Mechanical Unit Operations: Cross Flow Filtration
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Lecture 29
Cross Flow Filtration

Welcome to the MOOCs course Mechanical Unit Operations. The title of the lecture is Cross flow Filtration. In previous lectures what we have seen, we have seen working principles of cake Filtration and equipment, and different industrial equipment for cake filtration. Now, in this lecture we will be discussing a few details about the Cross Flow filtration and what are the equipments used and working principles of a few cross flow filtration processes would be discussed in this and in coming lecture.

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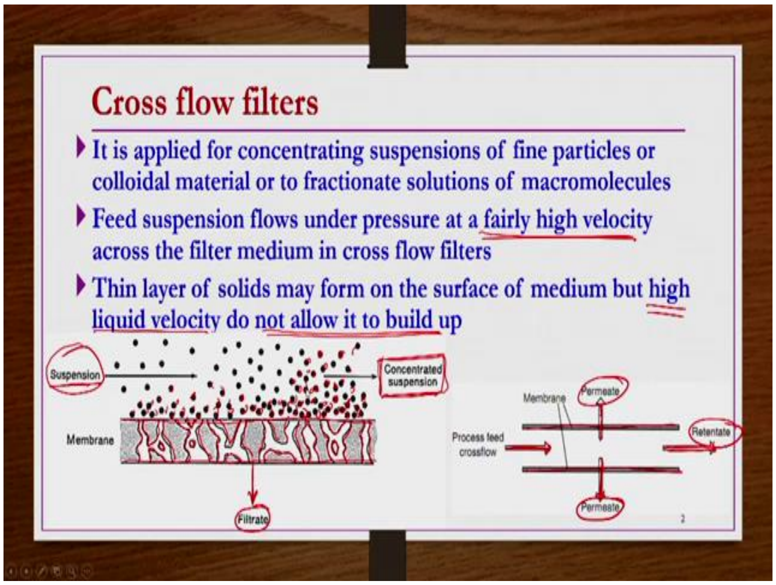

So what is Cross flow filters? As we have already seen the basics of filtration process, Cross Flow filtration: where we have a kind of a, a kind of membrane as a kind of a filter medium. So, this membrane may be having a kind of a porous structure, which may be a kind of almost channel kind of a structure or which may be having a kind of a connecting porous structure, something like this shown here, right? So, some of the channels openings are connected to the other porous openings.

Some are independently destined; in whatever way they are coming; just passing without any inter connection with other porous structure. So, this kind of membranes are in general used as filter medium for a cross flow filters. And then cake filtration we have seen, they are used in general for a coarse or large amount of solids; whichever the slurry or suspension that we take, in general, they have coarse particles and large amount of solid should be there then we usually use the Keg filtration.

But cross flow filtration we do usually when small amount of particles are there in the slurry, then we use cross flow filtration. Because you know small amount, but the particles are very fine, there are very small size particles existing in the suspension. If you use the (cross), cake filtration for such kind of slurry where small amount but fine particles are there; these fine particles, if they are allowed to form a cake, then they will be forming a kind of a, almost a dense layered particles which may not allow further permeation to take place once this layer is formed.

So almost a kind of a thin impermeable layer will be formed because of the very fine slimy particles, right, because of such problems of using such kind of solutions where small particles, fine particles are there in less amount; that is the problem of using the cake filtration. So, because, in order to avoid such kind of problems we use cross flow filtration process for such kind of solutions where small amount of particles would be there and their size would also be very fine, like you know few micron particles or something like that, right?

And these processes then you know, will not separate the slurry to the, almost two independent pure phases like pure filtrate or pure permeate and then almost like pure solids like cake as we have seen in kind of cake filtration. Such kind of separation is not possible here in this cross flow filtration. Here in the cross flow filtration whatever the suspension containing fine particles are there, they are allowed to flow cross the membrane surface at high velocities, at high velocities.

So what happens? Whatever the fine particles are there, they will be separated or they will form a kind of a, they will be deposited on the surface of the membrane like this, okay? As shown in the picture, and then you know what happens, they permeate, the clear permeate, almost clear permeate will be collected as a kind of a filtrate from the bottom like this, right? So, but you know what are forming, what are deposited on the filter medium or membrane surface are not allowed to build up as a kind of cake because of the high velocity of the suspension, suspension is allowed in general at high velocity.

And then, so whatever the high concrete retained is there, that is collected as a concentrated suspension in the other direction, okay? On the other side of the membrane, so that is how we do in general in a cross flow filtration. So, basically it is used for slurries, solutions where we are having small amount of particles but their size is very small; in microns or something like that then only we use this kind of cross flow filtration or then only if we use cross flow filtration the process would be efficient

And other point to remember, in this process we do not get almost kind of pure phases like in the almost kind of solid as a cake and then pure liquid as a kind of a permeate that whatever we get in cake filtration; such kind of thing we do not get, we get almost kind of a pure filtrate depending on the membrane and the process conditions, but other phase would be kind of a concentrate suspension, it will not be kind of a only highly loaded particles like cake.

It is not a kind of cake but highly concentrated suspension whereas the feet suspension is you know low concentrate suspension. The same process pictorially, we can also represent as a kind of a other way as shown here. Only thing is that we have kind of two membranes, right? So, between the two membranes, the low concentration solution; whatever the low concentrate solution having the particles, is allowed to flow cross the membrane surface in the parallel direction as shown here in this picture.

And then whatever, the permeate is there, that will be, that is the clear liquid, that will be collected as a kind of a permeate as shown here. And then concentrated suspension, whatever is there, that will be collected a as kind of a retentate as shown here, right? So, now is applied for concentrating suspensions of fine particles or colloidal material or to fractionate solutions of micro molecules; that is the main purpose of cross flow filtration where membranes are used a s a kind of a filter medium.

Feed suspension flows under pressure at fairly high velocity across the filter medium in cross flow filters. So, the thin layer of solids may form on the surface of the medium but high liquid velocity, whatever is being maintained, that will not allow particles to build up as a kind of cake. So cake formation would not be there because of high velocity for field liquid.

That will be carrying away particles along the flow direction because of the high velocity. That is the reason, pictorially we can also see, in the retentate side here in this picture more particles are there compared to the other side, because more particles are being carried in the flow direction as a kind of a retentate because of the high velocity of the feed, whatever feed that we have taken.

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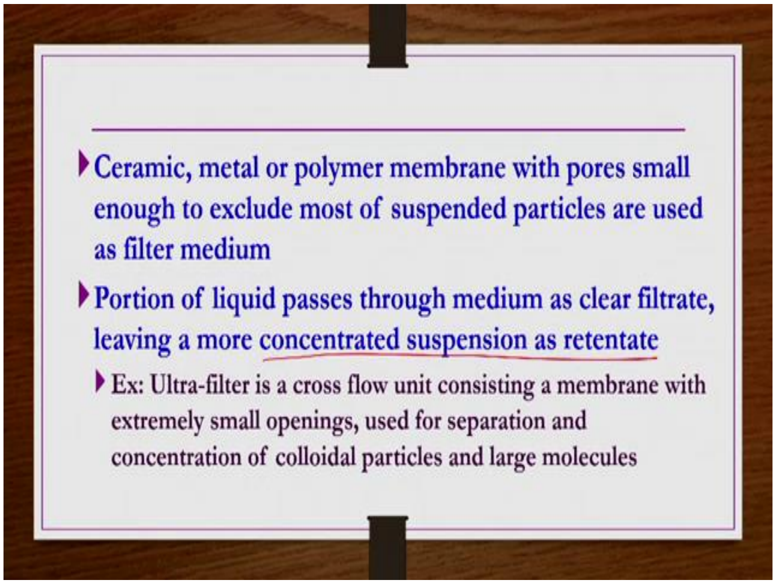

So we understand that membranes are a kind of filter medium for this kind of cross filtration. So what kinds of membranes are in general used? Usually ceramic, metal or polymer membranes are used. These membranes should have a kind of a pores small enough to exclude most of the suspended particles, you know when these membranes are used as a kind of a medium okay? Then, portion of liquid passes as a clear filtrate, as I mentioned, leaving more concentrated suspension as retentate.

So, separation of these suspensions, suspension of these liquid into two pure phases, almost pure faces is not possible here. One you get almost clear liquid kind of thing, having very small or negligible particles as a kind of a filtrate or permeate you will get. Whereas the other phase would be concentrate suspension which is known as the retentate in membrane terminology.

Example: Ultra-filters is a cross flow unit consisting a membrane with extremely small openings, used for separation and concentration of colloidal particles and large molecules.

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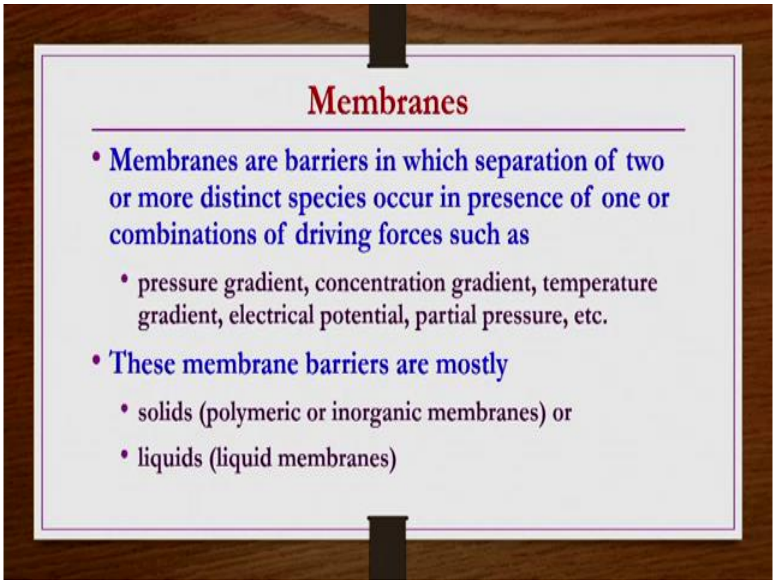

Now, after realising that this cross flow filtration would take place only if you have a kind of a membrane as a kind of medium, it is important to know basics of membranes. What is membrane, what kind of driving forces are there, you know, what kind of properties are there that are going to affect this operation process and then the different types of membranes available, how the membranes are prepared and then what kind of modules are available industrially.

