Membrane Technology
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Lecture-23
Basic principles, advantages of MF, cross-flow and dead-end MF, membranes and modules

Good morning students. Today is lecture 23 under module 8. In last class we have discussed Micellar-enhanced ultrafiltration and affinity ultrafiltration and bioseparation. Today and next class we will devote for microfiltration. So we will today learn about the basic principles of microfiltration, the cross-flow, dead-end flow microfiltration. The types of membranes and modules as well as the transport mechanism. So let us begin.

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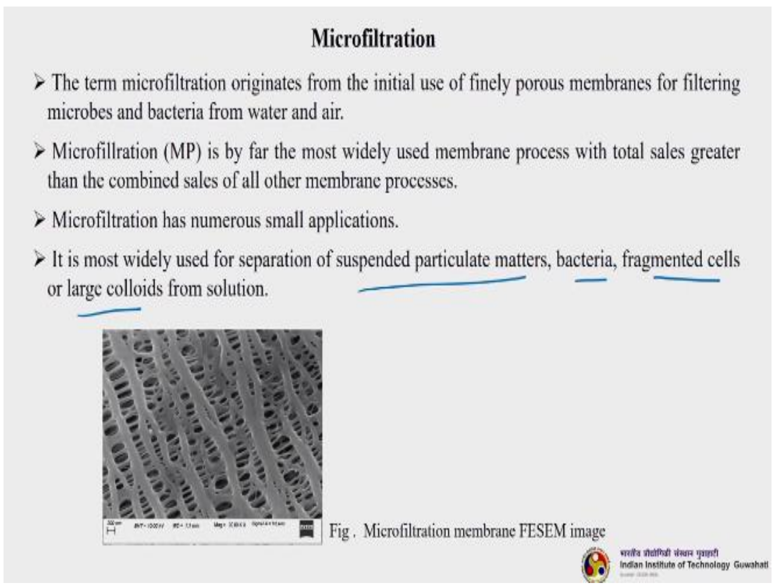

You know, the term microfiltration originates from the initial use of finally porous membranes for filtering microbes. So that is why this microfiltration has come into picture and bacteria from water as well as air. Now microfiltration is by far the most widely used membrane process with total cells greater than the combined cells of all other membranes. It may be a reverse osmosis, nanofiltration then dialysis membranes or your RO membranes.

Microfiltration has numerous applications it is almost widely used for separation of suspended particulate material, bacteria, fragmented cells or large colloids from the solution. You can see this is a FESEM image of one of the microfiltration membrane, you can see how the pores are looking and you can observe the distinct pores actually; the pore size is very distinct and more or less they are very uniform.

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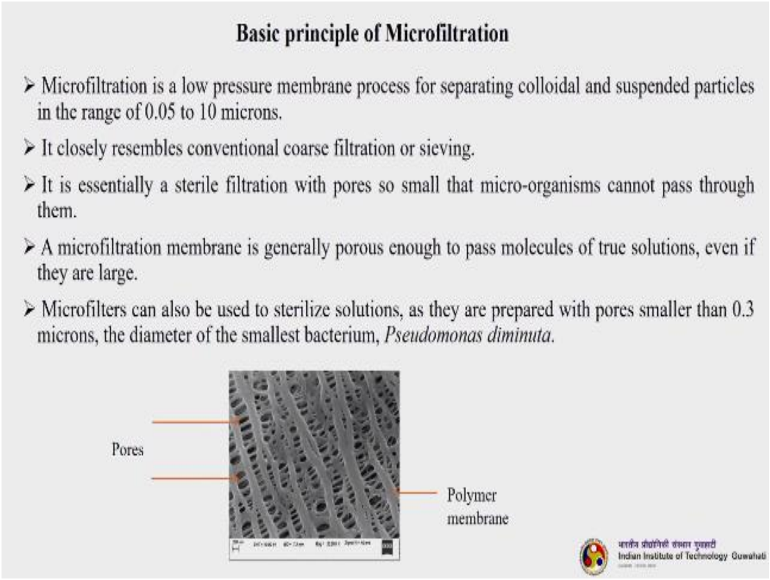

So microfiltration is a low pressure membrane process for separating colloidal and suspended particles, in the range of 0.05 to 10 microns. So it closely resembles conventional quartz filtration or sieving. It is essentially a steroid filtration with pore so small, that microorganisms cannot pass through them. So a microfiltration membrane generally is porous enough to pass molecules of true solutions even if they are large.

Micro filters can also be used to sterilize solutions as they are prepared with pores smaller than 0.3 microns, the diameter of the smallest bacterium that is known as Pseudomonas diminuta. So this is a polymer membrane you can see these pores how distinctly and uniform pores are there.

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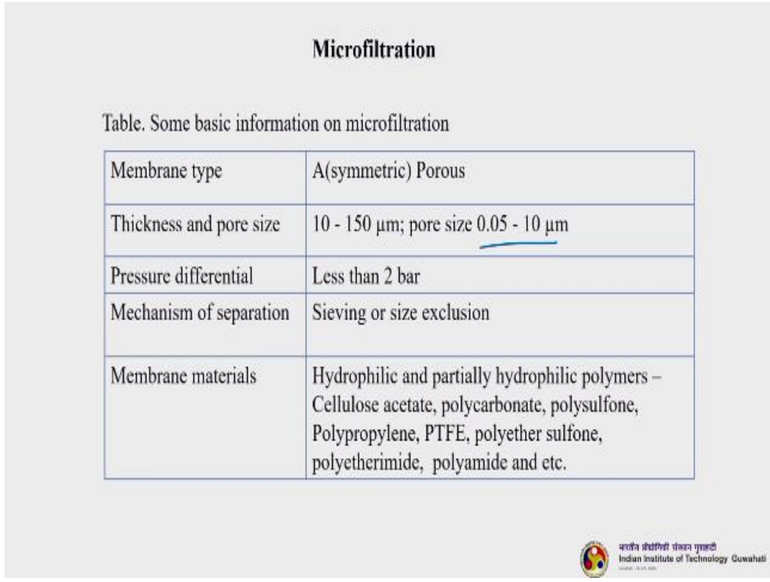

Microfiltration

Table. Some basic information on microfiltration

Membrane type	A(symmetric) Porous
Thickness and pore size	10 - 150 µm; pore size 0.05 - 10 µm
Pressure differential	Less than 2 bar
Mechanism of separation	Sieving or size exclusion
Membrane materials	Hydrophilic and partially hydrophilic polymers – Cellulose acetate, polycarbonate, polysulfone, Polypropylene, PTFE, polyether sulfone, polyetherimide, polyamide and etc.

So some basic information, so membrane type is basically asymmetric porous A is their bracket symmetrical. So it can be a symmetry or asymmetry. The thickness and pore sizes thickness is around 10 to 150 micron, pore sizes usually as you know that 0.5 to 10 micron, 0 5 to 10 micron. pressure difference pressure that is required to carry out microfiltration operations is usually less than 2 bar.

The mechanism of separation is usually sieving or size exclusion. And there are different types of membrane materials which can be used to prepare microfiltration membranes. There may be hydrophilic or partially hydrophobic polymers such as cellulose acetate, polycarbonate, polysulfone, polytetrafluoroethylene polyethersulfone PS which is not very well known and polyamide and etcetera.

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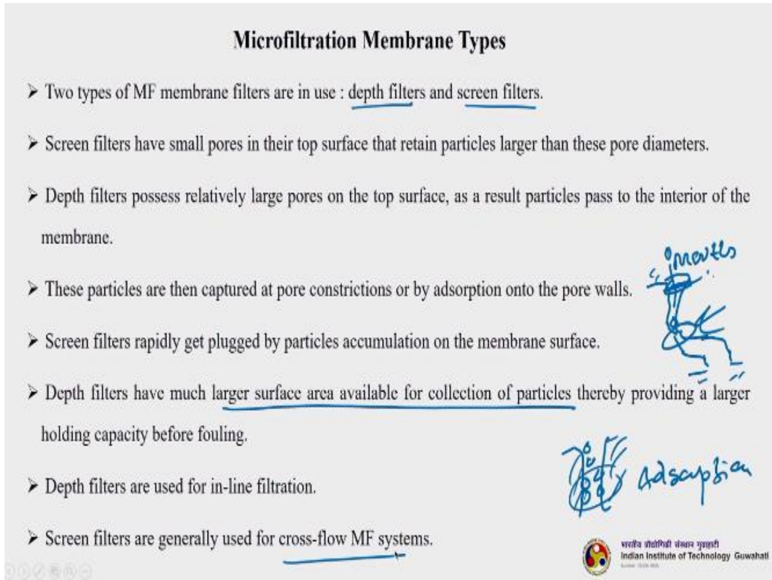

So 2 types of microfiltration membranes are basically used. So one is called depth filter another is called screen filters, these are the basic this one distinction or division of the types of microfiltration filters. So screen filters have small pores in that top surface that retain particles larger than these pore diameters. But depth filters possess relatively large pores on the top surface, large pores means with respect to the screen filters.

So as a result particles pass through the interior of the membrane and these particles have been captured at pore constrictions or by adsorption onto the pore walls. So if the pore, let us say this is a pore as I have told you earlier also. And this is a pore constriction so this is your pore mouth And, so there is a constriction up on that, again the pore is getting wider up and then it is the final end you can see?

So it can happen that these are solutes it will pass through the membrane. Because its size is smaller than the pore diameter, but however due to this constriction inside the pore they are getting trapped here, the solute is getting trapped here. So it cannot pass through, though the solute size is larger than the pore diameter, so now it is very important to again to tell you that whenever you characterize pore diameters or pore size whatever you are talking about.

So is basically we are talking about the pore mouth we are characterizing the top surface unless until you characterize see the cross-section and then characterize it so most of the times it is the surface, surface characterization so the pore mouth or pore diameter this is what actually being we characterize, so but inside that there are constrictions, constriction or constrictions that we do not know.

So due to that externally these constrictions that many times solute though they pass through the pore, they get retained on the surface inside the pore due to this constriction. So in other cases adsorption, so let us say this is a pore the solutes are passing small solutes but however they are getting adsorbs to the surface wall so due to some sort of charge based interaction among the solute and the pore wall of the membrane material basically.

If the membrane pore is not filled with anything, it is just a blank membrane you can say like that or a m membrane. So this happens, due to adsorption and this is due to the constriction, so screen filters rapidly get plugged by particles accumulation on the membrane surface. Depth filters have much larger surface area available for collection of particles, thereby providing a larger holding capacity before they get fouled actually.

