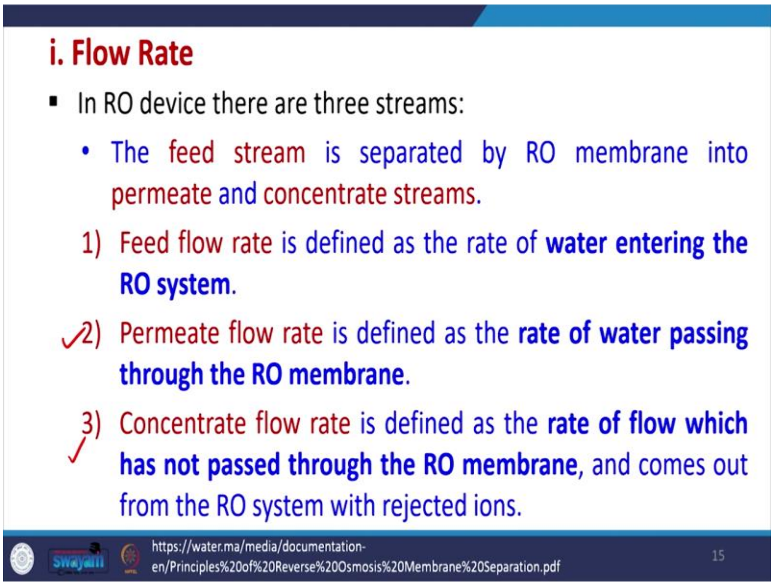

Now first we will understand the flow rate. So, in RO device there are three streams, the feed stream, the permeate stream and the reject stream. So, the feed stream is separated by RO membrane into permeate and concentrate steam or reject steam. So, this is there, so already we have earlier discussed this.

So, we will not go further into this. Now the permeate flux, the performance will depend upon the flow rate or any of these fluxes concentrate or permeate because, and this will be dependent upon the pressure under which we are operating as well as the different physico-chemical characteristics of the membrane itself.

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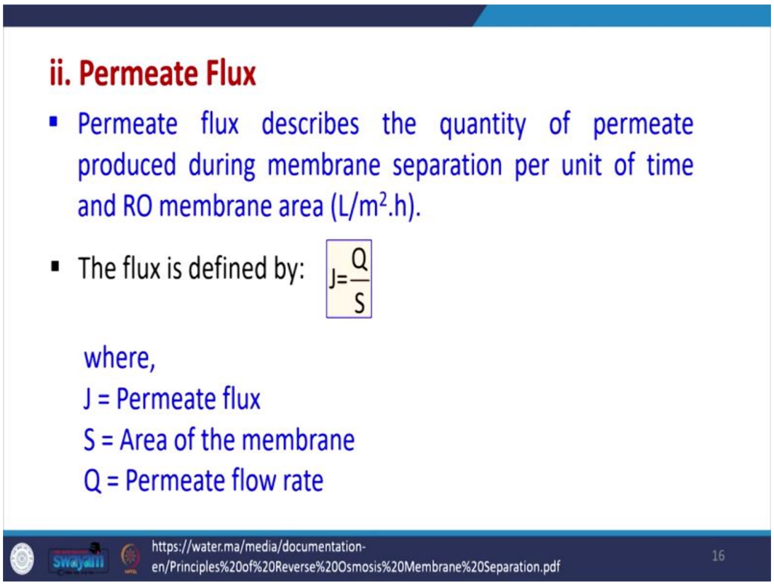

The flux is defined by:

$$J = \frac{Q}{S}$$

where,

J = Permeate flux

S = Area of the membrane

Q = Permeate flow rate

Now the permeate flux is the one which we desire the most. So, permeate flux describes a quantity of permeate which is produced during the membrane separation per unit time and per unit RO membrane area. So, this has already be defined earlier also.

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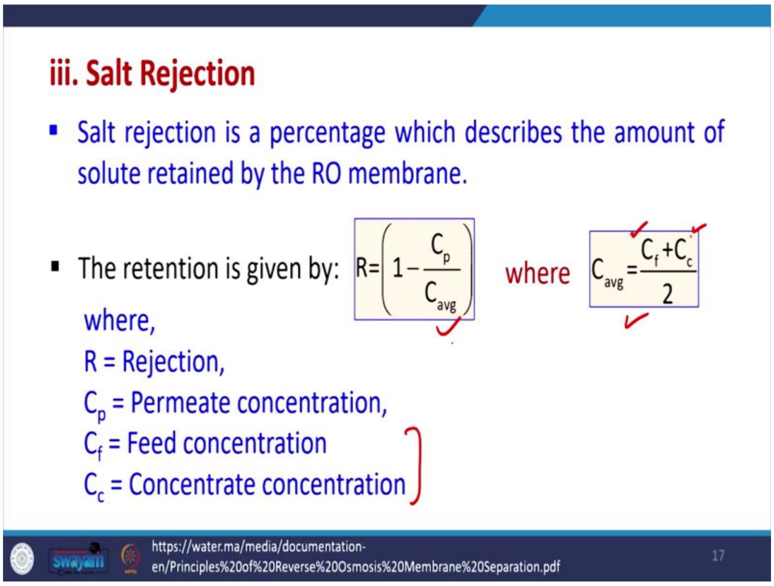

The retention is given by:

$$R = \left(1 - \frac{C_p}{C_{avg}}\right)$$

where, $C_{avg} = \frac{C_f + C_c}{2}$

where,

R = Rejection,

C_p = Permeate concentration,

C_f = Feed concentration

C_c = Concentrate concentration

Then there is a term which is called as salt rejection. So, it is a percentage which is describes the amount of solute retained by the RO membrane. So, this will be R is equal to Cp upon C average and C average is like a concentration, in the feed concentration as well as concentration in the, concentrate or reject system. So, both, we can take average of that and Cp is the permeate flux concentration. So, through this we can find out that how much amount of salt has been rejected or retained on the before the semi permeable side.