You know, you need to have a kind of large surface area, you know, in the membrane, so then how you kind of have a continuous process using, you know this process, etc. and different modules etc. those kind of things we are going to discuss in this particular lecture, because now the membrane is a kind of filter medium here. Membranes are semi permeable barriers in which separation of two or more distinct species occur in presence of one or combinations of driving forces.

So, you take a membrane, now you allow a kind of a suspension or solution to flow through this membrane. So, depending on the porous structure of the membrane, permeate will pass through and then particles would be retained. So, this membrane separation processes in general can be dead end as well as the cross flow filtration also. We will be discussing only cross flow filtration, dead end that is across the surface of the filter medium, that you know membrane surface that is known as kind of a dead end filtration, membrane separation.

Let us says, this is the membrane separation, the solution will come in this direction and then permeate will be passing through or particles will be, let us say high concentrate retentate would be retained on the membrane surface. So, this is a dead end process but we are taking only cross flow processes only and theses membranes are kind of a semi-permeable barriers where they selectively allow one or two species to pass through and one or two other species retain, they will not be allowed to pass through the barrier right?

So, how this separation would occur? Though these membranes are semi-permeable and then selective to specific spaces, they will allow those species, other species they will not allow. But there should be a kind of driving force for such kind of separation to occur as well. So, what kind of driving forces are used in general? There are several types of driving forces are there. These driving forces may be used as individually, or in combination of several driving forces used in general depending on the applications.

So, such as pressure gradient, concentration gradient, temperature gradient, electrical potential gradient, partial pressure, etc. are used in general as a kind of a driving force for separation to occur using these semi-permeable membranes, okay? Now, these membranes in general can be solid or liquid membranes. Solid membranes can be organic or inorganic membranes. Organic membranes are something like polymeric membranes; inorganic membranes are something like carbon membrane, etc. are used. Then liquid membranes are also available.

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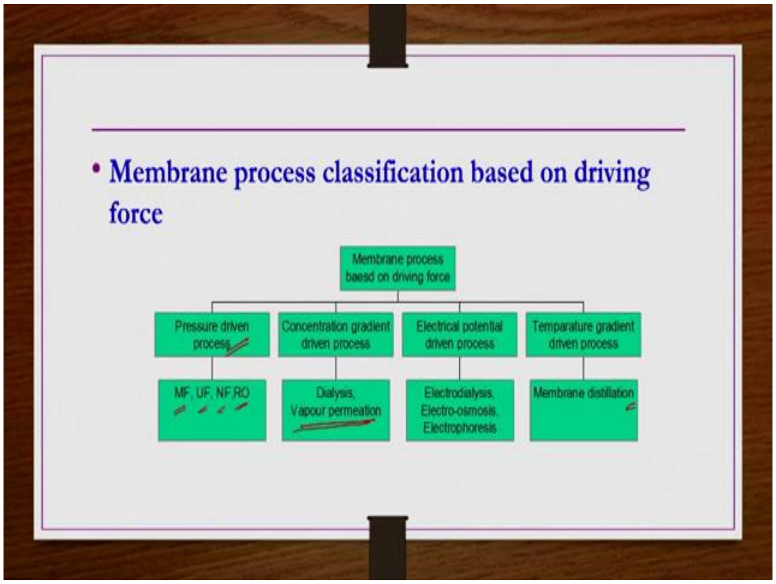

Then membranes process classification based on driving force. As we have seen the separation is occurring based on the, you know, type of driving force applied. So it is possible that when a particular type of driving force is applied, whatever the membrane processes are there, they may be designated as a kind of or named as a kind of certain membrane processes. So, based on the driving forces how we can classify these membrane forces that we are going to see now here.

So, let us say that pressure is the driving force for the separation to occur through the semi-permeable membrane, and then we have micro-filtration, ultra-filtration, nano-filtration and reverse osmosis coming in this category. If you have a concentration gradient as a driving force then we a dialysis, permeation, gas separation, etc. those kinds of things are coming into these kinds of processes where concentration gradient is driving force.

If electrical potential is driving force, then electro-dialysis, electro-osmosis, electrophoresis, etc. will come into this category. If you have temperature gradient as a driving force for separation, then membrane distillation kind of processes would come into the picture under this category. And as I already mentioned that it is not necessary that only one type of driving force is only required for a given separation technique.

It is also possible that for a given separation process, more than one driving force is also applied. Let us say vapour permeation or gas separation mixtures in general, not only concentration gradient but pressure gradient would also be acting a as a kind of driving force. Similarly, like in membrane distillation, it is not necessary that only temperature gradient is acting as a kind of driving force but in addition to that one there may be a kind of a concentration gradient as well as pressure gradient.

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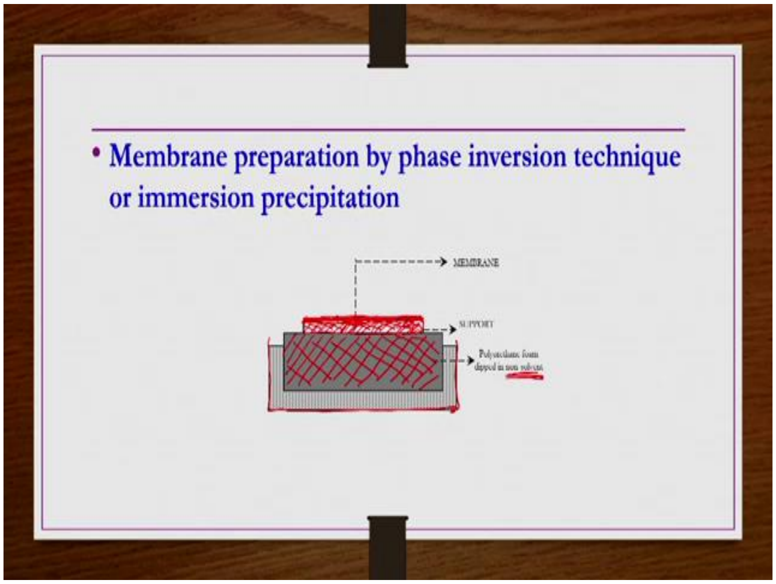

Now, membrane preparation, how to prepare these membranes? There are different methods of preparing membranes, we will not be going to see all the details because membrane is itself a kind of a, or membrane separation technology is itself a kind of a separate subject in general for chemical engineering students. So, we cannot cover all the details in one or two lectures, so we will be discussing only a few details. So, one of the membrane preparation techniques I am discussing here though there are many other types of membrane preparation techniques.

So, this technique that I am discussing here is phase inversion technique or immersion precipitation technique. Here, what happens, let us say you are preparing a kind of polymeric membrane, so for that polymer you have to find out a non-solvent as well as the solvent, because polymer, you cannot use as it is a kind of precursor for membrane preparation. It has to be made a solution, so for that you have to find out a solvent.

So you take 5 % or 15 % polymer in the solvent and prepare a polymer solution depending on the thickness of the membrane and porous structure of the membrane, you have to decide how much percentage of polymer solution has to be taken. And you should also find out a kind of non-solvent for that kind of non-polymer, right? So, let us say that you have found a kind of non-solvent for the polymeric membrane that you are preparing so that you take any kind of container that you here like this, right?

And then into that one you, what you do, you dip a polyurethane foam, something like this as shown here, so you are dipping here. The polyurethane foam is a kind of a, having porous (structure), micro-porous structure, you are having here in the urethane foam in general. So, then what happens, all the porous structure of this foam will be occupied by the non-solvent, would be occupied by the non-solvent because of the diffusion. So, initially, there is no non-solvent in the porous structure of the foam.

Then when it is dipped in container in which non-solvent is there then the porous structure would be occupied by the non-solvent. Now, on to this foam: what you take, you take support, right? Let us say you are preparing a supported membrane. The support in general is a macro porous structure again but porous structure besides the pore are much smaller compared to the porous structure of the foam, polyurethane that you have taken. Compared to that one the porous structure of this, you know, support is small right? The pore sizes are small here.

So, now when you keep this support on, so different types of support are there; let us say clay support right? You have a clay support that you are keeping on the surface of this foam. Then whatever the pores are there within the support, the pores initially are empty, right? Or are occupied by, you know, some gases or something like that vapour or something like that; so those would be replaced with the non-solvent. So because, why because? That support has been kept on foam whose pores are already occupied by the non-solvent.

So, now that non-solvent would permeate or you know occupy the porous structure of this support. Now this support is formed, now this support, pores of this support, macro porous support is also occupied by the non-solvent. Onto the surface, support surface, now what you do? You take a definite amount of solution, whatever the polymer solution that you have prepared; 10 % or 15 % polymer solution that you have prepared, you measure a definite amount as per the requirement of the thickness of the membrane as well as the porous structure of the membrane.

That solution you pour on the surface and spread it like this. When you spread it and then after spreading it you just leave it for air-drying kind of thing. In general air drying is done, it can be done at a, it is a kind of better process, so that slow evaporation of this solvent will take place, whatever the solvent that you have taken to make this polymer solution, slowly that will start evaporating and then the polymer layer, whatever you have formed, by the solution of the polymer solution whatever layer you have formed gradually as time progresses.

The solvents keep evaporating and then because of that evaporation there will be a kind of porous structure would be formed on the surface of the support. On the support the polymer layer is there, on that layer porous structure would be developed depending on the degree of evaporation of the solvent form this layer. So once all this solvent is evaporated, that polymer layer would almost be dried kind of thing and then once dried polymer layer is formed on a kind of support.

Then that can be taken and then further dried in a oven at a lower temperature like, you know, 50 $^{\circ}$C or 40 $^{\circ}$C, depending on the temperature sensitivity of the polymer, okay? Then that is how the membrane is prepared by this phase inversion technique, right? So, why this non-solvent is required here? If you do not take the non-solvent and then if you do not allow the porous structure to be filled or occupied by non-solvent, whatever the polymer solution is there, that, you know, that will go inside the porous structure of the macro porous and then that will block the pore.