So depth filters are used in in-line filtration, screen filters are used usually for the cross-flow microfiltration systems.

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So you can see this picture, actually taken from the book R.W Becker. So you can see that this is screen filter, how the pores are looking so uniformly distributed also and mostly they are of same size, you can see the sizes also. They are mostly same size, these are pores so this is 0.5 micron pores screen filter, here it is a nominal point 4 micron depth filter, you can see how they are actually distributed here.

And so this is again why the screen filter, this is cross-section and this is depth filter the arrangement of the fibers, you can see inside a screen filter and a depth filter, so this is the cross-sectional comparison.

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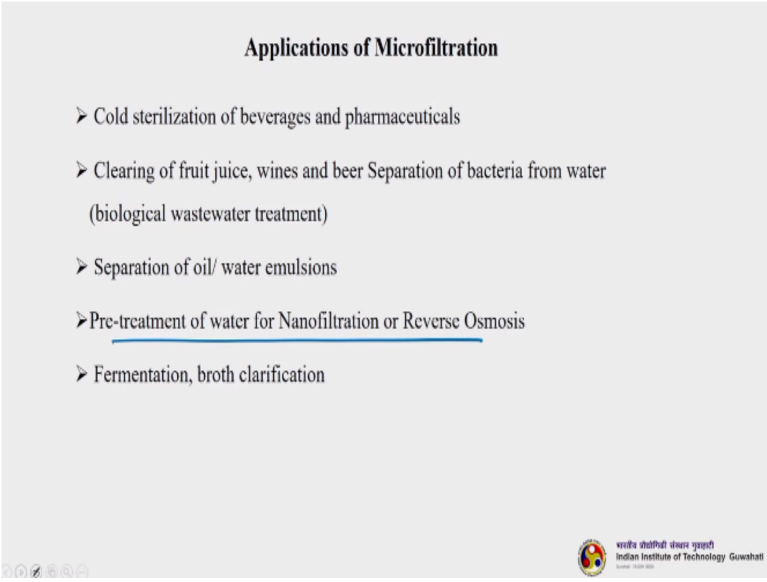

So there are so many applications, just a few I have listed. So cold sterilization of beverages and pharmaceuticals, clearing of fruit-juice, wines and beer separation of bacteria from water, so you can call it a biological wastewater treatment also. Separation of oil/water emulsions, pretreatment of water for nanofiltration and or reverse osmosis and fermentation broth clarification. This is one of the most important application in industries, where we have talking about desalination plants and all.

So many times you have to pre-filter it. We have discussed this during our discussion, on RO and NF that we need many times a pretreatment of the saline water or brackish water, before it is being fed to the NF or RO system, so at that time microfiltration will do the prefiltration

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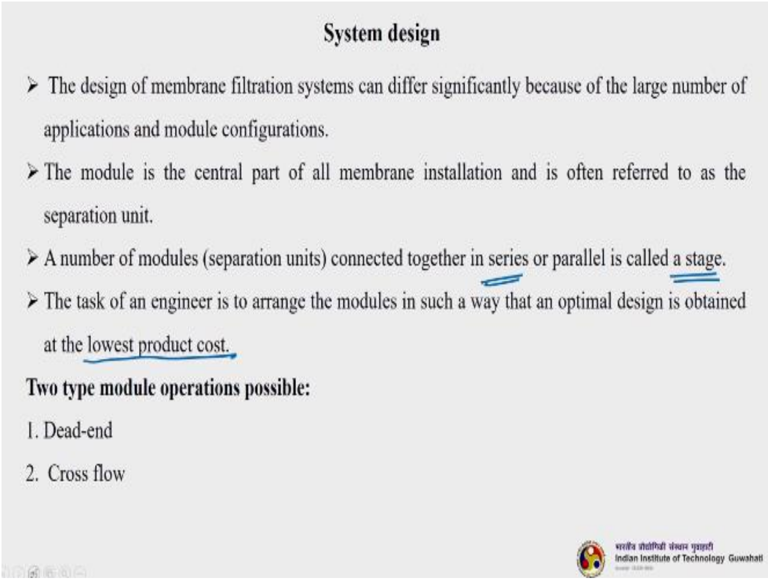

The design of microfiltration membrane systems can differ significantly, because of the large number of applications and module configurations. So the modules are same as we have discussed during ultrafiltration or in general, whatever we have discussed about the modules so they are the same types of modules will be using here. So the module is the central part of all membrane installation and has often referred as the separation unit.

And number of module separation units connected together in series or parallel is called a stage, so the task of an engineer is to arrange the module in such a way that an optimal design is obtained at the lowest production cost. Please underline the lowest product cost, this is very important, because in industry parlance whatever process you develop you adapt, whatever you do any techniques.

So it should be feasible and sustainable in a long way, the feasible means technically feasible. Sustainable means it should be the process, technical sustainability of the technology, should be adapted. If you run it continuous also nothing will happen, 2nd thing is that sustainability due to low cost or the cost. So the cost factor has to be taken into consideration because otherwise what will happen this subsequently.

The final product cost will increase, as we discussed earlier also again we will quickly go through, so there are two different types of microfilter system operation one is dead-end flow, another is cross-flow.

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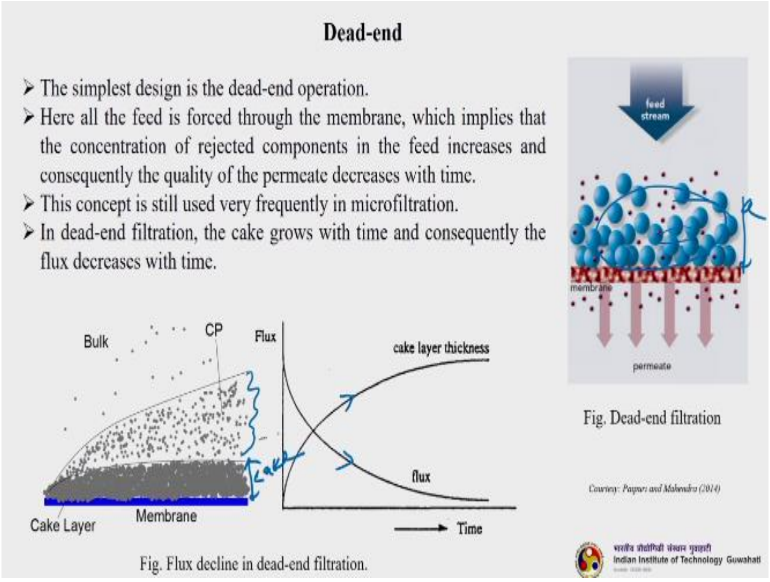

So the simplest design is the dead-end operation, here you can see this how it is happening, so here all the feed is forced through the membrane which implies that the concentration of the rejected components in the feed increases and consequently the quality of permeate decreases with time, so everything is getting deposited on the surface of the membrane and the permeate is coming here. So the concept is still used very frequently for microfiltration system.

So in the dead-end filtration, the cake grows with time and subsequently and consequently the flux decreases, so you can see how it looks like actually. So the flux decline profile is extremely fast and little steep in case of dead-end filtration. You can see how the flux is getting on decline and how the cake layer is getting increased, this cake layer. So initially there will be a deposition of this type of solute deposition then after sometimes it will become a cake.

And this is your concentration polarization layer which is staying above the just above your this one a cake layer and then there is the bulk of the feed.

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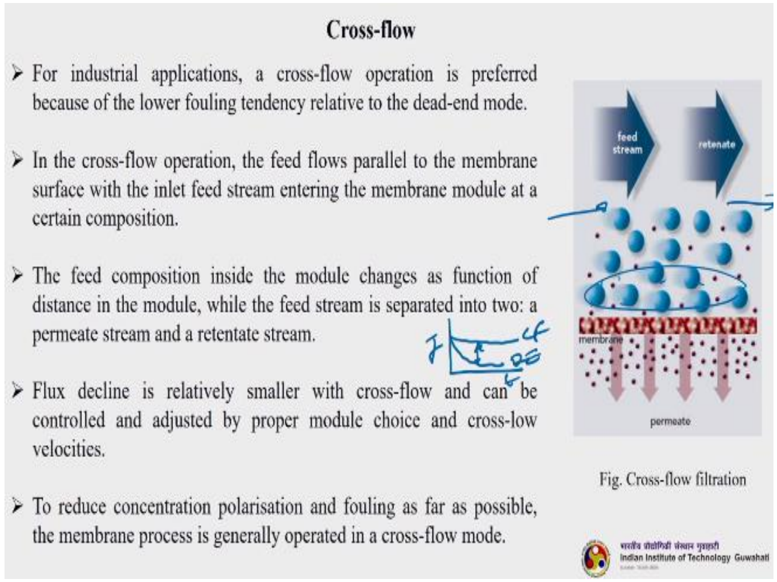

So in that cross-flow system the mostly industrial application cross-flow systems is preferred because of the lower fouling tendency, why it is lower fouling tendency? You just imagine see the feed is flowing here the retentate is going there, so it is flowing like this, so what is happening is that, so what about that solutes that is getting deposited on the surface are subsequently getting worst to certain extent by the feed flow rate.

So that is why we have discussed that one of the technique to reduce concentration polarization and subsequent fouling is to increase the feed flow rate but every module and the membrane can withstand a certain up to a certain limit of the feed flow rate. So I cannot go beyond that so 5 meter per second 6 meter per second or something like that so beyond that we cannot go every module has certain restrictions, so up to that we can go.

So theoretically, we can imagine that a high feed flow rate is washing away that the solutes, that is getting deposited on the surface of the membrane, at the same time it has to be noted that if the resistance time is too low the membrane area is not getting properly utilized then separation efficiency is decreasing, so this is also has to be taken care of. So in the cross-flow operation the feed flows parallel to the membrane surface with the inlet feed stream entering the membrane module at a certain composition.

So the feed composition inside the module changes as a function of distance in the module while the feed stream is separated into two a permeate and retentate, so flux decline is smaller. So you can there is no space, here I still try to draw, see let us see the flux decline, so you have seen another flux decline profile is very sharp in microfiltration. So this is dead-end, so here it will be like this. So this is cross-flow, so this is the only difference.

So, but you can see there is a magnitude of difference, so this is your flux with respect to time or whatever any other thing parameter also can be considered, though there is flux decline, it is not as steep as that of the dead-end. So to reduce concentration polarization and fouling, as far as possible the membrane process is generally operated in a cross-flow model.

