Basic Environmental Engineering And Pollution Abatement
Professor Prasenjit Mondal
Department Of Chemical Engineering
Indian Institute Of Technology, Roorkee
Lecture 38
Tertiary Treatment 2

Hello, everyone. Now, we will discuss on the topic Tertiary Treatment part 2. In this class we will discuss on membrane processes.

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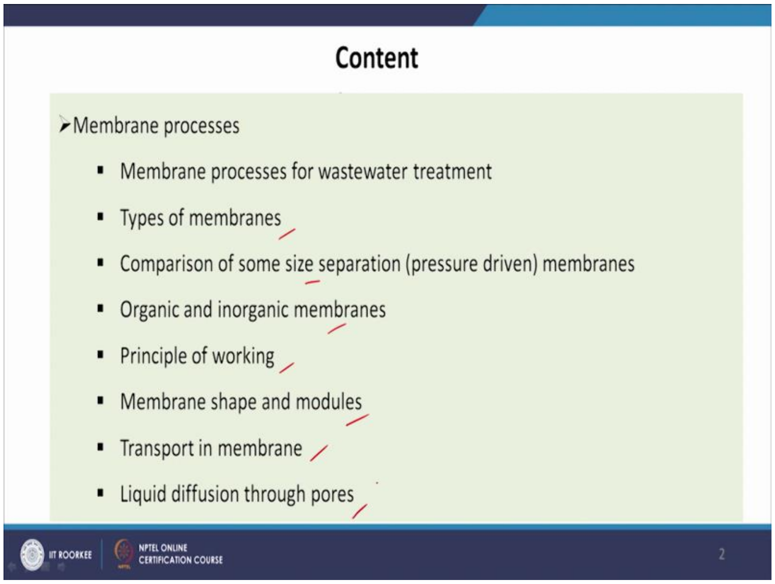

And content is membrane processes for wastewater treatment, types of membranes, comparison of some size separation membranes, organic and inorganic membranes, principle of working, membrane shape and modules, transport in membrane and liquid diffusion through pores.

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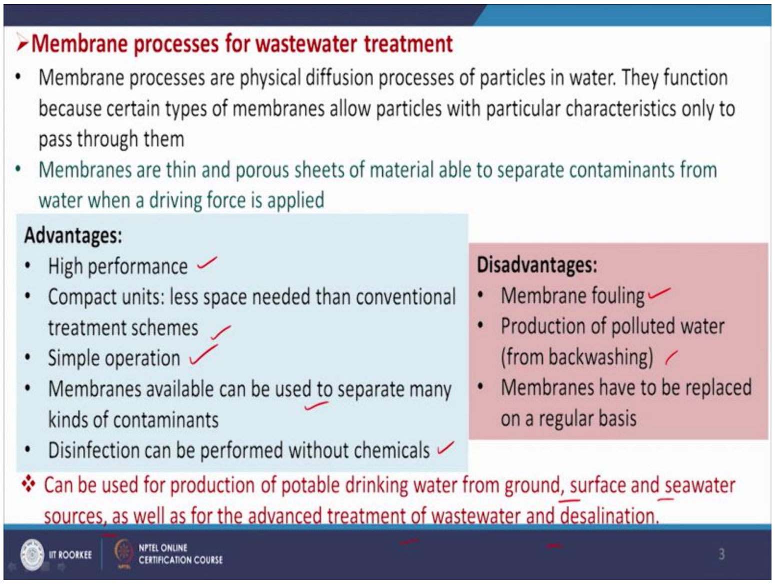

The membrane processes are physical diffusion processes of particles in water. They function because certain types of membranes allow particles with particular characteristics only to pass through them. And membranes are thin and porous sheets of material able to separate contaminants from water when a driving force is applied.

And this method has many advantages. Like say, performance is very high, it is very compact unit, it requires very less floor area, very less space is needed than conventional treatment schemes, and simple operation, membranes available can be used to separate many kinds of contaminants and disinfection can be performed without chemicals.

But it has some disadvantage also. Like say, membrane fouling. The pollutants are deposited on the membrane surface and also in the pores of the membrane and those are clogged and it loses efficiency. And production of polluted water, water molecule passes through the membrane and one side, we get the permit, and other side, we get the concentrate. So, this concentrate or retentate, this other side is called retentate so that retentate contents the pollutants and the concentration of the pollutants is very high in that part.

And membranes have to be replaced on a regular basis. So, it is costly method basically. And this process can be used for production of potable drinking water from ground, surface and seawater sources as well as for the advanced treatment of wastewater and desalination. This method can be used for different types of wastewater treatment basically, from home use to very large scale production.

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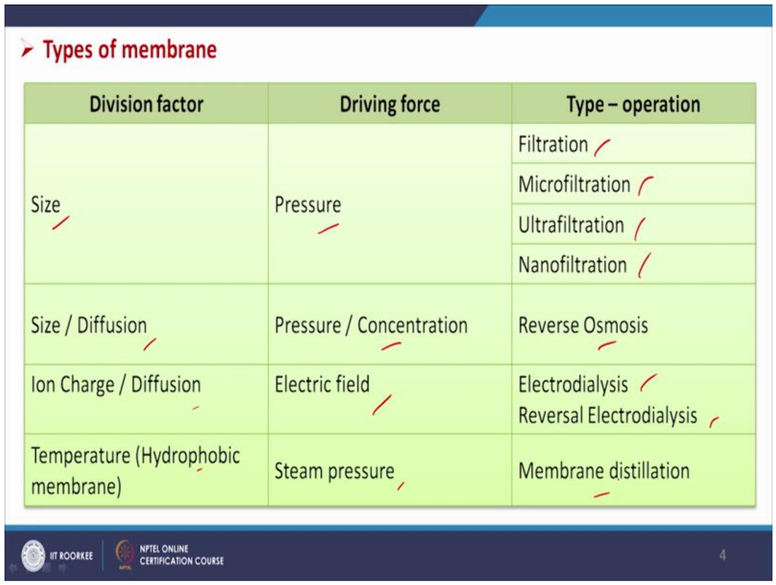

Types of membrane

Division factor	Driving force	Type – operation
Size	Pressure	Filtration Microfiltration Ultrafiltration Nanofiltration
Size / Diffusion	Pressure / Concentration	Reverse Osmosis
Ion Charge / Diffusion	Electric field	Electrodialysis Reversal Electrodialysis
Temperature (Hydrophobic membrane)	Steam pressure	Membrane distillation

Now we will see the types of membrane depending upon different driving forces and division factor, we can have different types of membrane and their operation. Like say when driving force is pressure and division factor is size, we can have filtration, microfiltration, ultrafiltration nanofiltration. So, where the size will be different for different filtration.