Rather than having a kind of membranes with proper porous structure, if you do not take this non-solvent, you know that polymer solution will go inside the porous structure of the support and whatever the macro porous structure of the support is there, across the length, that will be occupied by the polymer solution and then even that support will become non-porous. So that is the reason this non-solvent is there.

If the macro porous structure is already occupied by the non-solvent, then even if the polymer solution comes in, it will not be able to dissolve because the porous structure is already occupied by the non-solvent, okay? So, then because of that one the blocking of this will not take place and then as once this polymer solution, whatever is there, it is evaporated then gradually then, when you take out and keep it outside of the foam, the support; whatever the support. The porous structure of the support, whatever the non-solvent is there, that will also be gradually evaporating and that will also be kind of a, you know, porous structure in the membrane.

While these molecules of this solvent or non-solvent are crossing through the polymer layer, they will form a kind of a small, small pore structure. So, this is how, kind of, membranes are prepared by immersion, phase inversion technique or immersion precipitation technique. There are many other methods which may also be available, right? We are not going to all the details. This is just giving just a kind of information so you know how to prepare all the membranes in general.

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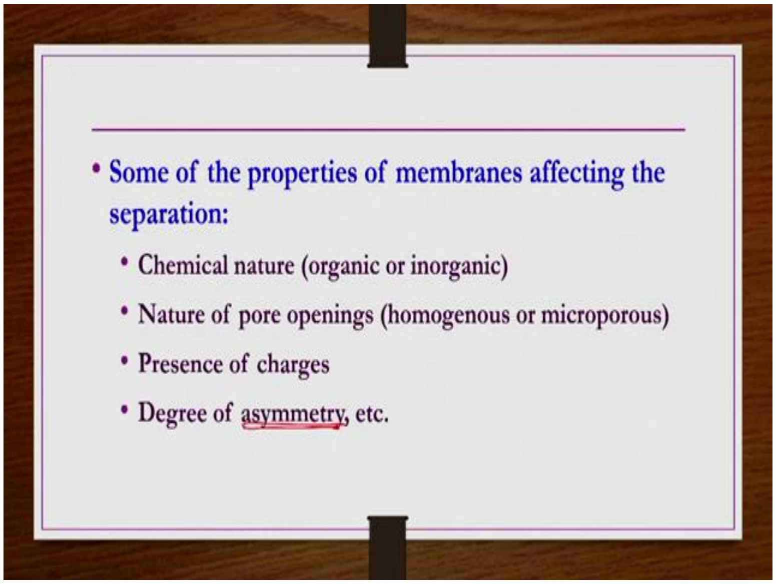

Now, we understand that you know the properties of membrane are definitely going to show a kind of effect on the separation process because depending on nature of the membrane, depending on charges, etc. there on the surface, you know definitely some of the properties, even depending on the pore structure; how narrow pore sizes are, how wide range of pore structure are there; depending on that one also the separation process is going to be affected.

So, what we understand form these couple of examples, definitely some of the properties are going to affect the separation of whatever the mixture that we have taken. So what are those membrane properties which may affect this separation process, we will see now, right? Chemical nature: whether organic or inorganic membrane that is going to have a kind of influence. Then nature of pore opening, micro porous, homogenous or symmetric, asymmetric or charge surface, membrane surface, etc. or membrane openings are also charged those kind of things are going to have an influence, that is nature of pore openings.

Then presence of charges, if at all, in general some membranes are having you know, functional groups on the surface. Or in general, artificially, chemically reacting, the membrane surfaces, you know, made to have a kind of charges, you know. Or, you know some kind of chemical groups will be attached to the surface through chemical reactions so that through those functional groups the membrane surface will attract some kind of charges so which can be useful in charge separation kind of thing.

Or separation based on the charges wherever is, under such conditions; you know membranes charge on the surface can be used so that it is also going to show affect. And degree of asymmetry: membrane is symmetric or asymmetric, that is again, you know, going to be having a kind of a role. If it is asymmetry, what is the degree of asymmetry that is also going to be important? We are going to see what this asymmetric membrane is very soon now.

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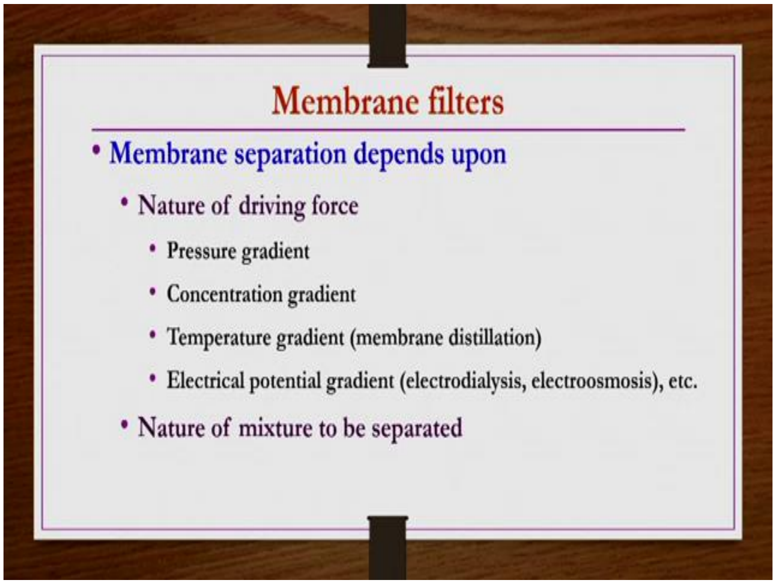

So, then membrane filters and how to classify them. Membrane separation depends upon nature of driving force that we have seen. So, given type of separation you need to find the appropriate driving force. According you need to do, if only one driving force is required, if more than one driving force are required, so then what are the other driving forces that you have to identify and accordingly you have to apply. So, that is nature of driving force that you is going to have a kind of effect.

And membrane separation is going to depend on nature of driving force such as pressure gradient as already seen, temperature gradient, concentration gradient, electrical potential gradient etc. Then nature of mixture to be separated, whether the gases mixture or liquid mixture, what are we separating that also has a kind of influence on the membrane separation process.

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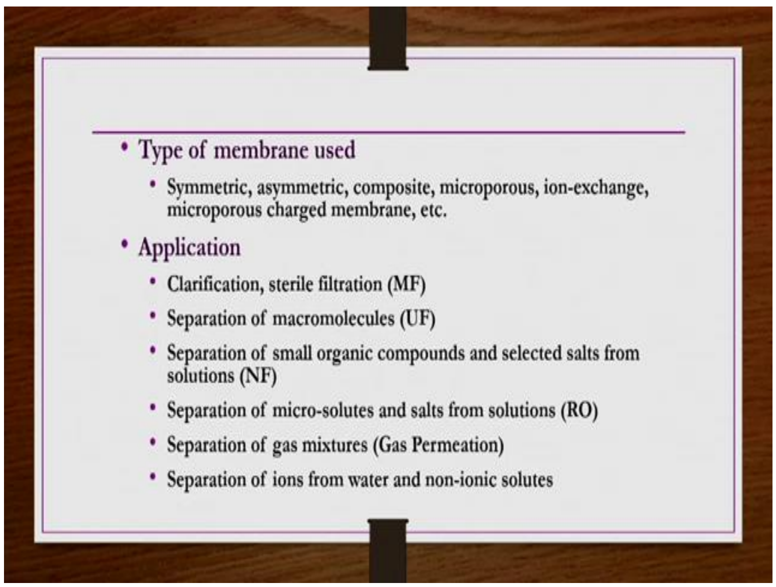

And then types of membranes used, different types of membrane processes. Different type of membranes are used, like sometime symmetric membranes are good, sometimes asymmetric membranes are good, like that in composite, micro porous, ion-exchange, micro porous charged membranes, etc. are also available so what type of membrane are we using, that is also going to have a significant role in the membrane separation process.

So, the selection of membrane is very essential. Then sometimes, application oriented also you have to select appropriate membranes for a proper process. That is, application is also going to have a affect for a given membrane separation process, okay? Let us say you take a membrane which is more suitable for a kind of a micro filtration or ultra-filtration but such membrane if you are using for reverse osmosis, the performance may not be good enough.

So, application oriented also this membrane separation is going to be affected by the application. Something like clarification, sterile filtration, if you have to do, it is better to use micro filtration membranes. If you want to separate macro molecules then ultra-filtration is better, then accordingly you have to choose a membrane. If you want to separate small organic components and selected salts from solution then membranes which are suitable for nano-filtration should be used.

If you want to separate micro solution salts from solutions then reverse osmosis based membranes are better. Like that, keep on listing, if you have a gas permeation is the kind of mechanism that is leading to the separation for gas mixtures, then gas permeation process and corresponding membrane should be used like that. Application is going to be a kind of very much important factor which is leading to the, you know, which is deciding the separation process.

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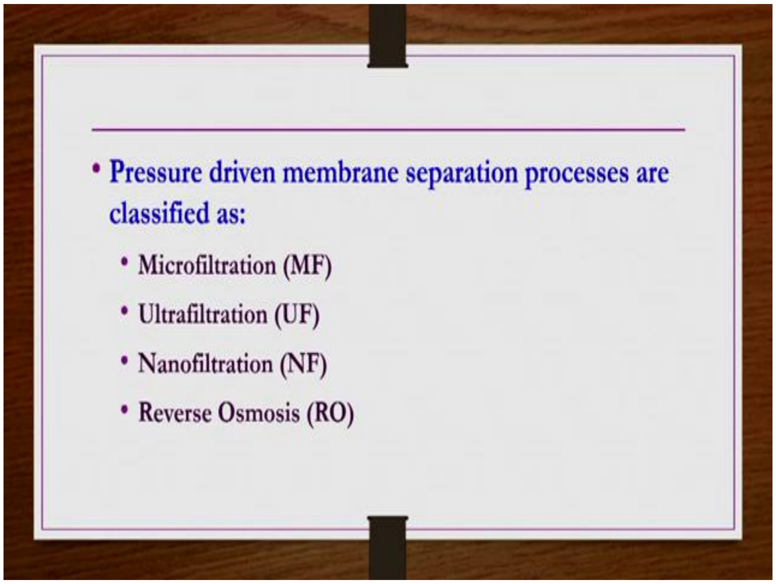

In this lecture we will be discussing only those separation processes which are based on the pressure gradient driving force, why because whatever the filtration those things we have been seeing, we are primarily considering only the pressure based, or you know vacuum based, or centrifugal force based filtration processes only we consider which are better for a filtration process. So, membranes there are several types of driving forces are there.

