Chemical Process Intensification
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Lecture 11.2 (lec32)
Membrane Engineering in Process Intensification

Welcome to massive open online course on Chemical Process Intensification. So we are discussing Process Intensification by membrane under the module 11 and in this lecture we will discuss something more about that membrane engineering in process intensification. In the previous lecture we have discussed the introductory discussion on this membrane processes.

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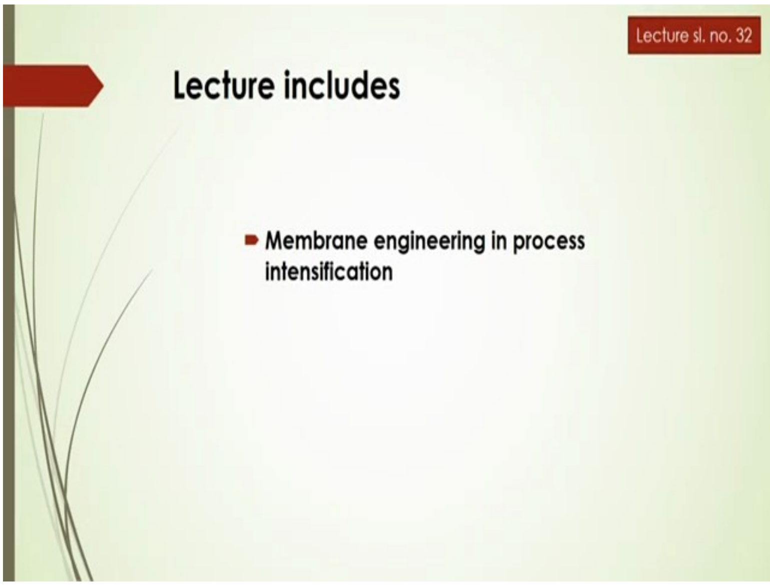

Now in this lecture will try to discuss more about that how to engineered that membrane to apply different chemical engineering process as per direction of process intensification.

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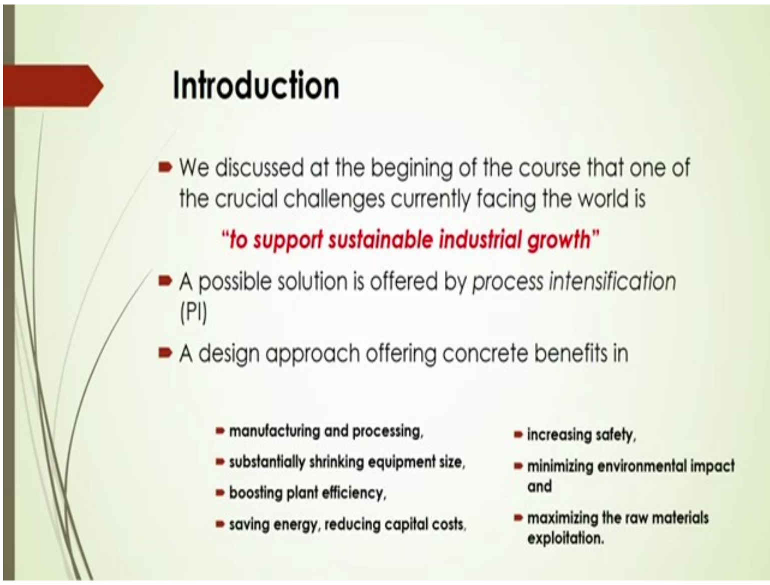

So we know that crucial challenges in the process intensification in chemical engineering process, where we need to have the support of sustainable industrial growth and in that case there are several possible solution to get that sustainable industrial growth. By that offering that process intensification in different aspects and we have already discussed in our earlier lectures different aspects of process intensification and how that process intensification apply in chemical process systems.

And in that case some design approach to be offered to concrete benefits in the manufacturing and processing and sustainability shrinking equipment size, boosting plant efficiency, saving energy, reducing capital costs, even increasing safety, minimizing environmental impact and also maximizing the raw materials exploitation.

So under this different categories that process intensification is actually discussed in our earlier several lectures also based on different case to case processes of chemical engineering. So in this lecture I will try to discuss that how the membrane also can be used for chemical engineering processes for their intensification.

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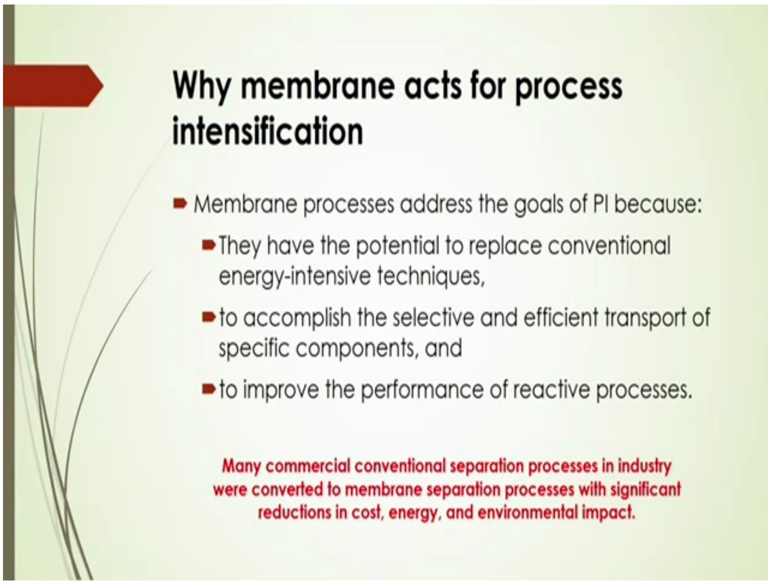

Now we have already discussed that why membrane acts for process intensification. You know that membrane processes address the goal of process intensification because they have the potential to replace conventional energy- intensive techniques. And also this membrane is being used to accomplish the selective and efficient transport of specific components. And also you can say that this membrane can be used to improve the performance of the reactive processes.

We have already discussed that how membrane is used for hybrid processes of membrane area distillation processes there. We have also shown several aspects of membrane and how it can be used for reactive distillation. The distillation Processes after distillation how that different components are being separated by membranes. And based on which that many commercial conventional separation processes going to direct to that membrane separation processes and also it is significant because of its reduction in cost, energy and environmental impact there.

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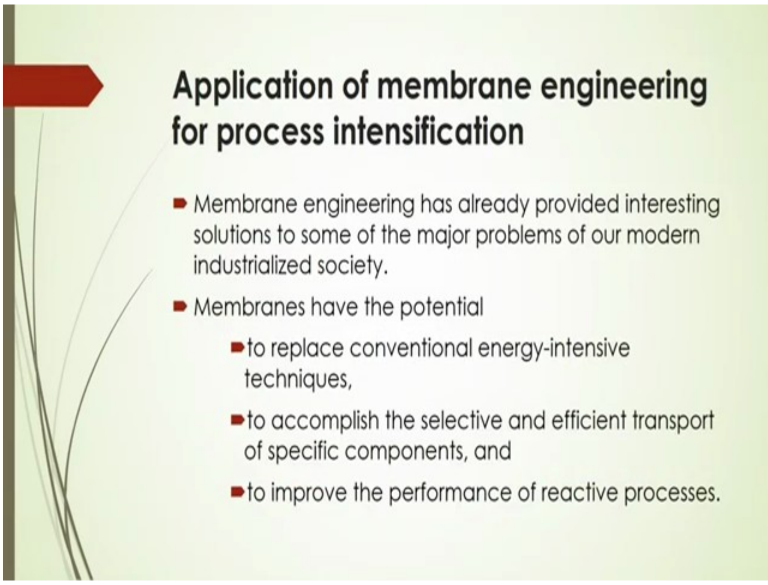

And also this membrane engineering has already provided interesting solutions to some of the major problems of our modern industrial society. Also we can say that this membrane, since they have the potential to replace potential energy intensive techniques for carrying out different chemical processes. Mainly for separation processes, and in that case this has being used for selective and efficient transport of specific components there and also is used to improve the performance of reactive processes.

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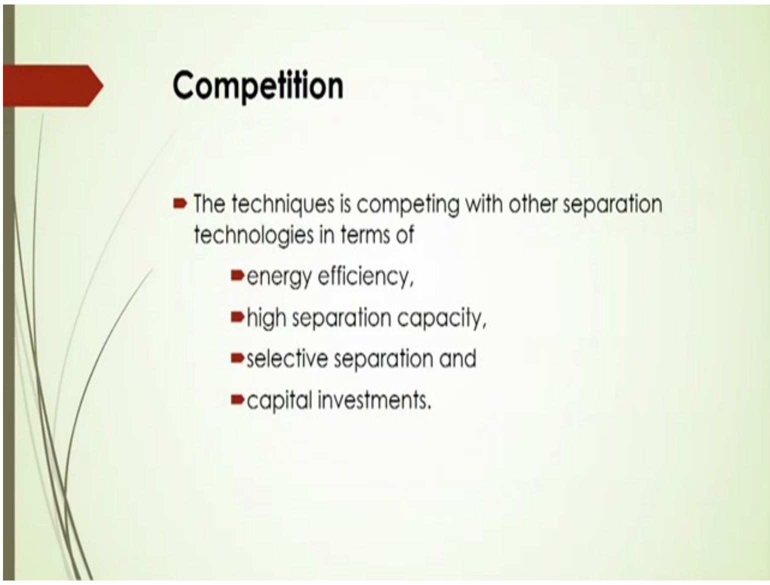

Now of course this membrane process whenever you are going to use for process intensification, there should be some competition compared to the other process intensification process. In that case whether it should be giving high energy-efficiency or not, it will give you that high separation capacity or not, and also in terms of selective separation whether it will be suitable or not, whether the capital investment whenever we are considering them, this membrane separation will be competitive or not.

So these things also to be considered whenever the membrane is being used for process intensification for the separation process.

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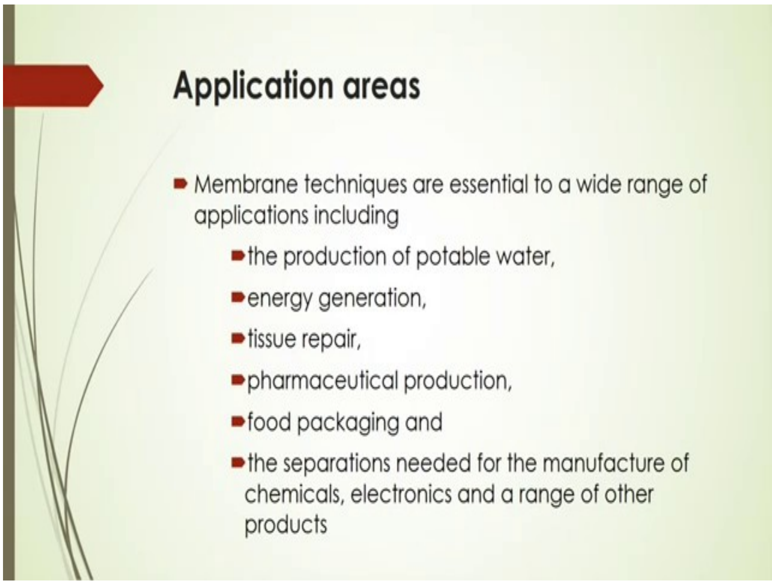

Now what are those application areas where this process intensification by membrane is possible? And like some example here that tissue repairing by membrane, pharmaceutical production, food packaging, even production of potable water even energy generation these are the broad area where that membranes can be used as an potential process intensification device. In that case you will see that this membrane can be used for separations which are needed for the manufacture of chemicals, electronics and ranges of other products based on this different broad area.