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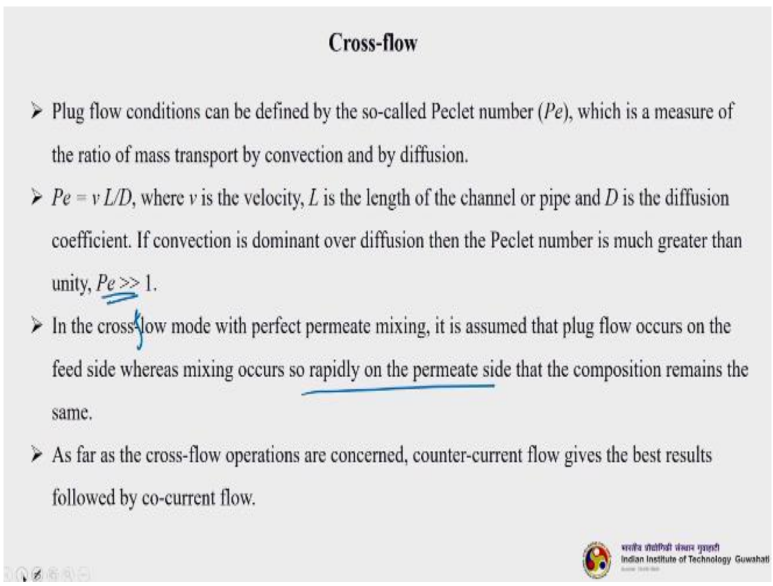

So plug flow conditions can be defined by the so-called Peclet number, which is a measure of the ratio of mass transfer by convection to that of the diffusion. So Peclet number is V L by D where V is the velocity, L is the length of the channel or pipe and D is the diffusion coefficient. So if the convection is dominant about diffusion, then peclet number is much greater than unity. so Peclet number is much much higher than 1.

So in the cross-flow mode with perfect mixing it is assumed that plug flow occurs on the feed side whereas mixing occurs so rapidly on the permeate side, that the composition remains the same. So as far as the cross-flow operations are concerned, counter-current flow gives the best results followed by co-current flow. So these things, we have discussed in one of our classes.

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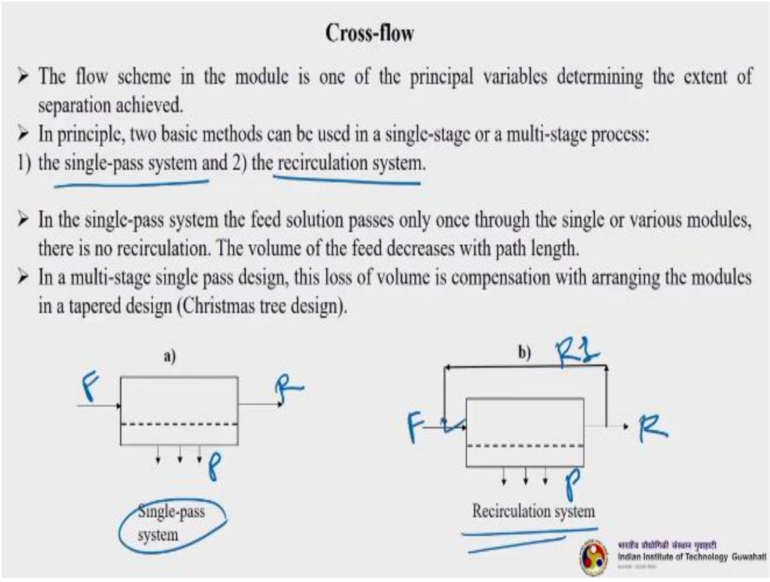

Different modes of operations; a counter flow, cross-flow perfectly mix things, permeate mixing and complete mix and all these things. So the flow scheme in the module is one of the principal variables determining the extent of separations achieved in principle, 2 basic methods can be used in a single stage or multistage process. So one is called the single-pass system, another is the recirculation system.

This is the single-pass system, so what is happening in this, so the feed solution passes only once through the single or various modules. So there is no recirculation so the volume of the feed decreases along the path length. So in a recirculation system so; this is feed, this is retente, this is permeate, a part of retentate let us say R1 is getting recirculated back to the feed, so why it is happening?

Because in a single-pass system. As I told you that the volume of the feed is continuously decreasing, so that is affecting the process dynamics or the separation efficiency also get decreases, so to maintain the feed volume we is recirculate or part of the retentate back to the feed and mix it here. So this is called a recirculation system, so this is very efficient systems when you talk about industrial parlance

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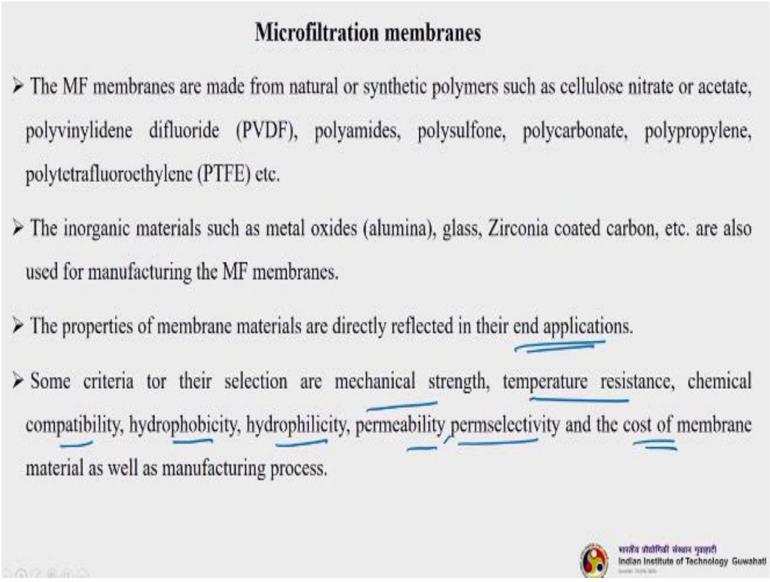

Microfiltration membranes are made from natural or synthetic polymers such as cellulose nitrate, acetate, PVDF, polyamides, polysilicon, polycarbonate, polypropylene, PTFE. Polytetrafluoroethylene, the inorganic materials such as metal oxides like alumina, glass, zirconia coated carbon etc, are also used for manufacturing the microfiltration membranes. The properties of membrane materials are directly reflected in there and applications.

So, actually what is the end application? Depending upon that, we can choose a particular membrane material and we can peller make a membrane, so some criteria for the selection are mechanical strength, temperature resistance, chemical compatibility, hydrophobicity hydrophilicity, permeability, permselectivity and the cost of the membrane material as well as the ease of manufacturing ease of manufacturing and ease of reproducibility are two most important factors that is taken care when you go for a commercial production of membranes.

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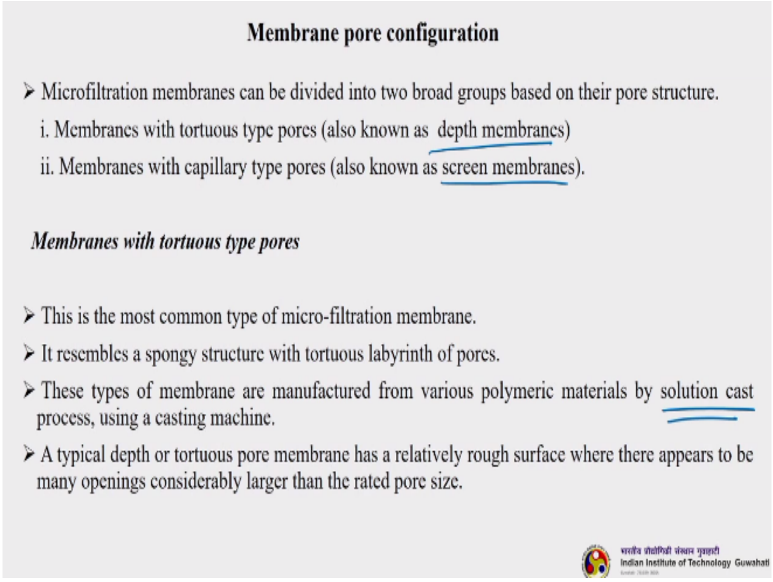

So microfiltration membranes can be divided into two broad groups, based on their pore structure membranes with tortuous port type, also known as depth filters membrane with capillary pore types known as screen membranes. We just discussed about screen and depth filter so will discuss little more in detail about the different types of depth and skin membranes and their properties.

So, a tortuous types of membranes are the most common types of microfiltration membranes. It resembles a spongy structure with tortuous labyrinth of pores. So I will show you one image in the next slide, so these types of membranes are manufactured from various polymeric materials, by solution casting using a casting machine so a typical depth or tortuous pour membrane has a relatively rough surface. Where there appears to be many openings considerably larger than the rated pore size.

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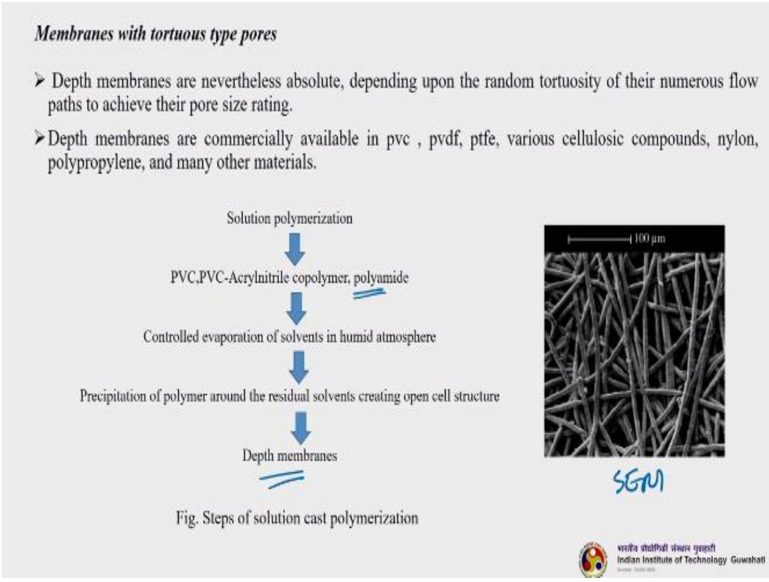

So you can see how actually, it looks like so this is again the same image. So depth membranes are nevertheless absolute depending upon the random tortuosity of their numerous flow paths to achieve their pore size rating depth membranes are commercially available in PVC, PVDF, PTFE various cellulosic components; nylon polypropylene and many other materials. So this is the steps for doing the solution casting polymerization.