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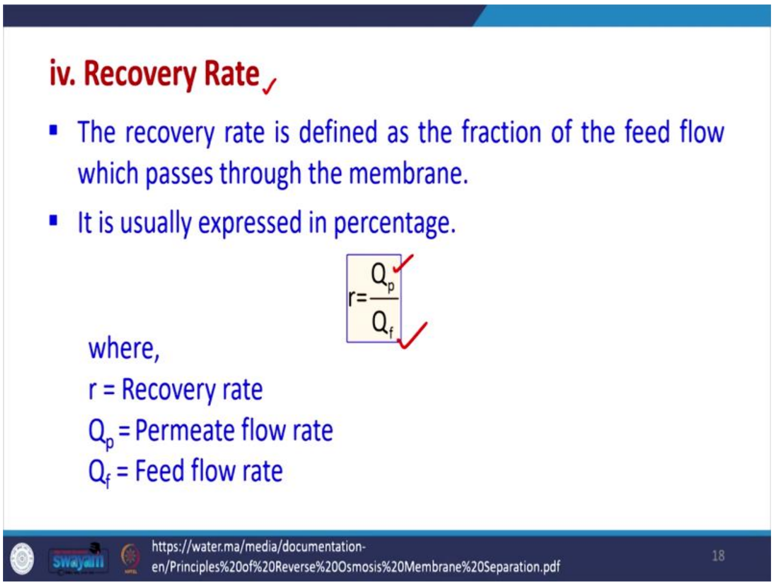

Recovery Rate is usually expressed in percentage:

$$r = \frac{Q_p}{Q_f}$$

where,

r = Recovery rate

Q_p = Permeate flow rate

Q_f = Feed flow rate

Now the recovery rate is with respect to the rejection is with respect to salt but recovery rate is with respect to water. So, recovery rate is defined as the fraction of feed flow which passes through the membrane and this gives the idea that out of the total feed, how much amount of permeate we are getting. So, we always want to be higher so that the rejected stream is lowest possible and this is very very important for any industry.

So, suppose any industry is treating thousand litre of water, now out of that they will always want to recover maximum amount of water. So, they will always want at least 800 or 900 meter cube or litre of water is retained and only 10 to 20 percent is going at reject and that because they have to still manage that reject water because that will contain lot of solute and its concentration will be very very high.

So, reject water management is one of the very big issues with respect to reverse osmosis. So, that is why they always want to have the highest recovery rate possible.

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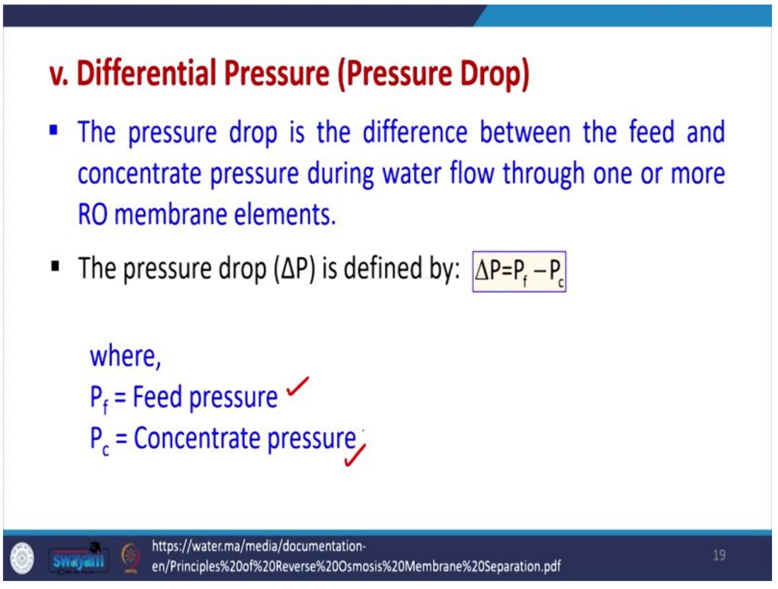

The pressure drop (ΔP) is defined by:

$$\Delta P = P_f - P_c$$

where,

P_f = Feed pressure

P_c = Concentrate pressure

Now what is the differential pressure under which we are operating? So, the pressure drop which is between the feed and the concentrate pressure during like feed pressure and the concentrate pressure so that is called as the differential pressure or the pressure drop and across the RO membrane.

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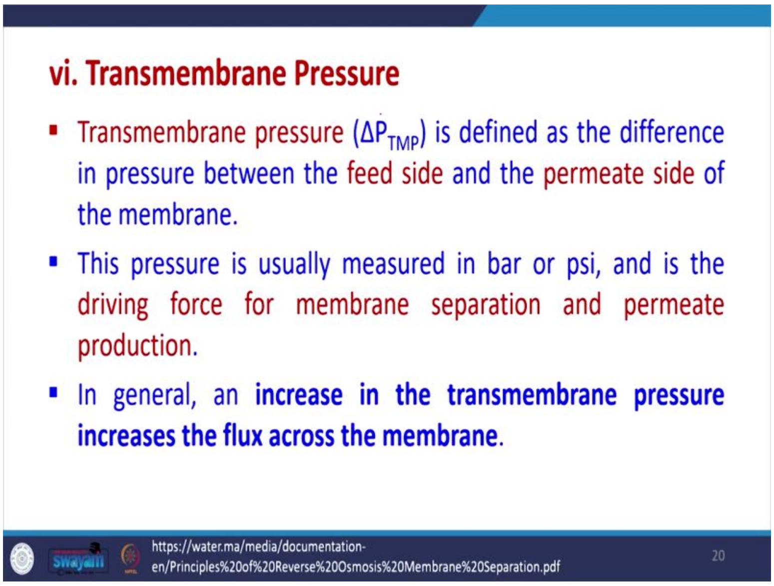

Then similarly there is another term which is called as trans membrane pressure. So, transmembrane pressure is defined as the difference in pressure between the feed side and permeate side. So, remember this pressure will be the pressure is usually measured in bar or psi and is the driving force for membrane separation. In general an increase in trans membrane pressure will increase the flux across the membrane.

So, we always have to see that what amount of trans membrane pressure we have to maintain and depending upon that that flux will be there. So, permeate amount of permeate that will be getting is highly dependent upon this transmembrane pressure which is applied.