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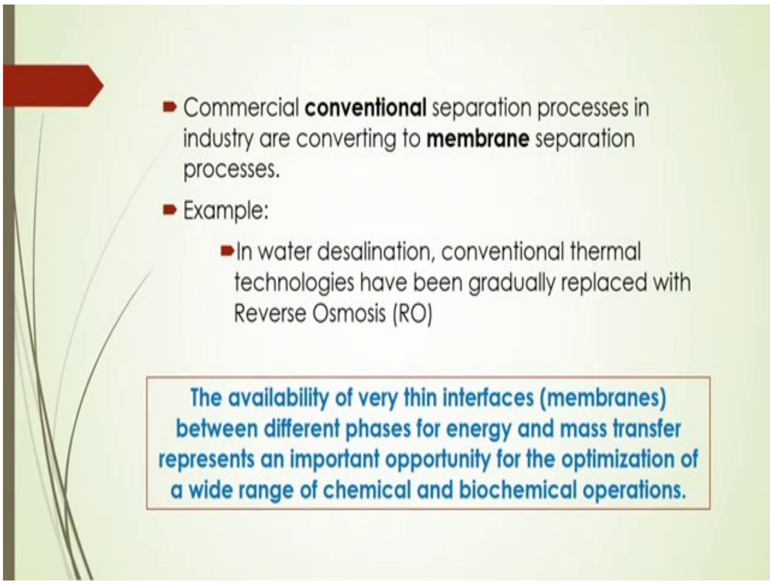

Now commercial conventional separation processes in industry are actually converting to membrane separation processes. Like that in water desalination and also conventional thermal technologies that have been gradually replaced with reverse osmosis there. And in this case will see that while membranes are actually being used for process intensification mainly in the case of that water desalination and even other conventional thermal technologies based membrane separation and also that reverse osmosis.

Because in this case the availability of very thin interfaces are actually in the membranes and the interfaces is basically between different phases for energy and mass transfer. And it represents an important opportunity for the optimization of a wide range of chemical and biochemical operations. So these are the application where this commercial conventional separation process in industry are converting to membrane separation processes.

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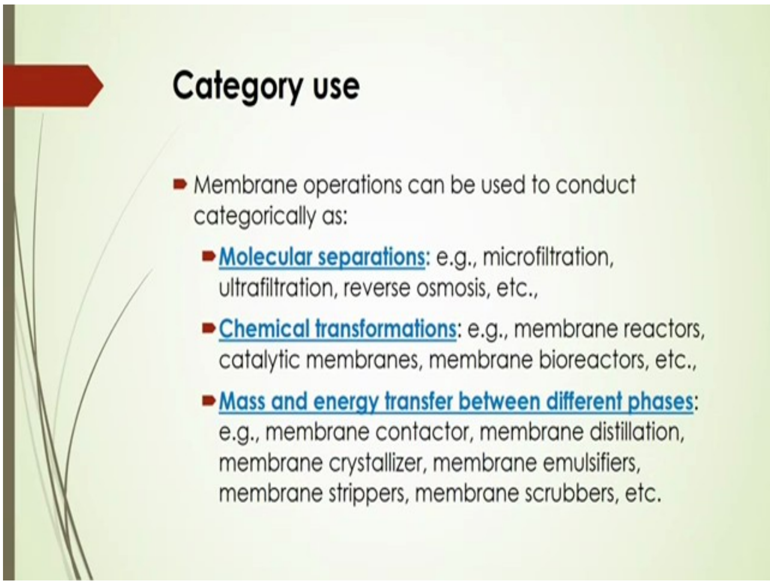

Categorically we can actually access this membrane for different applications like membrane operations are in the several aspects like molecular separations even chemical transformations, mass and energy are transfer between different phases.

In the case of molecular separations, in that case you are generally using that microfiltration, ultrafiltration, reverse osmosis base membrane. And in case of chemical transformation like that membrane reactors, catalytic membranes, membrane bioreactors et cetera and also mass and energy transfer between different phases. In that case you will see that membrane contactor, membrane distillation, membrane crystallizer even membrane emulsifiers, membrane strippers, membrane scrubbers, et cetera are being used in that area of mass and energy transfer between different phases.

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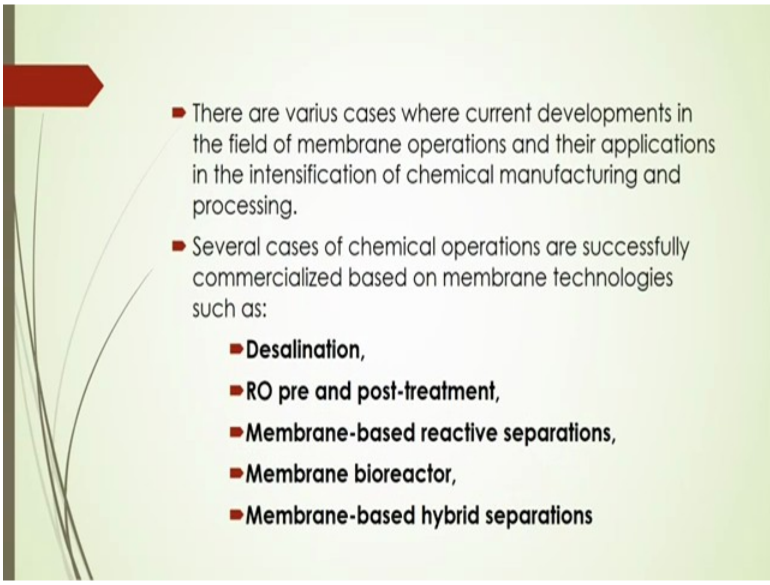

Now out of this various cases where current developments in the field of membrane operations are carried out and also their applications in the intensification of chemical manufacturing and processing. So by using that different aspects of membrane you will see that several cases of chemical operations are successfully commercialized based on membrane technologies.

Now such as you can say that desalination process, reverse osmosis pre-and post-treatment, even membrane-based reactive separations, membrane bioreactor, membrane based hybrid separations. All are actually being different aspects of application of membrane in different process intensification in chemical engineering processes.

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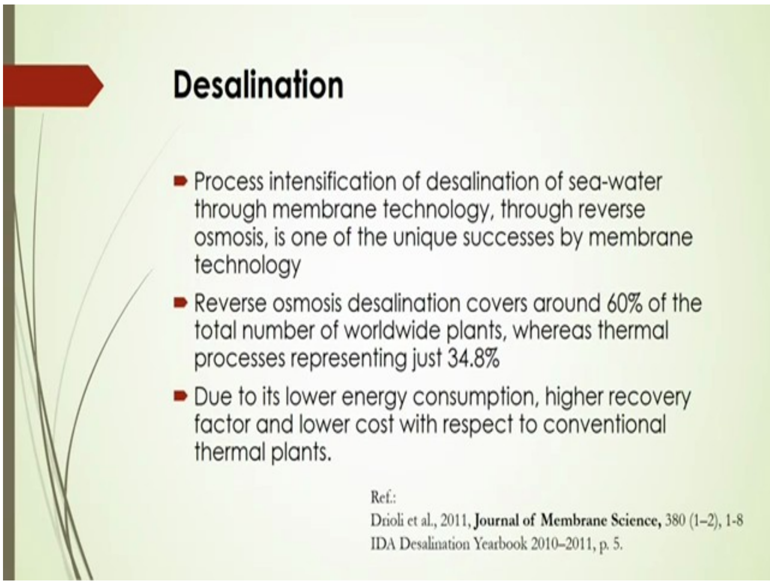

Now if I talk about the desalination process in the membrane. In that case you can see that if you are actually doing desalination of seawater through the membrane technology, you will see that this membrane technology basically that reverse osmosis which is one of the unique successes by membrane technology. And in this case you will see that it covers around 60% of the total number of worldwide plants, whereas thermal processing representing just 34.8%.

Generally there are two types of where desalination process one is thermal and another one is membrane that is reverse osmosis process. So as compared to that thermal process, this reverse osmosis is having the 60% of the total number of worldwide plants and there you will see that whereas thermal processes representing just 34.8%. That is why the wide application that is based on that membrane process intensification is that in scientific and in research communities are gaining day by day interest.

And due to its low energy consumption, higher recovery factor and lower cost with respect to conventional thermal plants it is actually nowadays gaining daily there because of several advantages of this reverse osmosis base membrane for the desalination process.

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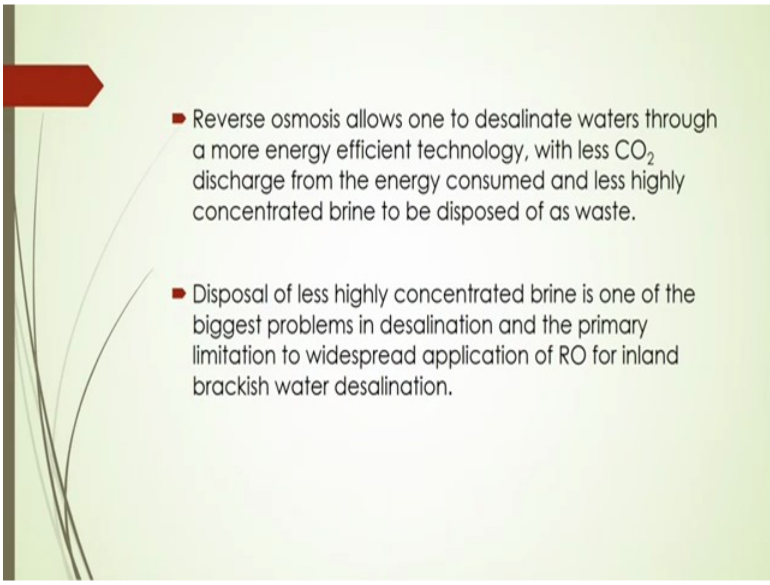

Also in this case it is important to know that this reverse osmosis will allow one of the desalinate water through a more energy-efficient technology, with less carbon dioxide discharge from the energy that will be consumed and also less highly concentrated brine that is to be disposed as a waste. And in that case you will see that the biggest problem in desalination and the primary limitation to widespread application of RO or that inland brackish water desalination because in this case disposal of less highly concentrated brine is one of the main problem.

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And for that you have to develop some sustainable process for this desalination process. And that is why this process intensification is coming for that analysis of the desalination process by the membrane process, membrane technology to solve this problem. In that case sustainable and efficient desalination processes can be achieved in the future through the integrated membrane systems.

