Chemical Process Intensification
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Principle Features

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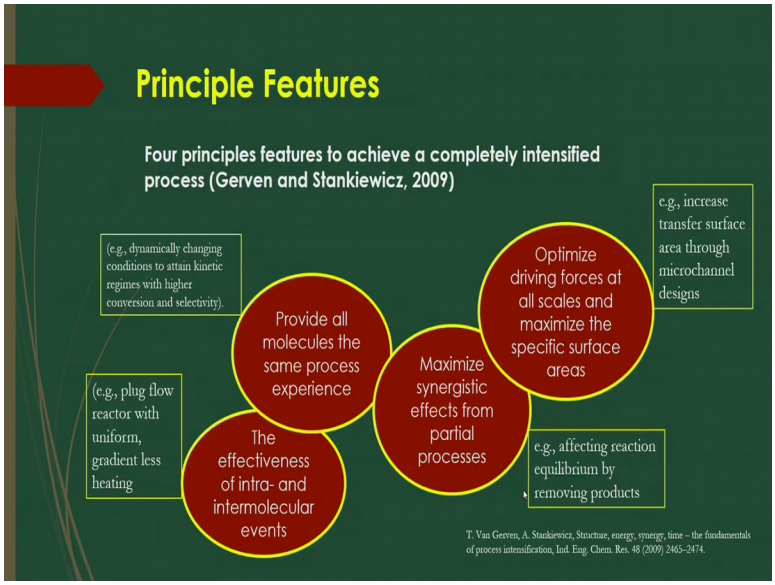

Welcome to Massive Open Online Course on Chemical Process Intensification. In this lecture we will learn about some principle features of this chemical process intensification. So, in the previous lecture we have discussed about the brief history of this process intensification as well as some features. Here also we will discuss something more about that features and also some examples according to the different type of features.

Generally, four principle features are generally followed to achieve a completely intensified process. As per Gerven and Stankiewicz, 2009, they actually told that these four basic principles as shown in here in the slide like here, this case like first one is the effectiveness of the intra and intermolecular events. Actually, the process intensification that starts from the molecular level and based on that molecular interaction the effectiveness of that intra and intermolecular events and based on that principle actually the process can be intensified.

How molecule will be actually interacting to each other and based on this how that molecule will actually enhance the process like any chemical reactions or any other physical phenomena of that particular material that depends on that intermolecular event, intermolecular phenomena.

And also, you will see as a feature of that process intensification, it will provide all molecules the same process experience. In that case you will see that molecules you will see have whether that molecules will be actually giving the same experience of traveling those, you know that free path like you know Brownian motion, there how molecules will be moving;

Even if there is any convective force, convective processes or heat transfer or mass transfer process in convective mode, there how molecules will be actually traveling and how those molecules will be interacting to each other so based on which the process can be intensified. And also, many factors that affect on that particular intermolecular phenomena of any chemical process. So, in that case some, you know that effect should be, you know maximized to actually giving that particular process yield.

So, they are, you know maximize synergetic effects from the partial process which will be actually considered before going to that particular intensification of the process. And also, you know that there are several driving forces are acting in a process. Like mass transfer there will be driving forces concentration.

So, you have to actually optimize that driving force for your process and also based on that what should be that, you know some coefficients of that phenomena of what is that processes like, you know that mass transfer in that case suppose adsorption reaction, that adsorption of any, you know molecules, that depends on that concentration gradients in the phases.

So, if we consider how much actually molecules will be transferred from one phase to another phase for that particular adsorption operation. In that case that rate of adsorption depends on the concentration gradient and the proportionality constant it is called that you know the transfer coefficient. So, this transfer coefficient depends on different operating variables of the processes.

Like if you are doing that adsorption of, you know that some carbon dioxide gas or gas phase adsorption in a liquid medium, in that case overall mass transfer coefficient is considered as a proportionality constant. Now that constant depends on that you know different geometric variables of the unit, even physical properties of the system and also thermodynamic properties. Of course, there is dynamic variables that is very important.

So, in that case you will see that this mass transfer coefficient depends on that, you know dynamic variables like flow rate of the fluid and physical properties, what are the fluids that

is being taking part actually there in reactions or adsorption process, that physical properties of the system that will affect that mass transfer coefficient.

And also, the geometric variables, size of the reactor, diameter of the column, even length of the column are the important factors for actually changing that you know mass transfer coefficient. And also, other variables like temperature and pressure, those are called thermodynamic variables. These thermodynamic variables also make effect for the physical, even reactive separation of the processes.

So, whenever you are going to actually maximize or optimize the yield of the process there you have to actually consider all those variables and also driving force and these generally affect the scaling of the processes. Whenever you are going to scale the process from the laboratory scale to the industrial scale that you have to consider all those mass transfer coefficients and that mass transfer, how those mass transfer coefficients will be depending on the different operating variables.

And also, important thing is that whenever you know that dynamically changing conditions to attain kinetic regimes with higher conversion and selectivity, in that case, this molecular effect is important. And also, you will see that some performance of the processes, that depends on flow regimes, whether it is plug flow or turbulent flow, laminar flow or slag flow, different types of flows, flow patterns are there in the multiphase systems because you know every reaction or any physical operation that actually involving more than one phases. So, it is called multiphase flow.

So, fluid, how it will be actually flowing, whether it will be in plug flow phenomena or uniform actually heating gradients throughout the columns or not, that will actually affect that molecular interactions and also you know that other performance or yields of the processes. And whenever you are going to maximize the synergetic effects from partial processes that you have to actually consider the equilibrium of the reaction.

So how this equilibrium of the reactions is affecting by the variables as well as even if you are just removing the products that also will affect that, the equilibrium condition of the reactions. And of course, that to optimize those processes that you have to operate the processes based on you know that suitable operating conditions and also if it is interfacial phenomena reactions then you have to increase the transfer surface area through the specially designed conduit or reactor there.

There are several different types of reactions are there and different, actually you know designs can be done based on that increment of the surface area. Like you know if there is a gas-liquid reaction you can supply the gas through the liquid medium as it as it is dispersed phase of the bubbles. So, there you can increase the surface area of the bubbles or increase the interfacial area through which the mass transfer will happen.

So, these are the basic four principle features that is given by Gerven and what is that Stankiewicz in 2009. So, we can have these features and based on these features sometimes this intensification is being done.