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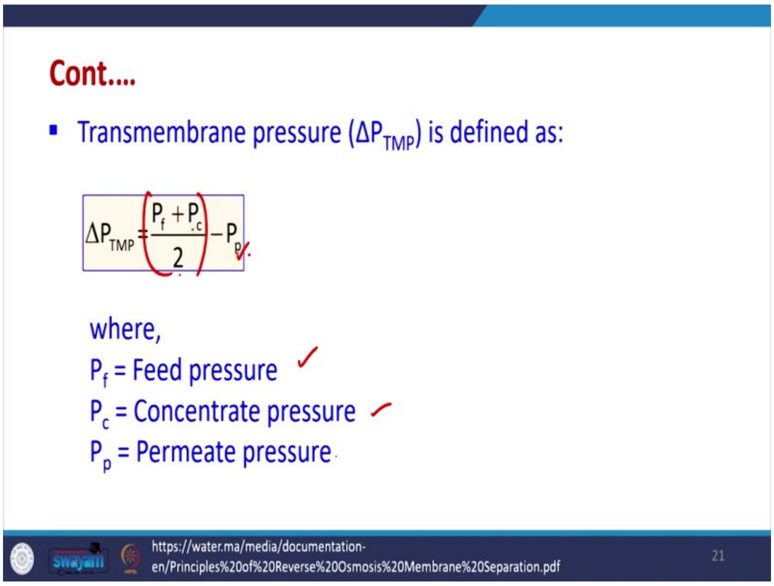

Transmembrane pressure (ΔP_{TMP}) is defined as:

$$\Delta P_{TMP} = \frac{P_f + P_c}{2} - P_p$$

where,

P_f = Feed pressure

P_c = Concentrate pressure

P_p = Permeate pressure

So, it can be defined as Pf plus Pc divided by 2, so that means average we are taking minus Pp where Pf and Pc are the feed pressure and concentrate pressure where Pp is the permeate pressure which is there. So, this is how this is defined.

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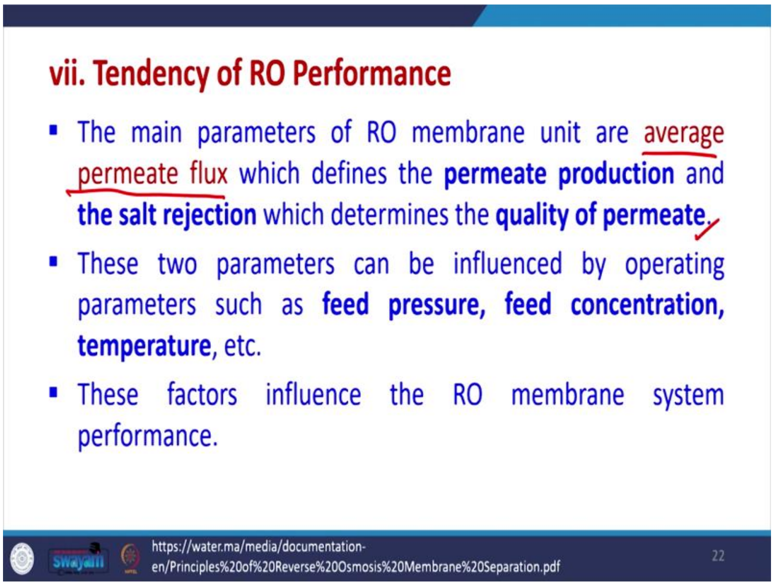

Now tendency of RO performance, will try to understand. There are many parameters of RO membrane, the main parameters include the average permeate flux that we get because we always want this to be on higher air side and how much amount of permeate production is taking place? What is the salt rejection and if both are there that determine the quality of permeate and amount of permeate.

So, we always want the quality of permeate to be best possible with highest possible rejection and the quantity of permeate we always we want to be higher. Now these two parameters can be influenced by number of other parameters like feed, pressure feed, concentration, temperature etcetera. So, we will try to understand the RO performance with respect to these parameters.

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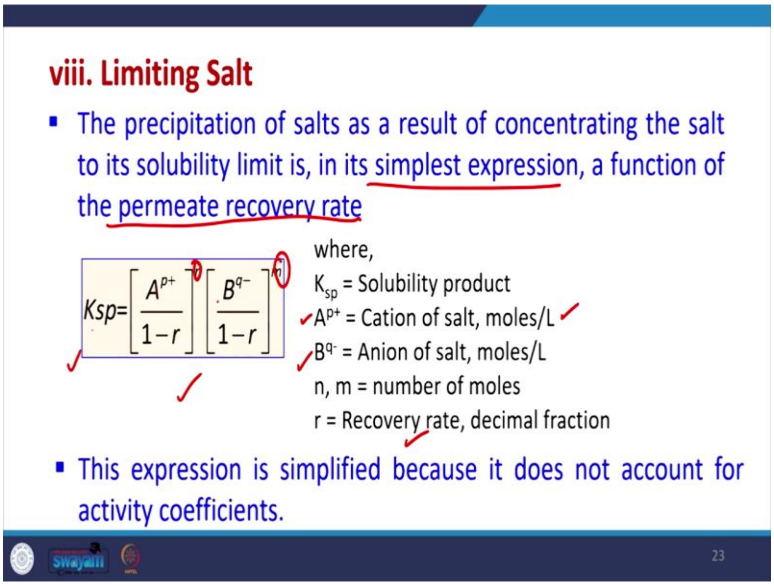

The precipitation of salts as a result of concentrating the salt to its solubility limit is, in its simplest expression, a function of the permeate recovery rate

$$Ksp=\left[\frac{A^{p+}}{1-r}\right]^{n}\left[\frac{B^{q-}}{1-r}\right]^{m}$$

where,

K_{sp} = Solubility product

A^{p+} = Cation of salt, moles/L

B^{q-} = Anion of salt, moles/L

n, m = number of moles

r = Recovery rate, decimal fraction

In addition, the salt, what is the limiting concentration of salt up to which it can operate well, otherwise precipitation of salt will start occurring because it will reach the maximum concentration limit or limiting concentration. So, this is there.

So, we always try to find out what is the solubility limit of the salt that we are separating and in its simplest expression, it is a function of permeate recovery rate. So, here it has been defined the Ksp is equal to, Ksp is the solubility product, Ap plus is the concentration of salt cations in the water and that is in moles per litre.

Similarly, Bq minus is the concentration of anions in the water, in moles per litre, n and m are the number of moles which are there. So, we can see here n and m and then R is the recovery rate in the decimal fraction. So, we can always find out, the expression is simplified here because it does not account for activity coefficients etc.