So you do the solution polymerization first that means, what then you go for this PVC about this copolymer and all these things so then you go for control evaporation of solvent in humid atmosphere then you go for precipitation of polymer around the residual solvents creating open cell structure you get a death filter. So sometimes it happens that you may need some further polishing step depending upon if you wanted to impart certain functional groups to the membrane.

Or you want to make a charge based member and either importing a cationic groups or anionic groups it depends again on your application.

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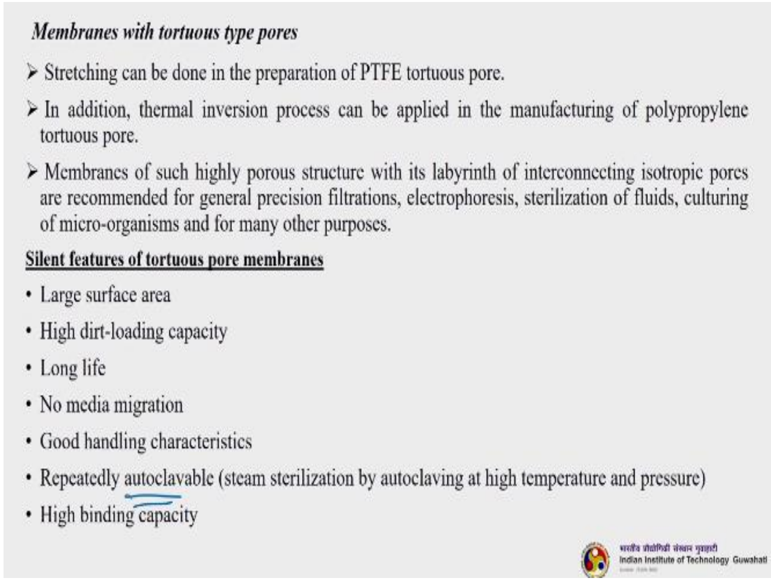

So stretching can be done in the preparation of PTFE tortuous pore in addition thermal inversion process can be applied in the manufacturing of polypropylene tortuous pore membranes of such highly porous structure with his labyrinth of interconnecting isotropic ports are recommended for general precision filtrations, electrophoresis, sterilization of fluids culturing of microorganisms and for many other purposes.

The silent features of tortuous membrane is there they have large surface area they have very high dirt loading capacity because they have a surface area is huge, so that loading capacity will be more long life no media migration good handling characteristics repeatedly autoclavable this is very important actually when you talk about biotechnological applications or biopharmaceutical applications steam sterilization by autoclaving at high temperature and pressure high binding capacity.

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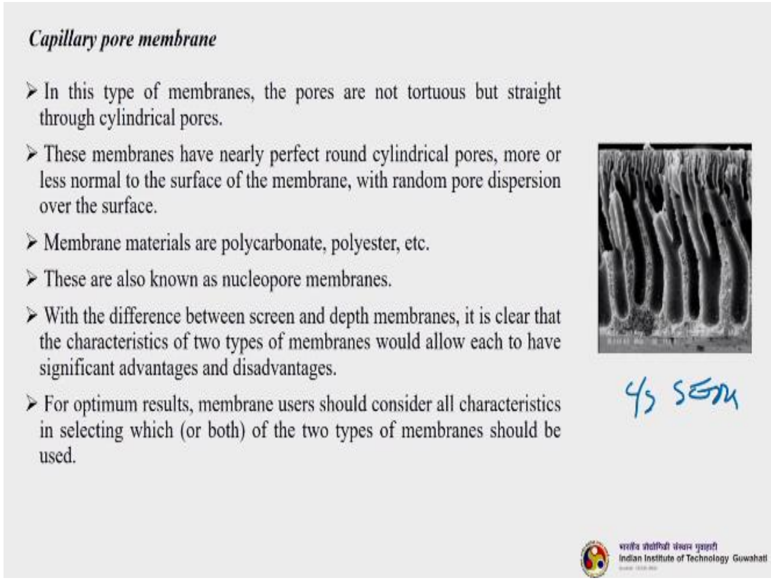

Usually binding capacity that term is used for the proteins. So the next one is capillary membranes so in this type of membrane the pores are not purchased but straight through cylindrical pores this is a cross-section SEM, so you can see how beautifully the pores are looking the cylindrical and straight pores so these membranes have nearly perfect round cylindrical pores more or less normal to the surface of the membrane.

With random pore dispersion over the surface so membrane material cell polycarbonate and polyester these are also known as nuclear pore membranes with the difference between screen and depth membrane it is clear that the characteristics of two types of membranes would allow its to have significant advantages and disadvantages. Now for optimum results membrane you just should consider all characteristics in selecting which are both of the two types of membranes should be used.

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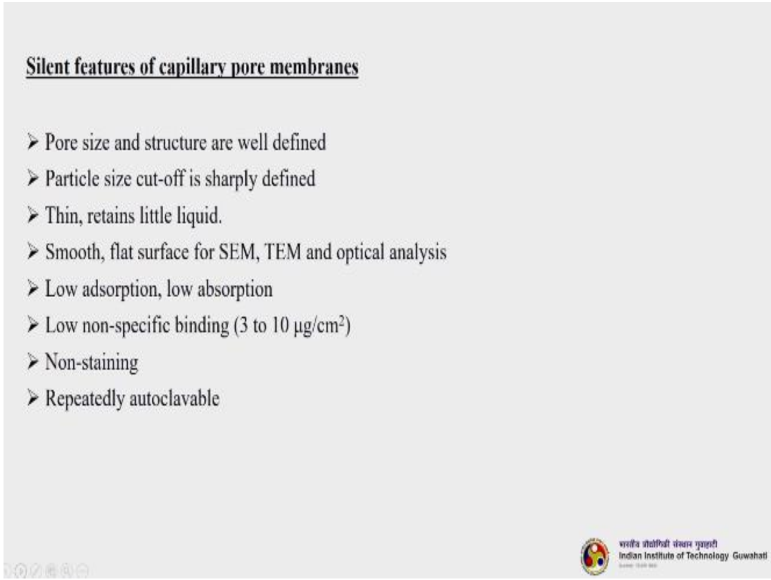

The silent features of the capillary pore membranes are; pore size and structures are very well defined as you can see that beautiful pores and well-defined structure, particle size cut-off is sharply defined, thin and it retains little liquid, smooth flat surface for SEM TEM and optical analysis, low adsorption and low absorption low nonspecific binding three to 10 micro gram per centimeter square, non-staining and repeatedly autoclavable. Most of the microfiltration membranes are autoclavable so now let us discuss the microfiltration membrane modules;

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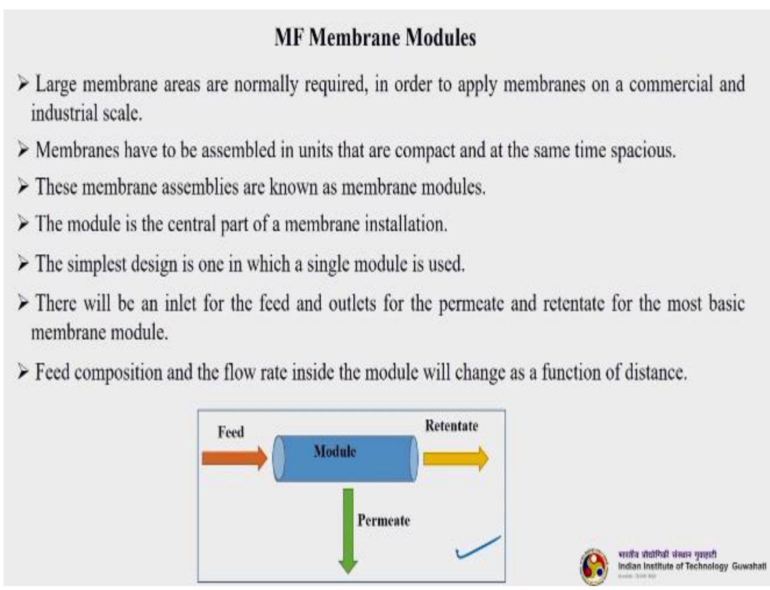

So we have discussed the modules in detail in one or two of our earlier classes. Today we will just quickly go through so large membrane areas are normally required in order to apply membranes on a commercial and industrial scale, membranes have to be assembled in units that are compact and at the same time specious so these membrane assemblies are known as membrane modules.

The membrane and the module is the central part of the membrane installation; the simplest region is the one in which a single module is used, so there can be many modules connected in series in a cascading system and many of them can be called a single stress also. So there will be an inlet for the feed and outlet for the permeate and retentate for the most basic membrane module just as given here, feed composition and flow rate inside the module will change as a function of distance.

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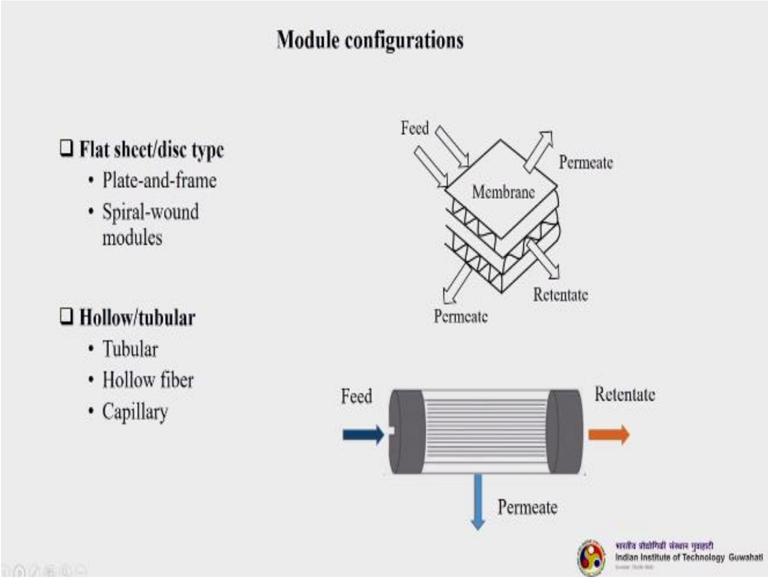

So various types of module configuration exists; so in flat sheet/disc type, we can have plate and frame spiral-wound modules. Under hollow fiber or Tubular you can have tubular modules, hollow fiber systems we have capillary tubes.