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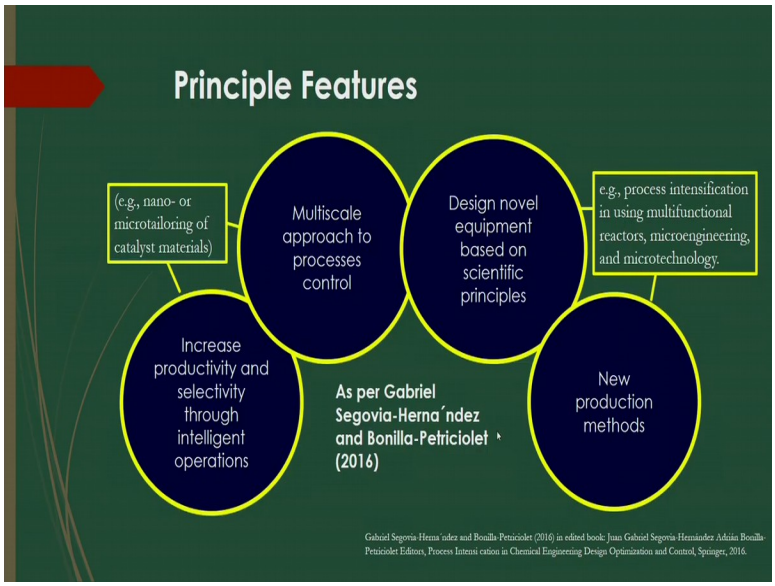

Now other features like this here, you know that one of the important principle feature of process intensification is you know that increase the productivity and selectivity through the intelligent operations. What is that intelligent operations? That case we will see sometimes. Some materials to be, you know developed to actually enhance the productivity of the process and also sometimes you know integrate the process in a suitable way so that you can increase the selectivity and the productivity of the processes.

Example like that nano or micro tailoring of the catalyst materials that you have to develop in such way that it will affect the productivity and the selectivity of an intelligent operation. So, based on this material characteristics you can intensify the process there. Even sometimes it is called that multiscale-approach-based process intensification. In that case the process will be controlled by multiscale approach for the process intensification.

And for the process intensification, other important feature is that the design of the novel equipment based on the scientific principles. Sometimes if you procure some or you can design some equipment in such way that it will give you the best, you know that productivity of the processes. Like you know nowadays micro reactors are coming. So micro reactors, micro channel-based reactors where the gas liquid reactions will be doing through that micro channel, even extraction processes, liquid-liquid extraction through the micro channel-based reactor.

In that case the reactors are being designed in such a way that will be, you know a very small reactor even to get the plug flow phenomena and also to get the more interfacial area, these types of reactors are being developed. Even there are several other different types of reactors are being developed based on different; you know that scientific principles like you know that microwave reactor. Even you will see that extractive distillation, even you know that there will be certain principles of electric field, electromagnetic field, how it will be actually used to, actually enhance the reaction performance, even you know that separation processes.

And also, there are some other processes like you know centrifugal action, even some other process like sono-chemistry, you know how to produce that, you know micron size bubble or micro bubble it is called, and to increase the interfacial area of the reaction processes for that gas liquid reaction. So, in that way sometimes the reactors are being designed, novel reactors are being designed based on these scientific principles. So, this is also one of the important features of process intensification.

Even you know other features like new production methods. You have to think about that how we can actually produce different types of products and also different methods to produce those products. So, you have to intensify the methods here. Like that you have to, you know that you cannot use the conventional process to produce; you know that, just separation processes. You have to intensify the process by developing new methods there. So that is also one of the important features. These four basic principles also are given by Segovia-Herna'ndez and Bonilla-Petriciolet in 2016. So, these are the some principles, basic features that is given by them.

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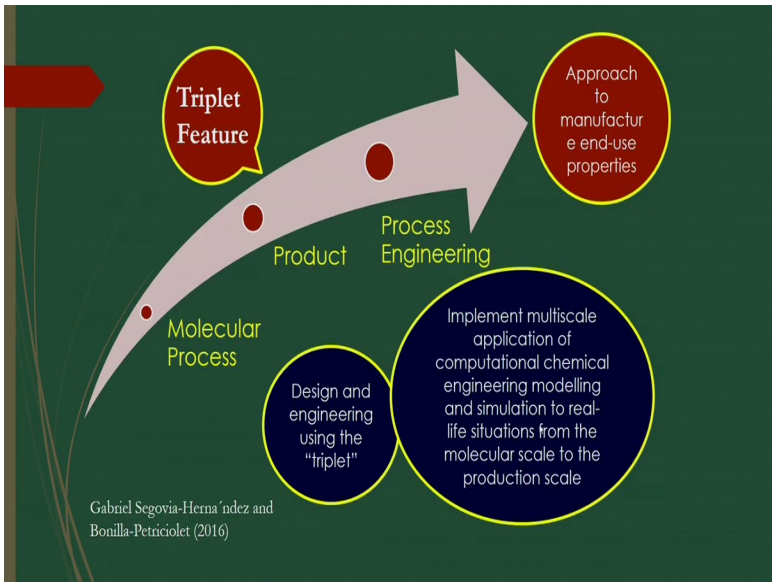

Another important principle of this process intensification, it is called triplet feature. That is given by this Gabriel Segovia-Herna'ndez and Bonilla-Petriciolet in 2016, they told that the basic principles of the process intensification should be as a triplet features like molecule, first it will be one is, molecular process, then from the molecular process it will go to the product side and then after that process engineering.

What is that actually? The molecular processes means here reactions to be done molecular level after that, after reactions some products will come and whenever products will be actually obtained that you have to separate those products and byproducts to give the certain, you know degree of purity and for that process engineering is very important in that aspect.

So, these are the triplet features of this process intensification. Now in this case, by these triplet features you have to approach to the manufacturer and manufacturer end use of, that is properties. Like that final product to get it, first you have to do the reaction, then product, then separation processes of that product mixture.

So, to get that product mixtures you have to intensify the process unit, you have to intensify the methods, you have to intensify the, you know that policy so that you can, you can get the final end use of the products that is being developed in your particular process intensification process.

And also, important thing is that design and engineering used in the triplet is also concerned about this triplet feature that, that case implementation of that multiscale application of computational chemical engineering, modeling and the simulation to real life situation from the molecular scale to the production scale is required.

So very important that after producing that product of course you have to develop some, you know that process principle or you know that, simulate that process by which you can say that ok, based on this, you know that operating conditions you can get this type of products. So, you need to have some simulation process based on those, you know the experimental observation for this process intensification way.

And in that case based on that simulation you can also, you know that scale of those processes for the commercialization, you know sector and you can get that more precise way to interpret those processes after development of this process method for this process intensification.

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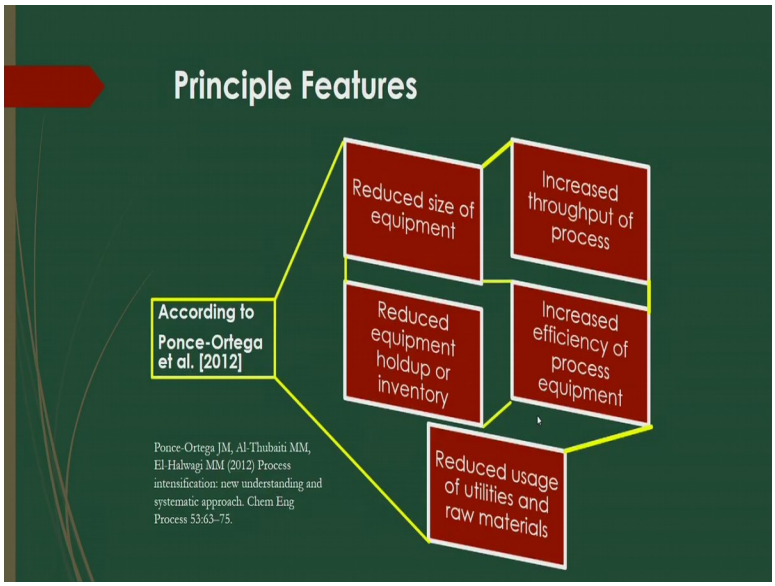

Now according to Ponce Ortega et al, 2012 they have given, they have suggested also some features of process intensification. Like that they told that, you know that to intensify the process you have to reduce the size of the equipment. And also, you know, you have to reduce the equipment holdup or inventory. That is why you will see that whenever there is a big process, like you know there are several equipments are being used for a particular process.

