Chemical Process Intensification
Doctor Subrata K. Majumder
Chemical Engineering Department
Indian Institute of Technology Guwahati
Intensification by fluid flow Process

Yeah, welcome to Massive Open Online Course on Chemical Process Intensification. In this module, the mechanism of intensification we will discuss in this lecture, the intensification by fluid flow process.

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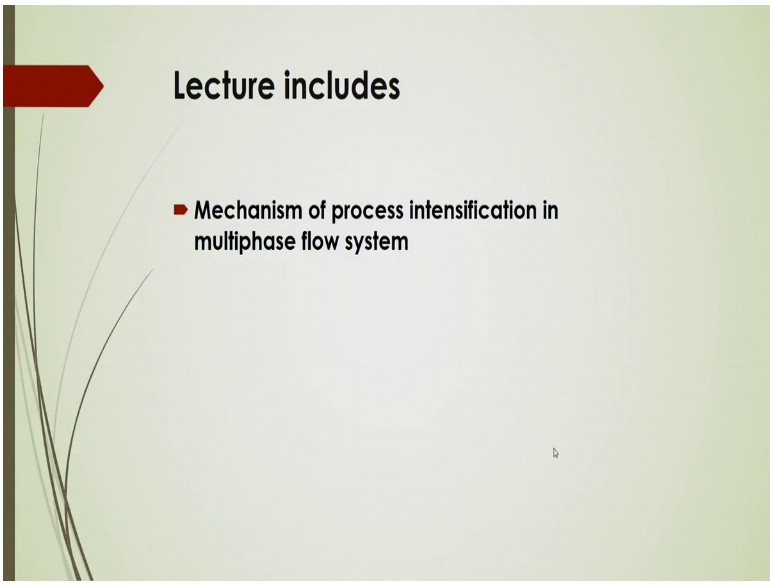

In the previous lecture we have discussed something about the strategic aspect of chemical process intensification. So, based on that strategy how intensification in the chemical engineering processes can be carried out, that has already been discussed. So as an extension that we can here describe something about what are the mechanism of that process intensification in multiphase flow system?

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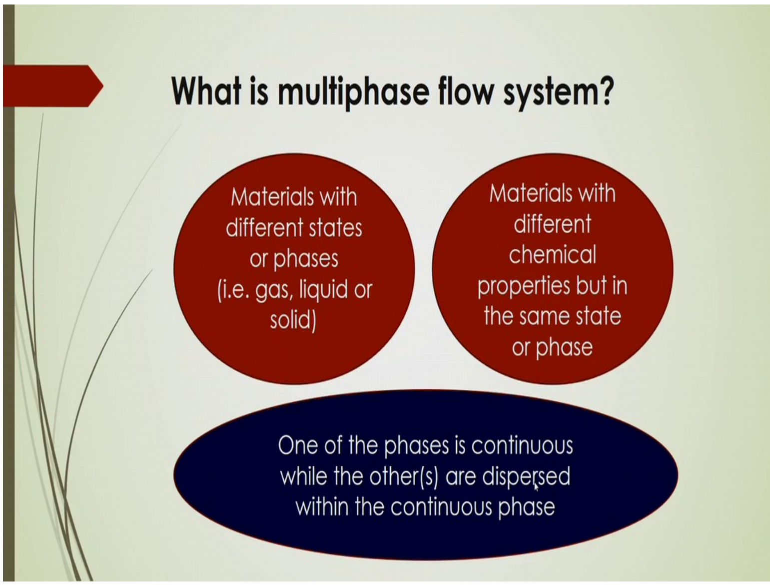

So, as you know that, in our different chemical engineering processes the different phases are directly or indirectly taking part for a particular process yield. So, in that case you have to know something about that, the multiphase flow system. So multiphase flow system, how it can be defined?

That the multiphase flow system can be defined as the system where the materials with different states or phases like gas, liquid and solid can be taking part for a particular process. So that is called multiphase flow system. And process is called multiphase flow process.

The multiphase flow also defined in different other way, like if there are two phases immiscible to each other in a particular flow then you can say that those phases will be different in their chemical properties. So, materials with different chemical properties but in the same state or phase can also be referred to as multiphase flow.

In this case, remember that whenever we are processing any chemical engineering system, in that case when multiphase are taking part for that particular process, in that case one of the phases is continuous while the others are dispersed within the continuous phase. Like if suppose gas is dispersed in a continuous liquid phase then we can say that gas is a dispersed phase and liquid is a continuous phase there.

So, in this case gas-liquid process like absorption process or some other reaction processes also, gas-liquid reaction, there also these two phases would be taking part but if that two phases would be taking place in presence of solid catalyst then you can see here there will be a three-phase flow. So, in that case, the two phases may be in that case discrete like gas and solid particles will be discrete where as liquid will be in a continuous phase. So, in any multiple or multi phase flow system, you can say that one phase should be discrete and another phase should be continuous.

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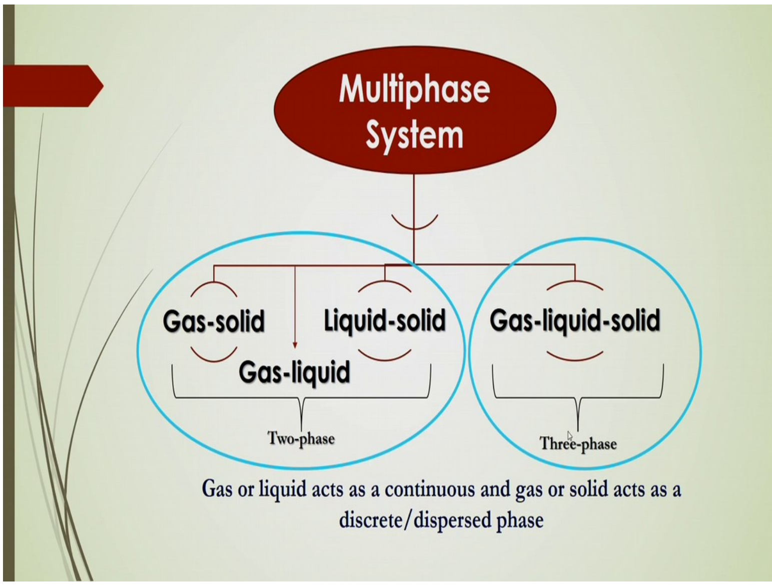

So, we can divide this multiphase system into two system like gas liquid system or two-phase system and then three phase system. But two-phase system, not only the gas liquid, there should be other like liquid solid, even gas solid system also. So, the two-phase will be as like gas-solid, liquid-solid, and gas-liquid. And three phase system gas-liquid-solid.

So, gas or liquid acts as continuous phase there somewhere in particular processes and gas or solid acts as discrete or dispersed phases. Sometimes if liquid is spraying as a dispersed phase of droplets in a gaseous medium then that case liquid droplets would be a discrete phase and gas will be continuous phase. So, gas phase may be either in continuous or discrete, both may be there as per particular application.

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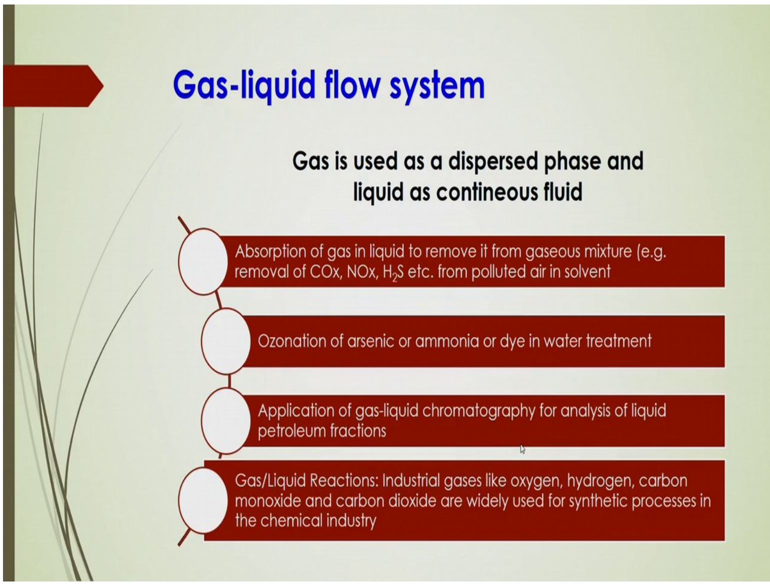

And let us have some application of that different multiphase flow systems first. So, what are those gas liquid flow systems? In this case gas is used as a dispersed phase and liquid as continuous fluid. Like absorption of gas in liquid to remove it from gaseous mixture, example mixture of CO_x, NO_x or hydrogen sulphide et cetera from polluted air in solvent. Like ozonation of arsenic to arsenate or removal of ammonia or dye in water treatment there. So in that case gas liquid operation is most important.