But for cross flow filtration, where membranes we are using, there you know, pressure based separation processes are essential. And then those pressure based separation processes only we are going to discuss in this lecture, okay? So, what are the pressure driven membrane separation processes which we have already seen they are: microfiltration, ultrafiltration, nano-filtration and reverse osmosis which is also known as hyper filtration. So, we are going to see a few details of this membrane processes only.

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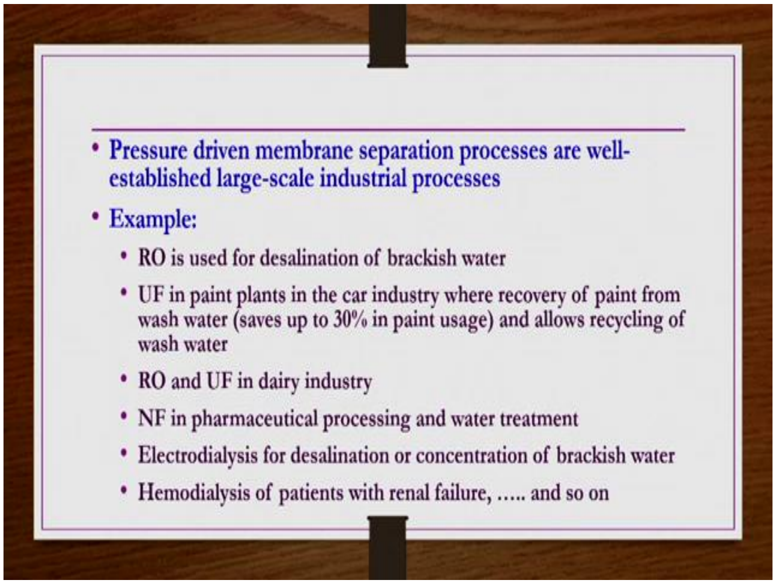

Pressure driven membrane separation processes are discussed primarily here, not only because of the restrictions but also because of they are established, their well-established industrial level. Especially in large scale industrial processes, these pressure based membrane separation processes are well established. So that is the other reason that we are primarily concentrating here in pressure driven membrane separation processes.

So, some examples where this industrial application has being done, so all know that reverse osmosis is used for desalination of brackish water. Many of the water purifying units, in general, we used at our household applications were also based on the reverse osmosis or ultra-filtration in general. Ultrafiltration in paints, right, in paints plants like you know car industries are there. Car industries you know, body parts of car in general are coloured in different paints, right?

So when you do this painting, large amount of paint goes waste and that paint has to be washed out. So, by using these ultrafiltration membranes, when you separate whatever the wash liquid is there, after the car, you can save up to 30% paint usage by using this ultrafiltration membrane. Whatever the clear or almost clear water that has been recovered from the washed water can be reused as a wash water by recycling it. That is the other applications.

Then in dairy industries, this reverse osmosis and ultrafiltration are very famously used in many of these dairy industries. Nano filtrations are very much used in pharmaceutical processing industries. Electro dialysis for desalination or concentration of brackish water is also used. And then Haemodialysis of patients with renal failure, etc., like that if you keep on listing, there are n number of applications. These pressure driven membrane separation processes are well-established.

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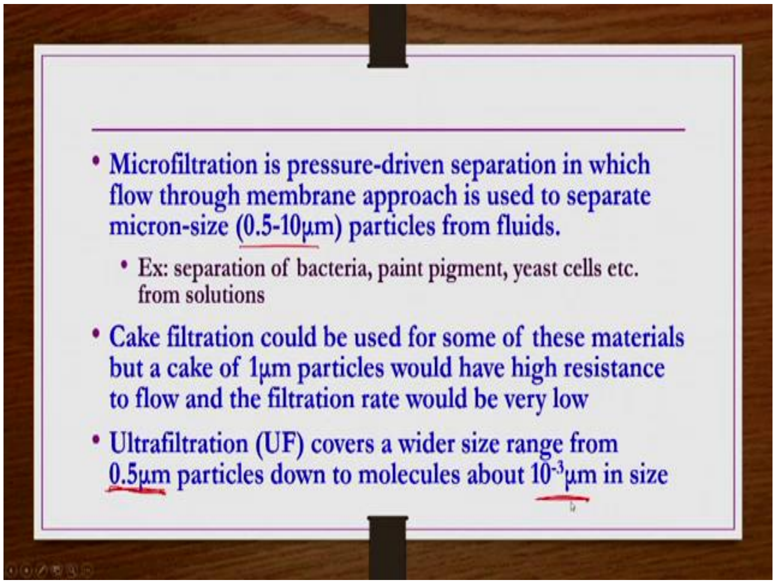

So, now we see one by one, details of this pressure driven membrane separation processes. Microfiltration is pressure-driven separation in which flow through membrane approach is used to separate micron size particles from fluids. The particle size in general 0.5 to 10 microns, right? When we have such kind of particles, you know, in general people may think, you know, cake filtration may also be used, but as I already mentioned, when you have such smaller particles they may be forming a kind of almost impervious, dense layer on the filter medium.

Or the membrane surface which will not allow further separation to take place or further separation to take place. That is the reason, you know this, you know this solutions were having such small particles; we do not use any cake filtration processes rather we go for cross flow filtration processes using one of the processes that we are going to discuss.

The particle size is in general between 0.5 to 10 microns, then it is better to go with microfiltration with pressure difference or pressure gradient having less than 0.5 atm. Some applications are given here, like you know, bacteria, separation of bacteria, paint pigment, yeast cells, etc. from solutions. On the other hand ultrafiltration covers wider size range; from 0.5 microns particles down to molecules as small as 10^{-3} microns,

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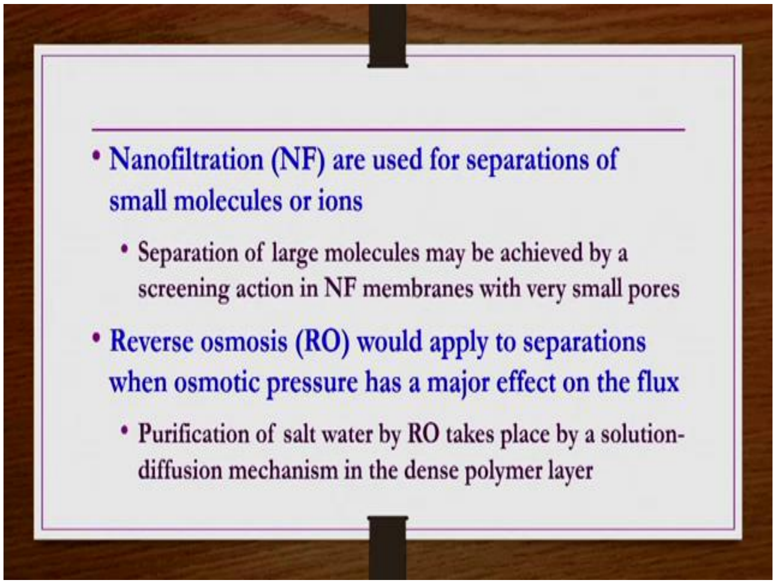

Whereas the nano-filtrations are used for separation for small molecules or ions, separation of large molecules might be achieved by the same nano-filtration where the screening action takes place using a kind of nano-filtration membranes with very small pores. In general, nano-filtration membranes are used or nano-filtration separation processes are used to separate very small molecules or ions.

But such membranes if you use, for you know, separations having large molecules then the separation will take place by a kind of screening action. Reverse osmosis would apply to separation when especially the osmotic pressure has a kind of major effect on the flux.

Something like purification of salt water by reverse osmosis takes place by a solution diffusion mechanism in the dense polymer layer.

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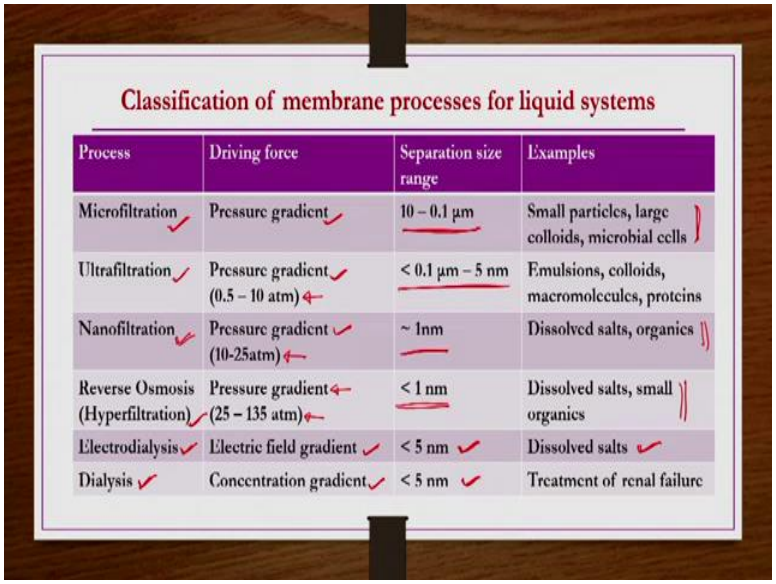

Classification of membrane processes for liquid systems

Process	Driving force	Separation size range	Examples
Microfiltration	Pressure gradient	10 – 0.1 µm	Small particles, large colloids, microbial cells
Ultrafiltration	Pressure gradient (0.5 – 10 atm)	< 0.1 µm – 5 nm	Emulsions, colloids, macromolecules, proteins
Nanofiltration	Pressure gradient (10-25atm)	~ 1nm	Dissolved salts, organics
Reverse Osmosis (Hyperfiltration)	Pressure gradient (25 – 135 atm)	< 1 nm	Dissolved salts, small organics
Electrodialysis	Electric field gradient	< 5 nm	Dissolved salts
Dialysis	Concentration gradient	< 5 nm	Treatment of renal failure

So, now we see classification of membrane processes for liquid systems, what are the processes, what are the size ranges and then what is the pressure gradient, what are some applications, those kinds of things we are going to see in a kind of tabular column? Now, here we can see if you have a kind of microfiltration process, then driving force is the pressure gradient and particle size range is in general 10 to 0.1 microns.