So, for intensification you have to reduce those, you know equipment numbers or equipment size also. So, by reducing the number of the equipment and also size of the equipments that can be possible to intensify the process. Also, in a particular, you know that reactor there are several, you know that inventory will be there. That is huge amount of inventory will be there.

So, you have one of the important features of the process intensification to reduce the holdup or inventory of the process. Because you know that for that higher inventory or higher holdup will give you the big size of the equipment. So, in that case, if you reduce the holdup or inventory based on which that process intensification to be done then of course you have to reduce the equipment number and equipment size.

And also, the process intensification can be done by increasing the, you know that throughput of the processes. Sometimes in the turbulent motion, turbulent flow based on which you will see there will be a intensification of the process. Because there at high throughput you can get more interaction of the molecules of the process as well as more mixing inside the bed.

So, their high throughput is also one important factor to increase the intensity of the mixing of the process and based on which you can get more, you know output of the process. Like in this case you know that heat transfer operation is also one of the important process and based on this intensity of the mixing.

As well as some multiphase flow systems there, mixing is important. So, you have to increase the throughput of the process to get the intensified, you know that way to produce different products. And also, efficiency of the process equipment, you have to increase to get the process intensification for the particular process. In that case how to increase the equipment? So, you have to design the equipment in such way that sometimes it may consume less energy.

In that case the design should be based on that physical principles of the flow and also the properties of the flow, there you know some liquids you will see will have some higher, you know the frictions because high viscous liquids to be actually sometimes to be used for the process. So, in that case you have to reduce the friction and based on that frictional resistance you have to design that equipment to get the better efficiency.

And also, if you use some materials, some raw materials if you use through a particular equipment that may corrode the equipments and it may not give the, you know that sustainable way of output there and the process will not be lasting long for that particular operation.

So, you have to design those equipments in such a way that you have to consider the raw material properties, whether it is high viscous or not, or some other characteristics of the materials you have to consider and based on which how to increase, how to increase the efficiency of the equipment that is required for the process intensification.

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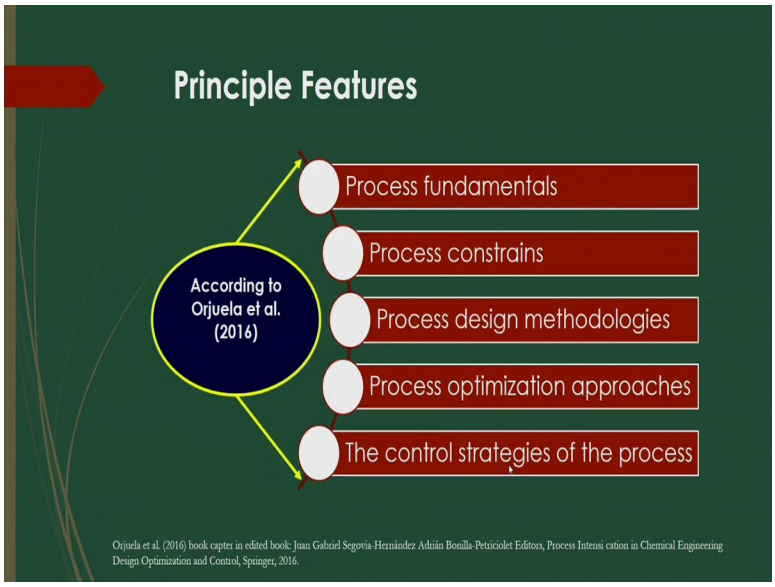

Other principles like you know that according to Orjuela et al, they have given in 2016, they told that process fundamentals is one of the important factors to intensify the process. If you do not know the fundamentals of the process then you will not be able to design that particular process equipment. And based on which you will not be able to intensify the process.

Even some constants also, there several variables are actually involving for the particular process. So, you have to reduce that variables to get the intensified way of the process. Sometimes, if you reduce the variables you have to operate that process or you have to consider the intensification of the process. You have to develop the new methods for that; you know process so that you can use less number of variables for that particular operation. So, you will get the less constraints for that particular process.

Also process design methodologies, you have to design that methods in such a way that it should be sustainable and also eco-friendly and economic there. And you have to use some, you know optimization process to identify those variables whose, that will be actually more intensive to give the output of the process. So, you have to optimize those process variables, that sometimes you have to segregate, you have to, you know remove some constraints to get the optimum value of that process.

And for that you have to, sometimes develop or you have to, you know integrate those other methods. You have to make a algorithm in such way that you can get the best way of solution for that particular process optimization. Because the intensification process there is complex method. You are considering different methods of intensification. So, their variables will not be involving in a single variable may be, you know that different variables may be involving. But that should be intensified where that should be more complex.

So, in that case you have to use suitable algorithm to actually optimize the process. And also, the controlling strategies also to be known, how those complex method can be actually that, controlled for that particular intensified process. So, these are the, also important features to design a particular process for your, you know intensified way to get the output. So this is, these are common, actually principle features for all process intensification.

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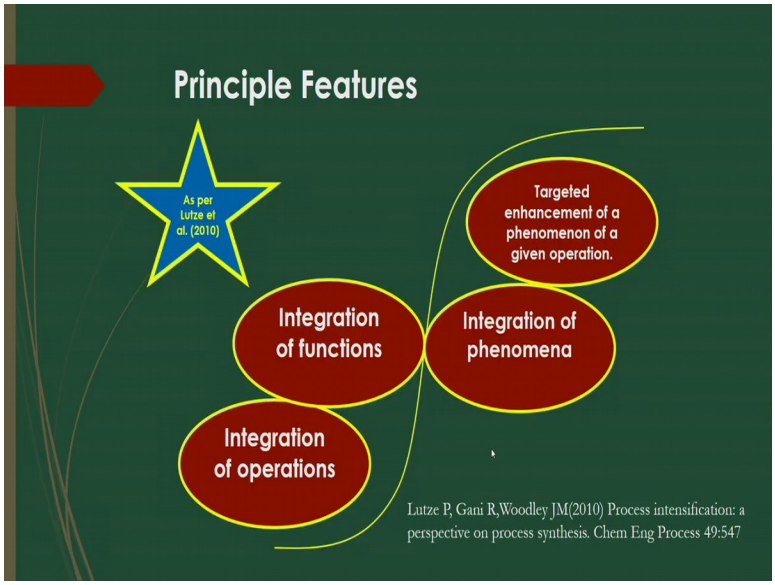

Another important features you know given by Lutze et al 2010, they told that Ok, the principal features of the process intensification should be that and other way like sometimes you have to integrate the process operation. Like you know that two process should be in a

particular unit. Like reactive distillation, reaction as well as distillation that is reaction and separation both will be in a single unit.