And also, some other applications like gas liquid chromatography for analysis of liquid petroleum fractions, in that case gas liquid both are taking part in this particular analysis. Even gas liquid reaction process like industrial gases like oxygen, oxygenation process, hydrogenation process, carbon monoxide and carbon dioxides those are widely used for synthetic processes in the chemical industry to produce different type of hydrocarbons. So in that case gas-liquid systems are important.

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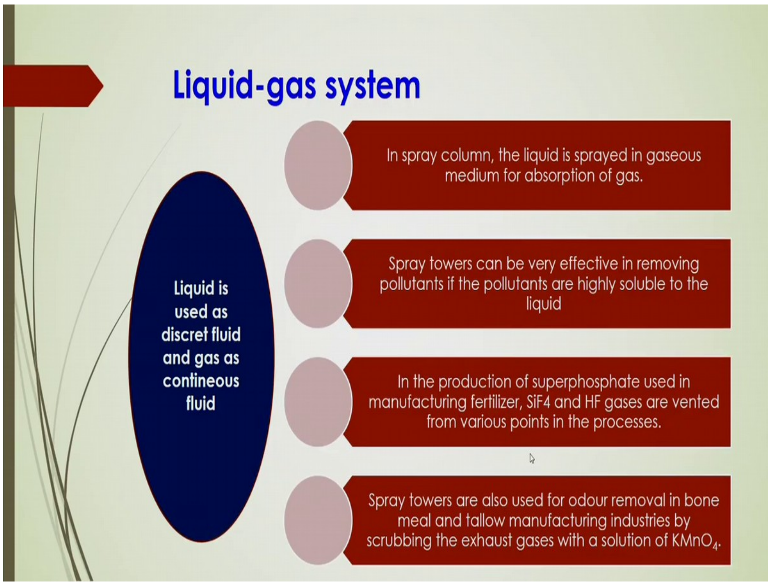

Liquid gas systems, as an example here in this case, liquid is used as discrete fluid and gas as continuous fluid like in spray column, the liquid is sprayed in gaseous medium for absorption of gas where as spray towers can be very effective in removing pollutants if the pollutants are highly soluble in the liquids there.

And also, in the production of superphosphate used in manufacturing fertilizer they are also this liquid will be used as a discrete phase, and also production of silicon tetraflouride and hydrogen flouride gases are vented from various points in the process where this gas-liquid operations for the production of superphosphate used in manufacturing fertilizer, silicon tetrafluouride and hydrogen flouride gases.

And spray towers are also used for odour removal in the bone metal and tallow manufacturing industries by scrubbing the exhaust gases with the solution of potassium permanganate. So, these are some applications where liquid and gas will be taking part. In that case liquid will be discrete and gas will be continuous phase.

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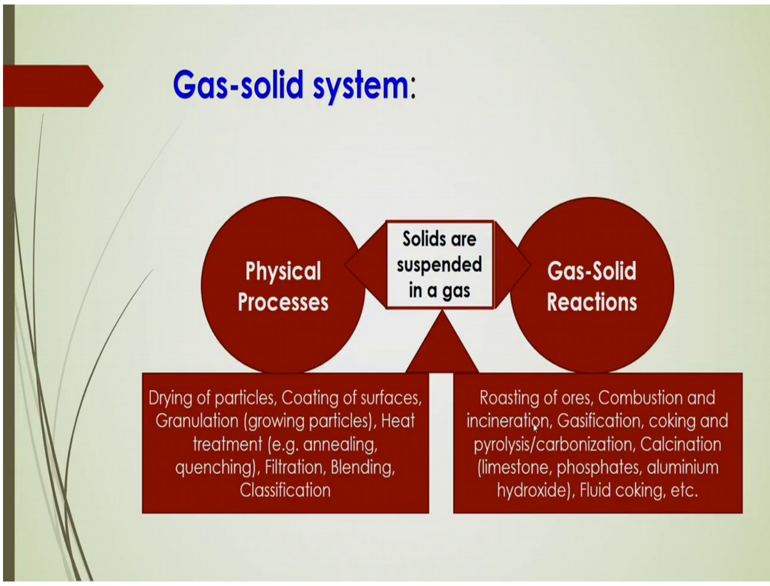

The gas solid system you will see there are several applications of this gas solid system, the chemical engineering process and the heart, it can be said that the gas solid operation are the most important and diverse application in chemical industry. In that case, there are two processes like physical processes and even some reactive processes, gas solid reactions are there.

In physical processes like drying of particles in that case, fluidization operation is very important. Coating of surfaces, granulation, even you know heat treatment and also you can say that filtration, blending and segregation or classification of the solid particles in fluidized bed. So, these are actually gas solid operations.

Also, in gas solid reactions like roasting of ores, combustion of coal to produce different types of hydrocarbons, even for power plant operation to produce the power there, of course, this coal is combusted and there different types of gaseous products are coming out and separating those gaseous products, they have been used for several purposes

And also, those are used for unwanted gas also sometimes producing the steam by, just by burning coal and that steam will be used for, or is being used for the production of power and thereby just by rotating the turbine. So, in that case that gas solid operation is important. And also, calcination and limestone phosphates, even aluminum hydroxide, fluid coking etc for that, these gas solid operations are very useful.

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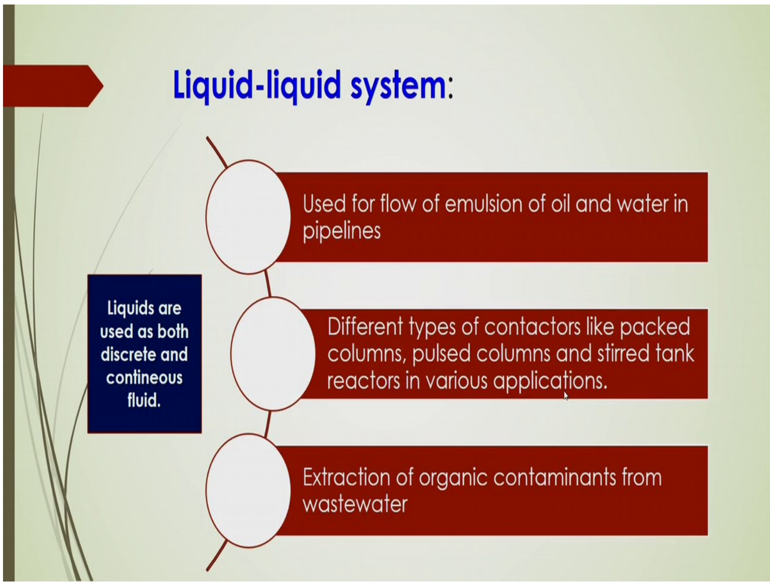

And also, liquid-liquid system, there are several applications for this liquid-liquid system. Liquids are used as both here, discrete as well as continuous phase. Like use for flow of emulsion of oil, and water in pipelines. Different types like contactors like packed bed, packed columns, pulsed columns and stirred tank reactors in various applications where liquid and liquid systems are important.

Also, liquid-liquid extractions, solvent extractions, to remove the contamination from the waste water, the extraction of that contaminants by another liquid component or organic liquid that is also important. So liquid-liquid extraction is also important just to remove some contaminants from the waste water or some other liquid medium where it will not be useful.