And in that case the main characteristic of membrane operations are their great flexibility, operational simplicity and mutual compatibility for the integration of the process.

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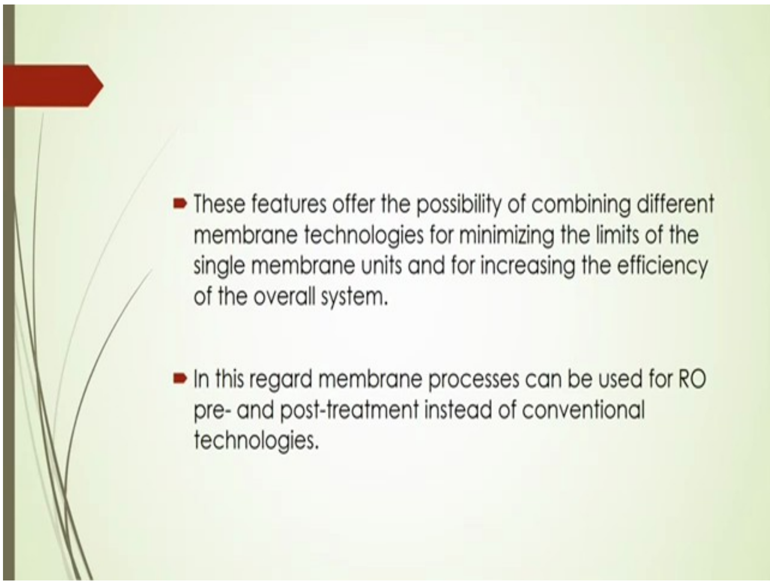

And also in this regard you have to note down that membrane processes can be used for RO pre and post-treatment instead of conventional technologies. And it offers the possibility of combining different membrane technologies for minimizing the limits of the single membrane units and for the increasing the efficiency of the overall system.

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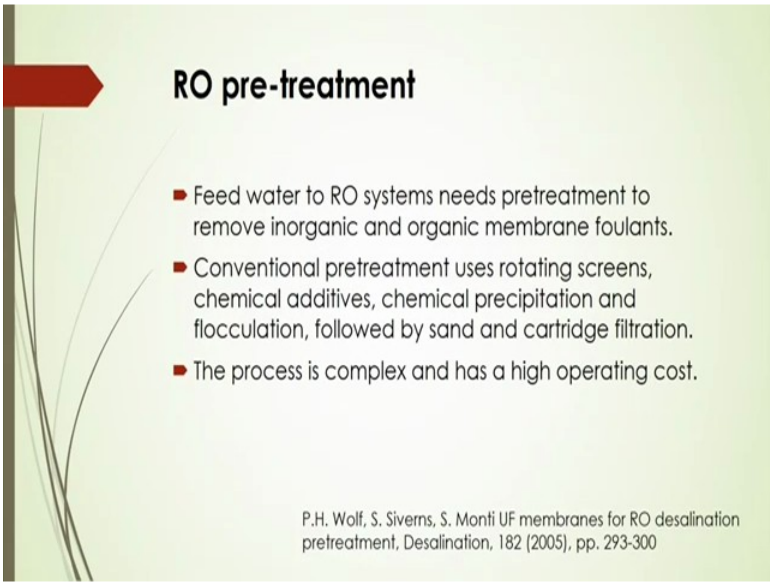

Now if you are talking about that reverse osmosis pre-treatment there are several chemical engineering process where that a stream to go into the main process. Sometimes it is required to treat it by several chemical engineering process like absorption adsorption and other processes to remove or control that contaminates in the mainstream. So in that case pretreatment of that stream is sometimes required to separate that inorganic and organic that pollutants for the further operations.

So Feed water to reverse osmosis systems needs sometimes pre-treatment to remove inorganic and organic membrane foulants. And also conventional pretreatment that uses sometimes rotating screens, chemical additives, chemical precipitation and flocculation that is followed by sand and cartridge filtration.

And the process is complex and has a high operating costs. So that is why this reverse osmosis process is coming just to replace that different mechanical based separations like rotating screens, chemical additives all those things.

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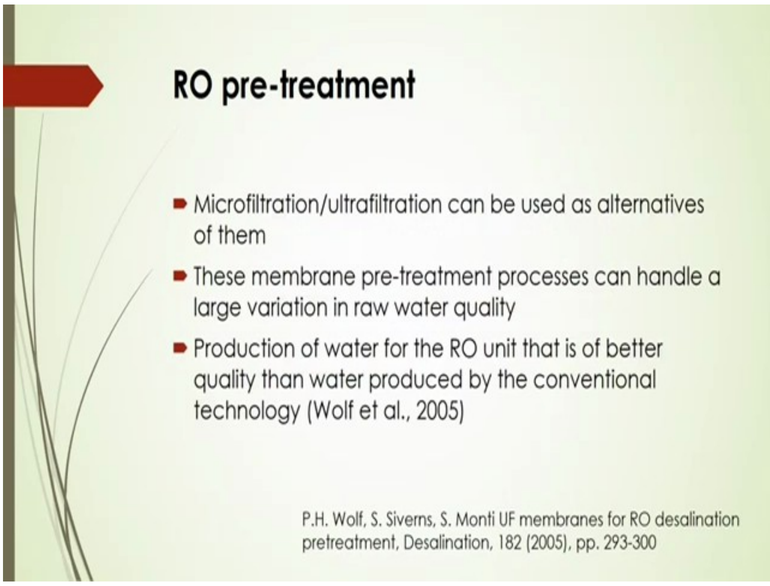

And in that case to remove those micron sized particles from its water stream you have to use that microfiltration or ultrafiltration based membrane where it gives that alternatives of those screen process like that precipitation process, flocculation, or other screening of that chemical additives or removal of chemical additives.

And if you are using that RO process you will see that it will give you that better quality than water produced by the conventional technology. So that is why the reverse osmosis based membranes are used for this process intensification based on microfiltration and ultrafiltration to have that intensified way of that process.

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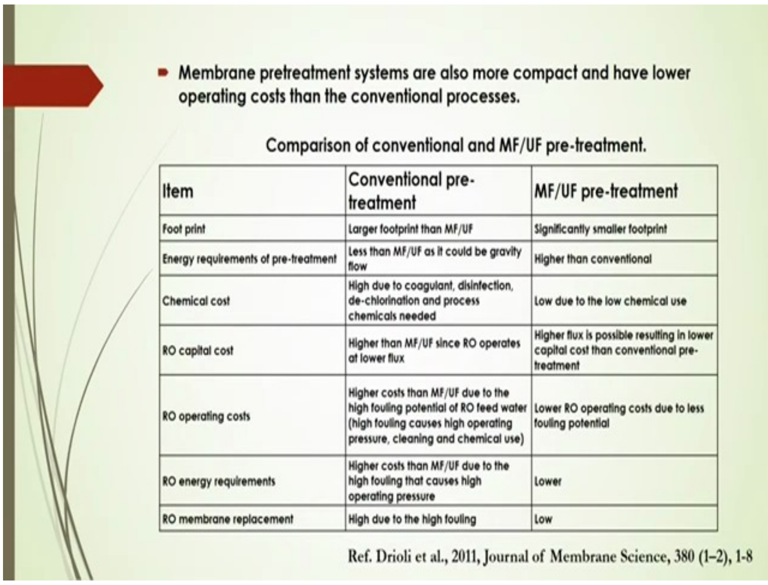

Item	Conventional pre-treatment	MF/UF pre-treatment
Foot print	Larger footprint than MF/UF	Significantly smaller footprint
Energy requirements of pre-treatment	Less than MF/UF as it could be gravity flow	Higher than conventional
Chemical cost	High due to coagulant, disinfection, de-chlorination and process chemicals needed	Low due to the low chemical use
RO capital cost	Higher than MF/UF since RO operates at lower flux	Higher flux is possible resulting in lower capital cost than conventional pre-treatment
RO operating costs	Higher costs than MF/UF due to the high fouling potential of RO feed water (high fouling causes high operating pressure, cleaning and chemical use)	Lower RO operating costs due to less fouling potential
RO energy requirements	Higher costs than MF/UF due to the high fouling that causes high operating pressure	Lower
RO membrane replacement	High due to the high fouling	Low

And membrane treatment systems are also more compact and have lower operating costs than the conventional process. Like there is a comparison is given in the slides. In a table as per Drioli et al. 2011 that the comparison of conventional and microfiltration and ultrafiltration pre-treatment are given here. Like some items here foot print, energy requirements of pre-treatment, chemical cost, RO capital cost, RO operating costs, RO energy requirements and even RO membrane replacement.

So in terms of those items, how actually these conventional pretreatment and also microfiltration and ultrafiltration based membrane technology for the pre-treatment of the streams are important.

In this case if you are considering that chemical cost in that case conventional pretreatment it will be higher due to the coagulant, disinfection, De chlorination and process chemicals that is needed. Whereas this microfiltration or ultrafiltration pre-treatment it will require low that chemical cost because of the low chemical use there. Also if you're considering that our RO membrane capital cost, in that case the conventional pretreatment process is actually higher then microfiltration or ultrafiltration since that RO operates at lower flux. And also higher flux is possible in case of microfiltration or ultrafiltration that results in lower capital cost than conventional pretreatment.

Also in terms of you are thinking about that energy requirements, conventional pretreatment generally require higher costs than micro-filtration or that ultrafiltration due to the high fouling that causes high operating pressures. Whereas in microfiltration or ultrafiltration generally it requires lower operating pressure.

And if you're considering that if you replace that RO membrane, conventional treatment for that you can have high possibility to replace this conventional pretreatment due to the high fouling. And also microfiltration or ultrafiltration in that case it will be low.

And energy requirements that will be less than microfiltration or ultrafiltration as it could be gravity flow in the conventional treatment. Whereas some energy requirements will be higher in the microfiltration or ultrafiltration treatment because of high resistance of the flow through the membrane there. So that is why you can say that there will be some pros and cons of this ultrafiltration and microfiltration compared to that conventional pretreatment.

May be case to case handle where this microfiltration or ultrafiltration may be more useful than conventional pretreatment. And we go for industrial scale sometimes this conventional pretreatment will be more acceptable then microfiltration and ultrafiltration. Whereas for the final particles to be removed in that case ultrafiltration should be required whereas conventional pre-treatment will not be useful there.

So that is why based on that the criteria of that application that you have to you sometimes this microfiltration or ultrafiltration which will be giving more intensification of the process to separate more final even more final particles.