And when pressure and concentration are responsible for this we can have the process that is Reverse Osmosis, and size and diffusion both are the division factor. And when we use the electric field as a driving force, we can get electrodialysis and reversal electrodialysis. In that case, ion charge and diffusion, both are considered as division factor.

And when steam pressure is used as the driving force, and then temperature is the division factor for hydrophobic membrane, we can say this is the application for membrane distillation. So, these are the different types of membrane on the basis of application and on the basis of driving force and division factor.

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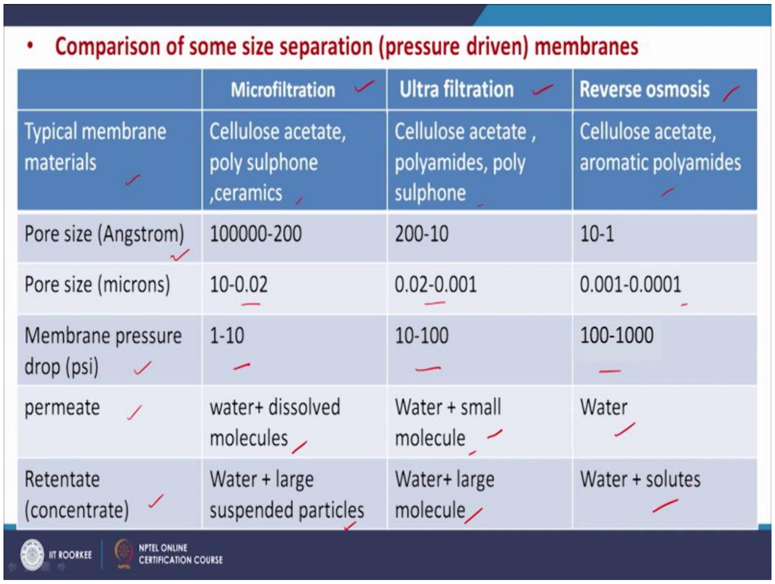

- Comparison of some size separation (pressure driven) membranes

	Microfiltration	Ultra filtration	Reverse osmosis
Typical membrane materials	Cellulose acetate, poly sulphone ,ceramics	Cellulose acetate , polyamides, poly sulphone	Cellulose acetate, aromatic polyamides
Pore size (Angstrom)	100000-200	200-10	10-1
Pore size (microns)	10-0.02	0.02-0.001	0.001-0.0001
Membrane pressure drop (psi)	1-10	10-100	100-1000
permeate	water+ dissolved molecules	Water + small molecule	Water
Retentate (concentrate)	Water + large suspended particles	Water+ large molecule	Water + solutes

Now, we will see the comparison of some size separation that is pressure driven membranes. So here, the parameters typical membrane material, pore size, membrane pressure drop, permeate and retentate, that is, concentrate. So, pressure driven processes are microfiltration, ultrafiltration and reverse osmosis, three have been chosen. And then, we will see the difference.

Typical membrane material, if you see, the cellulose acetate, poly sulphone, ceramics in case of microfiltration. ultrafiltration, cellulose acetate, polyamides, poly sulphone and reverse osmosis cellulose acetate, aromatic polyamides. That means, the materials are very similar. But pore size is different.

In case of microfiltration, that is 10-to-0.02-micron size, where ultra, this is 0.02 to 0.001 micrometer size, and reverse osmosis 0.001 to 0.0001 micrometer. So, we are seeing even very, very small particles or molecules or the pollutants can also be arrested here or be separated here in case of RO.

So, certainly, it will be requiring different pressure, that is in this case membrane pressure drop psi 1 to 10, here 10 to 100, and 100 to 1000, and permeate, in this microfiltration, maybe water and dissolved molecules and ultrafiltration water + small molecules, and reverse osmosis only water, even small molecules are also not able to pass through because the pore size is very, very small. And retentate, water for large suspended particles for microfiltration water + large molecule, for ultrafiltration and water + solutes, even the solutes are also not able to pass through the pores in case of reverse osmosis.

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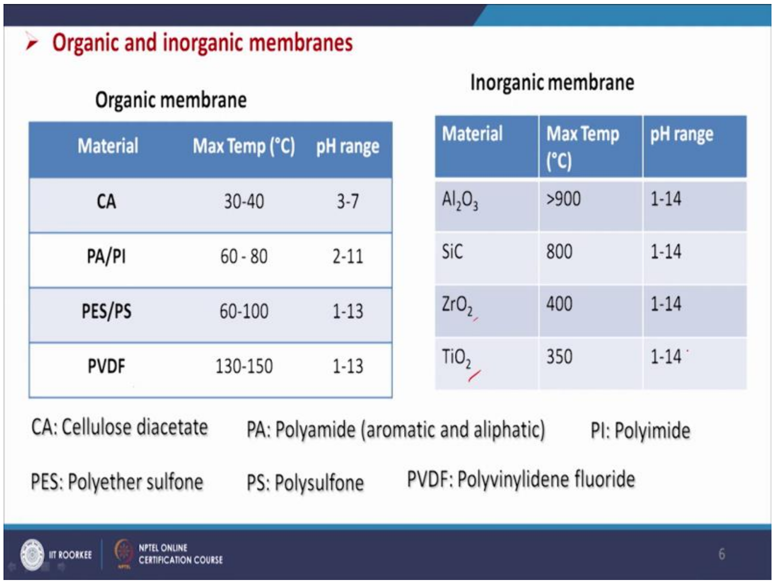

Now, we will see organic and inorganic membranes, different types of membranes and their applicability. Normally, the organic membranes are applied in lower temperature and inorganic membranes are used at higher temperature. So some examples are given here, that is cellulose diacetate and PA, that is polyamide are aromatic and aliphatic, and PI, polyimide, and PES Polyether sulfone, PS polysulfone, PVDF that is polyvinylidene fluoride.

And here we see the maximum temperature range, this can be used. And for inorganic membranes that is Al_2O_3, silicon carbide, ZrO_2, TiO_2, we see the maximum temperature range is much more than this organic membrane, and this can be used for a wider pH range. So, these are the different available membrane materials.