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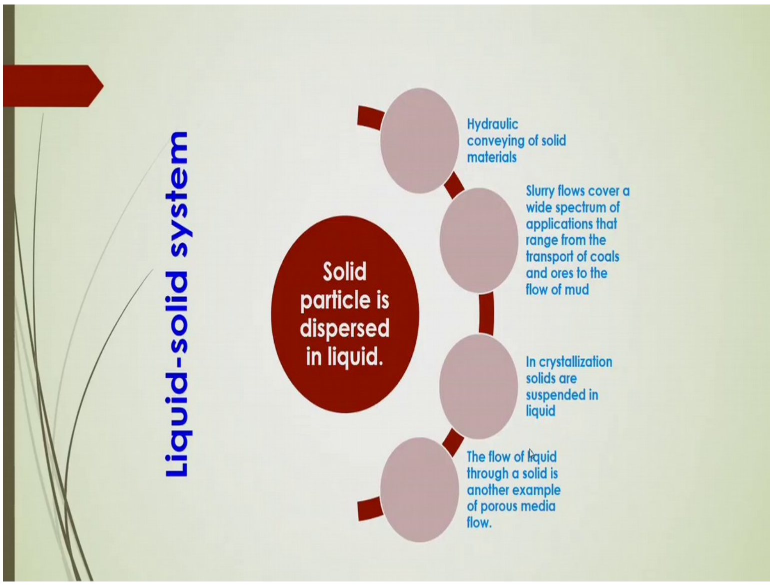

And liquid solid system where hydraulic conveying of solid materials are there, so it is important. And in that case solid particle is dispersed in liquid and slurry flow covers a wide spectrum of applications there. That ranges from transport of coals and ores to the flow of mud. And also, in crystallization you will see solids are suspended in liquid, and the flow of liquid through a solid is another example of porous media flow. So, these are the operation for the liquid solid system.

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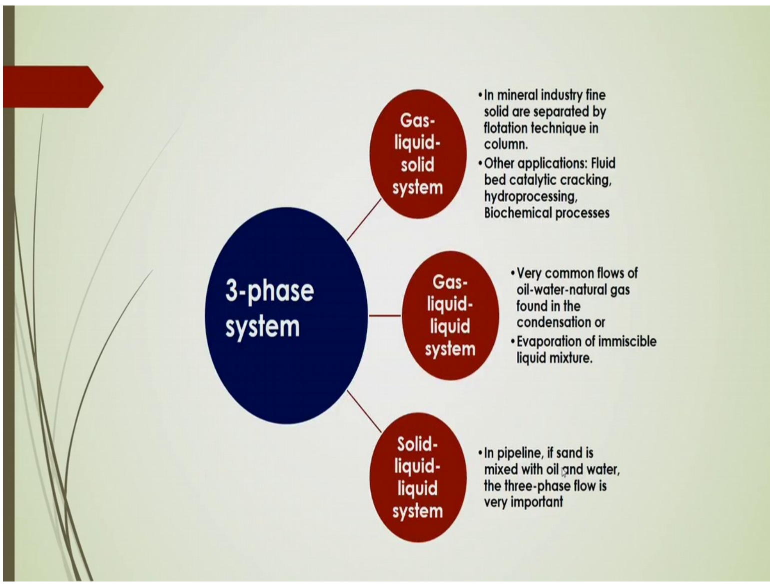

In three phase systems you will see some gas liquid solid system, if your combination of this separation of gas, liquid, solid you will see in the mineral industry, the flotation is one of the important process by which that metals will be separated from its ore. Valuable metals will be separated from the ores. In that case also the flotation process important and during that flotation this aeration is being done and during that aeration this gas and liquid and solid both, three phases will be taking part. And also, sometimes some, you know fine particles to be removed from the muddy water

Or you can say that milk, water where solid particles are suspended. To separate those fine particles this flotation process also important. In that case surfactant, some you know that products to be used so that, that as per froth flotation, that, these fine particles will be separated by aeration. So, in that case gas and liquid and solids, three phases are taking part. Other applications like fluid bed catalytic cracking in presence of some catalyst particles, hydro cracking, hydroprocessing and biochemical processes, those are involved in three phase systems.

And very common flows of oil water natural gas that is found in condensation or evaporation of immiscible liquid mixer. There also gas-liquid-liquid systems are important. And solid-liquid-liquid systems there you will see in pipelines that sand is mixed with oil and water the three-phase flow is important there. So, these are the various applications of the three phase systems.

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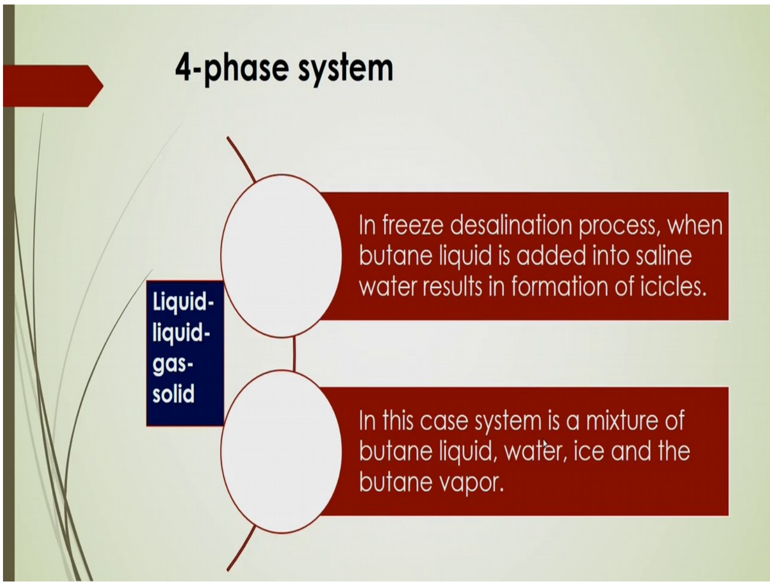

And four phase systems also, one application like in freeze desalination process, you will see that when butane liquid is added into a saline water that will results a formation of icicles, and in this case, system is a mixture of butane liquid, water, ice and the butane vapor. These four phase systems are there. That is why four phase systems are there it is considered. So, we have then seen the different applications of four phase systems.

In our daily life whatever products, we are getting, all processes by which these products are coming out are related to the multiphase flow systems. Whether it is gas liquid, liquid solid, or gas solid or gas liquid solid system even gas liquid solid and vapor system both are directly or indirectly related to the particular processes.

So, based on these multiphase flow processes, whenever we are going to perform this processes in a particular unit, that process can be intensified based on the development of the unit or equipment or based on the fundamental, like that phenomena, even sometimes the fluid phenomena, based on the fluid phenomena, based on the equipment size, based on the, you know that policy, so we can intensify the process in different aspects.

So, in this lecture we will discuss that based on these multiphase flow systems what are the different mechanisms of the process intensification which are being used in industry as per process intensification background.

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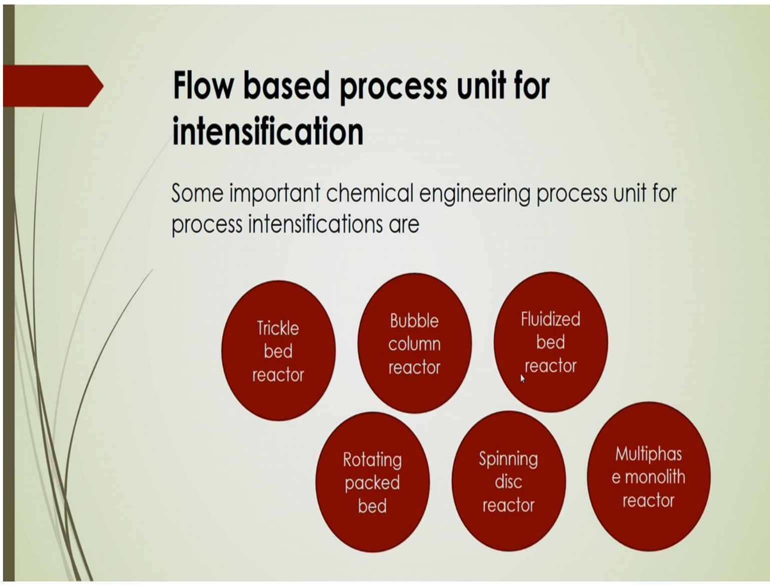

So, flow-based process unit for intensification you can say that some important chemical engineering process unit for process intensifications are like this, trickle bed reactor where liquid phase and gas phase are flowing through the packed bed and there liquid phase will be flowing as a, you know laminar stream just as called trickle phenomena so that is trickle bed reactor.