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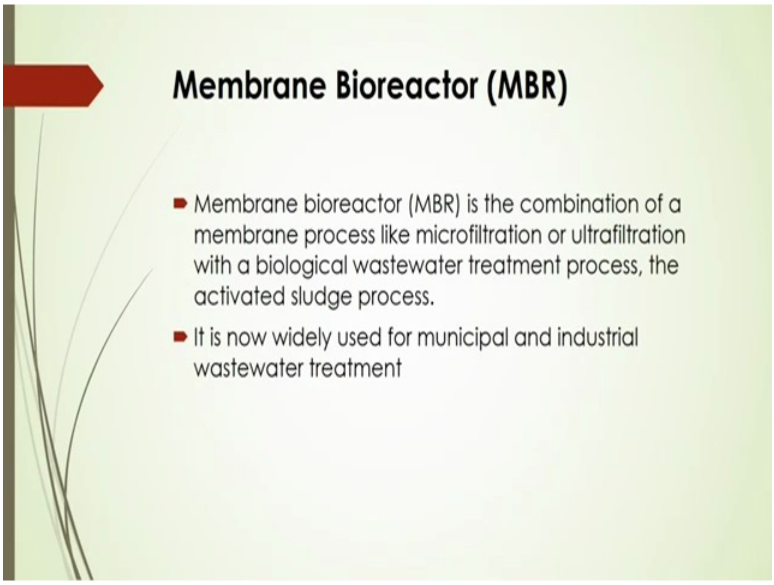

Now another aspects of that membrane is called membrane bioreactor. In this case it is generally combination of membrane processes like microfiltration or ultrafiltration with a biological wastewater treatment process. And also that activated sludge process. Now it is also being widely used for municipal and industrial wastewater treatment.

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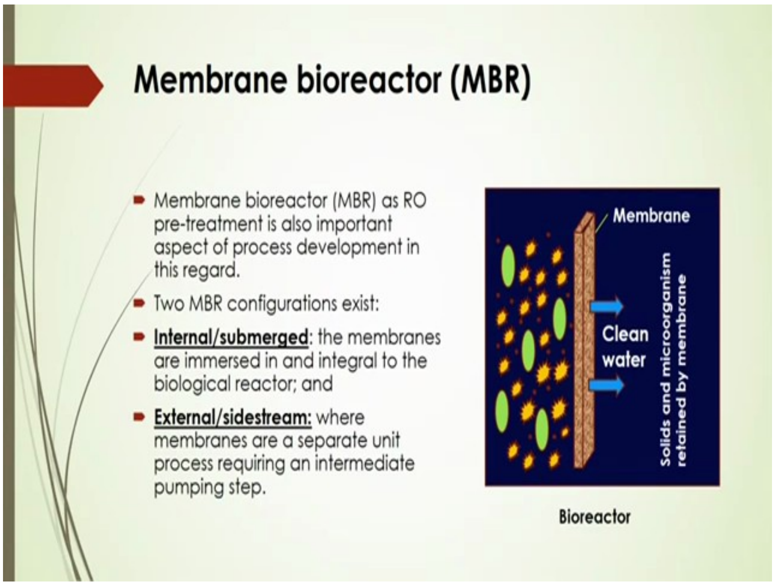

In that case here as shown in figure that membrane bioreactor as reverse osmosis pretreatment is also important aspects of process development in this regard. Now two membrane bioreactor configurations generally exist one is called internal or submerged membrane bioreactor and another is called as external side stream membrane bioreactor.

We will see that internal submerged bioreactor it is called it is generally membranes are immersed and integral to the biological reactor. And in the case of external or side stream membranes where you will see that membranes are separate unit process that is required an intermediate pumping step. So that is why these two types of membrane bio reactors are important for the process intensification.

Here it is shown in the figure some typical bioreactor mechanism where you will see that micro-organism and also other particles and how it will be separated by the membrane to get that clean water. And solids and microorganism retained by the membrane based on this membrane technology. So that is why it is that micro-organism separation is called membrane bioreactor.

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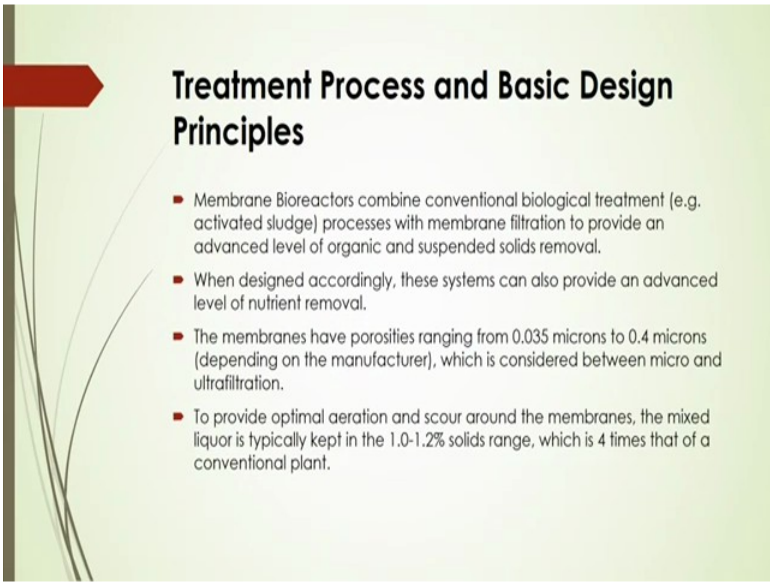

And in this case what are the basic design principles of this membrane bioreactor and also what is the treatment process? You will see since this membrane bioreactor combine conventional biological treatment example activated sludge, processes with membrane filtration which will give you an advanced level of organic and suspended solids removal. In this case when designed accordingly for this organic compounds separation. This system can also provide advanced level of nutrient removal. And this membranes have porosities ranging from 0.035 microns to 0.4 microns.

That of course depends on the manufacturer, they are actually procured or develop different types of membrane based on their porosities range and which is generally considered between micro-and ultrafiltration.

And in this case to get that optimal operation and secure microorganism separation by that membrane you have to develop the membrane in such way that the mixed liquor which is being used should be typically kept in the 1.2 percent solid range which is four times that of a conventional plant.

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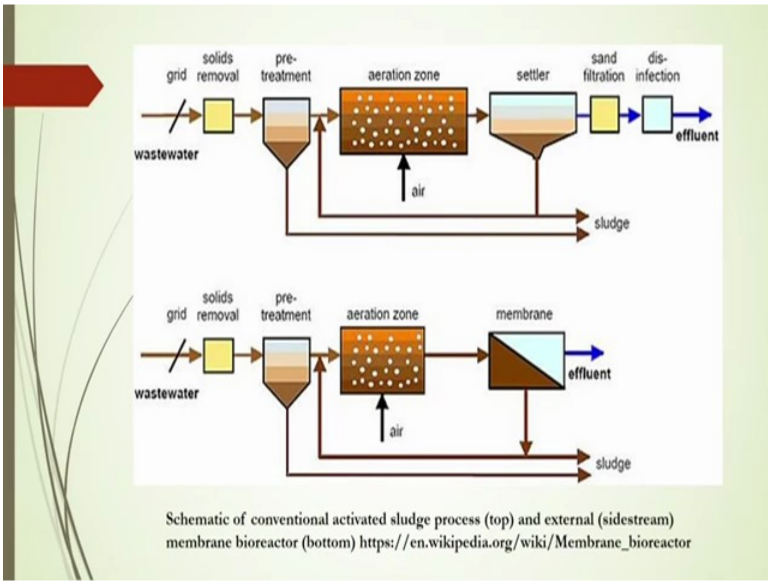

Now here one schematic conventional activated sludge process in the top and external side stream membrane bioreactor at the bottom. It is soon based on that Wikipedia membrane bioreactor. In this case you will see that wastewater whatever is coming to separate there it should be first to grid and then solid should be removed by pretreatment by that other mechanical devices.

And then pretreatment by reverse osmosis or some other processes and then aeration processes where you can separate solid particles by rotation, and then we have to settle then sand filtration and disinfection may be by ozonation or some other effluent will be there. And in case of external side stream here also the process is given by membrane process there. After separating that aeration zone that then you have to separate those very fine particles by this membrane even also that microorganism by this membrane.

Instead of conventional process that is used for that micro-organism separation, by sand filtration or that is disinfection process. So here instead of that disinfection and sand filtration it is replaced by this membrane to get that effluent after separation.

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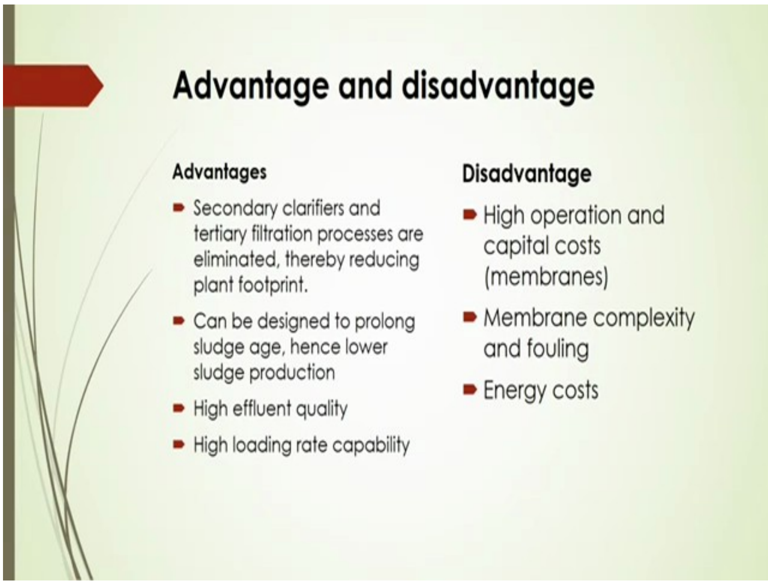

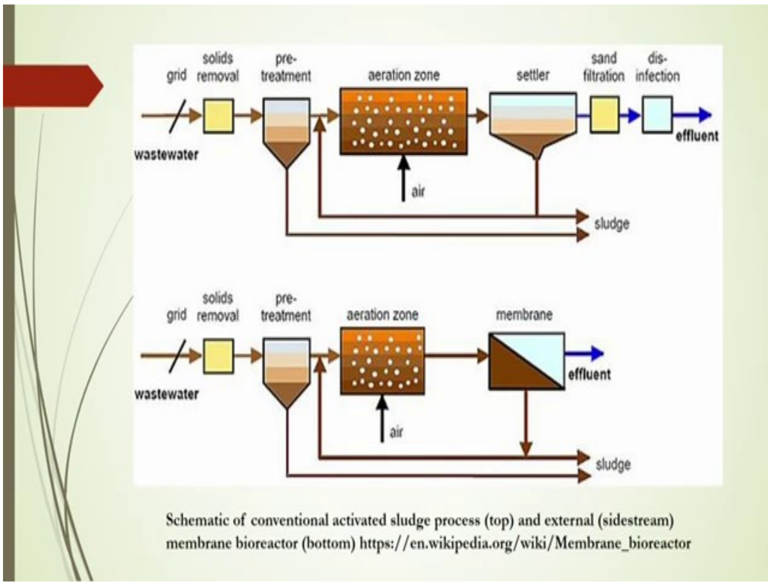

Now there should be some advantage and disadvantage of those membrane bioreactor whenever it is being used. Of course that advantages and disadvantage you can say that secondary clarifiers and tertiary filtration process are eliminated here we can see that this one. And also in that case the cost will be reduced and also plant other footprint will also optimized. And also it can be designed to prolong slug age, hence lower sludge production will be there. Even high effluent quality even high loading rate compatibility should be there.