So, original equation is much much tougher but we can use this equation to find out the Ksp and through this we can find out the different limit upto which the solubility will be there and if the limit is bridged then the precipitation of salt will happen and under those condition the fouling etcetera will increase. So, this is the problem that will happen.

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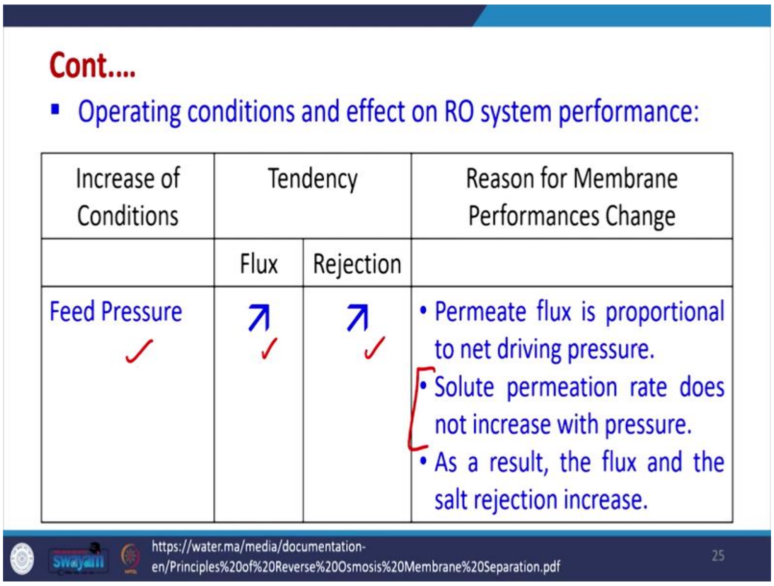

Now we will try to see the operating conditions and effect on the RO system performance. So, like a feed pressure, we increase the feed pressure then what will happen? Then the flux will also increase and rejection will also increase. So, this is there because the permeate flux is proportional to the net driving force.

So, if free pressure is increasing, the flux will also increase. Now the solute permeation rate does not increase with pressure. So, this is there but overall permeate flux will increase. As a result the flux and the salt rejection both will increase with increase in the feed pressure.

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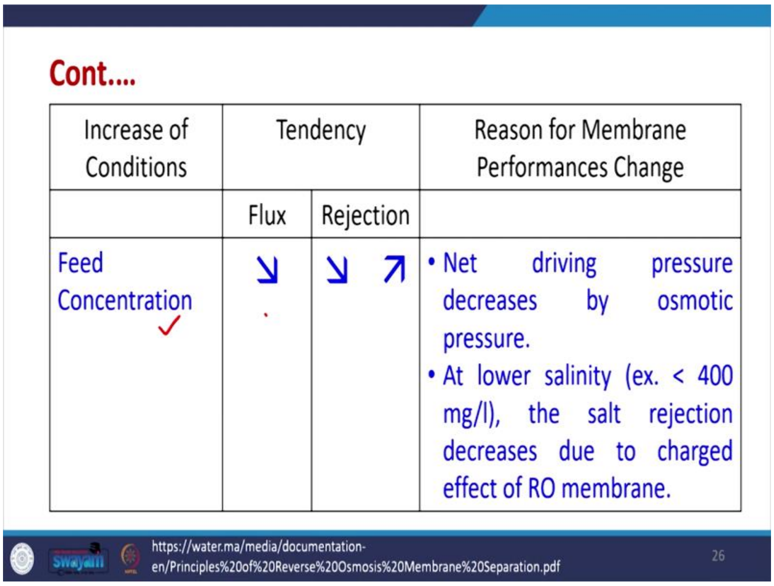

Now the second, suppose in the feed the amount of salt concentration increases, so under that condition, both flux will go down. Rejection will depend whether increase or decrease. So, net driving force decreases net pressure difference decreases because of the osmotic pressure conditions and when the feed concentration increases.

So, at lower cell in t, suppose like less than 400 milligram per litre, the salt rejection decreases due to the charged effect on the RO membrane. So, this parameter is dependent upon that what concentration range we are operating. So, depending upon that dismay, rejection may increase or decrease but flux will decrease with increase in feed concentration.

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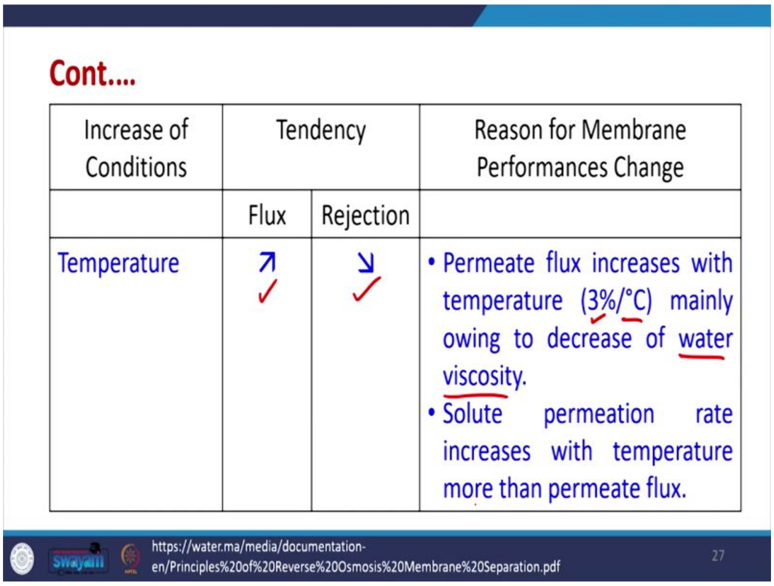

Now is the temperature increases, so under that condition the flux increases but the rejection rate decreases. So, permeate flux increases with temperature like feed percentage per degree centigrade rise in temperature and this is because of the decrease in the water viscosity. So, this is there.

Now the solute permeation rate increases with temperature more than the permeate flux so that is why rejection actually decreases. So, because the solute permeation rate is the increase in the solute permission rate is more than the water flux increase. So, that is why the rejection rate is decreasing with increase in temperature. But we are getting more amount of permeate.