So, in that case you will see that plug flow phenomena will observe. And then reaction efficiency or that, you know that process performance will be higher than the conventional processes for that particular process.

Bubble column reactor, there also it is being developed based on the increase of, or enhancement of the interfacial area between phases. Like in bubble column reactor if it is two phases, gas liquid operations or the physical operations like carbon dioxide gas will be absorbed in a sodium hydroxide solution there.

In that case, gas phase is dispersed in that column, as dispersed phase of bubbles in the continuous liquid medium there as a sodium hydroxide solution. In that case whenever bubbles will be forming there will be interface between the bubbles and liquid.

So, you can get that interfacial area through which there will be a mass transfer and based on that mass transfer you can say that absorption of that carbon dioxide gas in the gas phase mixer, this will be absorbed in a liquid medium through the interface. So, if you can increase the interfacial area you can have the more efficiency of the absorption process. So that is why the process intensification can be obtained based on this enhancement of this interfacial area.

Fluidized bed reactor also there are several applications of this fluidized bed operation, like you know the drying operation or roasting operation, whatever. Suppose coffee, we are getting, that is dust coffee we are getting in our coffee shop that is actually after several processes, initially that coffee bean, the raw coffee bean is green coffee bean.

And whenever it would be roasted, this being done in a fluidized bed you will see at a certain temperature, 400 like 50 degree Fahrenheit, that case you will see after roasting of that coffee bean in fluidized bed that here will be, you know that mixing of that coffee bean with the gaseous, hot gaseous mixer and there will be particle interactions and you will see heat transfer will be more important there.

And based on that heat transfer that coffee bean will be becoming that brown coffee bean and after that it will be becoming dust and to serve you as coffee. So, in that case the coffee bean is roasted in a fluidized bed.

So there, why fluidized bed is there, why not simply that in a, just in a bed, just we are heating it? Not like that. If you are heating that coffee bean or some other any particles you can see in a fluidized bed there will be intensification of process for better heat transfer, better interfacial heat transfer between the solid particles and the gas. So that is why the fluidization operation over there.

Even for mass transfer also, in the fluidized bed you will see for Fisher-Tropsch synthesis there, for better contact and better mass transfer, you are just doing that fluidization operation. So fluidized bed is one also important intensified process in chemical engineering. Rotating packed bed also to get the better contact of the gas and liquid and solid particles, we are having this rotating packed bed.

Spinning disk reactor also better mass transfer, heat transfer, this spinning disk reactor important there also, the making a thin film in this spinning disk reactor so that the mass transfer through the liquid film will be intensified there. So that is why this spinning disk reactor is important for this chemical engineering process where the intensification is being done.

Multiphase monolith reactor also is important nowadays. There, you know that, some catalyst particles in a particular fashion, in a particular, you know that structure; this catalyst particles will be produced and arranged so that the interfacial area will be more and then reaction will be better there. So, these are the various process equipments for process intensifications which are being used in chemical engineering processes.

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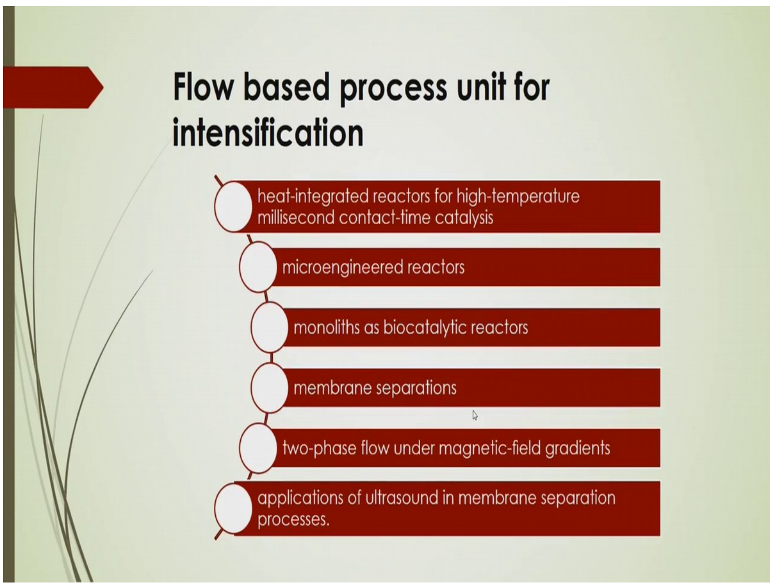

And you will see flow-based process unit for intensification like other heat integrated reactions for high temperature, millisecond contact time and catalysts also important for this process intensification. Micro engineered reactors are being developed nowadays for chemical engineering processes.

Monoliths as biocatalytic reactors are developed as a process intensification, membrane separations nowadays are widely used in chemical engineering process for separation of the particles, even nanosized particles are being separated by this membrane separation processes. So, this is also an important intensified process. Two phase flow under magnetic field gradient also important there, applications of ultrasound in membrane separation process nowadays are in research stage to apply for chemical engineering process.

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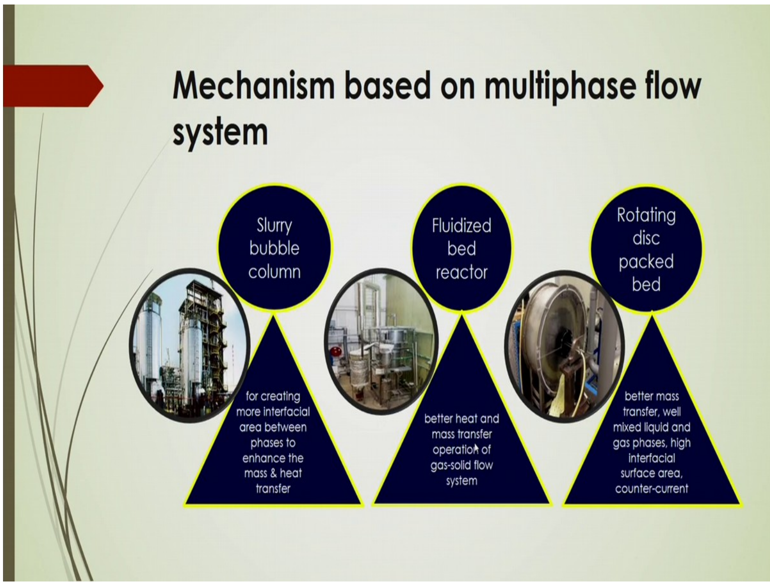

Various mechanisms like yes, slurry bubble column reactors, in that case for creating more interfacial area between phases to enhance the mass and heat transfer. So, slurry bubble column reactor is one important process intensified unit that based on the multiphase flow system.

Fluidized bed reactor for better heat and mass transfer operation of the gas liquid flow important, and also rotating disk packed bed in that case, better mass transfer, well mixed liquid, you can see and gas phases, high interfacial surface area, even you can operate it in counter current mode. So, these are some basic mechanism based on which this multiphase flow system-based process intensified unit are developed for chemical engineering processes.

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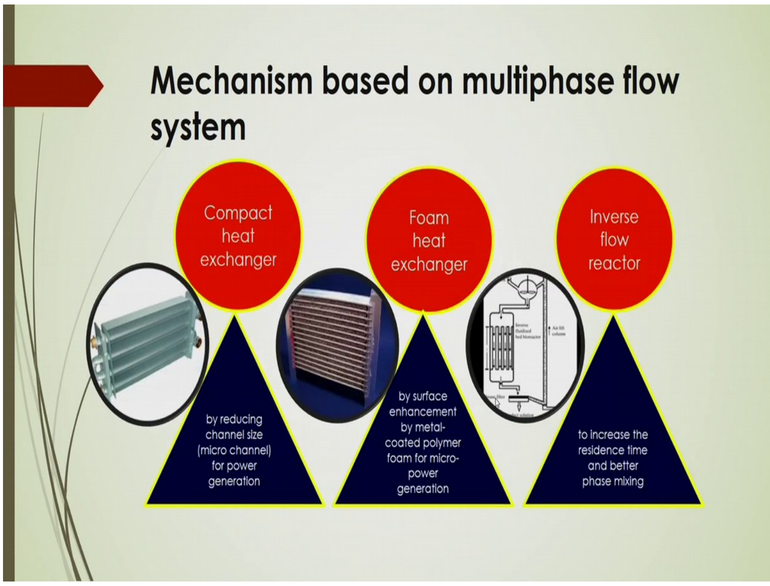

Even you will see compact heat exchanger like in that case, the reducing channel size will give you the better power generation. Even by surface enhancement, by metal coated polymer foam for micro power generation, foam heat exchangers are developed and based on the increase in residence time and better phase mixing, downflow system or inverse flow reactors are nowadays coming to get more contact time, even for more residence time of the phases in the reactor.