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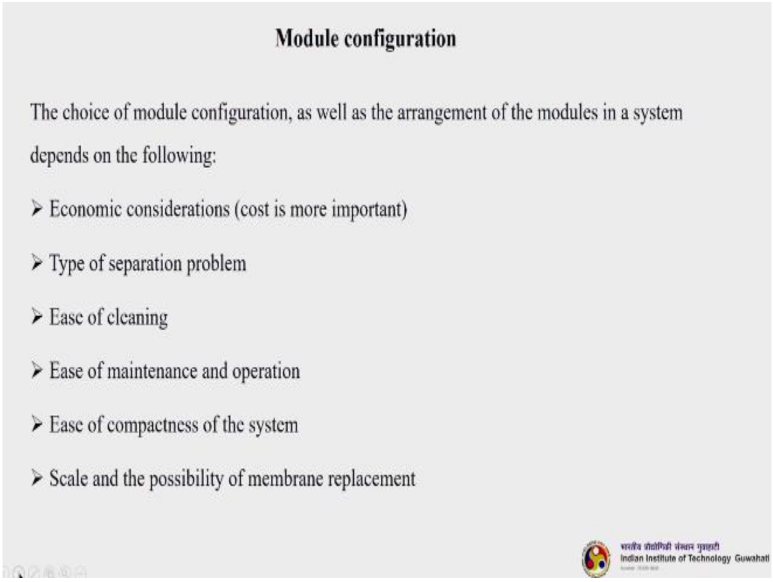

So the choice of module configuration as well as arrangement of the module in a system depends on the following; first is economic considerations, I have already told you why it is so important cost is very important so type of separation problem. So are you going for a liquid-liquid separation or a gas-gas separation or a liquid volatile organic component separation or what, so the ease of cleaning is also very important.

Ease of maintenance and operation, ease of compactness of the system, scale and the possibility of membrane replacement, that is also very important so transportation and handling is also important because you know we discussed during our tubular membrane ceramic membranes the ceramic membranes, their weight is too much so carrying in and they are brittle also so carrying them and from one place to another place is always challenging

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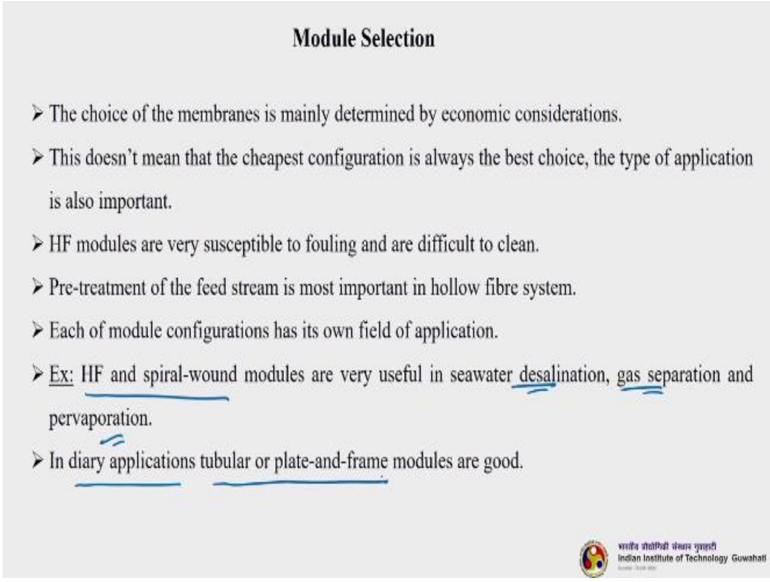

The choice of the membranes is mainly determined by the economy considerations this does not mean that the cheapest configuration is always the best choice, it is not the case so the type of application is also very important and other parameters that affect the membrane systems. Then hollow fiber modules are very susceptible to fouling and that difficult to clean pretreatment of the feed stream is most important in hollow fiber system each of the module configurations has its own filled up application.

For example hollow fiber and spiral wound modules are very useful in sea water desalination so gas separation as well as pervaporation whereas in diary applications we usually prefer tubular or plate and frame modules.

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Module selection

Table. Comparison of various membrane configurations

	Tubular	Plate and frame	Spiral wound	Capillary	HF
Packing density	Low	-	-	-	Very high
Investment	High	-	-	-	Low
Fouling tendency	Low	-	-	-	Poor
Cleaning	Good	-	-	-	Poor
Membrane replacement	Yes/no	Yes	No	No	No

This is a comparison of various membrane configurations so they are being compared under various parameters like packing density, the investment, fouling tendency, cleaning and membrane replacement so you can go through it later

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Table. Module designs most commonly used in the major membrane separation

Application	Module type
Reverse osmosis: seawater	Spiral wound modules dominate. Only one hollow fibre producer remains
Reverse osmosis: industrial and brackish water	Spiral- wound modules used almost exclusively; fine fibres too susceptible to scaling and fouling
Ultrafiltration	Tubular, capillary, and spiral wound modules all used.
Gas separation	Hollow fibres for high volume applications with low flux, low selectively membranes in which concentration polarization is easily controlled. Spiral wound when fluxes are higher, feed gases more contaminated, and concentration polarization a problem
Pervaporation	Most pervaporation systems are small so plate – and frame systems were used in the first systems. Spiral wound and capillary modules being introduced

Then module designs most commonly used in membrane separation applications overall I am talking about. So in RO actually when you go for sea water usually it is spiral wound membranes dominant, so now only one hollow fiber producer remains so RO application again for industrial and brackish water usually again spiral-wound modules, so fine fibers are too susceptible to scaling and fouling.

For ultrafiltration we can go for anything tubular, capillary, spiraoundl w for gas separation applications hollow fibers for high volume applications with low flux low, selectivity membranes in which concentration polarization is easily controlled spiral wound when fluxes are higher feed gases are contaminated and concentration polarization is a problem. So for pervaporation most pervaporation systems are small plate and frame systems spiral wound and capillary modules are also being introduced nowadays.

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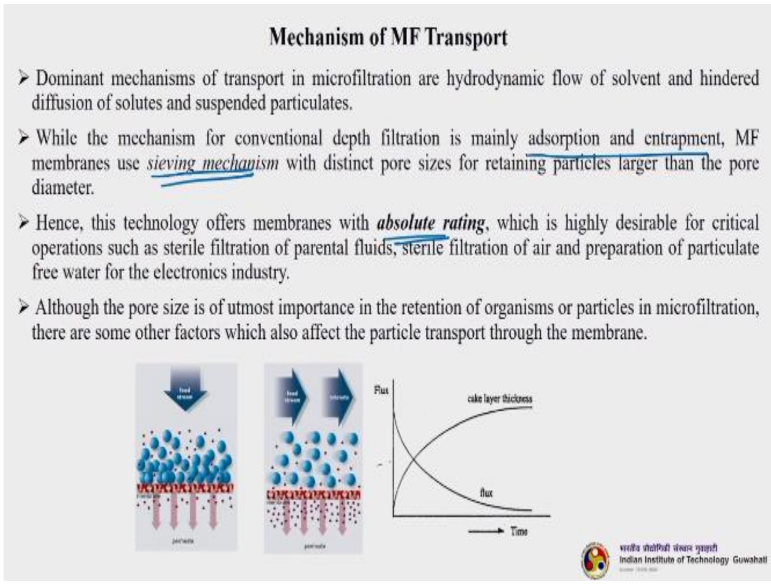

Now let us understand the mechanism of microfiltration transport, so a dominant mechanism of transport in microfiltration and hydrodynamics flow of solvent and hindered diffusion of solutes and suspended particulates. So while the mechanism for conventional depth filtration is mainly adsorption and entrapment microfiltration membranes use the sieving mechanism or size exclusion mechanism.

With distinct pore sizes for retaining particles larger than the pore diameter hence, this technology offers the membrane with absolute rating which is highly desirable for critical operation such as sterile filtration parental fluids sterile filtration of air and preparation of particulate free water for the electronics industry. So although the pore size is a utmost importance in the retention of organisms or particles in microfiltration there are some other factors which also affect the particle transport through the membrane.

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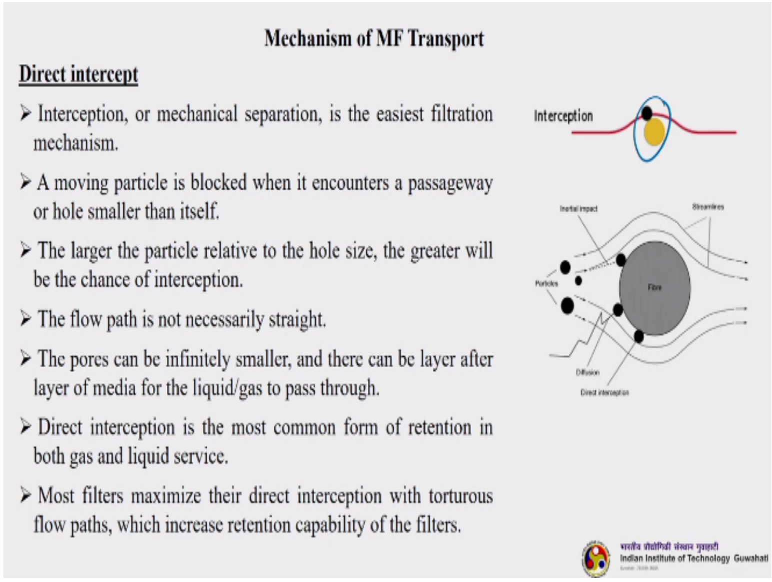

So let us try to understand the different other mechanisms which actually play a role in microfiltration transport the first one is direct intercept so interception of mechanical separation is the easiest filtration mechanism so you can see in this schematic diagram how interception happens, so a moving particle is blocked when you can encounters passageway or a hole smaller than itself. So you can see how it is happening here so the larger the particle relative to the hole size the greater will be the chance of interception.

So basically size based, so the flow path is not necessarily straight pores can be infinitely smaller there can be layer after layer of media for the liquid or gas to pass through so direct interception is the most common form of retention in both gas and liquid service. So most filters and maximize their direct interaction with tortuous flow paths which increase the retention capability of the filters.