So, you have to integrate the operations. That means here reaction as well as separation both will be simultaneously in a particular system. So that is called integration of the operation. Here integration of functions also, there are several functions will be there. There several variables will be there. So, both the variables or functions should be actually integrated in the process.

And integration of the phenomena also. You will see there are several phenomena, of the physical process, physical you know that theory will be acting on particular process. So, you have to integrate those, you know principles or phenomena of the, you know that system for that particular process intensification.

And also, you know that whenever you are going to have some targeted product by process intensification based on this integration of the operation you will see several, different phenomena will be acting simultaneously. So, you have to enhance that operation. You have to enhance the, you know that mode of the operation in such a way that phenomena-based separation can be obtained there.

So, this is also important that whatever target will be there, after separation what type of products you want to do, based on that you have to select some, you know that phenomenastic materials or some, you know that, some materials which will be more suitable in that particular process. You cannot use arbitrary materials to give that particular output.

So, you have to wisely, actually select those materials when you are going to have this, you know that your targeted product. So, you have to, you know consider those materials wisely for that process intensification. So, these are the features that is given by Lutze et al, 2010. These are also very important features that you have to keep in mind for the particular process intensification.

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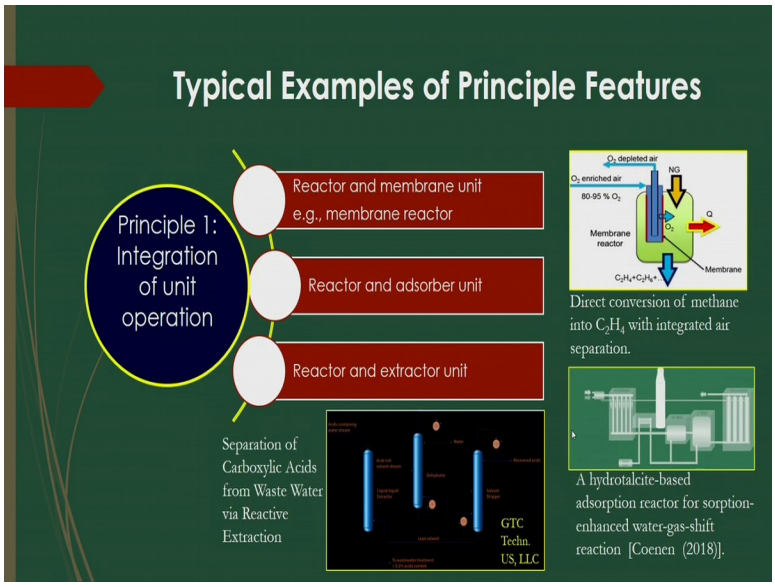

Some of the typical examples of the principal features of the process intensification like we can divide in different way, like different, several principal features. Let us see that principle one, integration of unit operation. In that case suppose there is a reactor and membrane unit. So you can develop the membrane reactor so that the reaction and separation both will be happened in that membrane reactor.

Like reactor and adsorber unit. Some reactive adsorption will be there. Suppose there is reaction, after that product will come and that product, from those products you have to separate that byproduct and main product there. And other, some other contaminants that will be separated.

So, some adsorber to be used, some adsorber like solid materials in a packed adsorber or some other intensified adsorber to be used so that the contaminant to be adsorbed on the materials and separated from the main product. So that way, that combination of this reactor and the adsorber unit that is also one type of process intensification.

And also extracting reactor, reaction as well as extraction both will happen simultaneously. So that is why the process intensification should be integrated with for that reactor and extraction so that is, it is called the reactive extractor unit.

So, separation like example, here separation of carboxylic acids from the waste water via reactive extraction. So, this is also one of the important methods by which you can do the

process intensification in a simultaneous way for this reaction and extraction process. So, example here.

As well as you know the direct conversion of methane with integrated air separation process there and some other examples like the hydro, you know that talcite based adsorption, reactor for the separation or enhanced water gas shift reaction they are reaction as well as the adsorption both will be happened in a particular operation. So integrated operation, so that is why we can say that one of the important features of the process intensification is called integration of unit operation.

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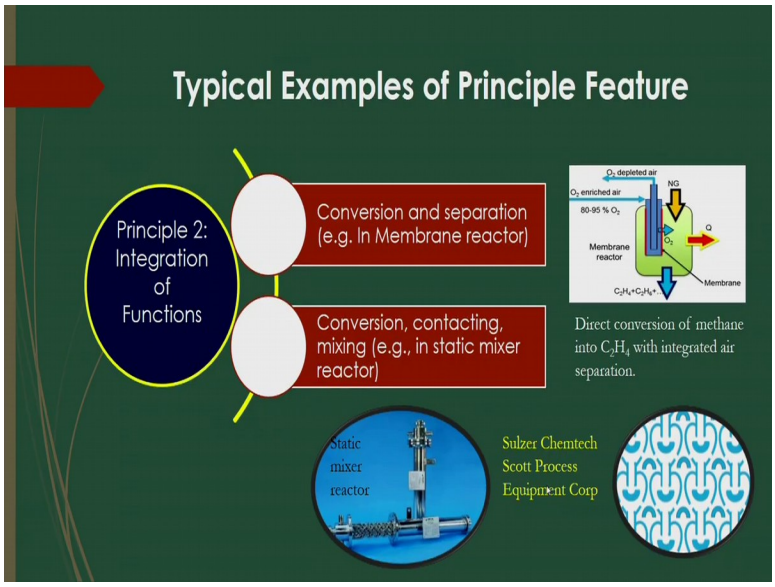

Now, integration of functions, what is that? In this case conversion and separation, example in membrane layer, both will be happened simultaneously, conversion as well as separation. Even conversion, contacting, mixing in a static mixer reactor also one example for this integration of the function.

Like you know that function means a conversion function. Even separation, this is one function. Even you know that contacting mixing, sometimes you know that you have to mix the fluid in intrinsic way. What is the degree of mixing there? That is also required to know. That is actually obtained by that estimation of the, you know that, that is one important parameter. It is called Peclet number based on which, if Peclet number is going to infinity that means here it will be, you know that less mixing where as it is zero, Peclet number coming to zero then it will be called as what is that higher mixing or complete mixing.

So, you have to intensify the unit to actually increase this process intensification phenomena based on this integration of the functions there. Like static mixture is one of the important units to mix the fluid intensively. So that is why static mixture is called unique intensified unit or static mixer reactor is called the intensified unit for, you know that simultaneous operation of reaction as well as, you know that mixing of the phases.

And direct conversion of methane into ethylene with integrated air separation is also one important, in that case conversion and separation are the functions and these functions are integrated in a intensification process, and also you will see that here, the picture shown in, you know slides that the how this intensified reactor can be developed based on the microchannel based reactor, micro reactor and also there is some static mixer which is being used for the intensification of the mixing there.