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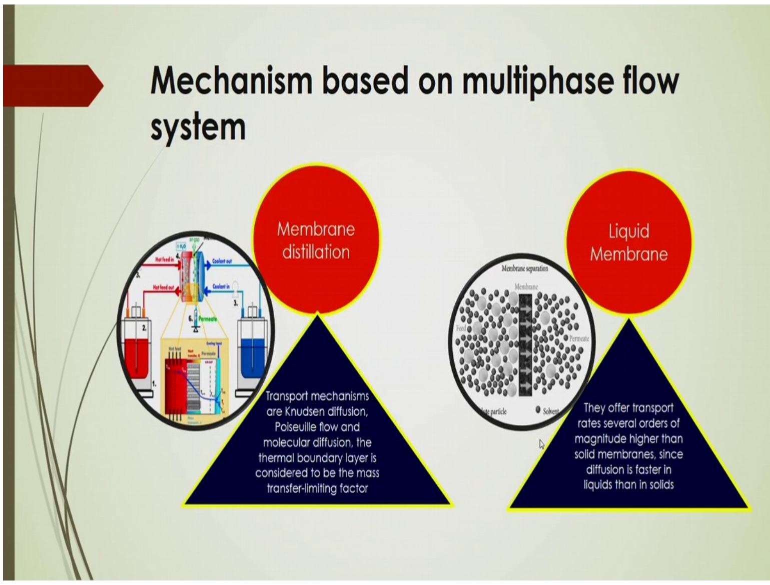

Membrane distillation is one of the important, you know that integrated system where transport mechanisms are Knudsen diffusion, Poiseuille's flow and molecular diffusion all these processes are simultaneously happened. And the thermal boundary layer is considered to the mass transfer controlling factor here in this membrane distillation process.

Even you will see liquid membrane system also one of the important process where diffusion can be enhanced by liquids then in solids, in that case transport rate several orders of magnitude higher than the solid membranes because their diffusions is faster in the liquids compared to the solids.

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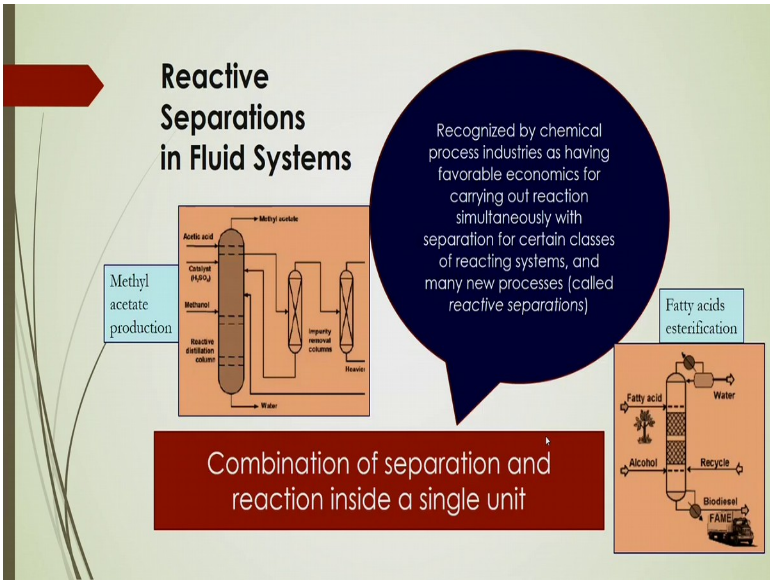

Reactive separation also nowadays important because you know that in fluid system the reaction as well as separation both will be combined in a particular unit and in that case chemical process industries, they are using this, they are following this integrated system to have the favorable economics for carrying out reaction and simultaneously with separation for certain classes of reacting systems and many new processes called reactive separations are carried out.

Like methyl acetate production, there you will see both; you know that reaction as well as distillation is being happened in a particular column. So, in that case here in this picture it is shown that how methyl acetate is produced in a distillation column.

Methanol is supplied and catalyst as sulphuric acid in that case, the reaction is being carried out in a particular zone. After that whatever products are coming out, those will be separated, that is the, what is that methyl acetate and the water to be separated after that distillation also.

And so here this reactive separation is one of the important mechanisms of process intensification. In that case combination of separation and the reaction inside the single unit happens. Like some of the fatty acid esterification also, one of the important, this reactive separation process there so the reactive separation is important as a process intensification.

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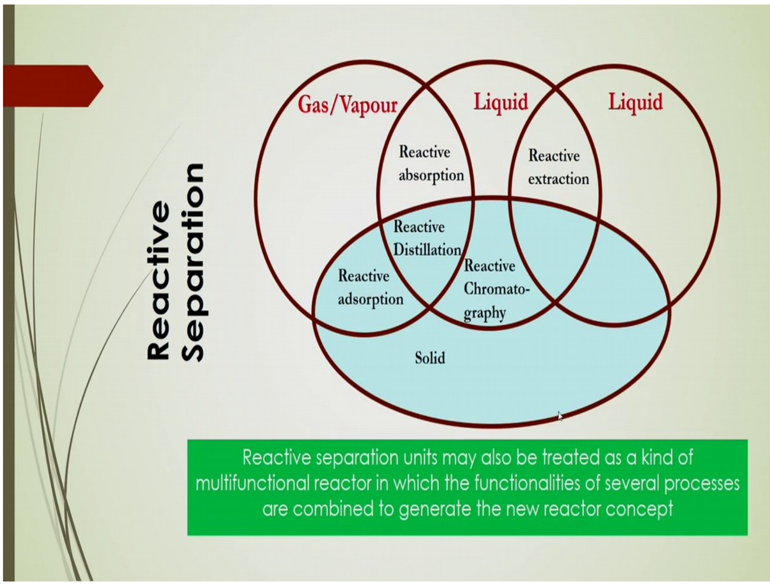

And the reactive separation units you will see may also be treated as a kind of multifunctional reactor in which the functionalities of several processes are combined to generate the new reactor concept. You will see in this diagram there if we are considering that gas and liquid there may be reactive absorption between that gas and liquid system. And reactive distillation also happens within this gas and liquid system. Reactive absorption also happens, this gas and liquid system.

Even gas and solid system there you will see that the reactive adsorption also important and liquid and solid system, there reactive chromatography this process is important and also liquid-liquid system, there reaction extraction is the example for that liquid-liquid system. So, this you can say that in multiphase process systems how different chemical engineering process can be intensified for a particular reaction based on that, you know that combination of unit operation like reactive separation, reactive distillation, reactive extraction in that direction.

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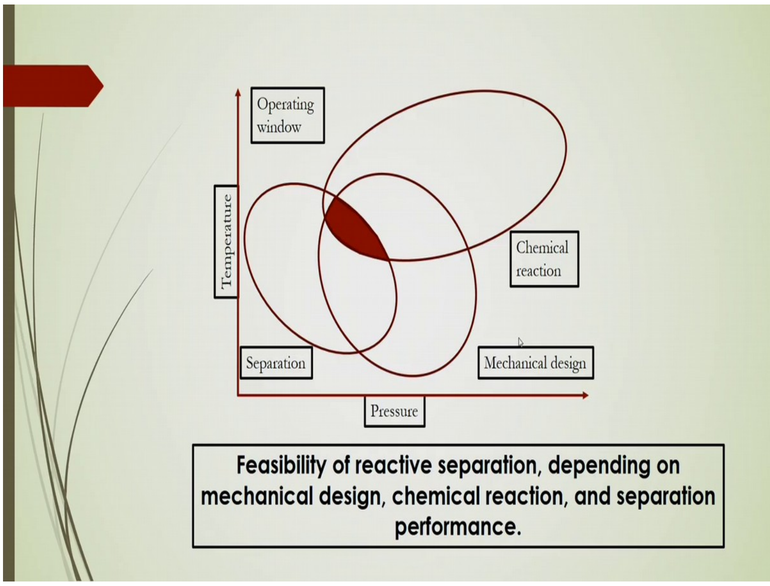

And feasibility of the reactive separation, that depends on various parameters like mechanical design, chemical reaction, event separation performance also. So, in this diagram you will see some, at a particular temperature and pressure you will see how chemical reactions are being taking place for a particular process intensification.