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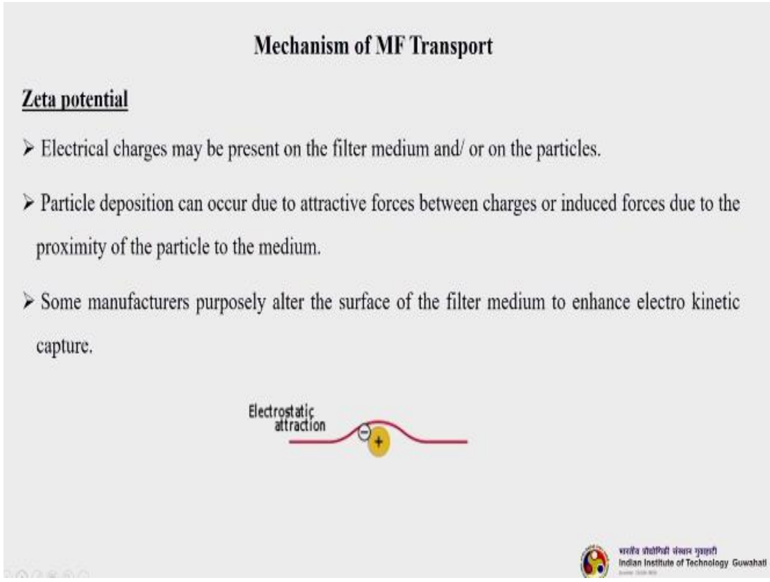

The next one is Zeta potential or charge by separation; so electrical charges may be present on the filter medium and or on the particle so charge the solute or the particles which you are going to retain on the surface of the membrane or rejected also beyond such as either + or - and the membrane a material of which the membrane is made up of also having some charges. So the particle deposition can occur due to attractive forces between the charges or induced forces due to the proximity of the particle to the medium.

Some manufacturers purposely alter the surface of the filter medium to enhance electro kinetic capture if we are extreme going for a charge based separation.

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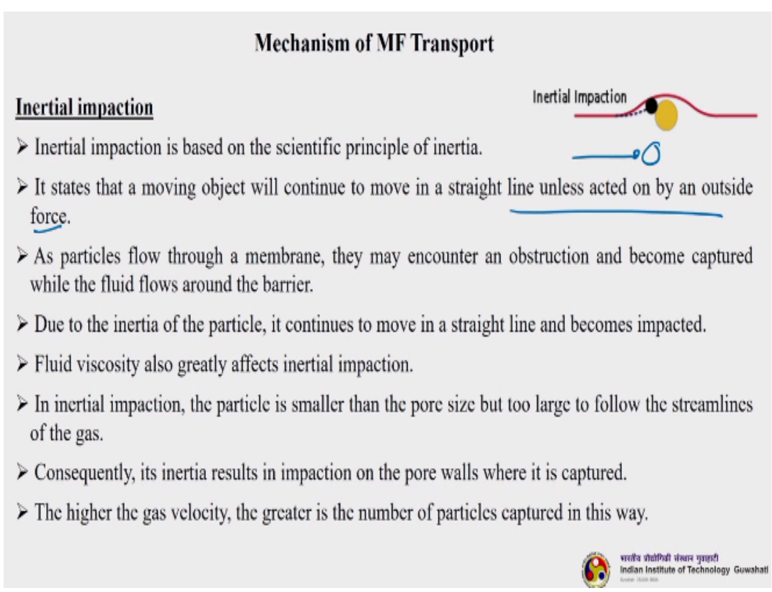

So the next is inertial impaction so what is happening here the inertial impaction is based on the scientific principle of inertia, so it states that a moving object will continue to move in a straight line unless acted by an outside force. So it will keep on moving unless the forces applied here, to balance it so counter it, so as particles flow through the membrane they may encounter an obstruction and become captured while the fluid flows around the barrier.

Due to the inertia of the particle it continues to move in a straight line and becomes impacted, so fluid viscosity also greatly affects the inertial impaction. In an initial impaction the particle is smaller than the pore size but too large to follow the streamlines of the gas so consequently its inertia results in impaction of the pore walls where it is captured the higher the gas velocity the greater is the number of particles capture in this way.

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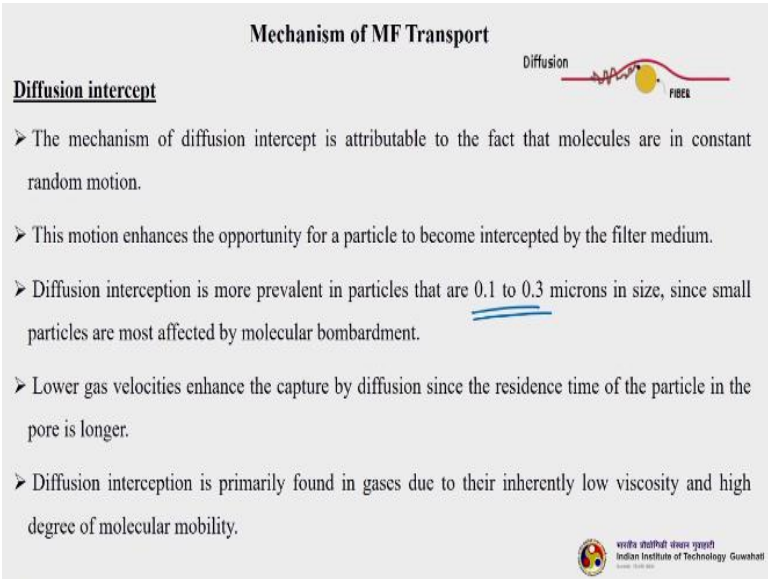

Next one is diffusion intercept so the mechanism of diffusion intercept is attributable to the fact that molecules are in constant random motion so mostly in case of pure gases separation of gas by separation so this motion enhances the opportunity for a particle to become intercepted by the filter medium diffusion interception is more prevalent in particles that are 0.1 to 0.3 microns in size since small particles are mostly affected by the molecular bombardment.

And lower gas velocities enhance the capture by diffusion since the residence time of the particle in the pore is longer, so diffusion interception is primarily found in gases to their inherently low viscosity and high degree of molecular mobility.

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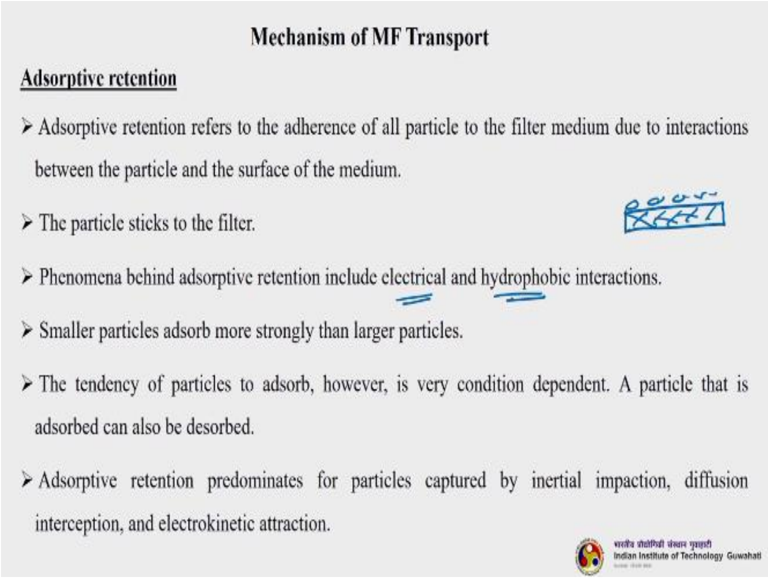

So the next one is adsorptive retention; so adsorptive retention refers to the adherence of all particles to the filter medium due interactions between the particle and the surface of the medium. So basically you can see on the surface of the membrane, so they are getting deposited basically the particle sticks to the filter. So the phenomena behind adapted attention include electrical or hydrophobic interactions or even both of them.

So smaller particles adsorb more strongly than the larger particles and that the tendency of particles to adsorb however is very condition dependent. So that means a particle that is adsorbed can also be deserved once the condition of the environment is gets changed. So adsorptive retention predominates for particles captured by inertial impaction diffusion interception in the electro kinetic attraction.

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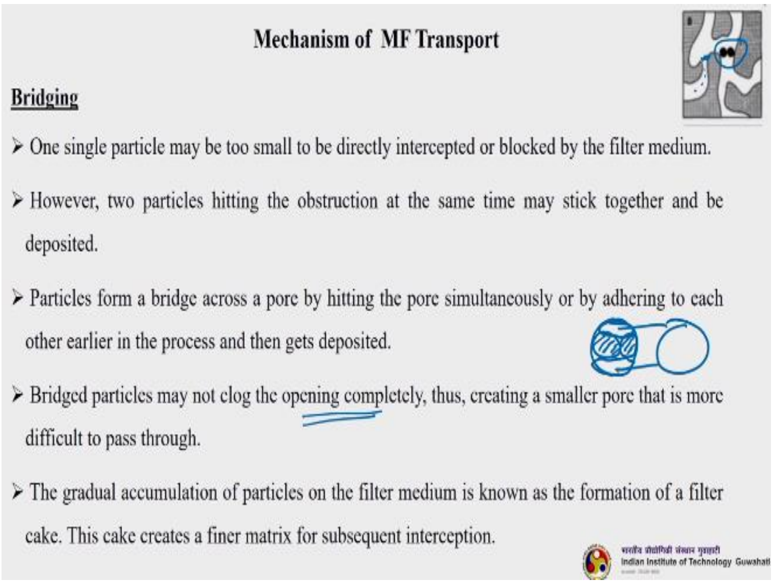

The next mechanism is called bridging, so what is happening here so one single particle may be too small to be directly intercepted or blocked by the filter medium. Now what happens when two particles hitting the obstruction at the same time they may stick together and be deposited this is what is exactly happening. So I am trying to draw again here so one small particle very small particles so that may come through.

Now the same size particle both are somehow getting deposited on the surface of the membrane same time, so they are getting bridged and blocked the membrane surface just like it is being shown here? So they stick to each other the particles are sticking to each other and thereby blocking the pore diameter, so their diameter of this bridged particles obviously it is much more than the pore diameter, and they are blocking the pore mouth.

So particles form a bridge across the pore that is why the name is bridging by hitting the port simultaneously or by adhering to each other earlier in the process and then gets deposited so bridge particles may not clog the opening completely, it may not clog so that is creating a smaller pore that is more difficult to pass through. So if you closely look at I will try to draw something. Let us say this is the pore diameter pore mouth from the top surface I am seeing.

So the bridged particle may develop something like this if there is a bridge, two particles are getting bridged but you can see now so there is still empty space here, empty space here. So through this particular space filtration may also occur however now you can see the pore size has been reduced something like this rather than the original pore size which was like this, so it is not that bridging is always blocking the enter pore mouth it is mostly reducing the pore mouth size.