As a disadvantage you can say that high operation and capital cost membrane complexity will be there because there will be fouling, there will be clogging of that membrane pores by that solid particles. And also the cleaning is very tough for this membranes to be used and also there are capital investment will be more compared to that other conventional process. So these are the some disadvantages there.

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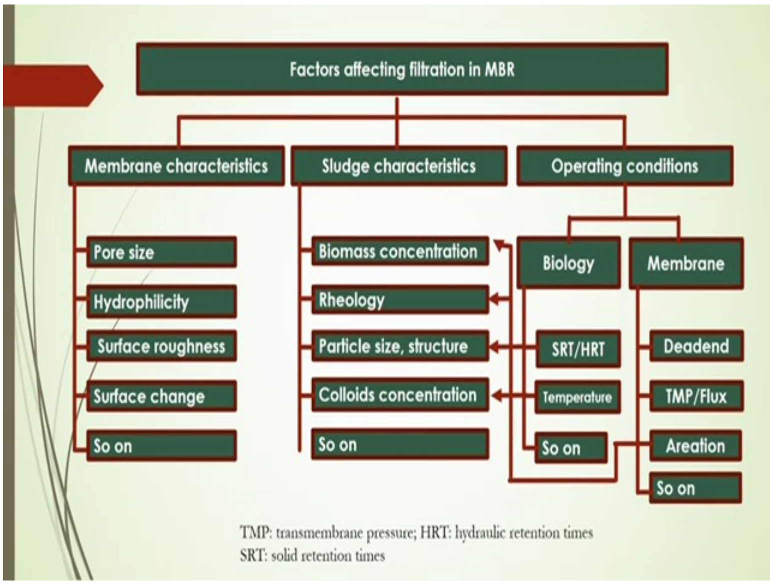

Now if we considered that membrane bioreactor, what are the different factors that affecting filtration by this membrane bioreactor. If you considered that membrane characteristics is a pore size, Hydrophilicity, surface roughness, surface change and other factors. In that case you will see that these are the different factors that may effect on the performance of the membrane bioreactor.

And also some other characteristics like sludge characteristics like biomass concentration, rheology, particle size, structure, Colloids concentration and other. So these are the different factors for sludge characteristics. And also if you're considering operating conditions also there will be a certain effect on this membrane performance there like that biology what type of biological spaces has to be separated.

And also how that membranes to be actually procured. What are the materials that also is important? And other operating conditions like temperature even flux, aeration and others. So these are the different factors that you have to remember to get that membrane efficiency for particular processes. So you have to consider these factors and based on this factors also you can optimize you can intensify the process by membrane.

So there are several aspects where you can intensify the process, of course it is under research that you can intensified the conventional process based on that pore size, Hydrophilicity, surface roughness, surface change and also some other rheological characteristic colloid concentration and even other materials based on which this membranes are procured.

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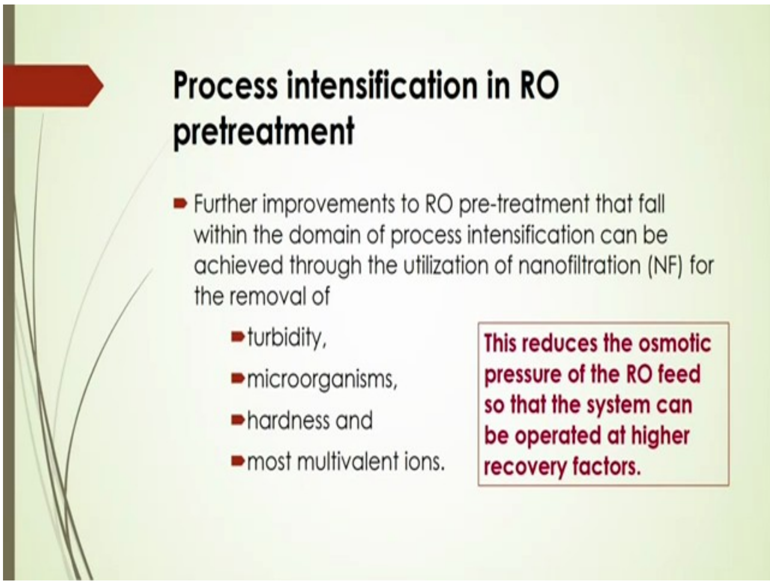

In that case this membrane bioreactor also being used for post-treatment as well as pretreatment also and further improvements to the reverse osmosis pre-treatment that fall within the domain of process intensification and that can be achieved through the utilization of Nano filtration for the removal of the turbidity, microorganisms, hardness and most multivalent ions. So this reverse osmosis when ultrafiltration or Nano filtration membrane is being used in that case you can reduce that micro-organism. Thus by reducing the osmosis pressure of the reverse osmosis feed so that the system can be operated at higher recovery factors.

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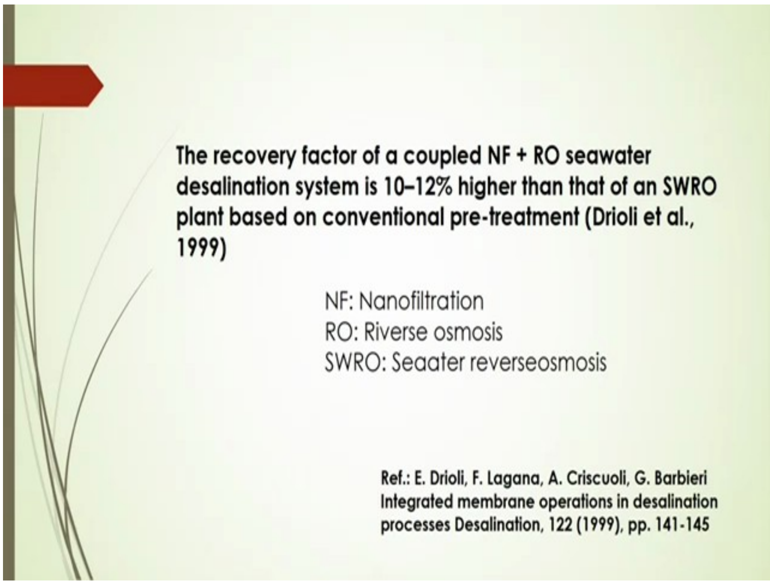

And that recovery factors of a coupled Nano filtration and the reverse osmosis seawater desalination system is 10 to 12 percent higher than that of a sewage water or reverse osmosis plant based on conventional pretreatment there. So it is actually reported by Drioli et al. 1999. So they have concluded that process intensification of this Nano filtration and reverse osmosis hybridization or you can say that combination of this two may increase the process efficiency to 10 to 12 percent higher than that conventional RO plant.

That is why whenever you are intensifying the seawater reverse osmosis process you have to conjugate that Nano filtration system with that RO process so that you can get more efficiency of that filtration and also separation process.

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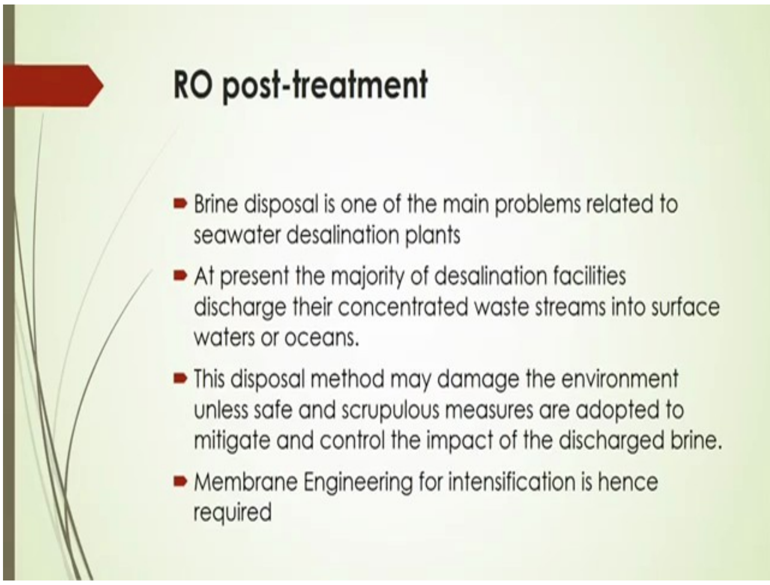

Now in case of RO post-treatment, in case of desalination process this Brine disposal is one of the main problems that is related to seawater desalination plants and presently that majority of desalination facilities discharge their concentrated waste streams into surface waters or oceans and this disposal method may damage the involvement unless safe and scrupulous measures are adopted to mitigate and control impact of the discharge Brine.

And in that case the membrane engineering for intensification is hence required. For this having better efficiency of that separation of Brine or you can say disposal of the Brine from that seawater desalination process.

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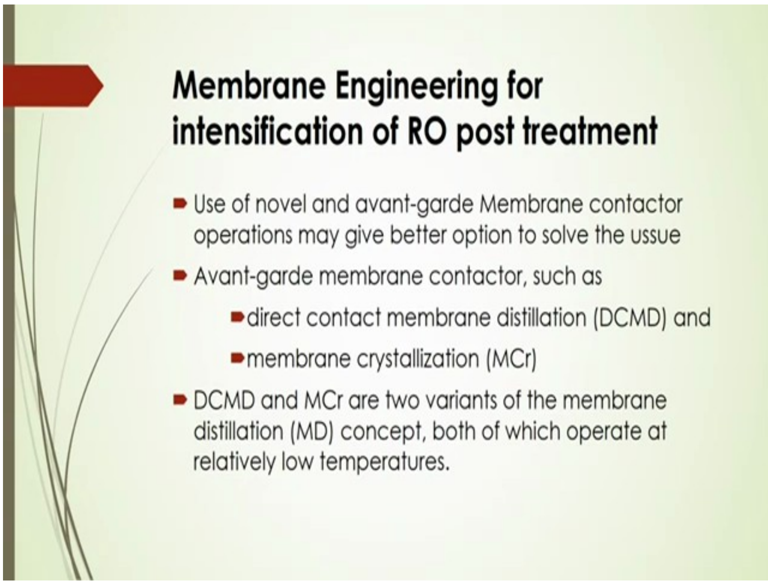

Now in this case if you are considering that membrane engineering for intensification of reverse osmosis post-treatment that membrane contactor operations may give better options to solve the issue. In that case avant-garde membrane contactors such as the direct contact membrane distillation and the membrane crystallization are the two important aspects of membrane process intensification to have the solution of that Brine disposal of that desalination of the seawater and in this case these two variants of the membrane distillation concept both of which operate at relatively low temperatures such as reported by Drioli et al in 1999.