Examples where they are used: Separation of small particles, large colloids, microbial cells, etc, then micro-filtrations are used. When you have a ultra-filtration membrane then pressure gradient is again driving force, the range of pressure difference is 0.5 to 10 atm and they are better suitable for separation size range, if it is less than 0.1 microns to as low as 5 nm.

Examples are emulsions, colloids, macro molecules, proteins separations from solutions, if you have a nano filtration; then again the pressure gradient is a kind of a driving force and then the pressure drop is in general 10 to 25 atm. They are used if the separation size range is approximately of nanometre size, examples area kind of dissolved salts, small organics, etc. Then reverse osmosis or hyper filtration if you have, there also pressure gradient is the driving force.

But the pressure drop is as high as 25 to 135 atm; used for separation size range is less than nanometre. It is used for separating dissolved salts or small organics etc. Electro dialysis, if the process is electro dialysis, then the electric field gradient is a kind of a driving force, good for separating the molecules of particles of size less than 5 nm, better for separation of dissolved salts from the solutions. If you have dialysis, then concentration gradient is a major driving force, then this is good for separating particles less than 5 nm. Examples: treatment of renal failure patients.

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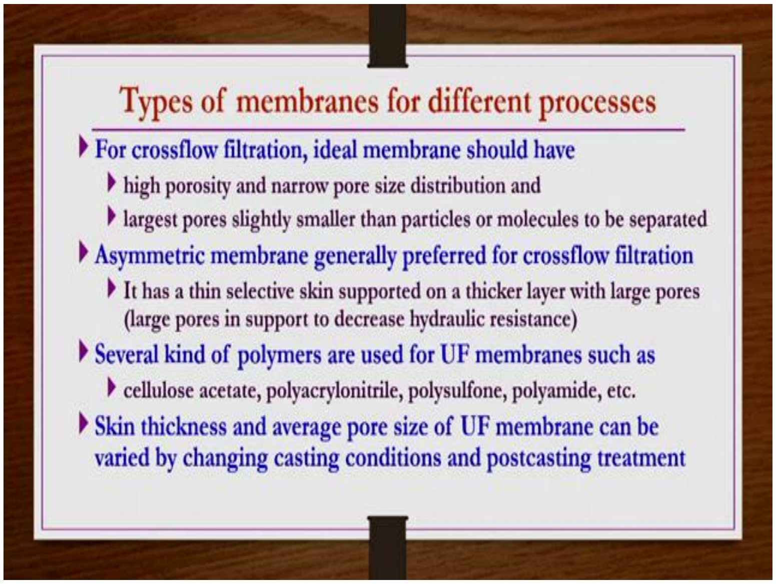

So, now what types of membranes are used? For different processes, different membranes are used. All these classification, are kind of, arbitrary kind of thing and even if someone wanted to do classification, this classification has to be done with respect to your particular property, right? So, let us say if you are doing kind of a process oriented classification of membranes if you wanted to do then how to do that.

So, let us start with the cross flow filtration because we are discussing for cross flow filtration, for cross flow filtration, the ideal membrane should have high porosity and narrow pore size distribution and the largest pore should be slightly smaller than the particles that are to be separated. And for such kind of cross filtration asymmetric membranes are preferred.

Asymmetric membranes, they have a kind of a thin selective skin supported on a thicker membrane.

So, there is a support, on that one there is a membrane skin is deposited, the support is macro porous and then the skin; whatever the layer polymer support is there, kind of a macro porous structure. So the molecules pass through the membrane, so they can easily pass through the support. So because of that macro structure of the porous support, the hydraulic resistance is also less. Several kinds of polymers are used for ultra-filtration membranes such as cellulose acetate, polyacrylonitrate, polysulfone, polyamide, polyemide, poly methyl methacrylate, etc.

These kinds of solutions polymers are used for ultrafiltration membranes. Skin thickness and average pore size of the membrane can be varied by changing casting conditions and post treatments. Like you know if you are doing the phase inversion technique for membrane preparation, so what are the casting conditions and then what are the post casting conditions. So, by playing around the conditions one can get a solution to properly then, you know, pore size.

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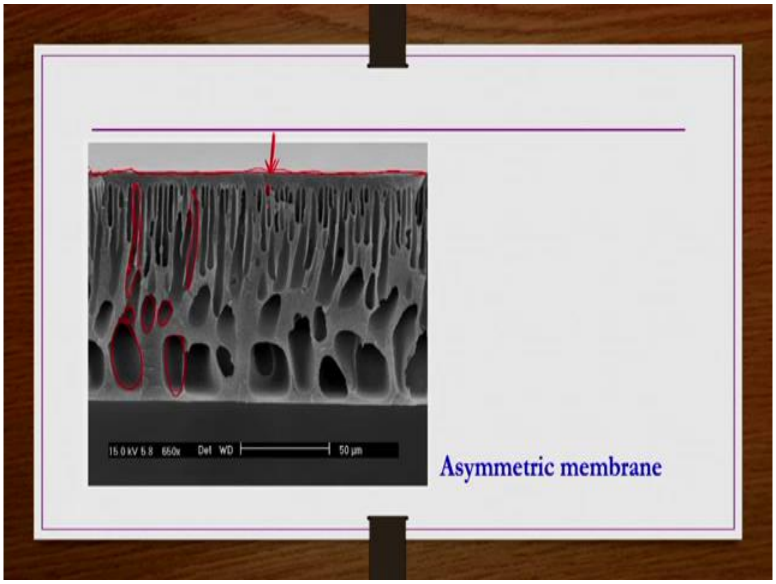

So, now we see an example or a picture of a asymmetric membrane to understand to understand what is this asymmetric membrane in general. Asymmetric membranes, in general, are supported on a kind of a porous support, okay? This porous support is also such a way that the porous structure, though the porous structure is in a macro porous range.

At the top of the support the porous structure opening is narrow but as you pass through, as you go through across the section of the support, the size of this pore gradually increases like this okay? And then on this support we have a kind of a casting of membrane layer which can be acting a as kind of a, you know, separating medium here. This polymeric membrane layer would have a kind of a smaller micro porous structure whereas the support will be having a macro porous structure.

So once the molecule, whatever the molecule will be permeating or passing through this membrane that will be easier to pass through because after that, you know, porous structure, the size of the pores are gradually increasing. So, because of that also hydraulic resistance would be decreasing for this kind of asymmetric membranes. This is one example of asymmetric membrane.

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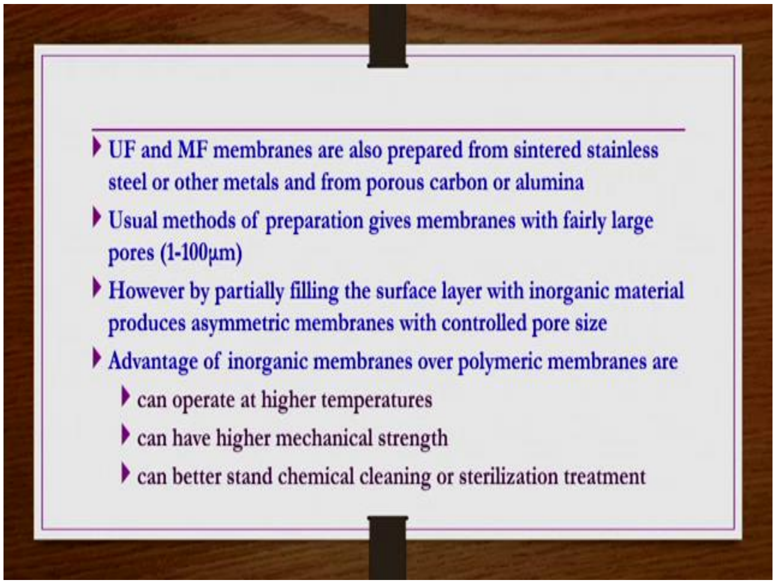

Then ultra-filtration and micro filtration membranes are also prepared from sintered stainless steel or other porous carbon or alumina as well. Usual methods of preparation gives membranes with fairly large pores varying from 1 to 100 microns, 1 to 100 microns is a very wide pore size distribution, so in general that is not good for a given application. So, it is better to have a pore size distribution narrower. So for that in general what you do? You can have a kind of partially filling surface layer with inorganic material so that to produce asymmetric membranes with controlled pore size.

That is one of the techniques to control pore size distribution. Then in general, inorganic membranes have advantages over organic or polymeric membranes. So, what are those advantages: these inorganic membranes can operate at high temperatures, can have a higher mechanical strength and can withstand a chemical cleaning or sterilisation treatment of the membrane after the treatment? So these are the three important, you know, advantages of inorganic membrane actually, polymeric membranes.

You cannot use at high temperatures because most of the polymers are sensitive with temperatures. If the temperature goes beyond 50-60°C then kind of changes in the polymer structure will start to take place, okay? And then mechanical strength also, if you apply large pressures, then, let us say in a pressure driven membrane process if you apply large pressures then polymeric membranes will be getting you know some kind of cracks, even breaking the entire membrane, that is possible.