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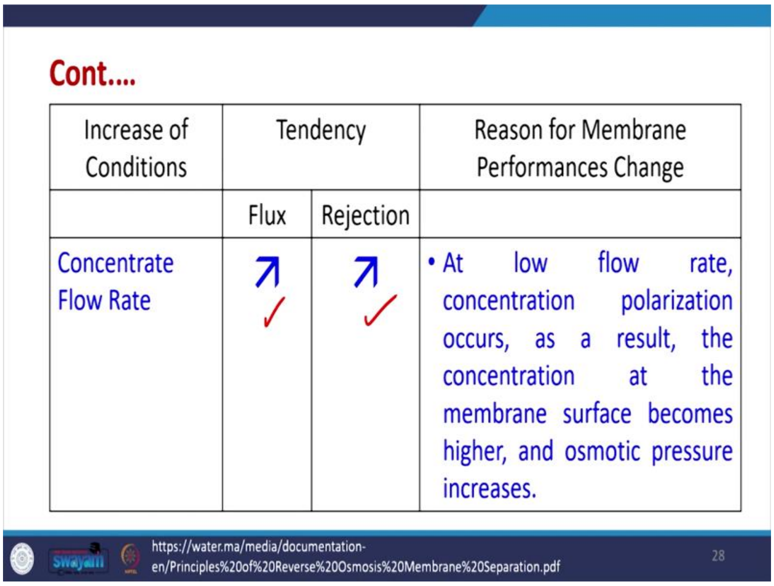

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Increase of Conditions	Tendency		Reason for Membrane Performances Change
	Flux	Rejection	
Concentrate Flow Rate	↗ ✓	↗ ✓	• At low flow rate, concentration polarization occurs, as a result, the concentration at the membrane surface becomes higher, and osmotic pressure increases.

Now, if the concentrate flow rate is increasing, the flux and the rejection both will be increasing and the reason is that, at low flow rate the concentration polarization occurs and as a result the concentration at the membrane surface will become higher and under that condition the osmotic pressure will also increase and because of that the flux will also increase and rejection will also increase.

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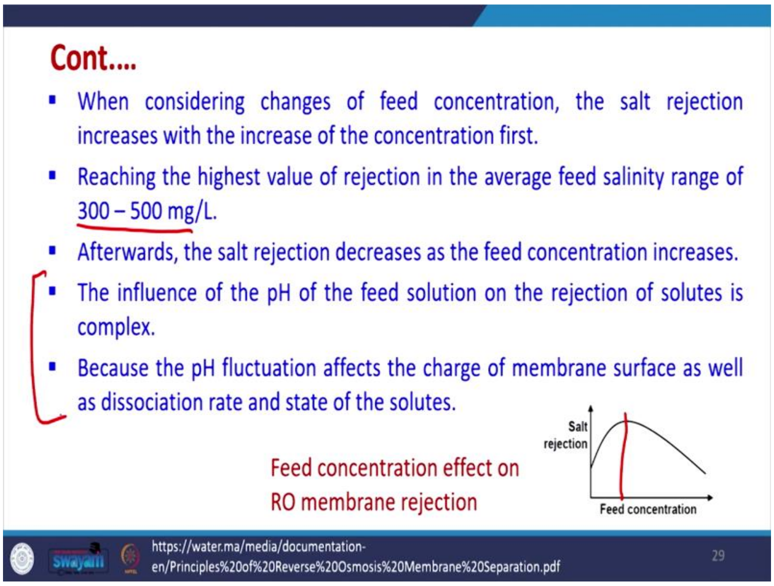

Now, when considering the changes in the feed concentration the salt rejection increases with the increase in the concentration first and it reaches a certain feed concentration value optimum value, in the range of 300 to 500 milligram per litre.

And afterwards the salt rejection rate will decrease as the feed concentration increases and the influence of pH of the feed solution on the rejection of solute is highly complex and because of pH fluctuation may also effect the change of charge of membrane surface as well as the dissociation rate and state of the solute. So, the effect of pH is different but with respect to salt this is shown here.

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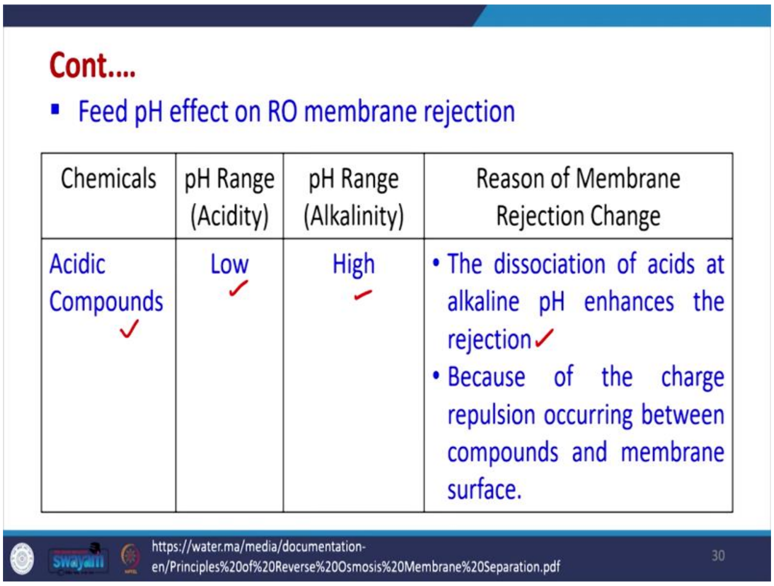

So, we will now see the effect of pH. So, if acidic compounds are there, the acidity pH will be low and the alkalinity will be high and here the change in the rejection rate will happen. So, the dissociation of acids at alkaline plate enhances the injection, rejection rate. So, this is there and this is because of the charge repulsion which occurs between the compounds and the membrane surfaces at under this pH range. So, this is possible at in the alkaline pH condition.