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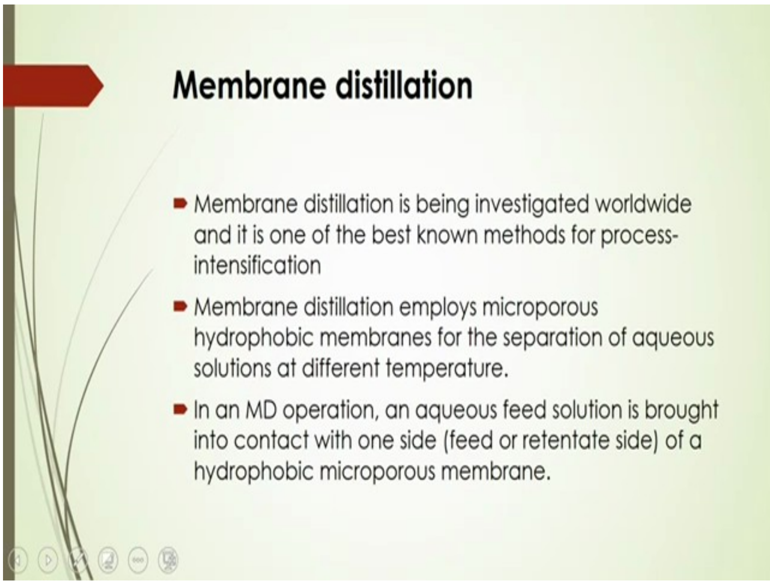

Now since we are talking about membrane distillation for the process intensification, in that case this membrane distillation is being investigated worldwide and it is one of the best-known methods for process intensification and membrane distillation employs micro-porous hydrophobic membranes for separation of aqueous solutions at different temperature.

And also this membrane distillation operation if you actually use this an aqueous feed solution is to be brought into contact with one side that is in feed or retentate side of a hydrophobic micro porous membrane.

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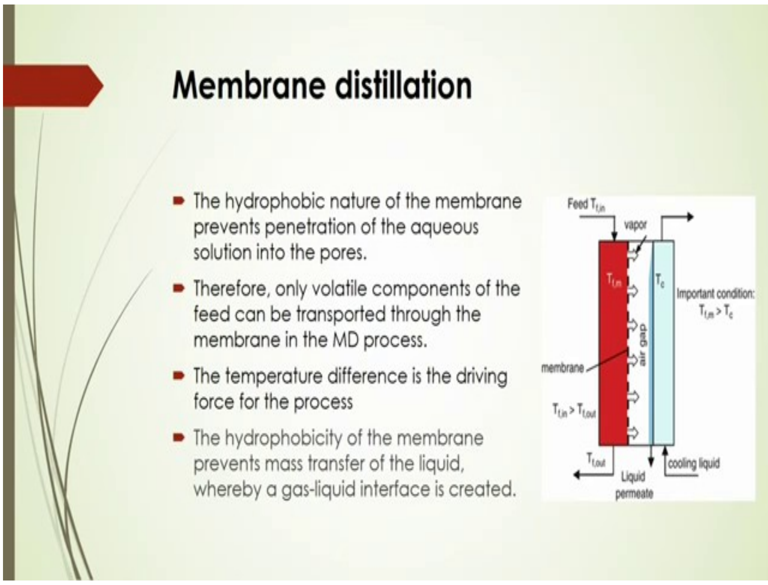

And in that case hydrophobic nature of the membrane that will prevent the penetration of the aqueous solution into the pores and also the temperature difference is the main driving force for this process and therefore only volatile components of the feed can be transported through the membrane in the membrane distillation process and hydrophobicity of that membrane that prevents mass transfer of the liquid, whereas say gas liquid interface is created.

As shown in the figure here in this slides that how this membrane distillation is being used or its works there in the slides it is shown.

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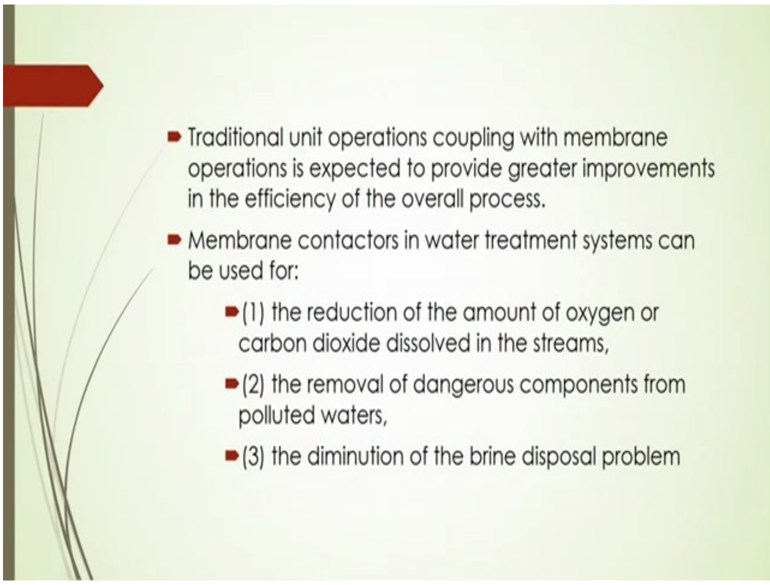

Also traditional unit operations that coupling with the membrane operations is generally provide greater improvements in the efficiency of the overall process and membrane contactor in water treatment systems can be used for that reduction of the amount of oxygen or carbon dioxide dissolved in the system in this case and also removal of harmful components from the polluted waters and also you can say that the diminution of the Brine disposal problem that can be solved by this membrane contactor coupling with that traditional unit operations.

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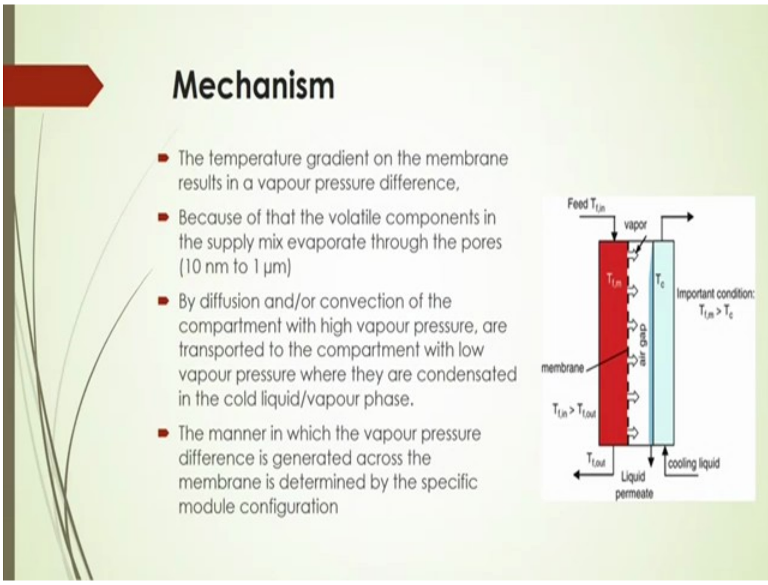

Now how it works actually? The temperature gradient on the membrane results in a vapor pressure difference there and because of that differ pressure you will see that volatile components in the supply makes evaporate through the pores. And by diffusion and convection of the components pass through the compartment of the membrane with high vapor pressure and also it will be transported to the compartment low vapor pressure where they are comdensated in a cold liquid or vapor phase.

And the manner in which this vapor pressure difference is generated across the membrane is determined by the specific module configuration there.

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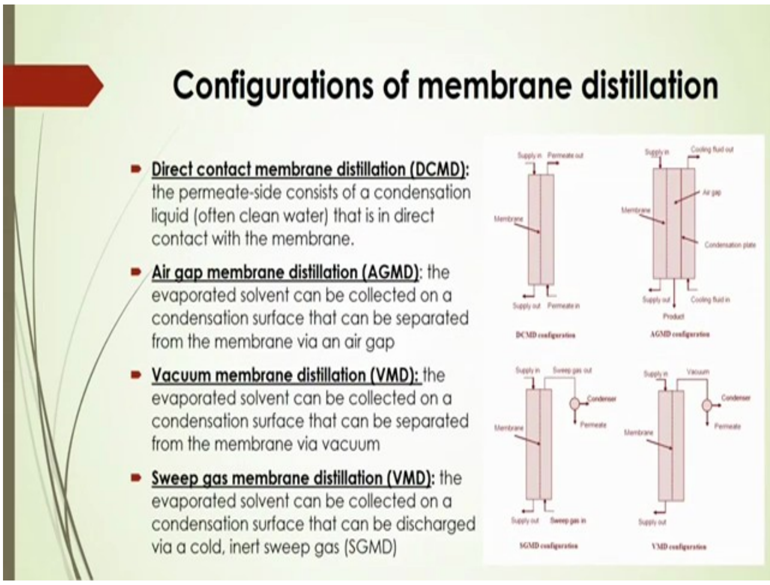

So what are the different configurations actually are available? Like, Direct contact membrane distillation modules, Air gap Membrane distillation, Vacuum membrane distillation, Sweep gas membrane distillation. These are the different kinds of membrane distillation configurations available and in case of direct contact membrane distillation you will see that permeate side consist of a condensation liquid that is often called clean water that is in direct contact with the membrane.

Whereas Air gap membrane distillation, in this case the evaporated solvent can be collected on a condensation surface and can be separated from the membrane via an air gap. And vacuum membrane distillation, in this case the evaporated solvent can be collected on a condensation surface that can be separated from the membrane via vacuum. In case of sweep gas membrane distillation, this evaporated solvent can be collected on a condensation surface that can be discharged via cold, inert sweep gas instead of just air gap or vacuum.

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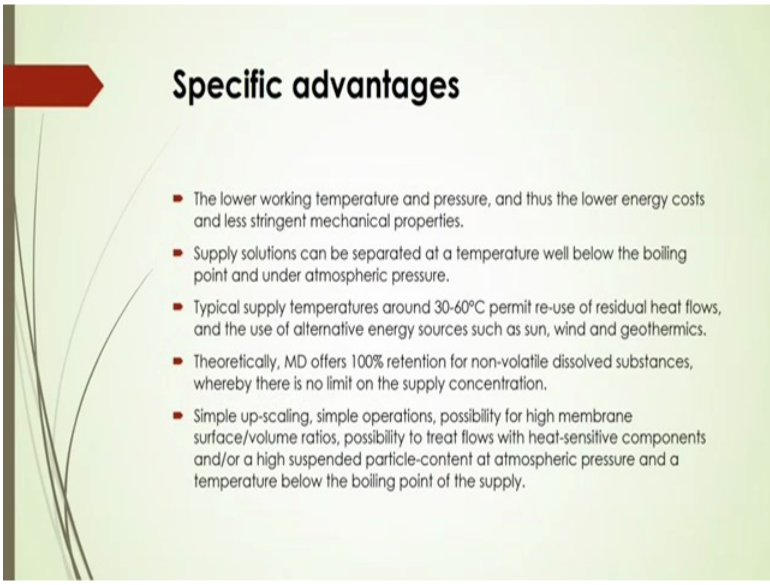

And in this case some specific advantage also you can get like lower working temperature and pressure and thus the lower energy costs and less stringent mechanical properties. And also it will be simple up scaling, simple operations, possibility of higher membrane surface volume ratios even you can get that high sensitive components and high suspended particle content at atmospheric pressure to treat.