But if you have a kind of you know inorganic membranes, carbon membranes, etc. that mechanical strength is also very high. Then sometimes, you know in industries, after the separation process is done, it is required to clean the membrane surface, so that it is, it should be ready for the next cycle kind of thing or next separation process. Under such conditions sometimes you maybe cleaning with some kind of chemicals depending on the nature of the particles that are deposited as a kind of layer on the membrane surface, right?

So, obviously when separation is taking place through the membrane medium, what happens is that it is not necessary that all or only permeate is passing through. Some of the particles may also pass through the porous structure and then some of the porous structure may be blocked. Cleaning of membrane is required in order to make them clear. So, if I use chemical cleaning then you know, polymeric membranes may be sensitive to different types of chemicals and they even may react.

But if you have inorganic membranes such as carbon membranes etc such kinds of problems will not be there. So that is indirectly inorganic membranes, how better mechanical, chemical and thermal resistance compared to the organic membranes.

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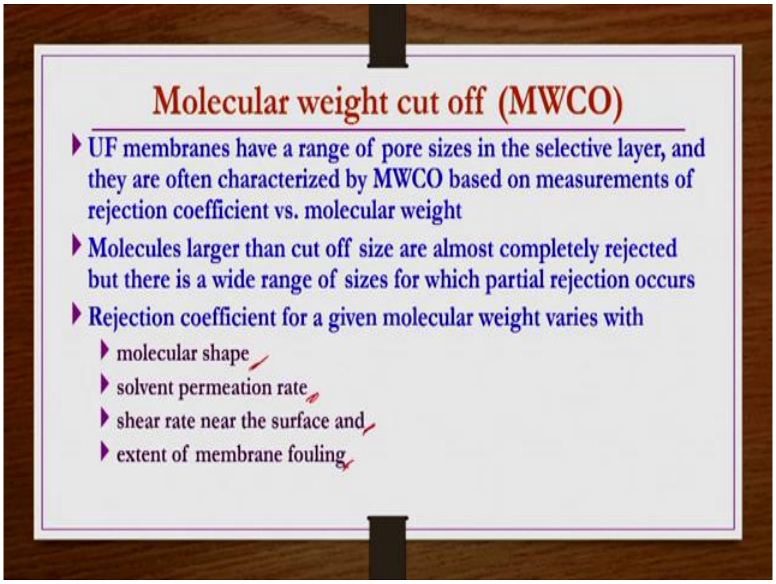

Then molecular weight cut off is one of the way of characterising the membrane which gives a kind of a clear idea or a prior information about the performance of the prepared membranes, like ultrafiltration membranes have arrange of pore sizes in the selective layer and they are often characterised by this molecular based cut off based on measurements of rejection coefficient versus molecular weight. What you do, you take some kind of molecular solutions which are having different kind of molecular weight.

Let us say polyethylene glycol you take, you can take polyethylene glycol of different molecular weight like 100, 500, 100 and 10,000 and up to 1 lakh molecular weight something like that. And then you make a solution of this PEG and then at a specified pressure, or the pressure at which you wanted to do the separation, you do the separation of this PEG solution and then you calculate the rejection coefficient for a given molecular weight solutions.

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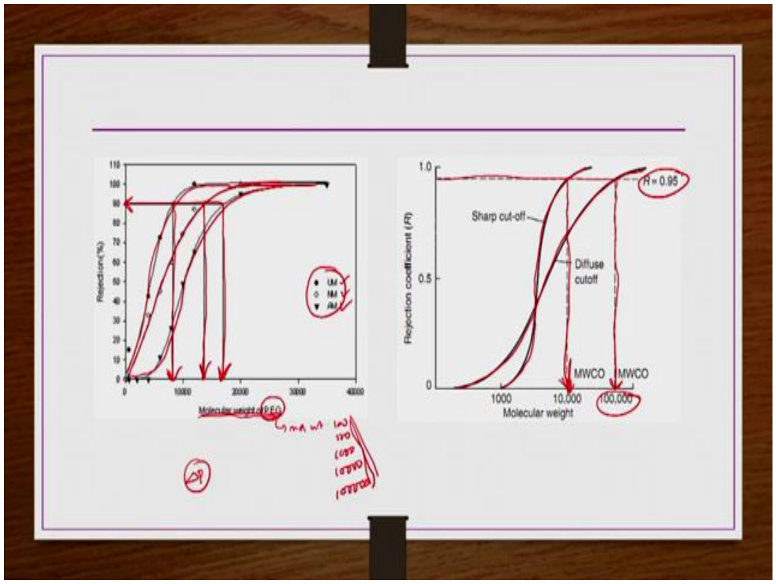

So, now we see couple of pictures about the molecular weight cut off. Now here in this first picture what we can see, we can say x axis molecular weight of PEG that means you know these are the different solutions, PEG solutions are prepared which are PEG of different molecular weights are taken like you know 100, 500, 1000, 10,000 like this, you know, up to 1 lakh molecular weight or even more are available.

These materials are taken and are dissolved in some kind of solvent to make a solution. So some PPM of this solution are taken and then there separation is tried out using the ultra-filtration membranes. Three different types of ultra-filtration membrane are used, so the pressure was fixed ΔP, okay it is fixed at one pressure drop it is, this experiment has been done, so now we can see for each of these three different membranes, let us say u m nm a are the three different types of the membranes.

So, we can see here the rejection versus molecular weight cause are having kind of almost similar size but they are different from each other, but they are different from each other. And now how to find out this molecular weight cut off, this is nothing but molecular weight at specified rejection percentage, this specified rejection percentage varies in in general people take 90 %, some people also take 95% or 99 % also depending on the degree of separation required.

So, now here corresponding to ninety percent rejection, let us say if you take the corresponding molecular weight cut off, let us say for u m membrane is approximately 8000 – 9000, so that means whatever the PEG molecular weight more than 8000 – 9000, they will almost be rejected or more than 90% of them will be rejected. But if you take a kind of nm membrane then this molecular weight cut off is almost like an 12000 – 13000, right.

For the other membrane am, so the molecular weight cut off corresponding to 90% rejection is approximately above 18000 or something like that. So, you can see for you know different membrane different molecular weight cut offs are there. So, further here this molecular weight cut offs are of almost similar nature, but not necessarily they can be like of this shape only, they can be very diffused, they can be very sharp as well.

Let us say, here in other picture, here you know, we have our two curves, one is very sharp curve and then one, another one is very kind of a very diffused curve here. So here, here now we can see it is taken 0.95 %, 0.95 rejections or 95 % rejection, right. So, that depends actually, okay some people take 90 %, some people take 95 %, some people even take 99 % rejection to find out this molecular weight cut off that depends on their applications.

Now, here from the sharp cut of curve if you see, the corresponding to 95 % rejection, the whatever the molecular weight cut off is there approximately 10,000, it is small, right. For the diffused curve, the corresponding molecular weight cut off, or the molecular weight corresponding to 95 % is almost, you know, 1 lakh, so for sharp cut off the molecular weight cut offs in general are kind of a smaller one, for diffused kind of curves the molecular cut off would be in general large, okay.

That means if you have a sharp cut of kind of curve then it is possible that you know pore structure is a kind of a very fine pore structure and then it is, it can give a kind of better separation for smaller molecule or this or molecules of small size. If you have a kind of diffused molecular weight cut off curve then it is possible that the porous structure is very wide or the pores are very you know, bigger in size so then suppression may not be good enough for small size molecules, okay.

That was kind of information we get from this molecular cut off and then according to this molecular weight cut off that membrane can be used for the application. Let us say if you, how to do the kind of a ultra-filtration membrane then it is better to prepare a membrane where you get the sharp molecular weight kind of cut off curve, okay. If you are going to a kind of micro filtration even if you get , if you prepare a membrane which is having a kind of diffused cut off kind of like shown here, that is also going to be sufficiently good enough, okay, like that, this MWCO is going to be useful.

Now membrane modules, actually we have seen few basics of the membranes only, but in general you know lab scales, if you do membrane, this membranes operation process are very slow permeation rate should be there in general, but industrially the permeation rate has to be sufficiently large, are large quantity of the permeation should be able to collect so then you have to give large surface area.

So, let us say something like you know 50 m^2 or 100 m^2 surface if you provide then large quantities can be collected but cannot have such kind of bigger surface, bigger equipment in general. So, in order to fulfil such kind of criteria industrially there are different modules are available, right, because of this modules, you know in the lesser space, one can have a kind of a you know more surface area and then more amount of liquid solution can be treated so that you know, the permeate rate is also sufficiently enough to you know do that separation by this membrane separation. So, what are those kind of modules that we are going to discuss now?

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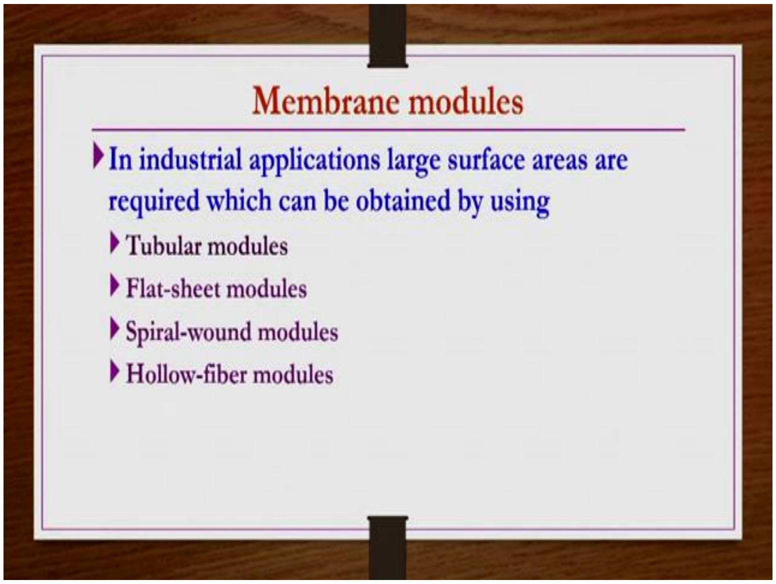

In industrial applications large surface areas are required which can be obtained by using tubular modules, flat sheet modules, spiral wound modules and hollow fibre modules, we see a few details of each of this four modules now.