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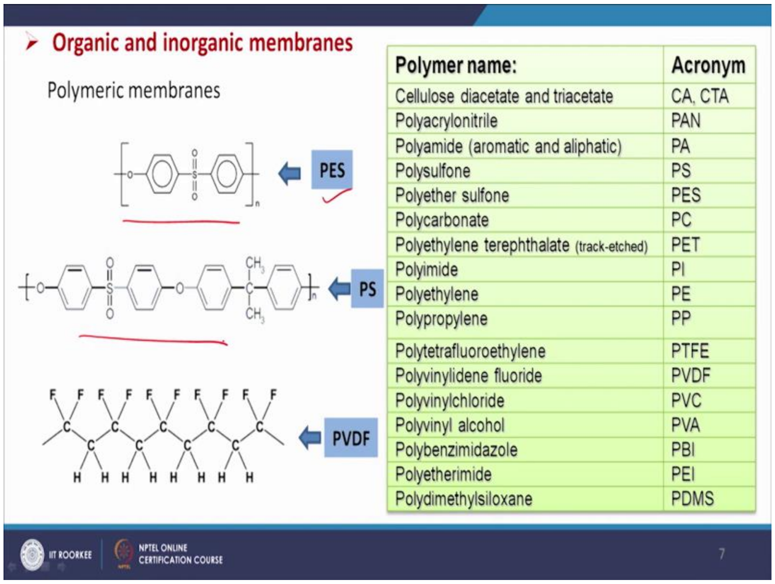

And here, the structure of some organic membranes are shown here like say PES has this type of structure, PS has this type of structure PVDF has this structure. And these are the different polymer name and they are acronym, which have been applied for different applications not only for water treatment, it has been used for different application.

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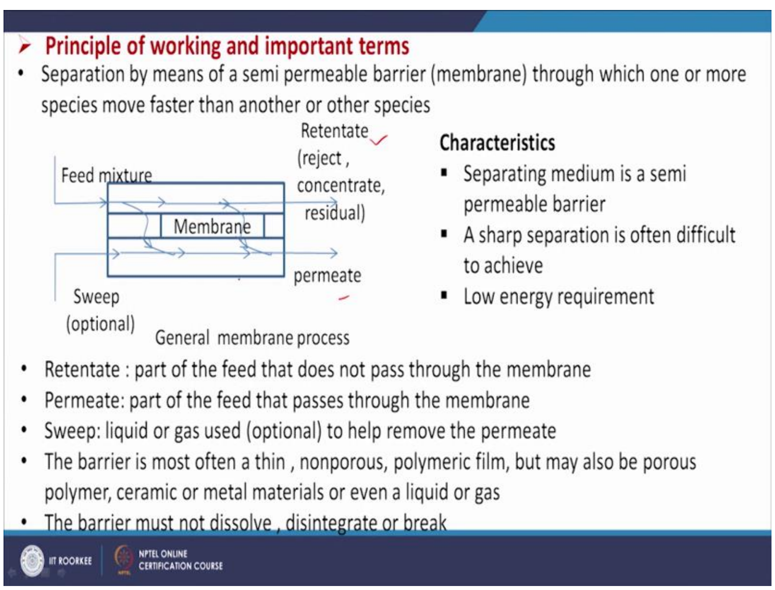

Now, we will see the principle of working and some important terms. As mentioned, in this process, feed mixture is passing through the one side of the membrane and other side, the sweep is sent as optionally. Otherwise, the water will be passing through it the membrane, and then the pollutants will be arrested here, that will not pass through.

So this part which we are getting, that is where you are getting retentate or reject, and this is concentrate. And here, we are getting the penetrate. So, pure water will come here and pollutants will be available in this, concentrated here. So, this is where we are getting retentate and this is where we are getting penetrate. So, this is the mechanism.

Then how these, water is passing through the pore size the molecules of the water size is lesser than the pollutants, so pollutants are being arrested, so water is going there. So, different terms we are getting, this retentate part of the feed that does not pass through the membrane. Permeate, part of the feed that passes through the membrane.

Sweep, liquid or gas used to help remove the permeate, and the barrier is most often a thin, nonporous, polymeric film but may also be porous polymer ceramic or metal materials or even a liquid or gas, and the barrier must not dissolve, disintegrate or break. So, these are the essential conditions for the operations of this membrane process.

And some characteristics are that separating medium is semi permeable barriers. So, this medium is semi permeable that means, some material will be allowed to pass through and some will not be allowed to pass through, and the sharp separation is often difficult to achieve and low energy requirements. So, these are the characteristics of this membrane process.

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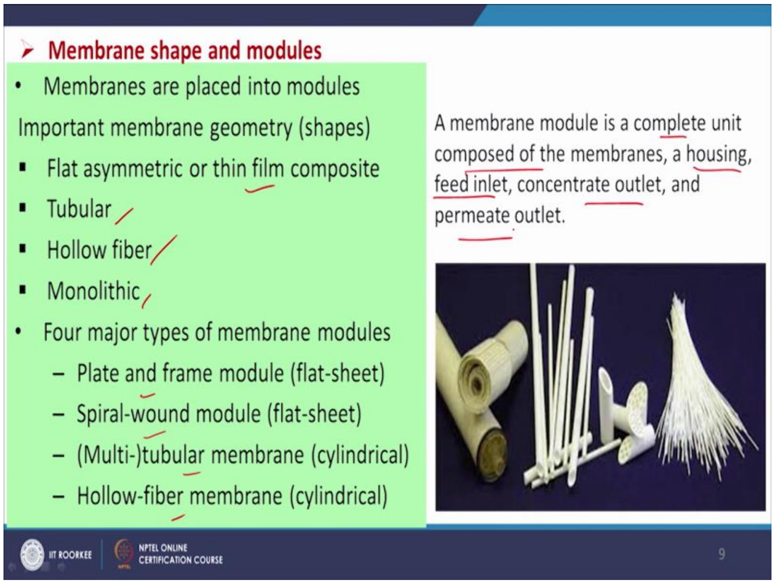

Now, we will see the membrane shape and modules. So, membrane may have different geometry and different shape like say flat asymmetric or thin film, composite membrane, tubular membrane, hollow fiber membrane, and monolithic structure. And there are four major types of membrane modules that is plate and frame module, spiral wound module, multi tubular membrane module and then hollow fiber membrane module.

Now, what is the module? So, membranes, we see which is used for the separation of the pollutants from it, and this is very thin layer of some organic or inorganic material, and the module is a complete unit composed of the membranes, a housing, feed inlet, concentrate outlet and permeate outlet. So, this is a complete module, and membrane is then important part.