And also a temperature below the boiling point of the supply that you can do the separation. And typically supplied temperatures around 30 to 60°C that permit re-use of residual heat that will flows, and also the use of alternative energy sources such as Sun, wind and geothermic also can be used for this. And supply solutions can be separated at the temperature well below the boiling point and under atmospheric pressure.

So these are the several specific advantages that you can get from membrane bioreactor by this RO treatment.

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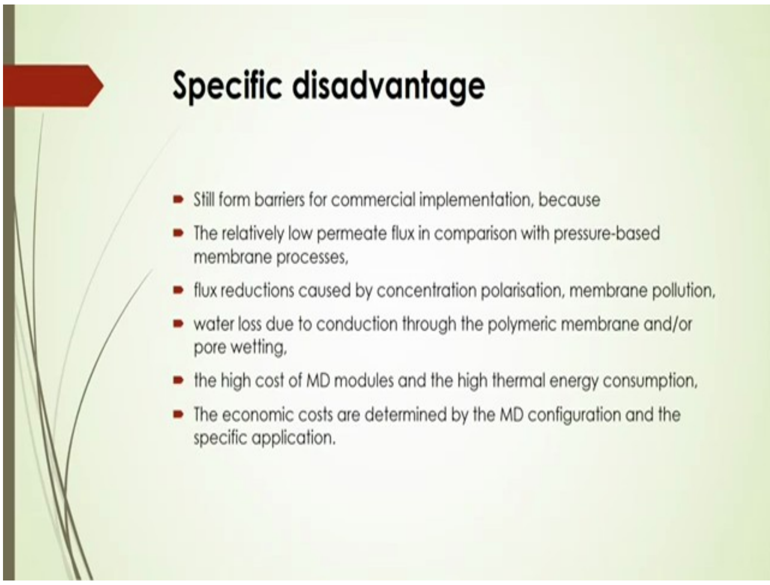

And also the specific disadvantages in this case still form barriers for commercial implementation because in this case the relatively low permeate flux in comparison with the pressure-based membrane processes. Flux reductions caused by concentration polarization, membrane pollution. Water loss due to the conduction through the polymeric membrane and pore wetting these are one of the notable disadvantages.

And also high cost of membrane distillation modules and the high thermal energy consumption is there. The economic costs are determined by the membrane distillation configuration so whatever cost will be based on that configuration may be that this disadvantages you can optimize based on the configuration design.

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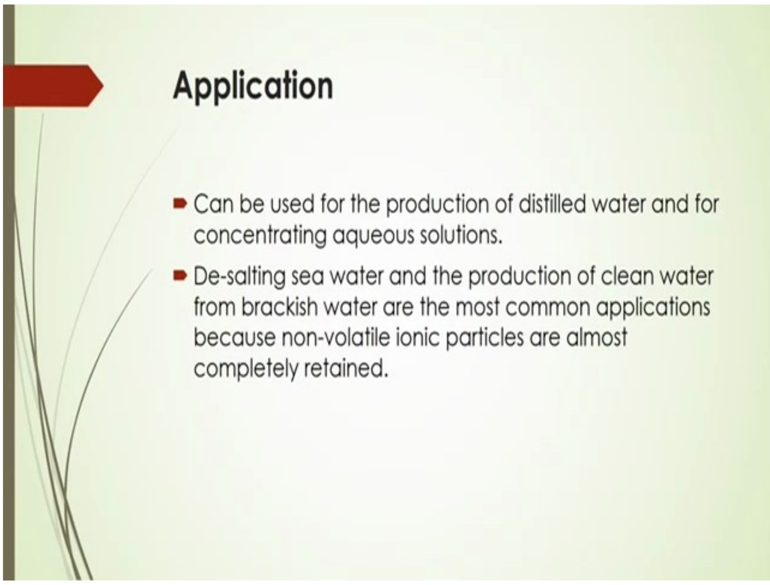

And you can use this membrane distillation process for the production of distilled water and for concentrating aqueous solutions. Also de-salting seawater and the production of clean water from the brackish water are also important applications that is considered because nonvolatile ionic particles are almost completely retained by this membrane distillation.

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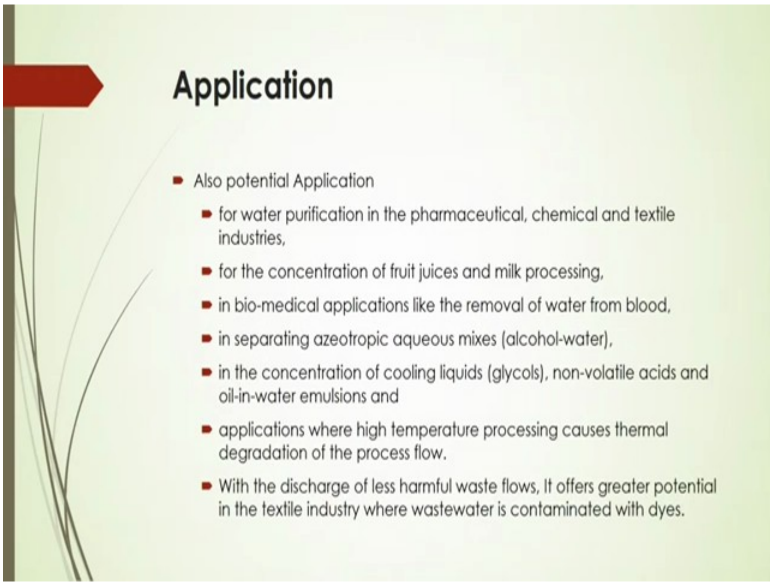

Also it can be applied for the water purification in the pharmaceutical, chemical and textile industries. And for the concentration of fruit juices and milk processing, applications where high temperature processing causes thermal degradation of the process flow there also you can apply. Even you can apply for the biomedical applications like removal of water from blood and also in this case you will see that to separate that harmful waste.

And in that case it offers greater potential in the textile industry where that wastewater is contaminated with dyes. So you have to separate those dyes by this membrane distillation process.

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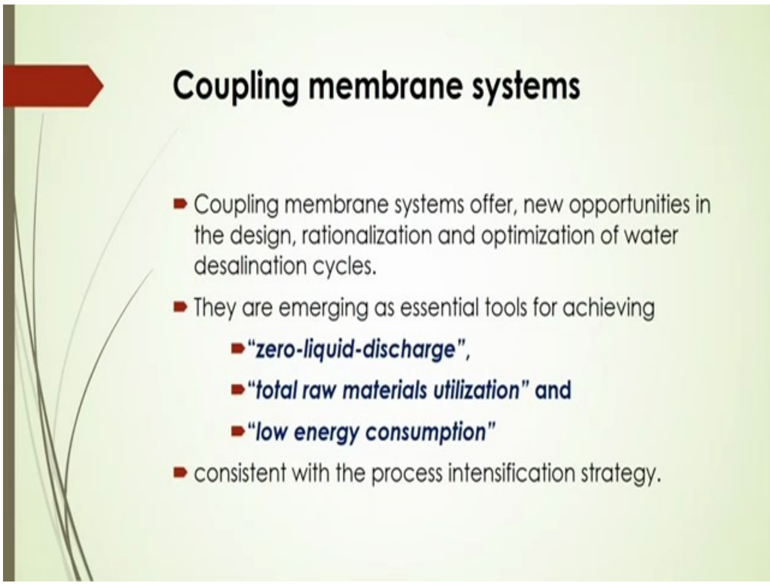

Now coupling of the membrane systems is also one of the important aspects of process intensification by membrane engineering. In that case this coupling membrane system offer new opportunities in the design, rationalization and optimization of the water desalination cycles. They are emerging as essential tools for achieving like zero liquid discharge, total raw materials utilization, and low energy consumption.

And generally it is consistent with the process intensification strategy of getting that low energy consumption even sustainable development.

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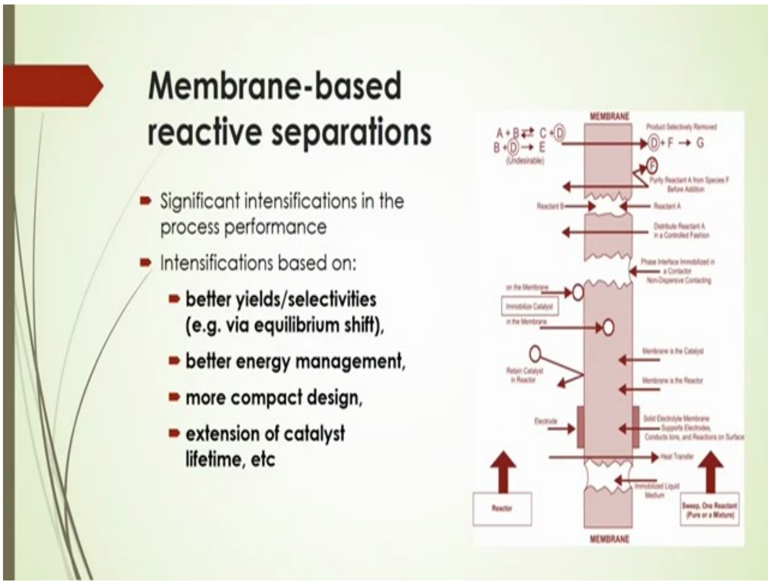

And if you are considering in this regard that membrane-based reactive separations already we have discussed in our earlier lectures that membrane assisted reactive distillation that is also one important membrane-based reactive separations. And in this case this hybrid separation of this membrane added process is significant, because it gives that better yields, selectivity via equilibrium shift, better energy management, more compact design, and even extension of catalyst lifetime, et cetera.

So based on this you can have this significant intensification of the process by this membrane.

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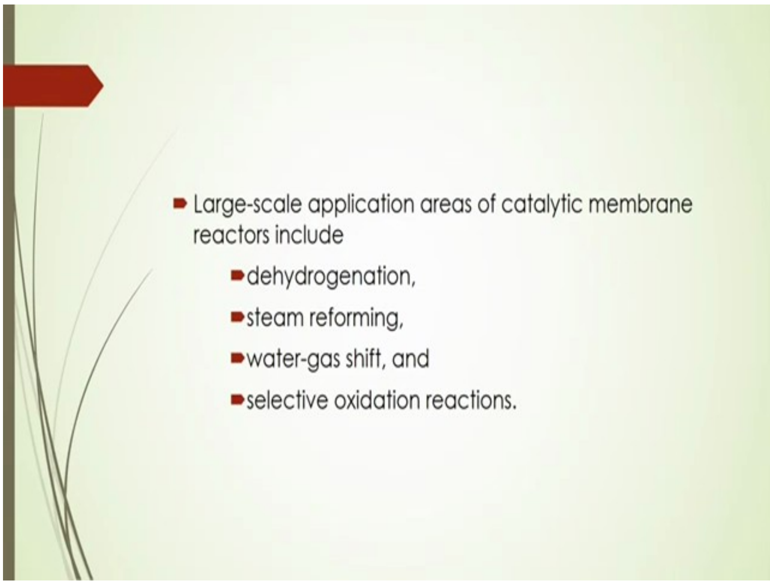

And also large-scale application areas of catalytic membrane reactors are also like dehydrogenation, steam reforming, water gas shift, and also selective oxidation reactions are also important application based on this larger scale application of the membrane.