So, there by what is happening is that the efficiency of the membrane decreases and the permeation rate decreases so the gradual accumulation of particles on the filter medium is known as the formation of a filter cake. So this cake creates a final matrix for subsequent interruption.

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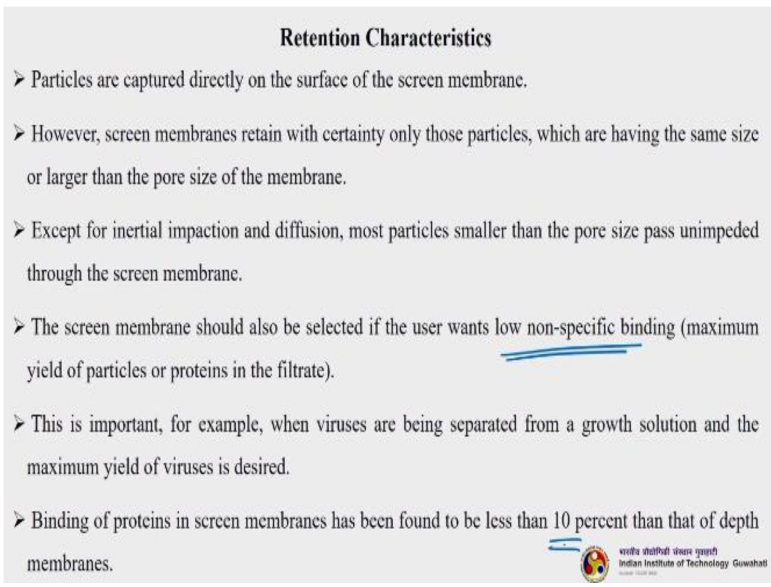

Now let us try to understand the retention characteristics so particles are captured directly on the surface of the screen membrane however screen membranes retain with certainty only those particles which are having same size or larger than the pore size of the membrane except for inertial compaction in diffusion most particles smaller than the pore size pass unimpeded through the screen membrane.

So the screen membranes would also be selected if the user wants low nonspecific binding some maximum unit of particles or proteins in the filtrate. So this is; that means I want most of the proteins or solutes to pass through the membrane to the filtered set of the permeate side so this is important for example when viruses had been separated from a growth solution and the maximum yield of viruses is desired shall let the viruses pass through the permeate. So binding of proteins in skin membranes has been found to be less than 10% then that of the depth membranes.

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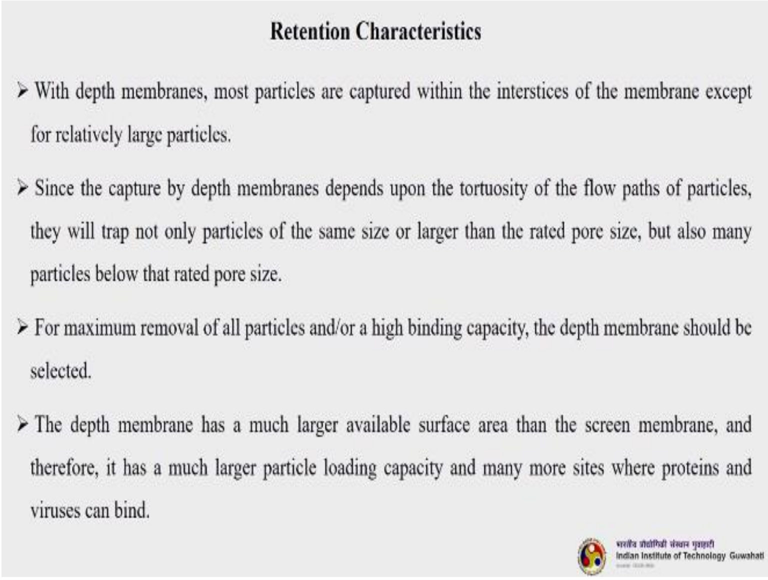

So with depth membranes most particles are captured within the interstices of the membrane except for relatively larger particles, so since the capture by depth membrane depends upon the tortuosity of the flow path of the particles they will trap not only particles of the same size or larger than the little pore size but also many particles below the rattle pore size so for maximum removal of all particles and/or high binding capacity that depth membranes should be selected.

The depth membrane has a much larger available surface area then the screen membrane and therefore it has a much larger particle loading capacity and many more sites where proteins and viruses can bind.

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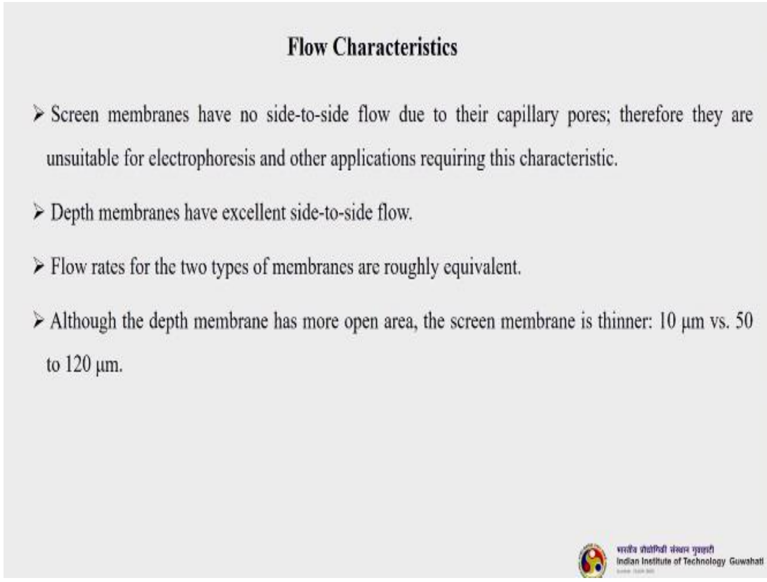

So now let us understand the flow characteristics; so screen membranes have no side-to-side flow due to their capillary pores therefore they are unsuitable for electrophoresis and other applications requiring this characteristics features, depth membranes are excellent side-to-side flow. Flow rates for the two types of membranes are roughly equivalent. Although the depth membrane has more open area the screen membrane is thinner 10 micron versus almost 50 to 120 micron.

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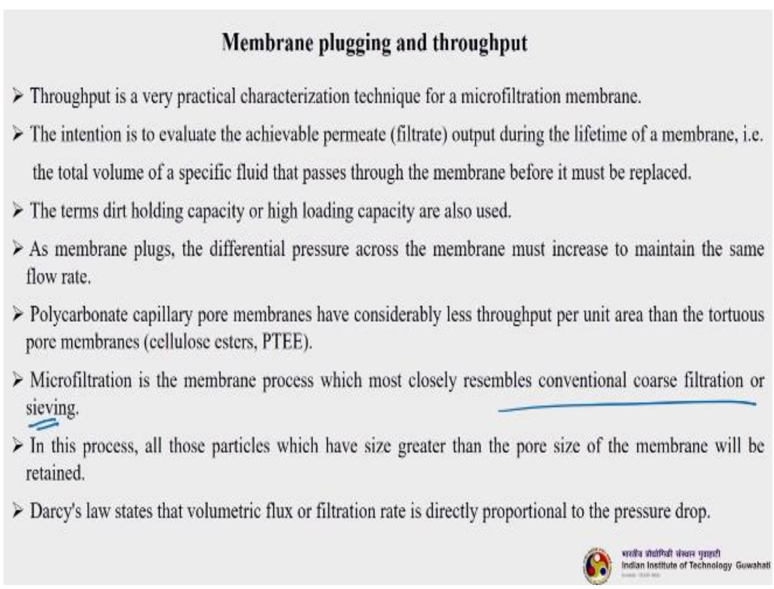

Now let us understand the membrane plugging and throughput. So throughput is the term which is essentially used for microfiltration as in ultrafiltration also, so throughput is a very practical characterization technique for a microfiltration membrane the intention is to evaluate the achievable permeate or filtrate output during the lifetime of a membrane. So that means a particular membrane during its lifetime, how much permeate or how much volume of permeate it will generate?

So this is what is throughput is all about before the membrane gets discarded completely, so that is the total volume of a specific fluid that passes through the membrane before it must be replaced. So the terms dirt holding capacity or high loading capacity are also used simultaneously as the membrane plugs the differential pressure across the membrane must increase to maintain the same flow rate.

So once you pressurize the system and the process is on, so permeate start will start coming initially will get more permeate because the membrane is clean slowly, slowly solutes will deposit on the surface of the membrane concentration polarization will build up and cake may build up so in that slowly, slowly you have to increase the pressure because if you do not increase the pressure.

If you carry out at a constant pressure and then flux decline profile will be very fast from the polycarbonate capillary pore membranes have considerably less throughput per unit area than the tortuous pore membrane as per example cellulose esters or your polytetrafluoroethylene. So microfiltration is the membrane process which most closely resembles the conventional of coarse filtration or sieving.

So in this process all those particles which have size greater than the pore size of the membrane will be retained so usually retention by separation Darcy's law states that volumetric flux or filtration rate is proportional to the pressure drop.

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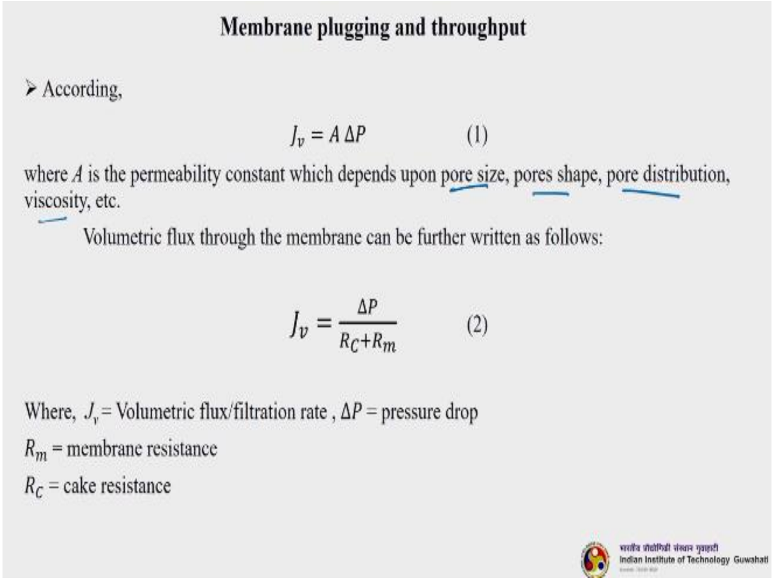

So here Jv equals to A into delta P where A is the permeability constant which depends on the pore size, pore shape, pore distribution viscosity etcetera. So volumetric flow flux through the membrane can be further written as Jv equals to delta P by Rc + Rm, so Jv is the volumetric flow rate or filtration rate delta P is the pressure drop, Rm is the membrane resistance and Rc is the cake resistance.