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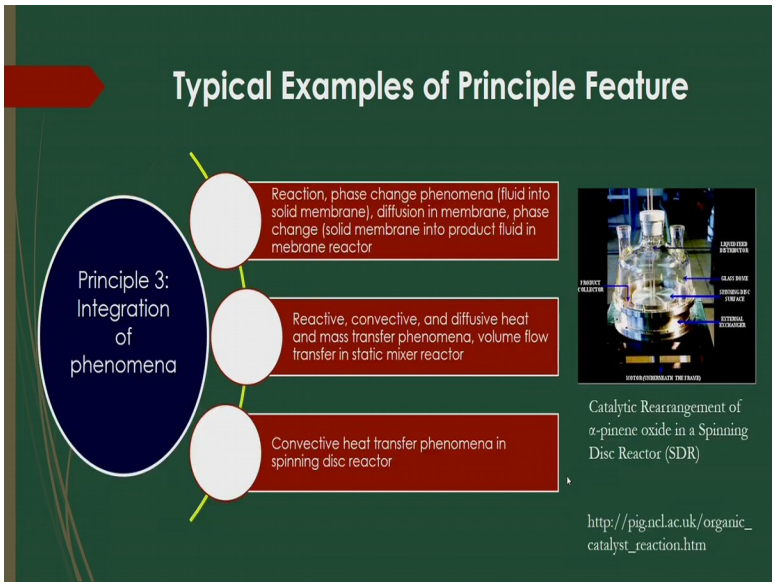

Like another important principle feature is called integration of phenomena. In that case what are those phenomena? Like reaction, phase change phenomena, fluid into solid membrane, even diffusion in membrane, you can say that phase change, solid membrane into product fluid in membrane reactor. These are the features of, that is you know integration of the phenomena you can say.

And some other phenomena like that; you know reactive, convective even diffusive heat and mass transfer phenomena. Even volume flow transfer in static mixer reactor. So these phenomena also to be considered for your process intensification. And convective heat transfer phenomena in spinning disk reactor, you know the spinning disk reactor there the

reactor will be rotating at a particular rpm that is called at particular rate, so that there will be a fluid mixing inside the reactor and based on that fluid mixing that convective heat transfer will be happened.

And also, you know that in the static mixer the reaction phenomena, convective and the diffusive heat and mass transfer phenomena will happen there in intensified mixing way. And you will see sometimes, you know that membrane reactor or some porous reactor there will be a phase change of the fluid in the reactor. And also, you can intensify the diffusion of the molecules in the membrane reactor and, you know porous material through the porous material you can enhance the diffusion of the process. So that is why these phenomena to be considered integrated way to get the process intensification.

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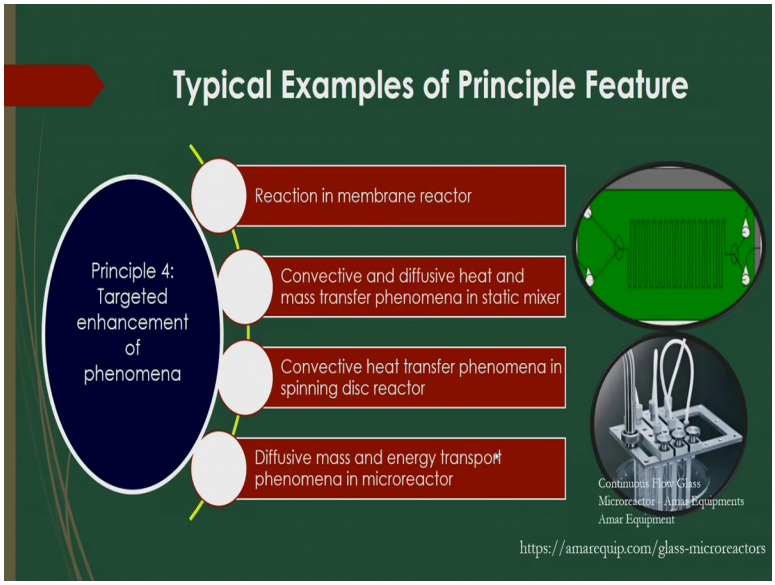

Like another important feature is called the targeted enhancement of the phenomena. That is here, in membrane reactor the reaction what should be there and also the convective and diffusive heat and mass transfer phenomena in static mixer and convective heat transfer phenomena in spinning disk reactor, even diffusive mass and energy transfer phenomena in micro reactor.

So, nowadays this membrane reactor, even static mixture, spinning disk reactor even micro reactor are coming in market for the process intensification and different company, they are actually using those, you know that commercialized product of, that is design based on this process intensification principles. And it is being used nowadays. And also, future aspect that since the space problem, even number of equipments and energy consumption based on

which we can say that this intensification can be done by integrating this unit operations and also the phenomena of the process equipment.

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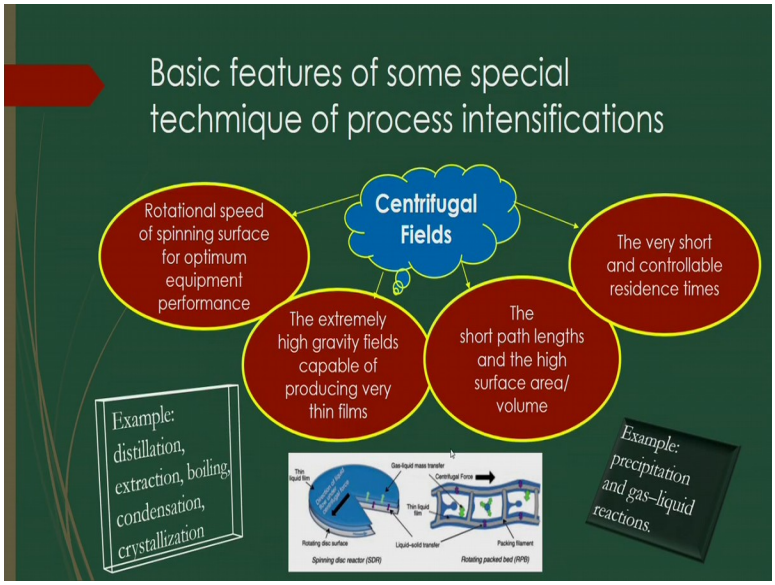

Basic principle of some special technique of process intensification there also, like here different, you know phenomena like centrifugal actions, even microwave reactor, even you know that some, you know that spinning operation or spinning phenomena based on these, how that the process intensification feature can be obtained or process can be intensified based on those phenomena.

Here like centrifugal fields in this case, rotational speed of spinning surface of optimal equipment performance. Here in this case if you remember reactor is spinning at a certain rate. You see there will be a fluid that will get some centrifugal action and based on which there will be a generation of, you know that secondary flow phenomena and based on which the intermolecular attraction will be more;

Molecular, you know that, interaction will be more and there will be, you know that mixing will be more, and also flow phenomena, that is plug flow phenomena will be there. And based on which you will get more; you know intensified way to get the product there. And also, there will be some optimum condition based on which you can design the process for the process intensification.

Sometimes, you know extremely high gravity fields also capable of, you know that producing very thin films there and if you producing very thin films there will be mass transfer, more

mass transfer because interfacial diffusion of the molecules will be enhanced there through the thin film and in that case mass transfer would be more. So that is why any chemical engineering processes for the separation, so you have to sometimes produce the thin film for the intensification of the mass transfer.

And also, another important thing is that for spinning reactor, you will see based on this centrifugal fields, you can produce higher, you know pores for mixing of the phases and also you can increase the contact time of the, you know that fluid mixer in a short path. So the short path length and the high surface area volume can be generated by the centrifugal action and because which you can get more mass transfer. Because mass transfer is directly related to the, you know that surface area per unit volume, that is called interfacial area.