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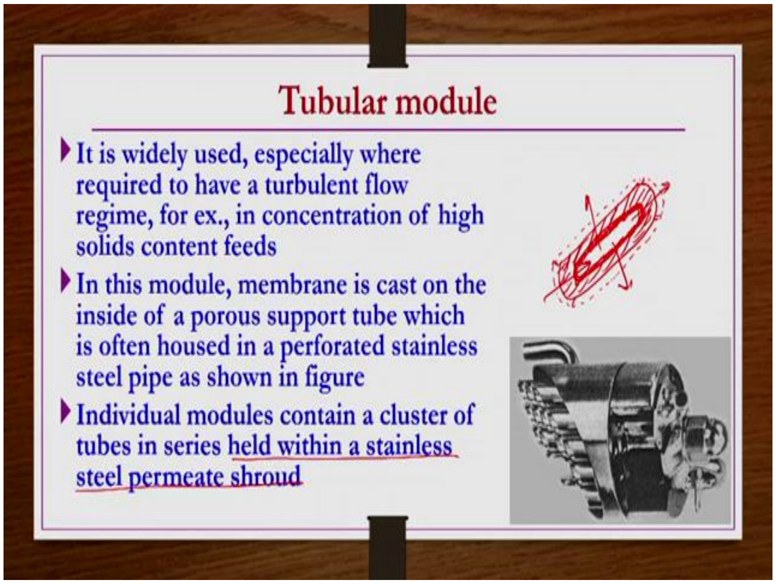

In tubular modules they are in general widely used specially where required to have a turbulent flow regime or you know like you know concentration of high solids content feed, etc. then this tubular modules are used. So what are these tubular modules, in this tubular modules membrane is cast on the inside of the porous support tube, what we have a kind of a porous support tube is, this tube is having a kind of a porous structure, right.

In this porous structure tube what we do, we take this structures and then inside whatever this inside surface of this porous stay that will be costing with the polymer solution if you are preparing a kind of a polymeric membrane like this, right, this in the surface of this porous, you know, support tube that we are casting with the kind of polymeric solution and this tube is in general housed in a kind of perforated stainless steel pipes like this, right.

And then they are not a kind, they are provisions to fix them, you know, they are not kind of useful kind of thing. And you know this structure have a kind of provision, you know, where the fluid comes in here, right and then you know separation will take place through this membrane so permeate will be collected from the other side and then retains are collected from the other side like this.

So in tubular model such kind of a, you know tubes, actually it is a supported tube, in the supported hallow kind of tube, inner structure, inner side of the tube, the membrane casting is done and this support tube is kept in a kind of perforated state, this is one set, like this there are n number of such kinds of things would be there, there are you know clustered in tube since this, right, within a stainless steel permeate shroud, okay.

So, then pictorial if you see then it is like this, you know all of them , you know this different kinds of things you can see, there are such kind of tubes like shown here. There now kept in a kind of stack kind of together and the separation is done so that you know large amount of fluid you know can be treated together and then continuously the permeate is clear liquid can collected, okay.

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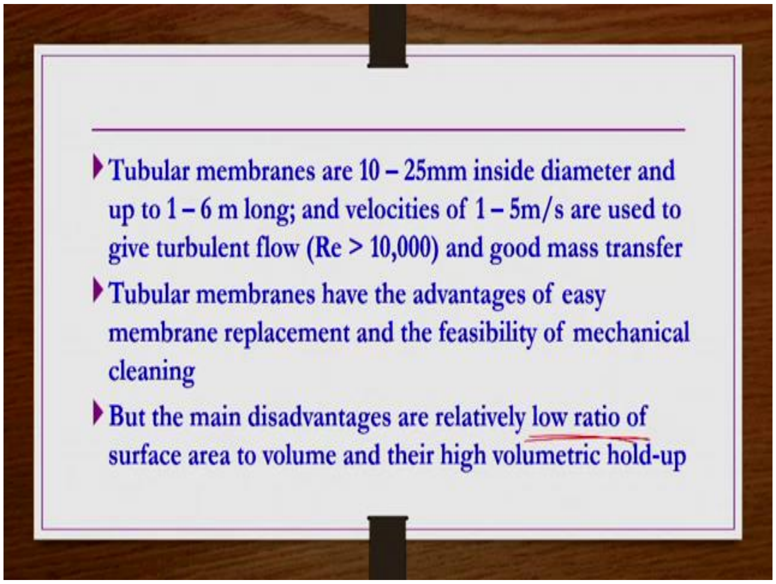

So tubular membranes or whatever the tubular modules, whatever the membranes are used usually 10 to 25 mm inside the diameter and up to 1 to 6 m long and velocities can be as high as 1 to 5 m/s which correspond to the turbulent flow where Reynolds number is greater than 10,000 in general because of that one good mass transfer would be there. Tubular membranes have the advantages of easy membrane replacement and feasibility of mechanical cleaning.

But the main disadvantages are relatively low ratio of surface area to the volume and their high volumetric hold up, so these are the two problems or disadvantages. If your capacity, required capacity is not very high then these membranes are, these tubular membranes are going to be the best one. If you want to have a kind of a very high capacity then you know it is better to go for a other modules as we have going to discuss now.

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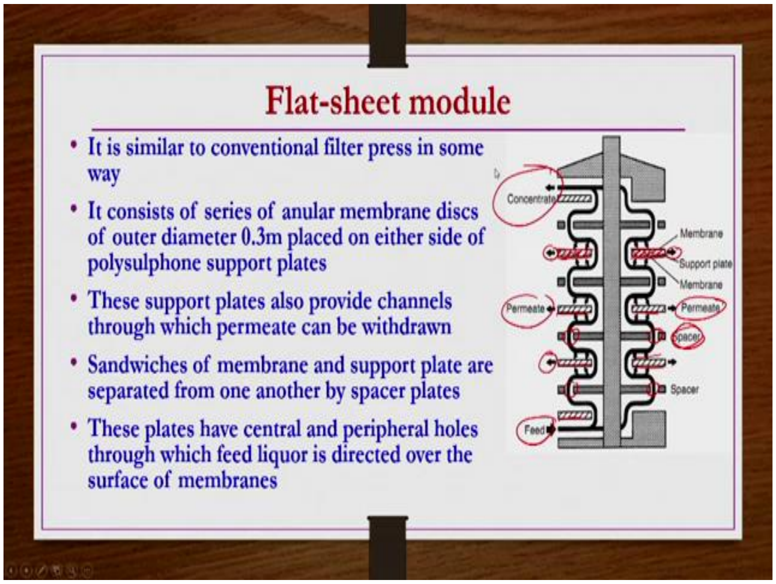

Next one is flat sheet module; it is qualitatively similar to conventional plate and filter press type, right, so that is somehow similar to conventional filter press in one way or other. So, it consists of series of annular membrane discs of outer diameter point 3 m, placed on either side of a polysulphone support plates. These support plates also provide channels through which permeate can be withdrawn and then sandwich of membrane and support plate are separated from one another by spacer plates.

These plates have central and peripheral holes through which feed liquor is directed over the surface of membranes. So, pictorially if you see you have kind of, you know support like this, okay polysulphone support like mentioned here. So either side of support we can have kind of a membrane casting, right, membrane, right. This now whatever the solution, feed solution is coming in there that is passing through here and then you know permeate is being collected like this, permeate is being collected.

And such kind of n number of membranes n number of membranes are kept in a series like this and these are separated by the spacers. These spaces are also having kind of holes in the peripheral as well as in the central so that the feed can easily pass through, right. So, now when the feed is coming here like this, that will pass through all the different membranes one after the other you know, passing through the spaces as well so then at every location we can collect the permeate, from each and every membrane. You know stake whatever you can collect the permeate and then at the end we can have a kind of concentrate.

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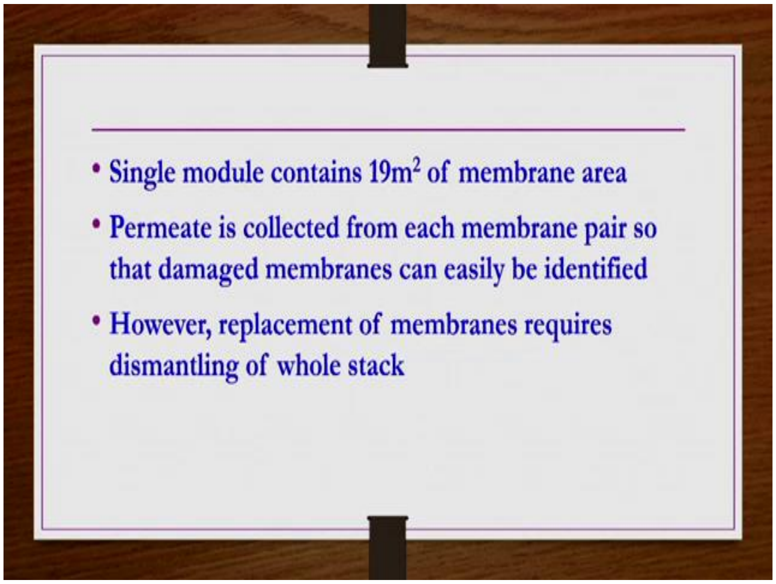

So single module contain in general 19 m^2 of membrane area, permeate is collected from each membrane pair so the damaged membrane can easily be identified. However, replacement of membranes require dismantling of whole stack, like you know if you can, since, the permeate is collected from each membrane pair, so what happens you can keep on observing any, through any membrane pair if you are going to get a kind of turbid solutions kind of things indicating that suppression is not taking place.

So then you can understand that you know that particular membrane pair is damaged. So, but the problem is that while the process is going on you cannot replace it, how to stop the process, dismantle the setup and replace the, you know, whatever damaged membrane pair.