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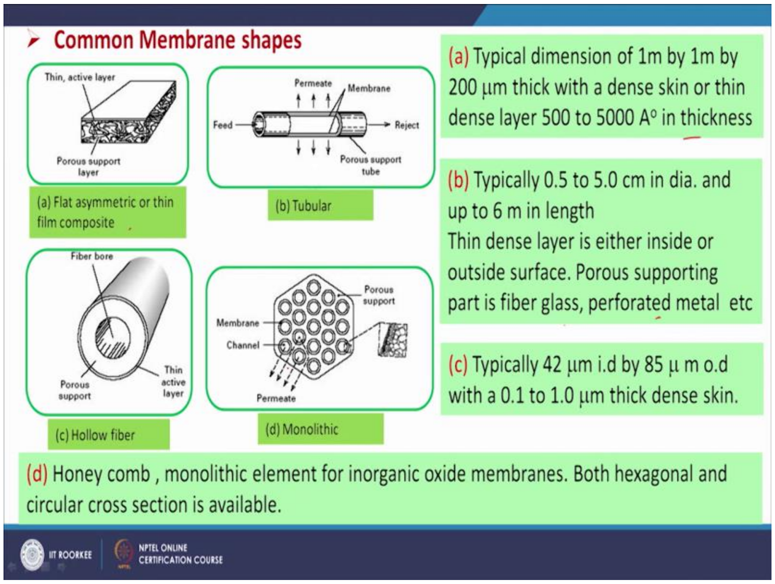

Now, we will see the common membrane shapes. So, we have seen there are four important membrane shapes, that is, flat asymmetric or thin film composite. Here, we see the thin active layer here, and this is porous support. So, we have porous support an active layer is our main fiber material.

And typical dimension of 1 m by 1 m by 200 µm thick, with a dense skin or with dense layer 500 to 5000 A° in thickness. So, that, I told you, that it is a very thin layer with this membrane material. And then, we see the tubular. So, we have feed inside, and from the outside we are getting the, permeate and from the inside we are getting the reject or the retentate, so in this case what will be happening.

A typically 0.5 to 5 cm in diameter and up to 6 m in length thin dense layer is either inside or outside surface. So, a porous supporting part is fiberglass, perforated metal etc. So, this is a tubular membrane shape.

And hollow fiber, here we see this is our fiber bore, and thin active layer, and we have a porous support. So, typically 42 µm id by 85 µm od with a 0.1 to 1 µm thick dense skin. So, this is a hollow fiber membrane, the hollow fiber and tubular, these are basically, differ, on the dimension also. And then monolithic type shapes is also available and this is basically for inorganic oxide membranes.

So, this is the Honeycomb we see here. So that monolithic element for inorganic oxide membranes, both hexagonal and circular cross section is available, that maybe, this cross sectional circular or hexagonal as shown here, can be available. So, we have a membrane and these are the channel and porous support. So, we get permeate from this. So this is a membrane shape.

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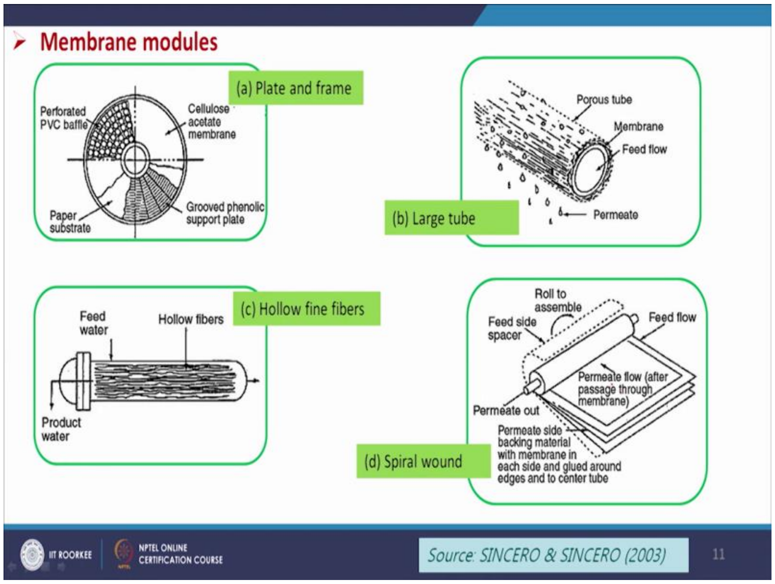

And then membrane module, we have plate and frame module. There is a plate and frame, just like plate and frame filter press, we have some, one frame and another plate inside we have some membrane. So that is one. And large tube so we have a tube, the porous tube and then either inside or outside, we have a membrane.

Then feed flow, if it goes inside, we will be getting permeate from the outside of it. And then hollow fine fibers so here also the similar way, the dimension is different in tubular and hollow fiber, we get here the feed water is coming from the outside. So, from the inner side will be getting the product.

And spiral wound, this is example of spiral wound. So here, feed flow in that direction, and then from the inner side, will be getting the, penetrate and these are the different permeate side backing material with membrane in each side and glued around edges and to center tube. So, this is a permeate flow from the out to inner, and then we are getting the permeate from the inner side of it.

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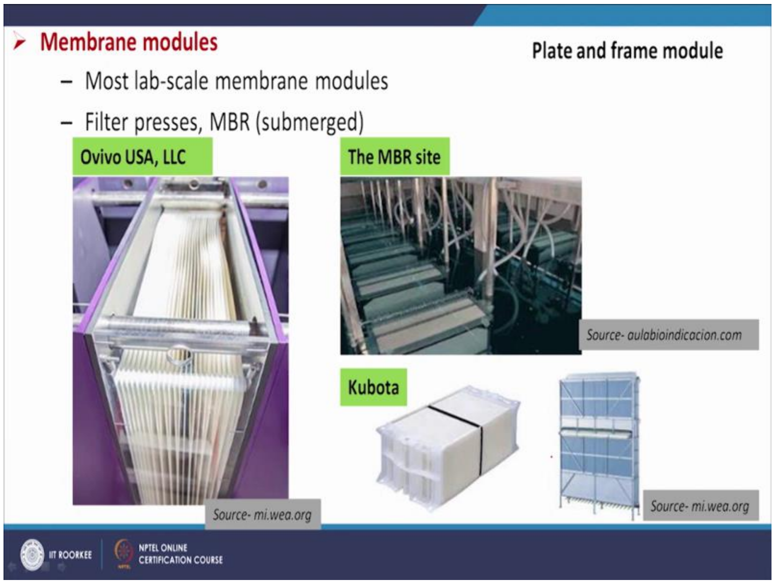

And now we will see some photographs and the concept will be more clear. Now, some example a plate and frame module, most lab-scale membrane modules, so, this is one, so, this is your plate and frame. So, that is Ovivo USA, LLC, their product, and MBR membrane bioreactor also, we have this plate and frame type module, plate and frame module of the membranes, and this is another example. These are also the plate and frame type of module.