So interfacial area and also contact time both are the main important factor for the intensification of the mass transfer and based on which the separation processes of the chemical engineering operation. And you know that residence time, that I told that the contact time is, that is called sometimes, how long these molecules will be residing in the particular reactor. Like if you are using the column reactor, sometimes if you operate some processes by developing soft particles of different gases or liquids it is sometimes called drop or bubbles.

So, in that case if you increase the residence time of the bubbles in the reactor or droplet in a reactor you can have more time to get the mass transfer there. Like you know that, if suppose consider a bubble column reactor in which gas is supplied from the bottom of the reactor. Like carbon dioxide gas is absorbed in liquid. In that case carbon dioxide gas bubbles will be produced from the bottom of the reactor as a dispersed phase of bubbles.

If you produce, you know that more finer bubbles you can get, you know more residence time there in the reactor because residence time depends on the buoyancy force of the bubbles. If you have the more buoyancy force then immediately those bubbles will go up and it would dissolve at the surface of the reactor.

So, if you reduce the size of the bubbles then your buoyancy force of the bubbles would be less. Then it will take more time to come into the top of the column. So that is why it will stay for long time in the column. Another way to increase the residence time is that if you supply those gas from the, you know that top against its buoyancy you can get also more residence time there.

Nowadays that one important operation, it is called downflow operation, downflow operation where the gas or liquid droplet, it is supplied from the top of the bubble column, top of the any column or mixing column you can say and there it flows by the downward movement of the liquid and against its buoyancy so that the higher flow rate or higher momentum of the liquid, it will actually drag that gas bubbles or liquid droplets against its buoyancy.

So that at a particular operation where the downward movement of the liquid is equal to the buoyancy force there you can have more residence time, that means at that equilibrium condition, bubbles or droplets will stay a longer time in the column. That is why the residence time of the column can be actually intensified in this downward operation or downflow column.

So that you have to, you know that control those residence time of the gaseous bubble or any substances or fluids there to get more mass transfer. Sometimes for fast reactions it may not be required to get the more residence time there. So, in that case you can operate the upflow reactor or upflow bubble column reactor for fast reactions. Whereas in such cases where the slow reactions will be there, so in that case you have to increase that, you know residence time reaction, residence time of the particles or fluid particles by downflow operation.

And you know that sometimes some catalyst particles, it will not be actually residing in a column because it is very lighter than water. So, in that case, you know that inverse fluidized bed is also an important intensification of the process where the catalyst particles can be actually controlled by controlling that, you know that movement of the catalyst particles in the downward direction against its buoyancy. So that is why the inverse fluidized bed is coming.

So, this is the centrifugal field by which you can say that you can increase the intensification of the process and some examples are given here, distillation process, extraction, boiling, condensation, crystallization, even some examples precipitation and gas-liquid reactions, these are very important chemical engineering operations. These operations can be intensified or these intensified operations are being done by the centrifugal fields and based on the phenomena of the centrifugal action of the fluid particles.

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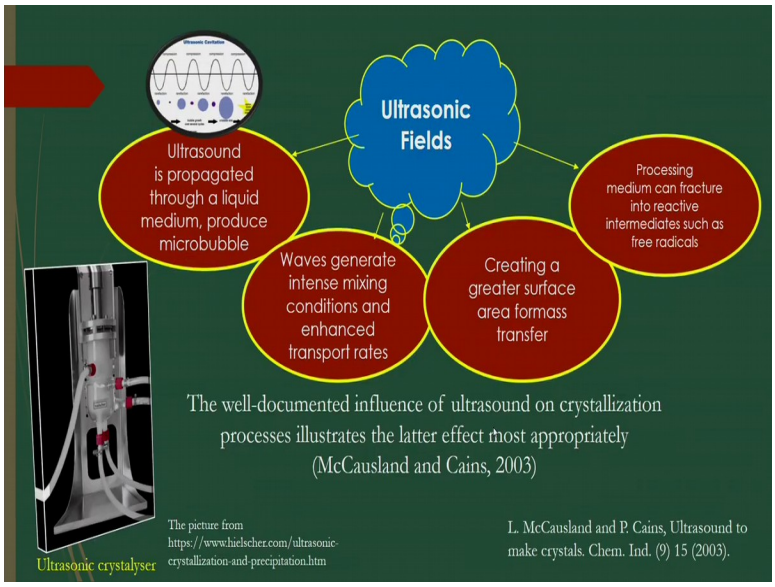

Another is the ultrasonic fields where you will see that ultrasound is produced through a liquid medium to produce the micro bubble there. So, generation of the micro bubble is important because, to get the more interfacial area for the gas-liquid mass transfer operation, there you have to produce more surface area. So, there you can produce the microbubble for intensification.

And ultrasonic method is one important, actually method based on which you can produce this microbubble. There are several other methods also available like you know that, venturi even high-pressure gyration systems are also able to produce the micron size bubble. Here ultrasonic field also important but you know that energy, high energy consumed for the initiation of micro bubbles.

Also, wave generate intense mixing conditions and enhance the transport rates. In this case, whatever ultrasonic waves are generating, there fluid mixing will be higher based on this ultrasonic wave and in that case the transport rates can be increased based on this ultrasound operation. Also creating a greater surface area for mass transfer because we can say that the here, microbubble production we told that, even nowadays even nano bubble also is produced for the medical operation there to get the more surface area for gene therapy when drug delivery operations in the cancer cell.

So, in that case you have to increase the surface area, when for mass transfer, even reaction for that, to get the reactive mass transfer in intensified way you have to use, you have to

produce the more surface area. Even extraction, liquid-liquid extraction, suppose if you want to extract that propionic acid from the water in some organic solvent so you have to produce that, you know more surface area to transfer this propionic acid from the water to the organic phases. So, in that case how to produce that surface area?

You have to produce droplet of those organic solvent as well as, you know that water, that is immiscible, two immiscible liquids are there, you have to produce the droplet of that, you know that organic solvent like paraffin or decanol. If you use decanol to extract that propionic acid from the water, you have to produce the droplet of the decanol or paraffin. So, through which the mass transfer will be happened there.

So, in this way you can use that ultrasonic wave to create more finer droplet there to extract those propionic acid from the water. So that is why intensification based on this ultrasonic fields for this particular extraction operation. Even processing medium can fracture into reactive intermediates such as free radicals also.

Sometimes if you use, you know that micro bubbles, they are even nano bubbles, you will see in, like ozonation process, nowadays intensification of the waste water treatment by advanced oxidation. They are like ozonation process. So like arsenic, you know that, removal from the water, how to do that. Generally, the ground water, generally the arsenic is staying as a, you know that arsenic 3 compound.

So, in that case it is very difficult to adsorb those arsenic III compound by adsorption process, simple adsorption process. So, you have to convert this arsenic III to arsenic V by advanced oxidation. In that case ozonation is one of the important advanced oxidation processes by which you can, this convert this arsenic III to arsenic V. Now for that ozonation process you will see, by formation of ozone bubbles for that reaction to convert this III to V, you have to produce fine bubbles.