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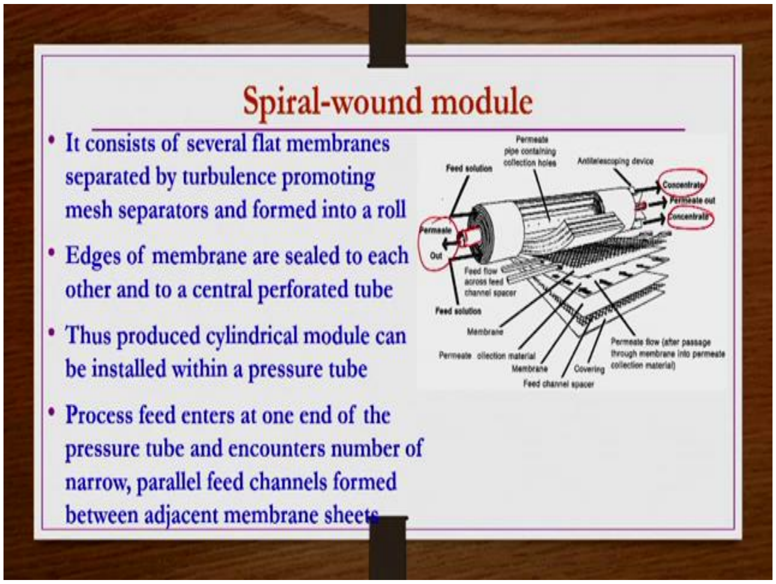

The next one is the spiral wound module, so here it consists of several flat membranes separated by turbulence promoting mesh separators formed into a roll. Edges of membrane are sealed to each other and to a central perforated tube, thus produced cylindrical module can be installed within a pressure tube. Process feed enters at one end of the pressure tube and encounters number of narrow parallel feet channels found between adjacent membrane sheets.

As we see here, pictorially, so what we have here, now we have n number of membranes are there, right and of course there is kind of a perforated tube the centre is there, perforated tube at centre, right, okay. On to this tube this n number of membranes are kind of rolled in kind of rolls, n number of membranes, okay? So, each of the membrane is also separated by a kind of a separator, so that you know that separators not only separate one membrane to the other, but also provide a kind of a high flow rate turbulence kind of thing will be generated.

And for each of this membrane there is a kind of provision to come for the feed and (permeate), concentrate to collect at the other end like this. So when the feed comes in, before this feed coming in, in this set-up what do we do, this set-up, different kind of rolls, different number of membranes separated by the kind of separator or rolled on to a kind of a porous supported tube as shown here like this. And then this entire set is kind of taken inside a pressure tube.

Now, from one side of the pressure tube when the feed comes, the feed, the solution passes through n number of membrane surfaces, the membrane filter medium so that separation takes place and through the centre the permeate is collected whereas the concentrate is collected from the other end. This is what happens in spiral one modules.

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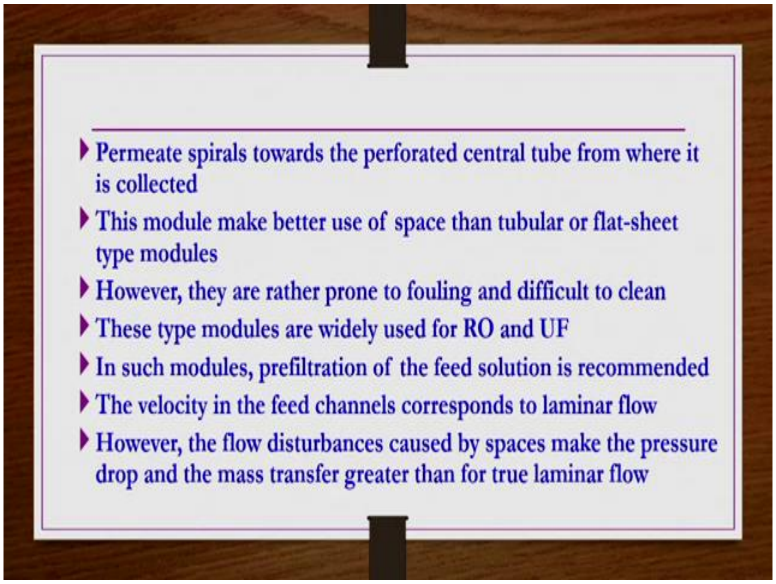

Then permeate spirals towards the perforated central tube from where it is collected. This module makes better use of space than tubular or flat-sheet type modules that we have seen. So, that means we can have a kind of a higher capacity operations with this kind of modules. However, they are rather prone to falling and difficult to clean in general. These type modules are widely used for reverse osmosis and ultrafiltration.

In such modules, pre-filtration of the feed solution is recommended to reduce the fouling kind of problems. Pre-filtration of the feed solution in the sense, let us say, it is not only containing only fine particles of less than point 1 or less than 10 microns but there are also particles which are bigger than 10 microns or something like that.

So, then it is better to separate the largest size particles before taking the feed to this kind of a spiral modules, so that that will avoid falling kind of thing. The velocity in the feed channels corresponding to laminar flow but however the flow disturbance caused by this apparatus whatever is there that makes the pressure drop and mass transfer greater than for true laminar flow whatever we have, okay.

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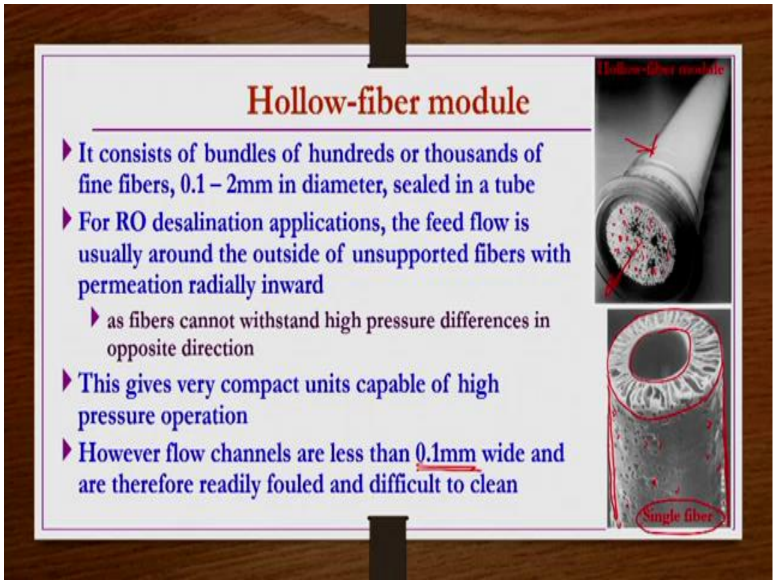

The last module is the hollow fiber module. Here what we have, it consists of hundreds or thousands of fine fibers, which are having the diameter in general, 0.1 to 2 m, they are sealed in a kind of tube. There are fibers, large numbers of such fibers which are of small size are taken in hundreds and thousands, in general, and they are packed in general in a tube, we will see pictorially as well.

For reverse osmosis, desalination application, the feed flow is usually around the outside of unsupported fibers with permeation radially inward whereas the other kind of applications, the feed entering and then permeation collection may be reversed as well. Fibers cannot withstand such high pressure differences in opposite direction. So this gives very compact units capable of high pressure operation.

However, flow channels are less than 0.1 mm wide and are therefore radially fouled and difficult to clean. Pictorially if you see, one single fiber, in general, is having this kind of shape so this, you know, very enlarged picture is shown here like this. This is only single fiber which is having a kind of diameter approximately 0.1 to 2 mm that is not more than 2mm diameter.

So such kind of fibers, large number of fibers are taken, about a few hundreds and a few thousands and they are packed in a tube so that to form this hollow fiber module. So, this is a kind of a tube in which, these are a kind of large number of single fibers, the hundreds of single fibers are taken and packed in this single tube here. In RO operations what happens, the feed comes in here like this and then permeation is taken something like this.

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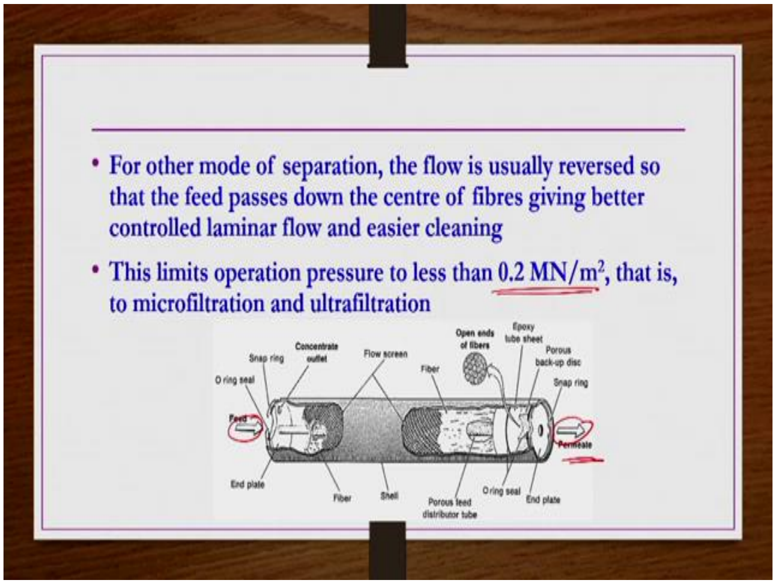

But in some applications what happens, like here feed maybe come to the centre like here and whatever the permeate is collected from the other side or something like that. That is also possible. For other mode of separation the flow is usually revered so that the feed passes down the centre of fibres giving better controlled laminar flow and easier cleaning of this module, this limits the operational pressure to less than 0.2 MN/m^2, that is to the range of micro filtration and ultra-filtration.

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Finally, the references, now the references for this particular lecture: most of the lecture is prepared from this book which is "Unit operations of Mechanical Engineering" by McCabe, Smith and Harriot. Other reference books are Ortega-Rivas and then this membrane module all those things are discussed form the book "Coulson and Richardson's Chemical Engineering by Richardson and Harker. So this is a very good book for a kind of membrane modules. Other references are "Transport processes and Unit Operations" by C.J. Geankoplis, "Unit Operations" by Brown et al, "Introduction to chemical engineering" by Badger and Banchero. Thank you!