Even mechanical design, how it will be giving you that process intensification for that particular operation. So, in this case we can say that any reactive separation process that depends on mechanical design, even chemical reaction performance and the separation performance.

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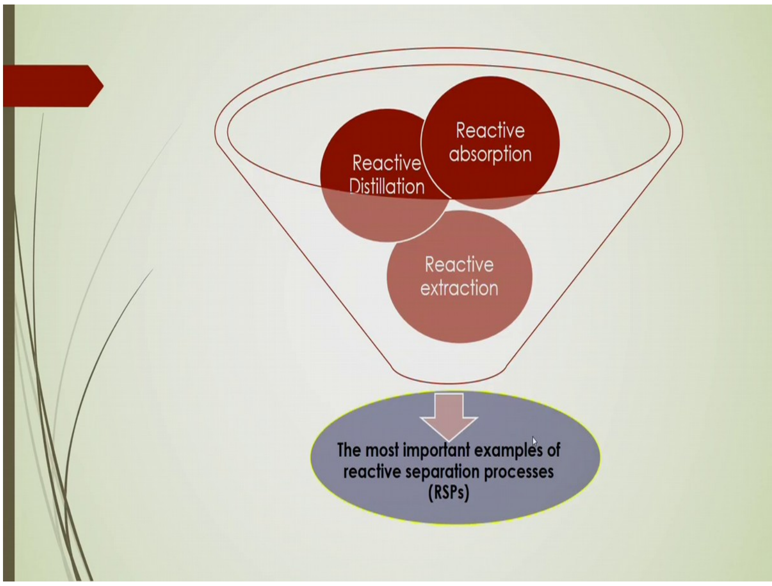

The most important examples of the reactive separation processes are reactive distillation, reactive absorption and reactive extraction processes.

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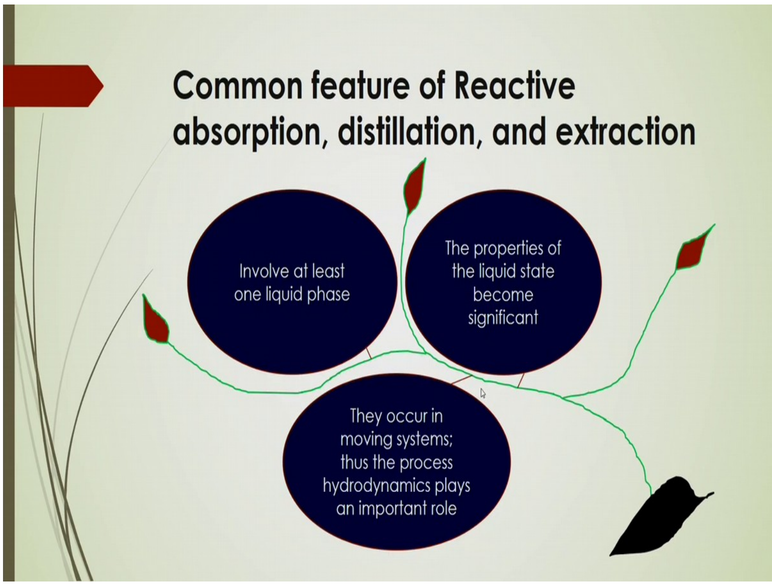

Common feature of that reactive absorption, distillation and extraction are that these processes involve at least one liquid phase and the properties of the liquid state become significant in that case. And they occur in moving systems. Thus, the process hydrodynamics play as an important role there.

Because all the process performance depends on the mixing processes, even some other particle interactions like is there any gas solid particles, if they are gas bubbles and solid particles, even solid and solid, then solid-solid interaction, gas-gas, gas-particle interaction, even bubble-bubble interactions like bubble-bubble coalescence, bubble breakups, if you are having more breakup of the bubbles you can produce more finer bubbles so that you can get more interfacial area.

Even if your process is more prone to coalescence, bubble coalescence in that case performance will be less. So, you have to design a unit in such way that some mechanical probition to be placed so that the breakage of the bubbles will be there. Even uniformity of the bubble flow will be there or interfacial phenomena will be created in such a way that the uniform mixing will be there, even the distribution of that phases will be there so that that you can get the better performance of the reaction and even processes.

So the properties of the liquid state become also significant there. In that case what we have to do that what type of fluid are being used, that whether it is corrosive or not that also you have to think about it so you have to synthesize a solvent which are not that much of hazardous and not corrosive. So even if it is corrosive you have to design the unit in such way that the wall surface of that unit should be non-corrosive. So, the process intensification should be in that directions.

So, the properties of the liquid state should be considered for that particular process intensification. And how to control that hydrodynamic cons are there. So if there is heterogeneous mixture, to make it homogenous, to get better performance you have to make a provision like sometimes you know that, to reduce the back mixing you have to use some waffle.

Or you have to design that unit like two dimensional or even microstructure system so that, that back mixing will be reduced. So, to get that reduced back mixing you can intensify the process intensifications just by allowing it as a plug flow reactor because plug flow phenomena will give you the better performance of the reactions and also other physical operations there.

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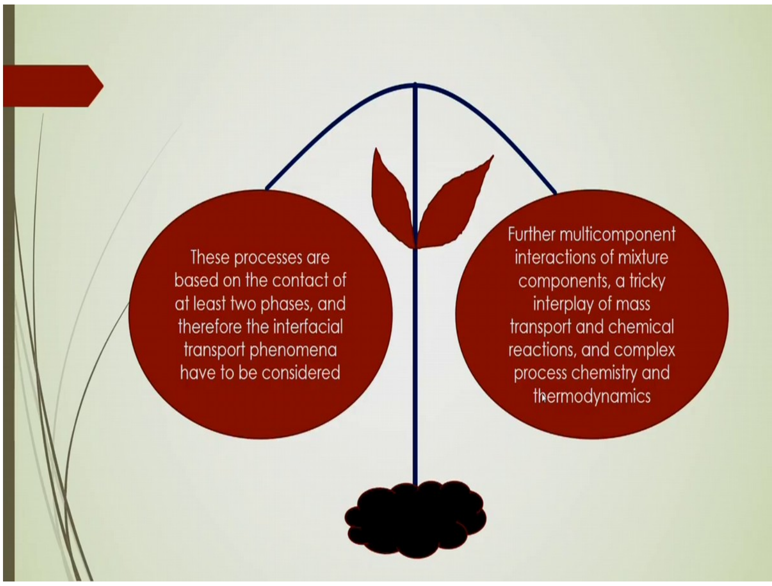

These processes are based on the contact of at least two phases also where these reactive separations or you know that absorption, distillation, or extraction are there. So for mass transfer through the interfacial area there of course two phases should be involved and therefore the interfacial transport phenomena have to be considered for process intensification.

And also, further multicomponent interactions of the mixture components, a tricky interplay of mass transport and chemical reactions and complex processes chemistry and thermodynamics issues should be considered. So those are involved in those particular process intensifications.