That fine bubbles, at its interface will produce some radicals, free radicals of, you know that waste radicals. So that waste radicals will take part into the reaction to convert this arsenic III to arsenic V easily. After that arsenic V you have to adsorb in a resin-based any adsorbent or some other thing, then you can easily separate that arsenic from the water. So, this is one of the ways to intensify the process for the separation of the arsenic from the water.

So main important thing is that you are producing here free radicals. That free radicals can be produced by that ozonation process and that ozone micro bubbles can be produced by this ultrasonic field. So that particular micro bubbles that ozone radicals will be actually attaching over the surface of the micro bubbles. And then these radicals will be acting in a reaction. Another, you know that crystallization process, that is ultrasonic crystallization, that is also one of the important process to get the intensification chemical engineering process.

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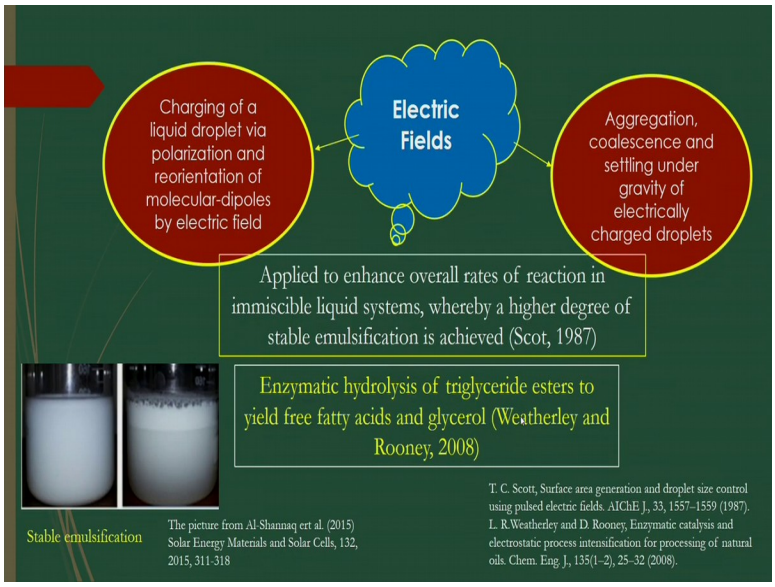

Now the electric fields like charging of the liquid droplet, sometimes you know that polarization and the reorientation of the molecular dipole by electric field, it is sometimes required for the process intensification. Like apply to enhance overall rates of reaction in the immiscible liquid systems whereby a higher degree of stable emulsification is achieved there by these electric fields.

Aggregation, coalescence and settling under gravity of electricity charged droplets there, so based on which you can intensify the process also. Like here in enzymatic hydrolysis of triglyceride esters to yield free fatty acids and glycerol where you have to use this stable emulsification based on this electric fields. So, in this way also you can get the intensification, process intensification there.

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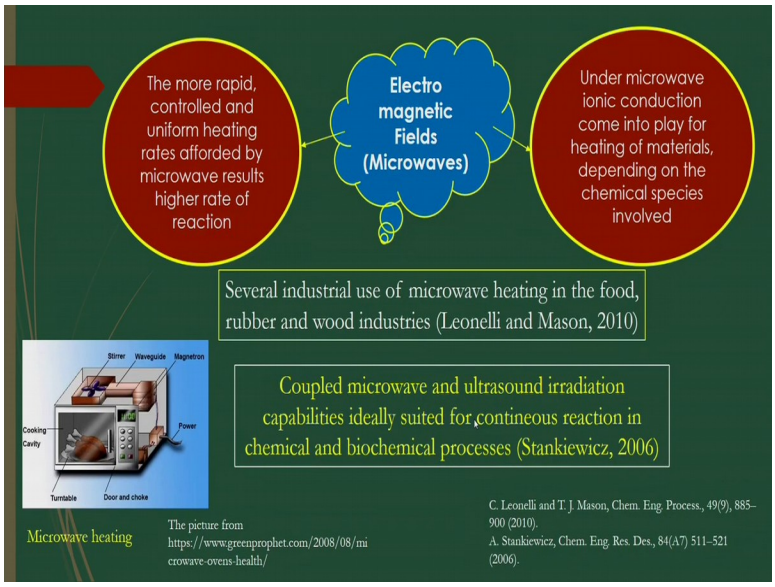

Like electromagnetic fields also, another important, you know that process intensification. Nowadays microwaves, everybody using that micro oven for this heating purpose. So more rapid, even controlled and uniform heating can be done by this microwave and which will result the higher rate of reaction also for the reaction process. And under microwave ionic condition came into play for the heating of materials that depends on the chemical spaces which are involved in that particular reaction.

Like several industrial use of microwave heating in the food, rubber and wood industries, they are using this microwave heating for their process. Coupled microwave and ultrasound irradiation capabilities also suited for the continuous reaction in chemical and biochemical processes. So, this process intensification, one of the important features that electromagnetic fields by which you can intensify the process.

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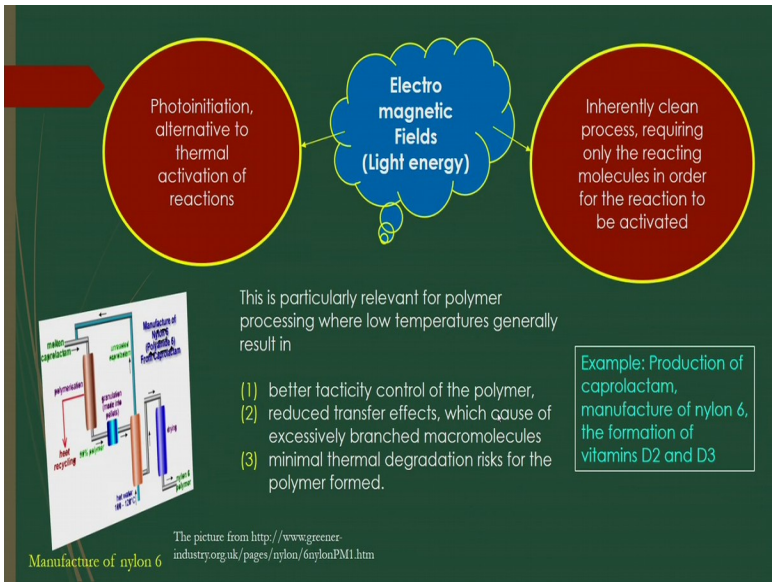

Even you know that light energy also important there for the photo ignition reaction. Even you know that for the clean process requiring only the reacting molecules in order for the reaction to be activated. So, in that case photo ignition actually, this is the alternative to the thermal activation of the reactions.

And this is particular relevant for the polymer processing where the low temperature generally result in better tacticity control of the polymer, reduce transfer effects which cause of excessively branched molecules, even minimal thermal degradation risks for the polymer formed, even production of caprolactam in the, you know pharmaceutical industry, manufacture of nylon 6, the formation of vitamins D2 and D3, for this process actually these electromagnetic fields that is light energy is being used for that process intensification.