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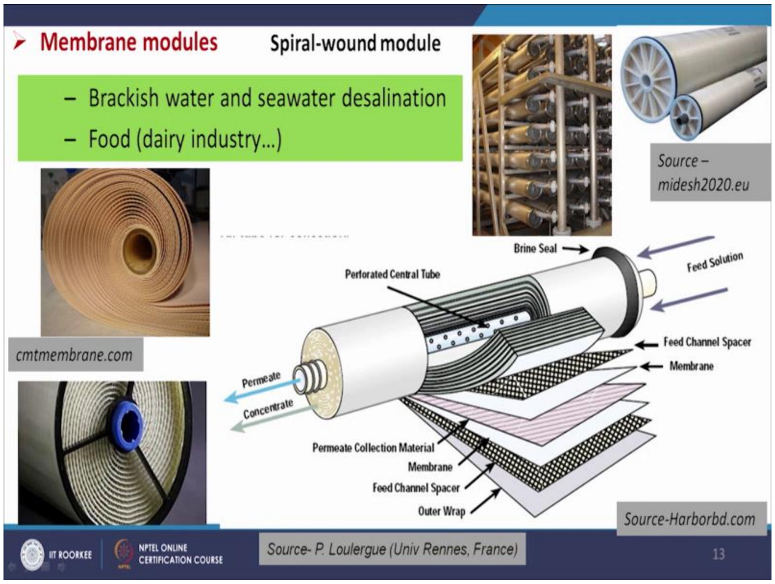

Then spiral wound module, you see here, how it looks. So, this can be used for brackish water and seawater desalination and for treating wastewater of food dairy, industry or distilled industry. So, this type of spiral wound module is used. So, here you see, this is our, penetrate and this is our feed solution.

So, that will be our permeate collection material and feed channel spacer, and membrane is here. So, again, we are seeing membrane and feed channel spacer. So, each water, inlet water is coming here. So, it will be from outer to inner side it will move and from the inner, we will get the, penetrate, and this type of arrangement is there that is called spiral wound module.

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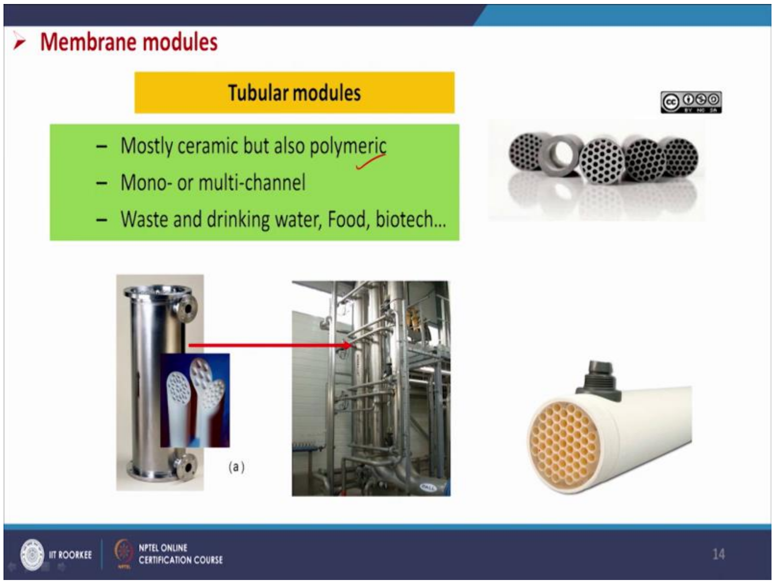

And then tubular modules, so mostly ceramic, but also polymeric. And mono or multi channel, it is possible, and waste and drinking water, food, for the production of biotech application, these modules are used as shown here.

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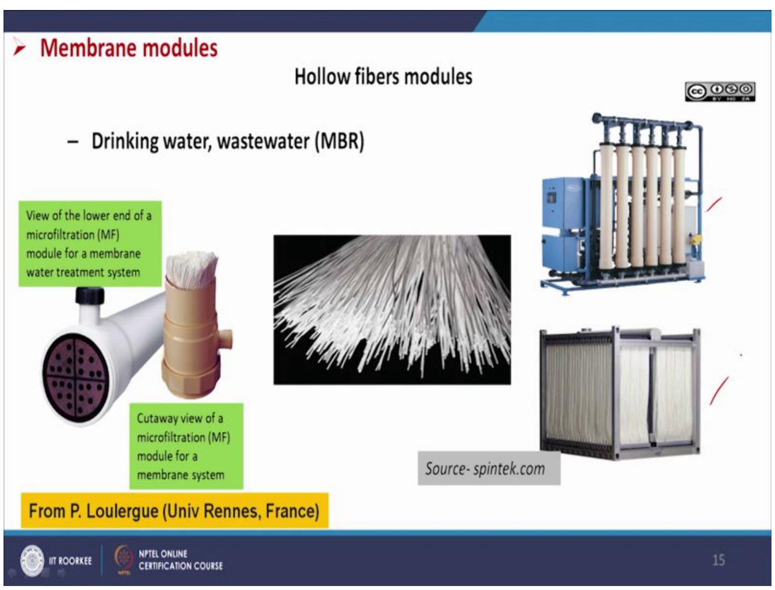

Hollow fiber module, so, that is used for drinking water and wastewater treatment. And you see here, these are the hollow fiber so, number of fibers are taken here. So, water maybe going from the outside and then from the inner side, we will be getting the, permeate, the treated water. So, this type of modules are available for different applications for drinking water and wastewater also, for the production of drinking water, and treatment of wastewater as well.