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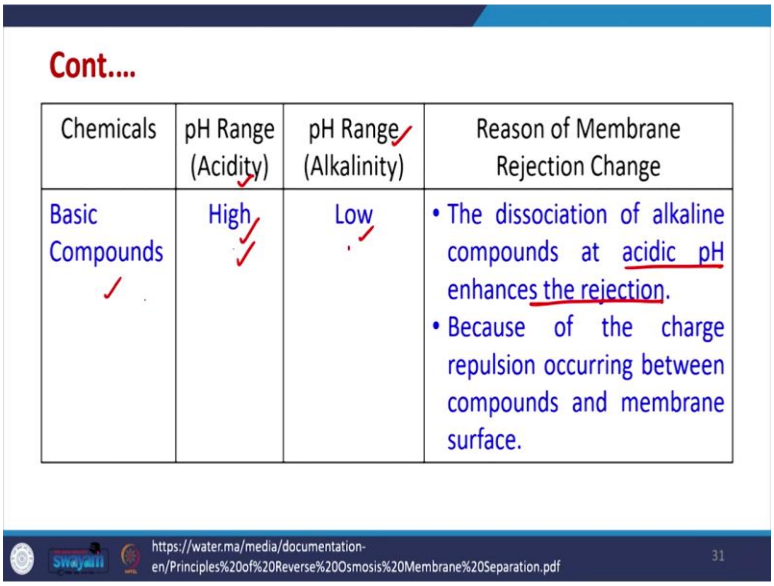

So, the effect of pH is highly complex, it cannot be generalized that much but still we can understand it better. If basic compounds are there so under, if pH range is acidic condition, we have the rejection rates will be higher and if the pH range or alkalinity is lower than the rejection rate, it will be lower. So, under high alkalinity condition the rejection rate will be lower.

The dissociation of alkyne compounds at acidic pH range increases the rejection. So, that is why we can see that rejection rate becomes higher in the acidic condition if basic compounds are present and this is because the charge repulsion occurs. So, this is the same as if acidic compounds are there rejection rate is higher, if the pH range is alkaline. Whereas it is vice versa for basic compounds.

So, this is how we can see the effect of, whether acidic compounds are present or basic compounds are there. But still we can understand this more, if we use understand the water chemistry, the salt chemistry and the membrane chemistries. All have to be mixed together for better understanding and so this is more complex. It is only simplified here for better, little bit understanding.

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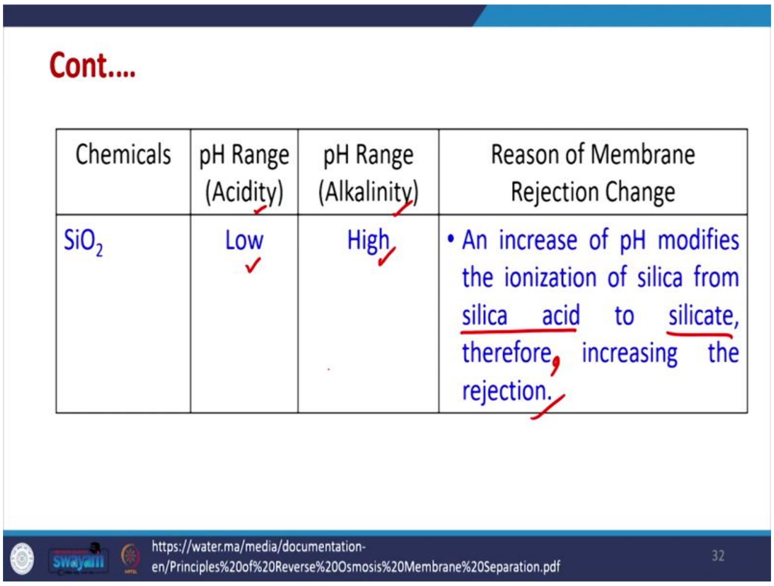

If suppose silica is present, then the rejection rate is lower in the acidic pH range and it is higher in the alkaline pH range. So, if amount of silica is more in the water, an increase in pH modifies the ionization of silica from silica acid to silicate at the higher pH condition and therefore it increases the rejection rate. So, this is why in the alkaline pH range, the rejection rate of with respect to silica is higher.

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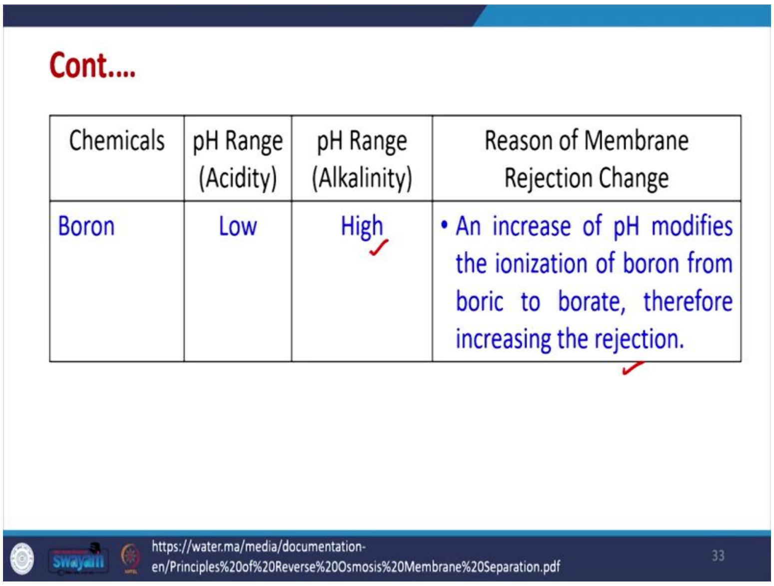

If boron is present again in the higher pH range, it is more rejected. So, increase in the pH modifies the ionization of boron from boric to borate and therefore increasing the rejection. So, we can go for finding out what are the different ionized species of different compounds under different pH conditions and by understanding the type of membrane and its chemistry or orientation under different pH range.

We can find out whether rejection will be there or not and vice versa we can do the opposite that we know that some chemical is present in the water and what is its natural pH? So, its natural pH is suppose acidic. So, we can modify or use the membrane in such a manner, we can select the membrane the one which will give the highest rejection possible. So, through these chemistries we can understand a lot of things for a reverse osmosis case.