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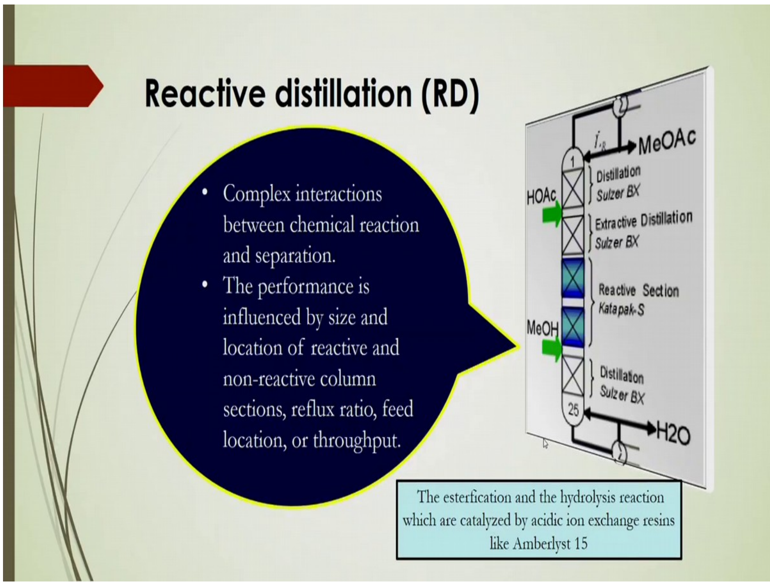

Now let us consider that reactive distillation, some features of that. In that case complex interactions between chemical reaction and operation and also if it is there, separations of course will be there, based on that complex interactions of the phases and the performance is influenced by the size and location of the reactive and non-reactive column and also you know that reflux ratio is one of the important parameters.

Feed location and throughput by which you can change the hydrodynamics in the column for that reactive distillation system. Like esterification and hydrolysis reactions which are catalyzed by acidic ion exchange resins like Amberlite 15, one of the important, you know that resins in which that, you know that reactive distillation as well as separation is being happened in a particular unit.

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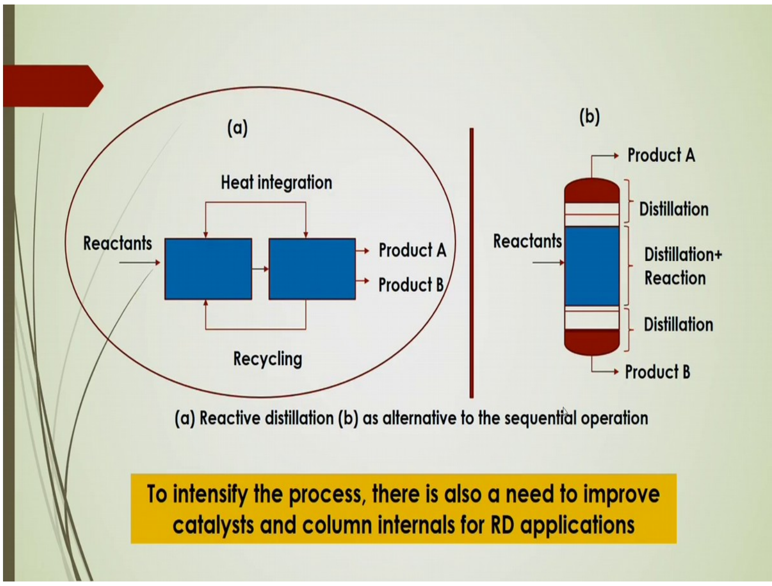

And you will see that reactive distillations where the reactants to be transferred into the reactor and heat integration is important phenomena and after that integration you will see whenever products are coming out, some unwanted or unreacted products, unreacted reactants to be recycled and then final products should be separated based on the separation principles.

And this successive, you know sequential operation of these reactive distillation can be organized here in the figure as shown in b. Here that reactant is supplied and in a particular zone that reaction as well as distillation, both will be happened and at the top and bottom sections that as far as you know that density difference and boiling point differences that products should be coming out or separated and from the top that product A will be coming out and from the bottom B that heavy products will be coming out.

So, in that particular unit the sequential you can say the, you know in some zone the distillation and reaction both will be happen in that and after that the distillation process will happen in that particular unit. So, to intensify the process we can say that there is also a need to improve the catalyst and column internals for the reactive distillation applications.

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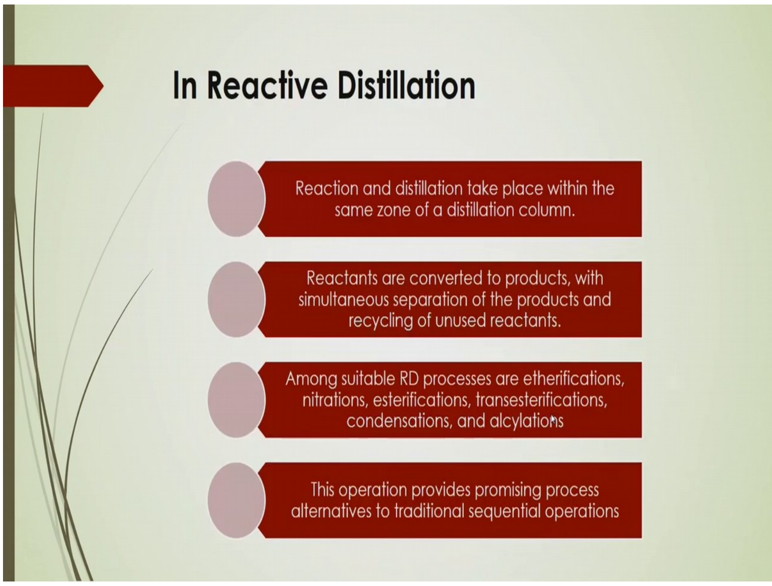

And also, reaction and distillation takes place within the same zone of the distillation column. Reactants are converted to products with simultaneous separation of products and recycling of unused reactants and among suitable reactive distillation processes like etherifications, nitrations, esterifications, trans-esterifications and condensations and alkylations are the most common applications in reactive distillation process. These operation provide, you can say promising processes, alternatives to traditional sequential operations for this particular operation.

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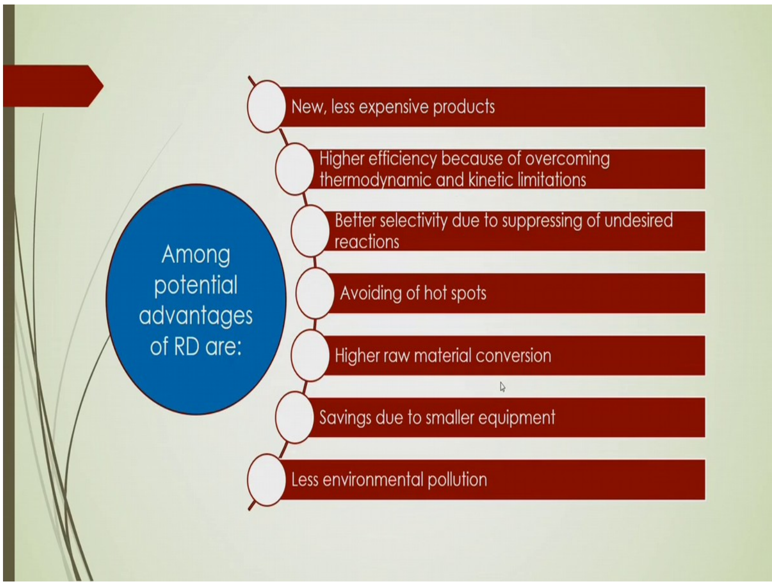

Now what are those, actually advantages for which that reactive distillations are being carried out in a single unit? In this case it is a new, you can say less expensive products, even avoiding some hotspots, saving due to smaller equipment you can say, less environmental pollution, higher efficiency because of overcoming the thermodynamic and kinetic limitations, better selectivity to suppressing of undesired reactions. So, these are the some, you know that potential advantages of reactive distillation system.

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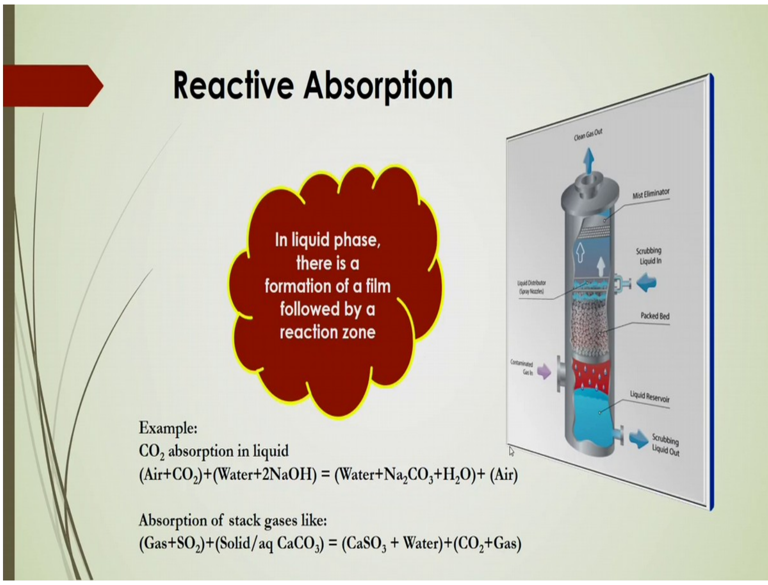

In case of reactive absorption, you will see some example here. Carbon dioxide absorption in liquid here, suppose air and carbon dioxide mixtures are being supplied from the bottom of the packed bed reactor, in that case water and sodium hydroxide solutions to be used for liquid and through that liquid in a packed bed this air plus carbon dioxide mixture will be supplied.