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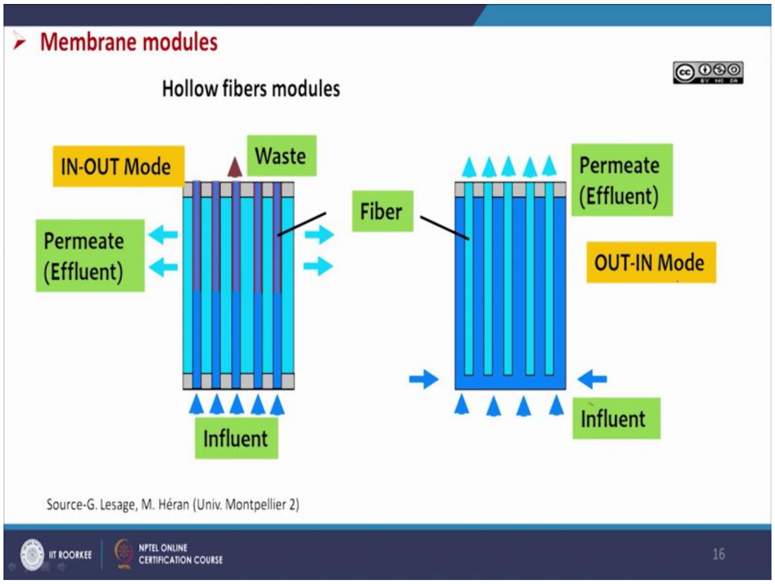

And this figures, shows us how the hollow fiber modules work. So, here, the influent maybe through the inner part of the hollow fiber. So the penetrate will come out from it. So, then this will be our waste or retentate and this is IN-OUT mode. So, influent from the inner side of the hollow fiber and from the outside, we are getting permeate. May be on the reverse case, this may be going from the outside, and from the inner side we can get the permeate. So, this our effluent and this is our influent, influent is coming here and we are getting the permeate here. So, that is OUT-IN mode. So, these are the fiber.

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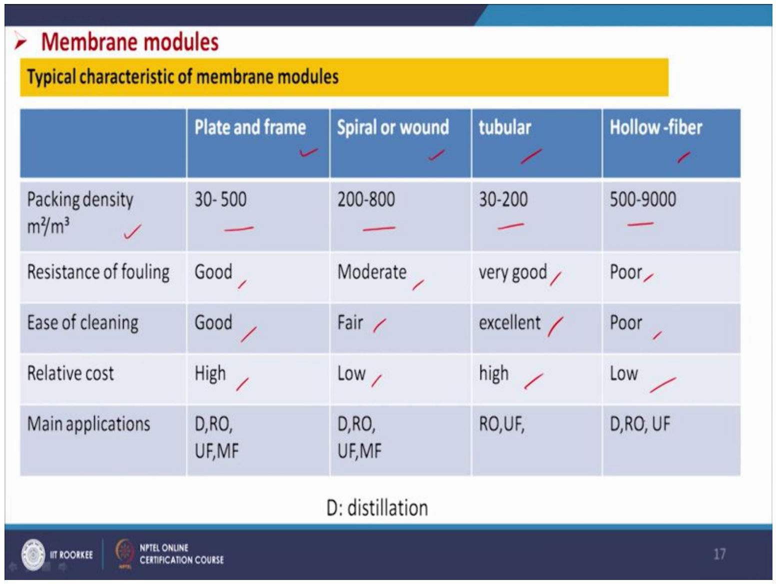

	Plate and frame	Spiral or wound	tubular	Hollow -fiber
Packing density m^2/m^3	30- 500	200-800	30-200	500-9000
Resistance of fouling	Good	Moderate	very good	Poor
Ease of cleaning	Good	Fair	excellent	Poor
Relative cost	High	Low	high	Low
Main applications	D,RO, UF,MF	D,RO, UF,MF	RO,UF,	D,RO, UF

D: distillation

Now, typical characteristics of membrane modules like say plate and frame, spiral or wound and then tubular and hollow fiber. So, packing density, m^2/m^3, so 30 to 500 plate and frame, 200 to 800 per spiral or wound type and tubular type 30 to 200, and 500 to 9000 hollow fiber.

So, hollow fiber, we see we get much packing density with respect to other, and resistance or fouling in plate and frame good resistance and spiral or wound, moderate, tubular, very good resistance and then this is poor resistance. And ease of cleaning, again ease of cleaning is good for plate and frame. After certain interval you can change it.

Spiral or wound, that is fair, and for tubular, excellent, and for hollow fiber, it is again poor. So relative cost, very high cost for plate and frame, spiral and wound, it is low cost, tubular, high and hollow fiber, low cost. And main applications, distillation, reverse osmosis, ultrafiltration, microfiltration for plate and frame, for spiral or wound, distillation, RO, UF, MF, and here for tubular RO, UF and D, RO, UF for hollow fiber membrane module. So, these are the different applications.

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Membrane modules

Module geometry	Advantages	Drawbacks
Plate and frame (for both organic and inorganic membranes)	Possibility to analyze permate at each stage (interesting for scaling)	Low packing density (compactness)
Spiral wound (organic membranes only)	High packing density Low cost	Cleaning-in-place is difficult to handle Pretreatment compulsory
Tubular (for both organic and inorganic membranes)	Limited pretreatment Well adapted to cleaning-in-place	Low packing density High energy consumption
Hollow fiber (mostly organic membranes)	Very high packing density Low energy consumption Low cost	Pretreatment compulsory for in-out mode

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And we can get some advantage and disadvantage, all these types of modules, like say plate and frame, for both organic and inorganic membranes. The advantage possibility to analyze permate at each stage, but low packaging density, this is the drawback. So, spiral or wound, that is organic membranes only. This is not applicable for inorganic membrane. So, high packing density low cost, and cleaning in place is difficult to handle.

And pretreatment is compulsory. And tubular type, for both organic and inorganic membranes, it can be used. And then limited pretreatment, well adapted to cleaning in place and low packing density, high energy consumption are the drawbacks. And hollow fiber, mostly organic membranes, and then very high packing density, low energy consumption and low cost are advantage, and pretreatment compulsory for IN-OUT mode. So, this is a drawback of it.

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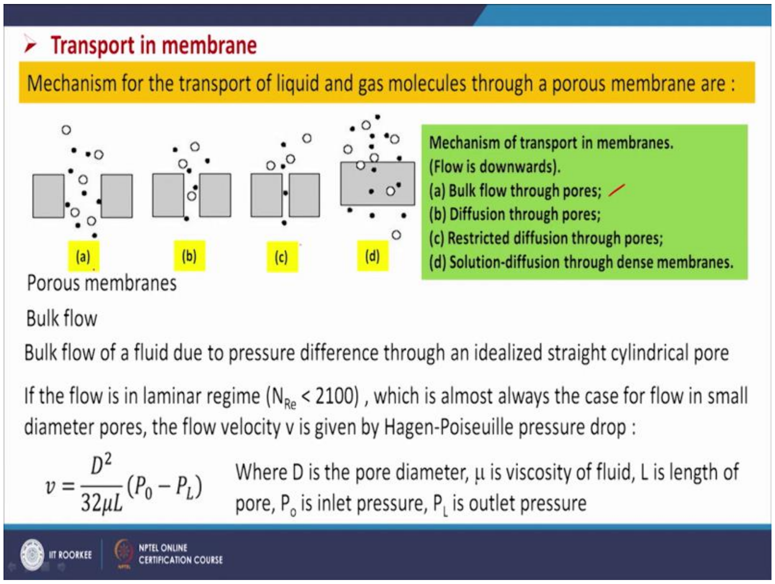

Now, we will see the transport in membrane. So what is the mechanism for the transport of the liquid and gas molecules through a porous membrane, that we will discuss here. So, we are showing here different situation when the pollutants and gas molecules or water molecules, both are passing through the pores. So, that is a, there is bulk flow through pores.