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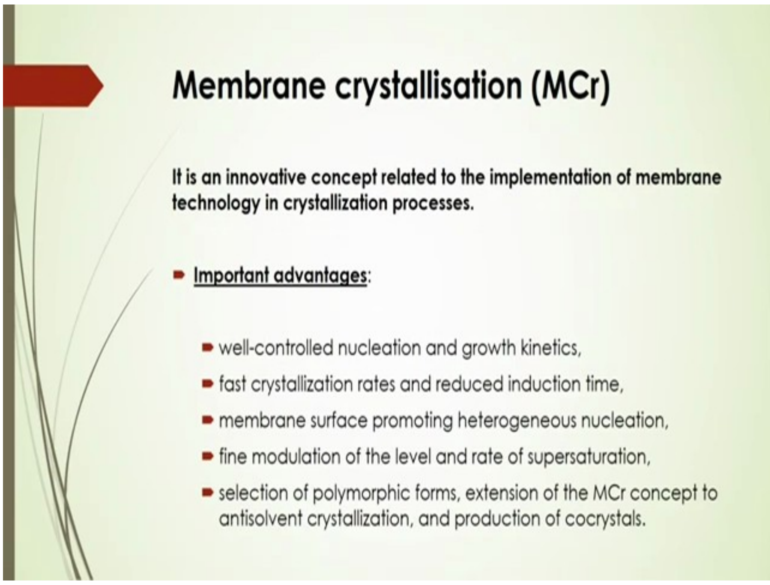

And the membrane crystallization is also another aspects of using membrane for the process intensification. It is an innovative concept related to the implementation of the membrane technology in crystallization processes. It is important because well-controlled nucleation and growth kinetics there, past crystallization can be possible and also you can reduce the induction time.

And also fine modulation of the level and rate of super saturation is possible. And in this case the membrane can promote the heterogeneous nucleation and also polymorphic forms, extension of the membrane crystallization concept to anti-solvent crystallization and production of cocrystals that can be selected based on this membrane crystallization process. So these are the several significance or you can say that advantages for membrane crystallization process.

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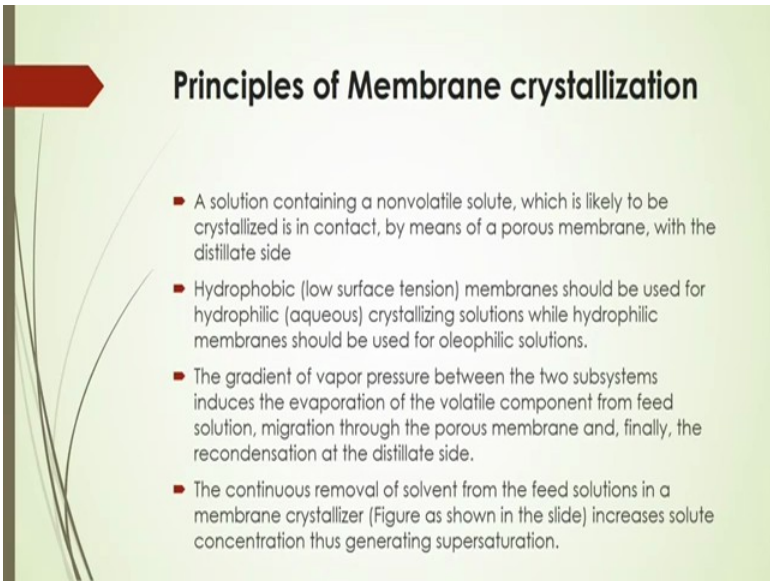

Whereas this membrane crystallization works basically based on that contact of phases by means of porous membrane with the distillate side. And in this case hydrophobic low surface tension you can say that membrane should be used for hydrophilic that is aqueous crystallizing solutions while hydrophilic membranes should be used for oleophilic solutions. And in this case you will see that the gradient of vapor pressure between the two subsystems induces the evaporation of the volatile components from the feed solution and also migration through the porous membrane and you can have the final recondensation of the distillate side based on this membrane crystallization.

And also the continuous removal of solvent from the feed solutions in membrane crystallizer is also there. And also the increase solute concentration thus generating super saturation as shown in the figure in the slides.

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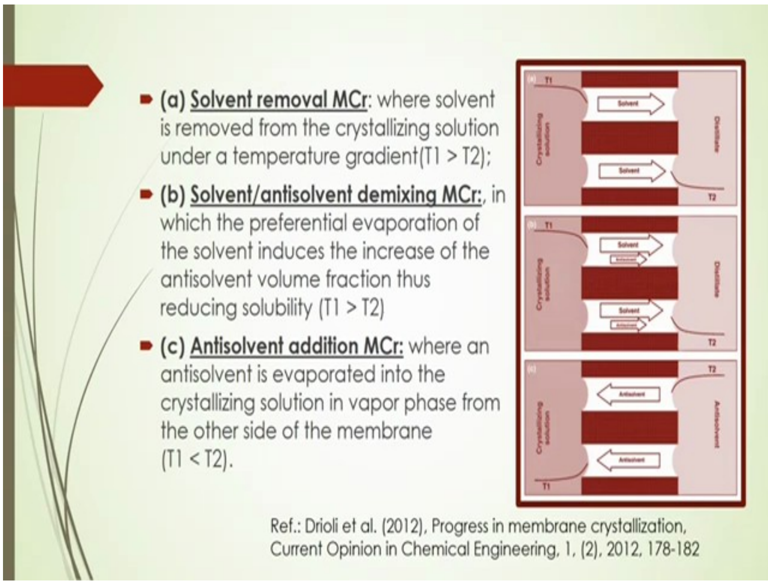

There are several aspects of that membrane crystallization like solvent removal membrane crystallization like where solvent is removed from the crystallizing solution under a temperature gradient where temperature 1 that is in the side will be greater than temperature of side 2. Whereas solvent or anti-solvent demixing by this membrane crystallization also possible in which the preferential evaporation of the solvent that induces the increase of the anti-solvent volume fraction thus reducing solubility.

Whereas anti-solvent addition where an anti-solvent is evaporated into the crystallizing solution in vapor phase from the other side of the membrane.

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So according to that Drioli et al, the membrane crystallizer, that crystallizing solution is in direct contact with the membrane surface, therefore solute membrane interaction is likely to occur that depends on the fluid dynamic regime. And also you can say that the effect can be due to both the structural and also chemical properties of the membrane surface.

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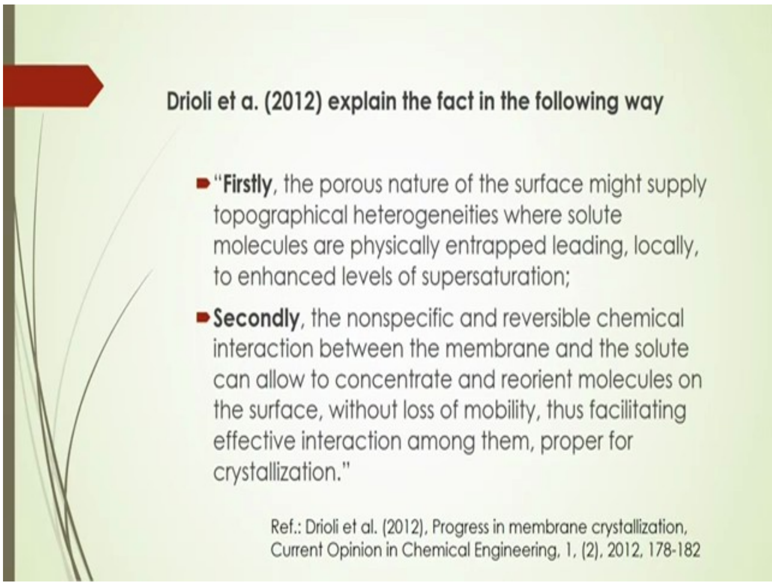

Drioli et al. 2012, they have explained the fact the following way, firstly you can say that the porous nature of the surface that might supply that topographical heterogeneities where solute molecules are physically entrapped leading, locally, to enhance that levels of super saturation. Whereas secondly you can say that non-specific and reversible chemical interaction between the membrane and the solute that can allow the concentrate and reorient molecules on the surface, without loss of mobility.

Thus in this case you can have the facilitation of the effective interaction among them and also get the proper crystallization.

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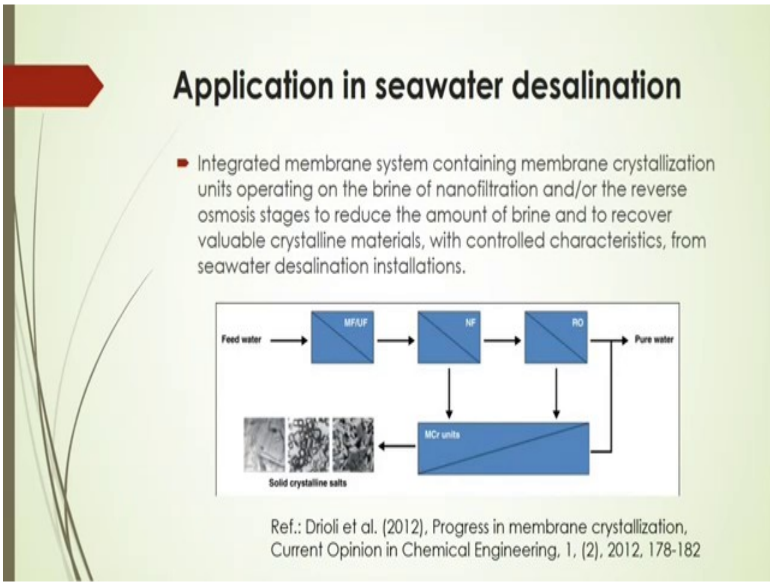

Now you can use this further application in seawater desalination. In this case integrated that membrane system that containing membrane crystallization units operating on the brine of Nano filtration and or the reverse osmosis stages to reduce the amount of brine and to recover valuable crystalline materials, with controlled characteristics from seawater desalination installations according to Drioli et al. 2012.

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So in this lecture we have discussed lot of things about that membrane applications and their mechanism. How the membrane can be intensified based on that its characteristics even how it can be conjugated with the other separation process to get that intensification of the overall processes and also we have discussed that application of that membrane bioreactors and also membrane distillation process based on that hybrid system and also their configuration how it can be used for the process intensification.

So I suggest you to go further for this membrane application in these references and also any other references of membrane separation processes. Thank you for your kind attention for this lecture today.