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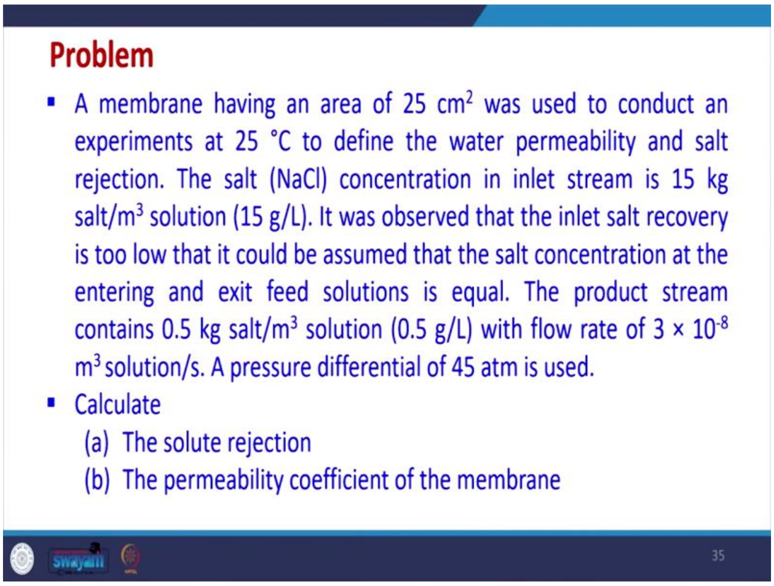

Now we will try to solve one problem before ending this particular section and this problem can be understood in a number of ways as we have discussed here but still will try to find out this, solve this problem. So, a membrane having an area of 25 centimetre square was used to conduct an experiment at 25 degree centigrade to find out the water permeability and salt rejection. So, define this.

The initial concentration in the inlet stream was 15 kg salt per meter cube. So, this is like, it is equivalent to 15 gram per litre. It was observed that the inlet salt recovery is too low and that it could be assumed that the salt concentration at the entrance and exit feed solutions was equal. Now the product stream is containing 0.5 kg per salt per meter cube of the solution with a flow rate of 3 into 10 raised to minus 8 meter cube per second.

A pressure differential of 45 atmosphere is being used. So, we have to find out the solute rejection and the permeability coefficient of the membrane. So, this is what we have to find out. So, again this salt rejection and the water permeability we have to find out using this data which has been given here.

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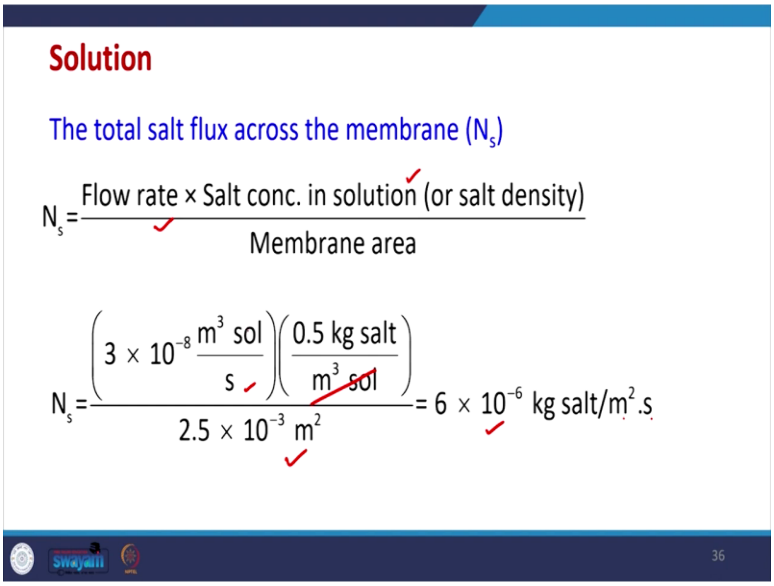

Now solving the total salt flux across the membrane can be calculated first. So, for doing this, we know the flow rate has been given. The salt concentration in the solution or the salt density has been given and the membrane area has been given. So, through this we can find out, so flow rate is 3 into 10 raised to minus 8 meter cube per second, already it is given and it is also given that the salt concentration is 0.5 kg salt per meter cube.

So, this is known and the membrane area that we are using is 2.5 into 10 raised to minus 3 meter square. So, if you solve it, it will be 6 into 10 raise to minus 6kg salt per meter square per second. So, this is how we will solve it. So, this meter cube meter cube is going off and we are getting these results with respect to salt flux which is there.

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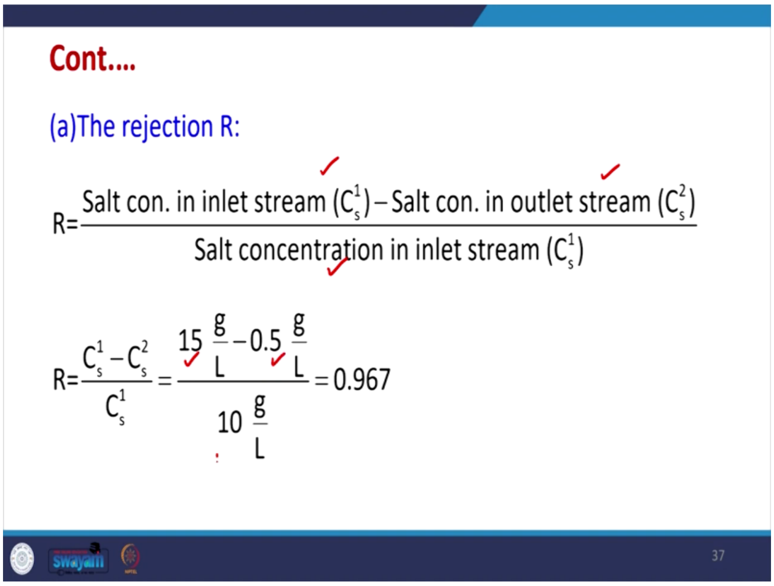

Now to find out the rejection, the salt concentration in the inlet stream, salt concentration in the outlet stream divided by salt concentration in the inlet stream is found out. Now these values are already given 15.5 and at the, this is again 15, so, if you solve it, it is 0.967 is the answer.