So, in that case, we are not getting the efficient separation or the pollutants from the water, but b, is diffusion through pores, through pores it is diffused. So, but c, restricted diffusion. And here some other type of mechanism is possible, that solution diffusion through dense membrane. So, dense membranes, not we are considering the pores, that has solution, that is coming inside it, and it is being diffused.

So, that way the smaller size molecules or which is having more affinity with the membrane material, they can pass through it easily with respect to other molecule. So, that is the mechanism for the purification of the water or the removal of pollutants from the water. And now, we will see the bulk flow.

So, in this case bulk flows. So bulk flow of a fluid due to pressure difference through an idealized straight cylindrical pore. If the fluid in laminar region, which is almost always the case of flow in small diameter pores, the flow velocity v is given by Hagen-Poiseuille pressure drop. That means, it is a flow through pores or porous media.

In that case, the Hagen-Poiseuille equation can be applied their

$$v = \frac{D^2}{32\mu L}(P_0 - P_L)$$

Where P_O is a inlet pressure, P_L is the outlet pressure, D is the pore diameter, µ is a viscosity of fluid, and L is the length of the pore.

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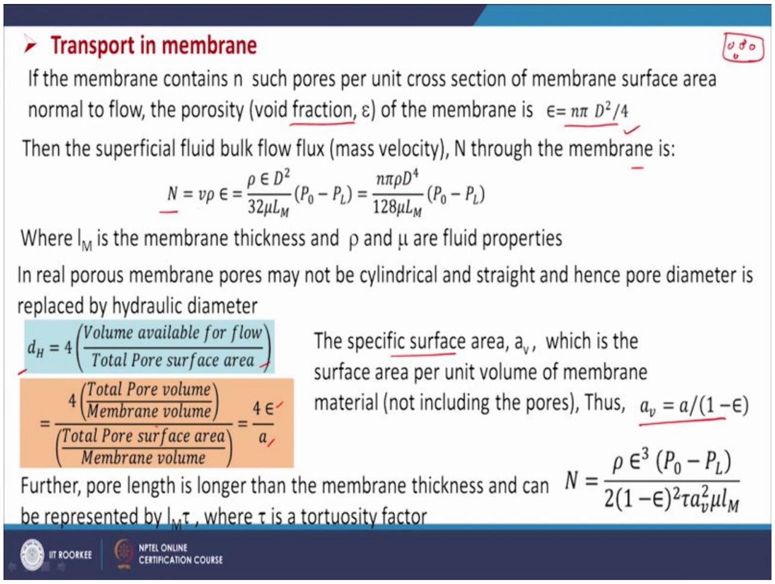

Now, if the membrane contains n such pores per unit cross sections, if you have a membrane of unit cross section. If we have n such pores or membrane surface area normal to flow, the porosity of the membrane is how much? Πr^2 for a single, so, $\Pi D^2/4$ for a single one. So, n * $\Pi D^2/4$, that is the total surface area covered by this pores. And total surface area of the membrane is 1, we have assumed.

So the void fraction, that will be the volume of the pores divided by volume of the filter. So, if we take the unit length once again, so, 1*1, the 1 volume and this will be n* $\Pi D^2/4$ * 1, that will be the volume of the pores. So, E is equal to volume of the pores by volume of the membrane, that is equal to 1. So, $n\Pi D^2/4$, that is equal to void fraction.

Then, the superficial fluid bulk flow flux, that is mass velocity, n through the membrane is,

$$N = v\rho\epsilon$$

So, we are considering unit cross section. So, n is the mass flux. So, that is why unit cross section is considered. So, unit cross section * v * E, that is the volume for the void * ρ.

So, that is the volume of the flux because the water will be passing through the void space only. So, that is equal to, we will replace the value of v now, with a Hagen-Poiseuille expression,

$$N = v\rho \in \; = \frac{\rho \in D^2}{32\mu L_M}(P_0 - P_L) = \frac{n\pi\rho D^4}{128\mu L_M}(P_0 - P_L)$$

Now, L_M is the membrane thickness and ρ and μ are the fluid properties. So in real porous membrane, pores may not be cylindrical and straight, and hence pore diameter is replaced by the hydraulic diameter.

So, this is one considerations, we assume when, to represent the real situation. So, d will be replaced by dH.

$$d_H = 4\left(\frac{\text{Volume available for flow}}{\text{Total Pore surface area}}\right)$$

And if we divide both numerator and denominator by membrane volume, so,

$$= \frac{4\left(\frac{\text{Total Pore volume}}{\text{Membrane volume}}\right)}{\left(\frac{\text{Total Pore surface area}}{\text{Membrane volume}}\right)} = \frac{4\epsilon}{a}$$

Where total pore volume/membrane volume is equal to E, and total pore surface area/membrane volume is equal to a.

So, this a can be correlated with the specific surface area like this, $a_v = a/(1-\in)$

The a_v, specific surface area is the surface area per unit volume of membrane material not including the pores. So, when we are considering the pores, then that will be , $a_v = a/(1-\in)$.

So, we will be putting this d in terms of d_H and d_H is in terms of 4E/a. So, then N value comes as

$$N = \frac{\rho\epsilon^3(P_0 - P_L)}{2(1-\epsilon)^2\tau a_v^2 \mu l_M}$$

Why this τ? Because, in this case, the l_M which you have considered, that may not be, the pores may not be a straight line. So, one tortuosity factor is consumed as τ.