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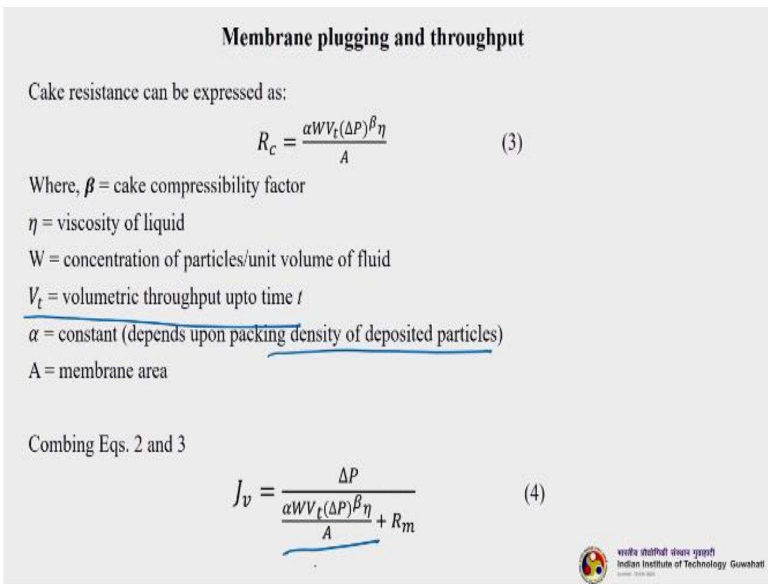

So cake resistance can be written as RC equals to alpha WVt delta P to the power of beta eta divided by A. So, were beta is called that known as the cake compressibility factor. It has viscosity of liquid then W is the concentration of particles or unit volume of the fluid, Vt is volumetric throughput up to time so this is what we are more interested to calculate alpha is a constant.

It depends upon the packing density of the deposited particles. A, is the membrane area. So if you combine the last two equations we can write Jv like this delta P by the say this is your Rc + Rm.

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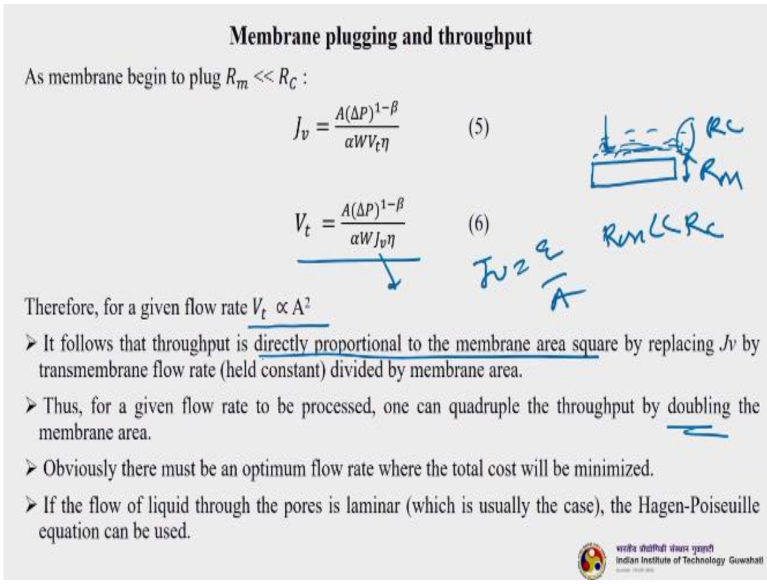

So what happens as the membrane begins to plug, here Rm will be much smaller than Rc. So this is you can say Rm so initially when the membrane is clean so then slowly solvent this cake layer our concentration polarization only started, so this is Rc. So when the process is on your Rm will be less, less than Rc so that means here RC will be the dominant resistance. So you can write Jv equals to A delta P to the power of 1 - beta divided by alpha WVt eta.

So Vt equals to this one you can see this for a given flow rate Vt is directly proportional to the A square A square means the membrane area square, so it follows that throughput is directly proportional to the membrane square area square by replacing Jv by transmembrane flow rate held constant. So we can write here Jv equals to Q byA. So that is for a given flow rate to be processed one can quadruple the throughput by doubling the membrane area.

So if you want a higher throughput you can just double the membrane area so you will get more throughput, so obviously there must be an optimum flow rate where the total cost will be minimized that is cost has to be taken care. If the flow of liquid through the pores is laminar so which is usually the case the Hagen poiseuille equation can be used.

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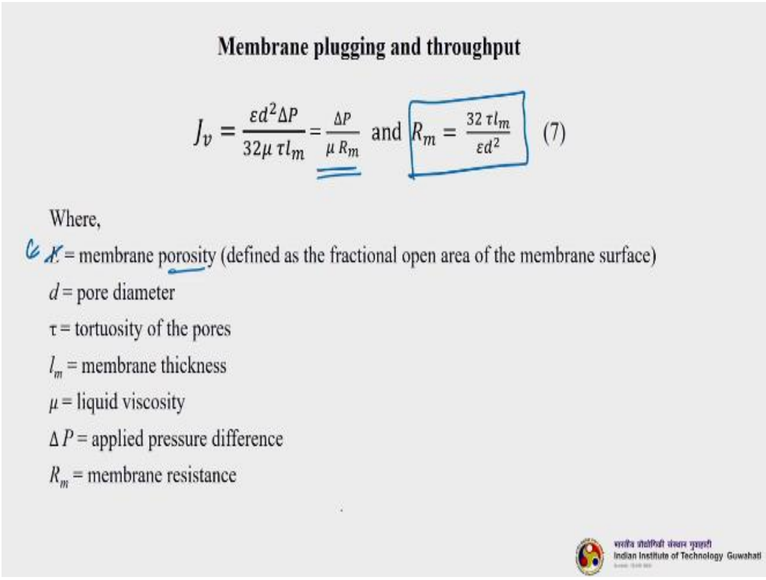

We know what is Hagen poiseuille, just showing it again so you can write Jv is equal to epsilon D square delta P by 32 mu tau lm that is nothing but delta P by mu Rm where Rm is this is a constant so E is the membrane porosity so it is not E actually it is epsilon so; d is pore diameter, tau is tortuosity of the pores, lm is the membrane thickness, mu is the liquid viscosity, delta P is the applied pressure difference, Rm is the membrane resistance.

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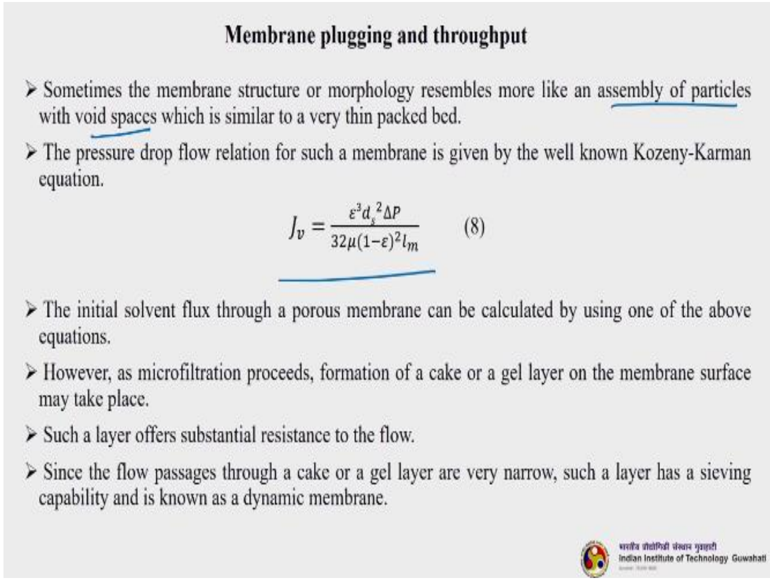

So sometimes the membrane structure or morphology resembles more like an assembly of particles with void spaces which is very similar to a thin packed bed. So you remember we discussed Kozney-Karman equation, this is the Kozney-Karman equation So in which it is assumed that the pores are interfaces between closely packed spheres of equal size so the initial solvent flux through a porous membrane can be calculated by using one of the above equation.

However as microfiltration proceeds, formation of a cake or a gel layer on the membrane surface may take place such a layer offers substantial resistance to the flow. Since the flow passages through a cake or a gel layer very narrow such a layer has a sieving capability and is known as the dynamic membrane.

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So with this today we conclude our lecture so most of the materials are taken from Professor Nath's book and little from Professor Becker's book you can please refer to them.

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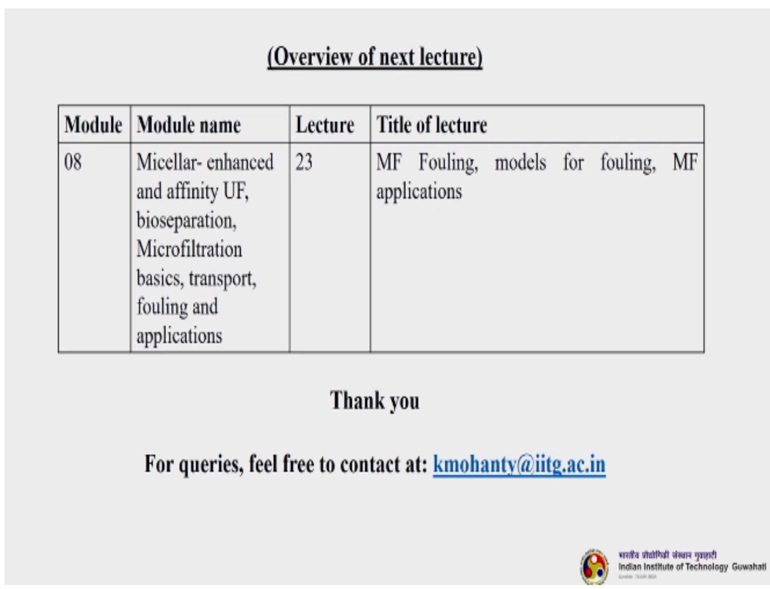

In the next class we will discuss, about microfiltration fouling, the models for microfiltration fouling and different microfiltration and applications. So thank you very much in case you have any query to please feel free to write to me at kmohanty@iitg.ac.in. Thank you.