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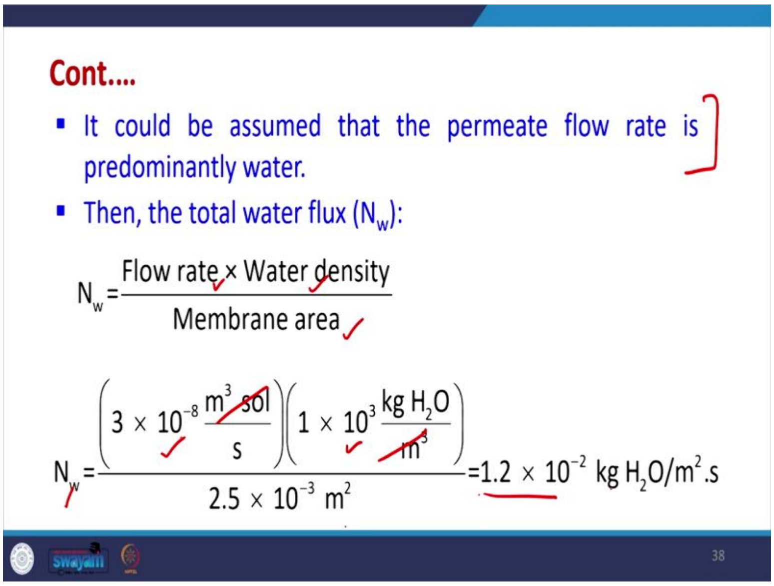

Now it could be assumed that the permeate flow rate is predominantly water. So, if we assume that only water is going through, then we can find out the water flux. So, using this assumption we can again the flow rate water density divided by membrane area. So, we can find out the water flux.

So, again the values are given here, so we know the water density and this is the flow rate of the water so meter cube meter cube, density is well known for water. So, we can find out in terms of kg so we have 1.2 into 10 raised to minus 2 kg of water per meter square per second. So, this is water flux is known.

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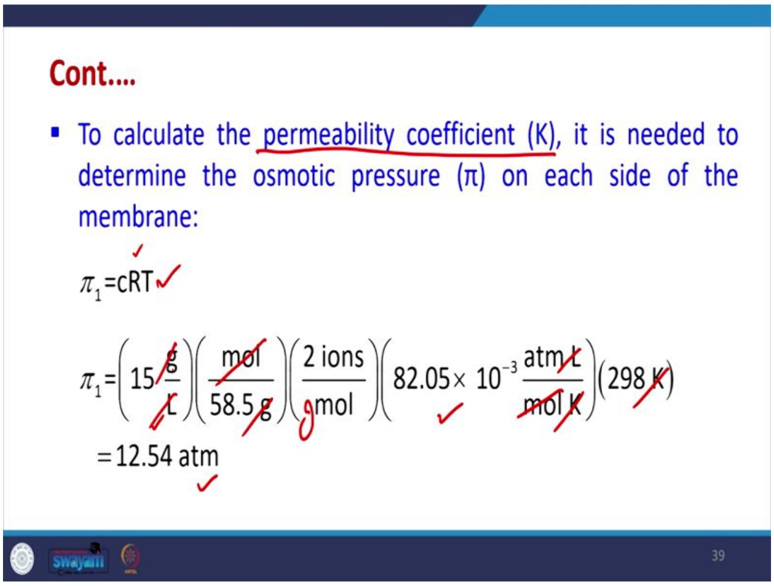

Now to find out the permeability coefficient which has been given, we need to find out the osmotic pressure on each side of the membrane and this can be known, if you know the concentration. So, concentration is also known, so we can find out the osmotic pressure on each side and then the total pressure which is applied. So, through this we can find out the net driving force.

So, for finding out this permeability coefficient we need to know the net pressure as well as the, so for finding out osmotic pressure first, we use this equation so already it was defined earlier. So, this is 15 gram per litre. So, now we are converting this into this particular equation, so gram per litre and we know the, we use appropriate unit of R, so that everything goes off and we have the actual answer in atmosphere.

So, we are using this particular unit and we can see here that everything Kelvin, Kelvin is going of, mol, mol, mol are going off and then we have gram per litre, so litre litre is going off. So, we are converting the, this is gram mol. So, we have gram, gram also going off. So, we every unit will go off and ultimately will be having 12.54 atmosphere.

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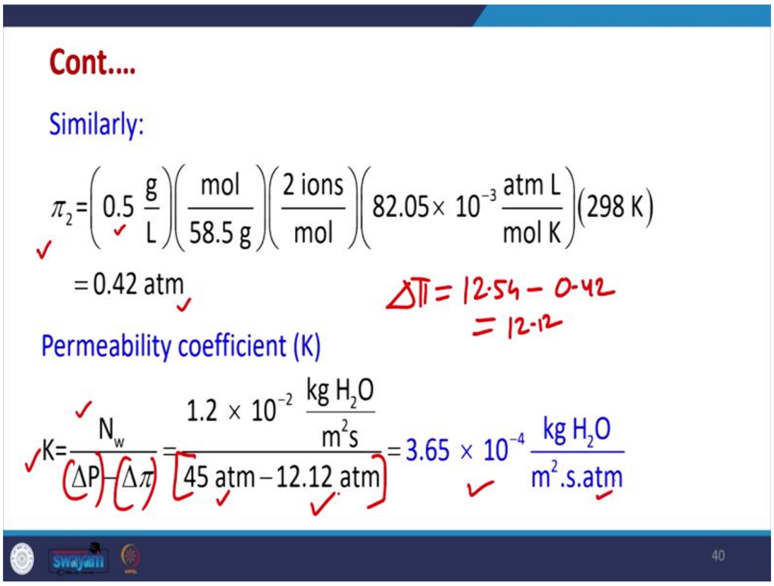

Similarly, we can find out for the second condition where only 0.5 gram per litre of the salt concentration is there. So, we have 0.42 so this way we know the difference in the osmotic pressure is there so that from what we do is that we subtract 0.42 from 12.54. So, through this we can find out the delta pi. So, delta pi will be is equal to ah 12.54 minus 0.42 and will get the answer 12.12 which is used here.

Now 45 atmosphere has already been shown. So, if we subtract this from here, we get the net pressure difference which is applied and if we know then we can find out the permeability coefficient because the tentative water flux is already known to us and we have calculated here. Previously 1.2 into 10 raised to minus 2kg H2O per meter square per second.

So, if perform this calculation we can find out the permeability coefficient for the our membrane that we are using. So, it will be 3.65 into 10 raised to minus 4 kg water per in meter square per second per atmosphere. So, this is what we have to report for that RO membrane if we are using. And already we have found that rejection rate. So, this is how we can perform the calculation.

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Many references have been used in all through. So, you can always refer to the differences for better understanding this RO prefixes and the membraned operations in general for water and wastewater treatment. Thank you very much. So, any of these references can be used. Thank you.