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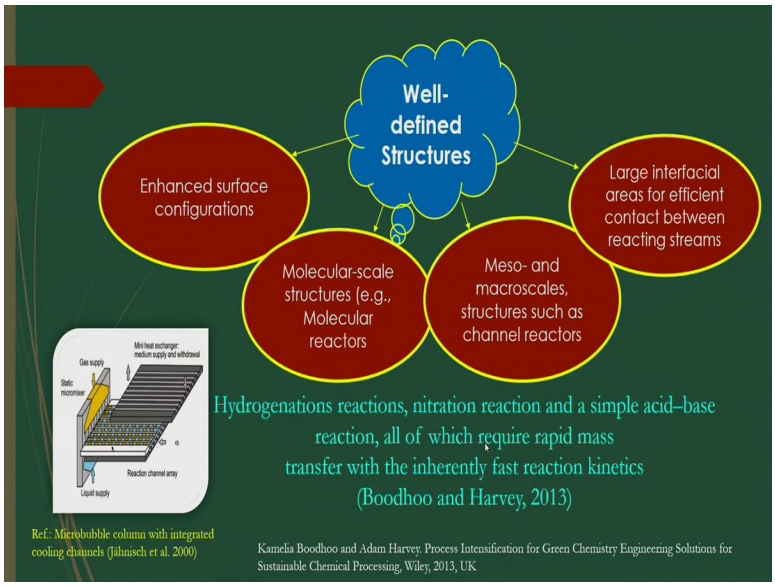

Even another important feature, it is called the well-defined structure. You have to develop the reactor in such a way that, you have to make a provision inside the reactor, some internal provision to actually obtain more interfacial areas for efficient contact between the reacting system like packed bed, trickle bed, even some other micro-structured, you know packing materials through which the fluid will be flowing and getting the more contact between the fluids and getting more mass transfer.

So, enhanced surface configurations can be done by this, you know that packing material structure, packing material, even sometimes the channel reactors, the micro-channels are being actually configured in such a way that to get the gas-liquid more mass transfer there. Even heat transfer operations, micro channel-based heat transfer or heat exchangers are being developed nowadays. Even some microbubble column reactors, they are to get the gas-liquid reactions by generating microbubbles there.

So, in that case, the configuration of the reactor also important for process intensification. So, enhanced surface configuration, molecular scale structures, example molecular reactors, meso and macroscale structures such as channel reactors that are important to process intensification, methods, large interfacial areas for the efficient contact between the reacting streams by generating that, you know that packing material structures, packing materials there.

Example like hydrogenation reactions, you know the nitration reactions, even a simple acid base reaction all of which require rapid mass transfer with the inherently fast, you know that reaction kinetics there. So, for those reactions, this structured configured process intensification method is important.

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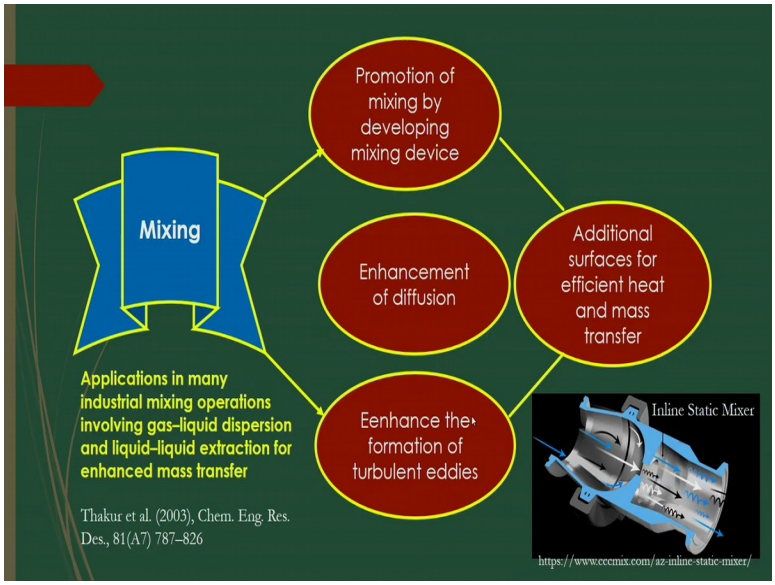

Also, another phenomenon is called the mixing, promotion of the mixing by developing mixing device there. You have to improve the device to actually intensify the mixing of the fluid mixer. So, in that case you can get enhancement of the diffusion, you can get the more turbulent eddies whenever the turbulence of the fluid mixer will be generated by that particular design of the devices. Even additional surface also you can get based on that fluid mixing which will give you the efficient heat and mass transfer for that particular operation.

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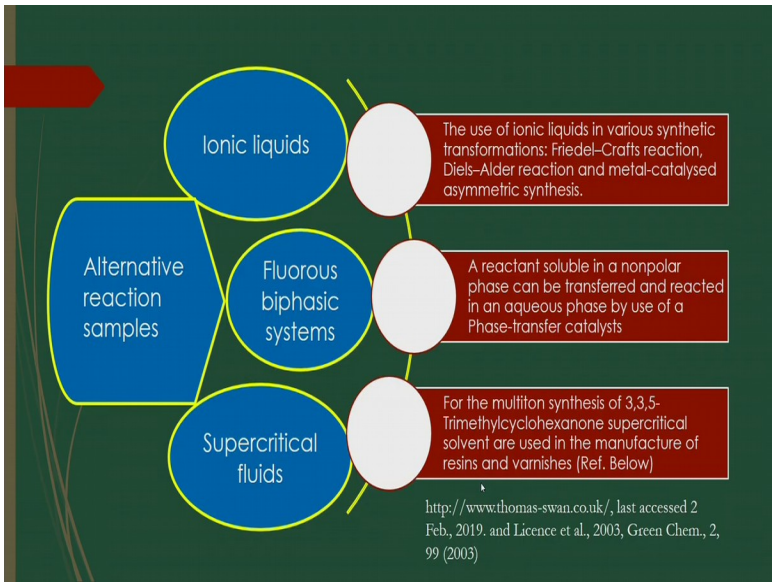

Even nowadays the intensifications of the process are being done based on the development of the, you know that fluid medium or other reacting substances. Or you know that development of the materials, like you know that ionic liquids, one of the important solvents by which you can intensify the process. Here, like you know that fluorous biphasic systems, there the ionic liquids are being used there. Even sometimes supercritical fluids are being used for the process intensification.

The use of ionic liquids in various synthetic transformations like Friedel Crafts reactions, even Diels Alder reactions, metal catalyst, enzymatic synthesis there these ionic liquids are being used nowadays for, as a process intensification. A reactant soluble in a non-polar phase can be transferred and reacted in aqueous phase by use of phase transfer catalyst there. So, phase transfer catalyst during that phase transfer are being used to intensify the reaction system.

And for the multiton synthesis you know that, of 3 3 5 trimethyl cyclohexanone supercritical solvent are being actually synthesized to use in the manufacture of resins and varnishes there. So, the supercritical fluids also, by generating or you know that developing the supercritical fluids, you can also intensify the process.

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So, we have discussed the different features here in this lecture, different features like that, you know intensification, you know equipment, based on the equipment, based on the phenomena, based on the, you know that interfacial area, even some other methods that we have discussed. So, I would suggest you to go through this, you know books to know more about these features of the process intensification. Thank you.