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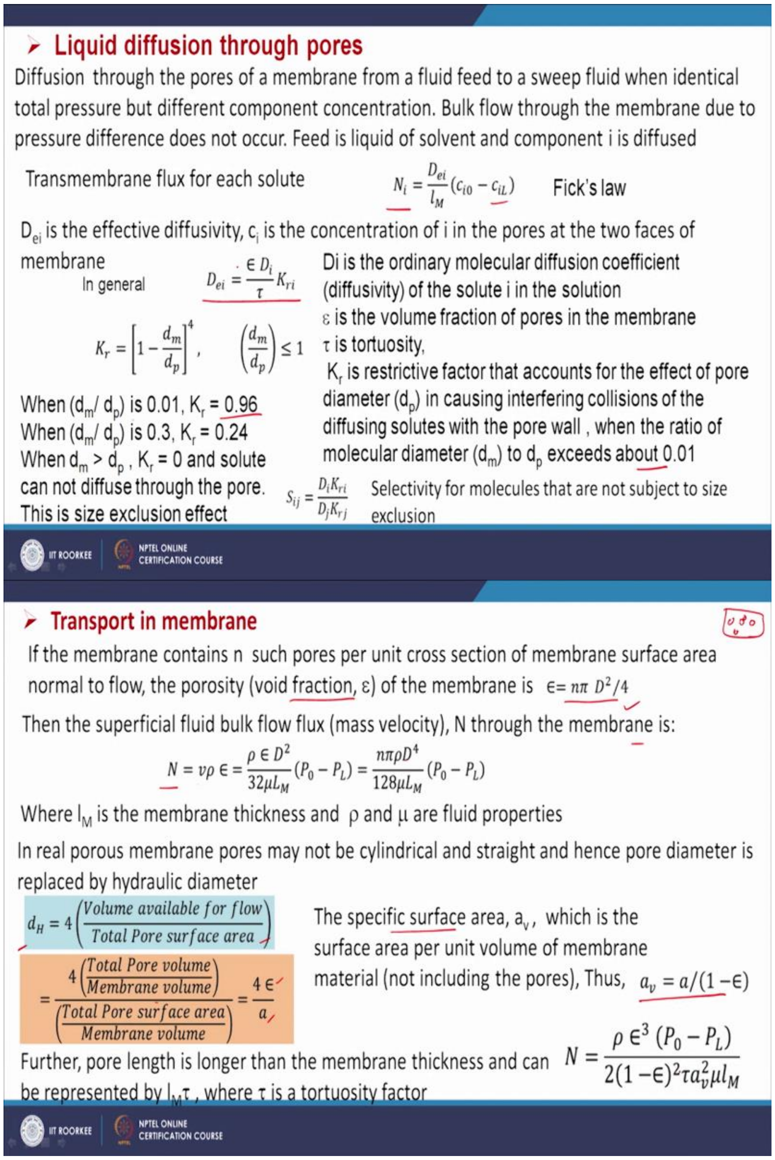

So, this is the flux through the pores. Now, we will discuss liquid diffusion through pores. So, diffusion through the pores of a membrane from a fluid feed to a sweep fluid when identical total pressure, but different component concentration is there. Here, pressure difference is not there, only concentration difference is there.

So, in that case, we can consider that Ni, transmembrane flux,

$$N_i = \frac{D_{ei}}{l_M}(c_{i0} - c_{iL})$$

Where Ci is the concentration of i in the pores at the two faces, that is inlet and outlet. And D_{ei} is the effective diffusivity. And then D_{ei} can be calculated by this formula

$$D_{ei} = \frac{\epsilon D_i}{\tau} K_{ri}$$

So, Di is the ordinary molecular diffusion coefficient of the solute i in the solution, and E is the volume fractions of pores in the membrane and τ is the tortuosity. And Kr is restrictive factor that accounts for the effect of pore diameter dp in causing interfering collisions of the diffusing solutes with the pore wall.

When the ratio of moleculer diameter dm/dp exceeds about 0.01, then Kr plays a significant role. Otherwise, when you see dm/dp, is is less than 0.01, in that case Kr is 0.96. So, this values almost 1 this Kr value is almost 1, but when this value is increasing, dm/dp is increasing. That means dm, size is increasing, then 0.3 so Kr 0.24, and when dm greater than dp, then Kr equal to 0. That means, there will be no diffusion of the material.

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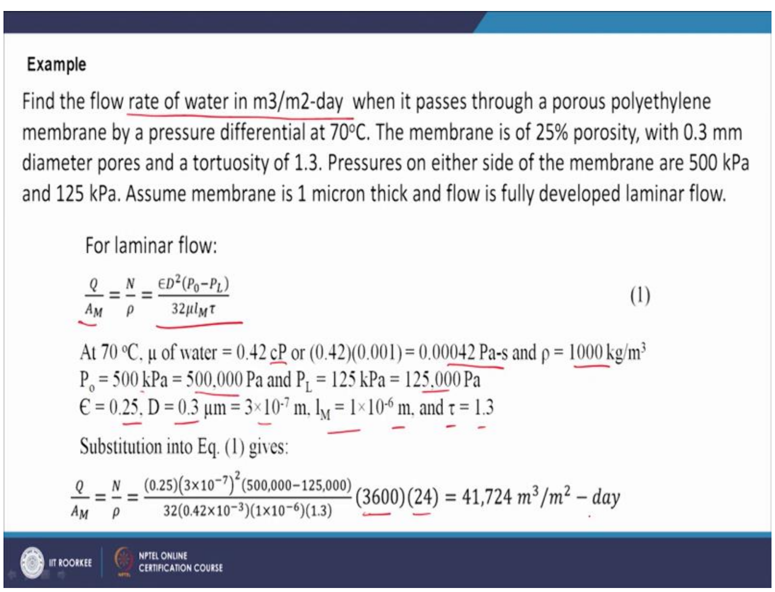

So, we will see one example here. Find the flow rate of a water in meter^3/m^2-day when it passes through a porous polyethylene membrane. By pressure differential at 70 °C. The membrane is of 25 % porosity, with 0.3 mm diameter pores and a totuosity of 1.3. Pressures on either side of the membrane are 500 kPa and 125 kPa. Assume membrane is 1 micron thick and flow is fully developed laminar flow.

So, we have the formula for laminar flow

$$\frac{Q}{A_M} = \frac{N}{\rho} = \frac{\rho \in D^2}{32\mu L_M}(P_0 - P_L)$$

At 70 ^oC, μ of water = 0.42 cP or (0.42)(0.001) = 0.00042 Pa-s and ρ = 1000 kg/m^3

P_o = 500 kPa = 500,000 Pa and P_L = 125 kPa = 125,000 Pa

Є = 0.25, D = 0.3 μm = 3×10^{-7} m, l_M = 1×10^{-6} m, and τ = 1.3

Substitution into Eq. (1) gives

$$\frac{Q}{A_M} = \frac{N}{\rho} = \frac{(0.25)(3\times10^{-7})^2(500{,}000-125{,}000)}{32\,(0.42\times10^{-3})(1\times10^{-6})(1.3)}(3600)(24) = 41{,}724\ m^3/m^2 - day$$

Up to this in this class. Thank you very much for your patience.