And you will see parallelly that reaction as well as absorption will happen. When reactions will happen in the packed bed there will be product like water and what is that, sodium carbonate and water and along with air, air will be coming out from the, you know that top of the packed bed as a clean air. So, during that operation you will see if we use the sodium hydroxide for absorption of carbon dioxide there the reaction as well as absorption both will happen.

Here reaction will be sodium hydroxide and carbon dioxide will react and it will give you the sodium carbonate solution and that sodium carbonate will be used for other application. So, in this case the scrubbing of this carbon dioxide is happened from this air carbon dioxide mixture and clean air will be coming out from the top of the column. Even absorption of stack gases like sulphur dioxide, gas plus sulphur dioxide mixture, if they are to remove that sulphur dioxide, if we use that calcium carbonate in a solid medium then you will see that calcium carbonate will react to sulphur dioxide.

It will give you the calcium sulphate and that calcium sulphate will be, you know precipitated and remaining, you know solutions will be reused and then carbon dioxide without sulphur dioxide will be coming out as a gaseous medium. So, in that case you can purify that gaseous mixture for the sulphur dioxide or stack gases by this reactive absorption.

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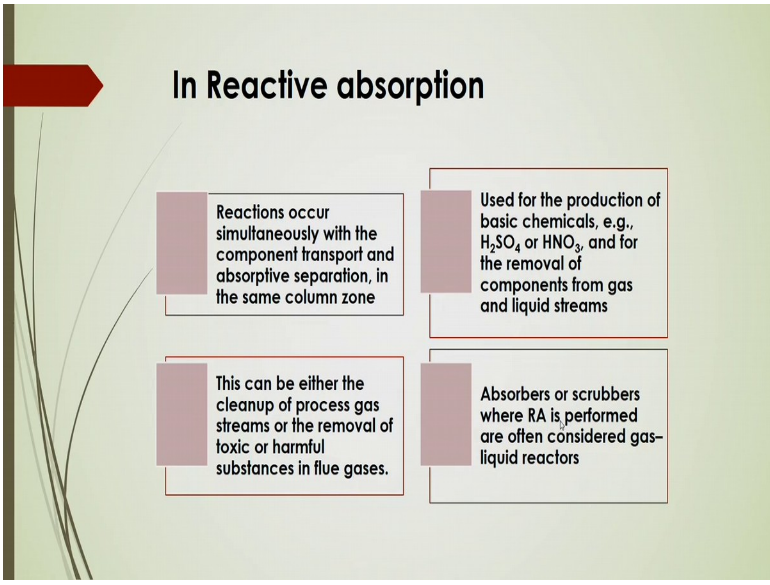

In this reactive absorption you will see that reaction occurs simultaneously with the component transport and absorptive separation in the same column zone and it is used for the production of basic chemicals like sulphuric acid, nitric acid and for the removal of components from the gas and liquid streams.

And also, absorbers or scrubbers where this reactive absorption are being carried out are often considered gas liquid reactors and this can either be the cleanup of all process gas and streams or removal of toxic or harmful substances in flue gases. So, the reactive absorptions are actually considered both to actually perform like reaction and absorption.

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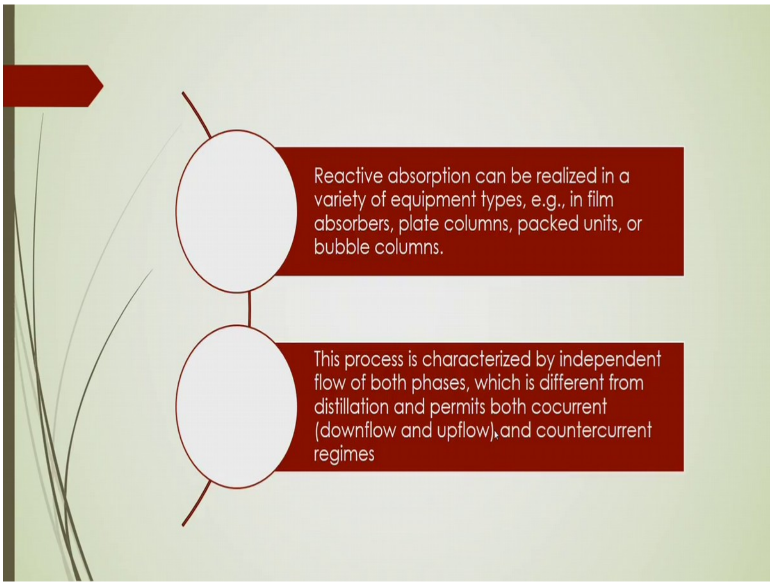

And it can be realized in a variety of equipment types here in film absorbers, plate columns, packed units and bubble columns. And this process is characterized by independent flow of both phases which is different from distillation and this will permit both cocurrent like downflow and upflow and also counter current operations.

So this reactive absorption you can intensify either by absorber reactors or by designing some other different types of columns like plate columns, packed columns, bubble columns, even intensification of bubble columns in two dimensions, three dimensions, even bubble columns, downflow bubble columns, even bubble columns with waffles, even some, you know that use of spargers, even producing more finer bubbles by using different types of spargers, in that direction you can intensify the bubble columns also. And this process can be characterized by; you know that different mode of operation.

In that case you can use the downflow system to increase the mixing as well as increase the residence time of the phases and upflow systems where the first reaction is being carried out, in that case upflow operations is important where counter current operations also important where you will see that physical separation or you can say that some mass transfer operations for mineral processing in that case this counter current operation is also important.

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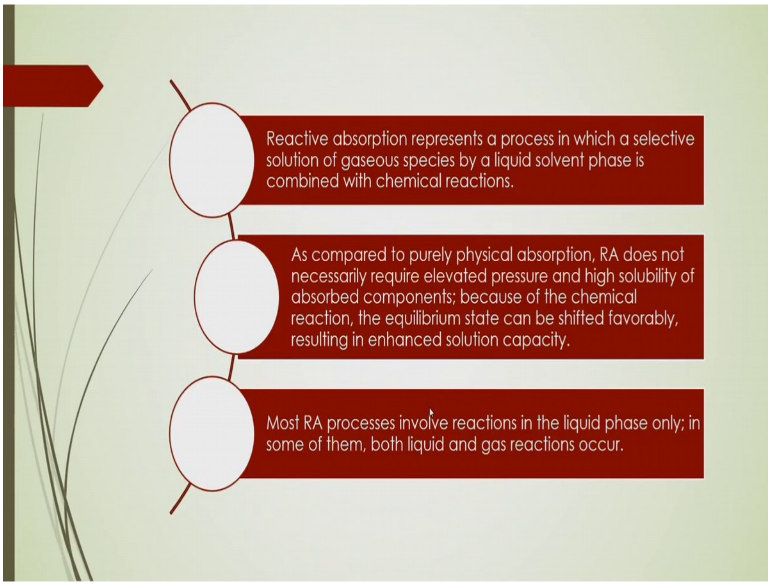

Reactive absorption represents the process in which selective solution of gaseous species by a liquid solvent phase which is combined with the chemical reactions and as compared to the purely physical absorptions, reactive absorptions does not necessarily require the elevated pressure and high solubility of the absorbed components because that chemical reaction in that case the equilibrium state can be shifted favorably resulting in enhanced solution capacity there.

So, we can say that most of the reactive absorption processes involves their reactions in the liquid phase only and in some of the cases both liquid and gas both will be taking places in the, as a medium so the medium also, the mode of operations and discretizing the system, discretizing the medium also sometimes way of the intensification of the process.

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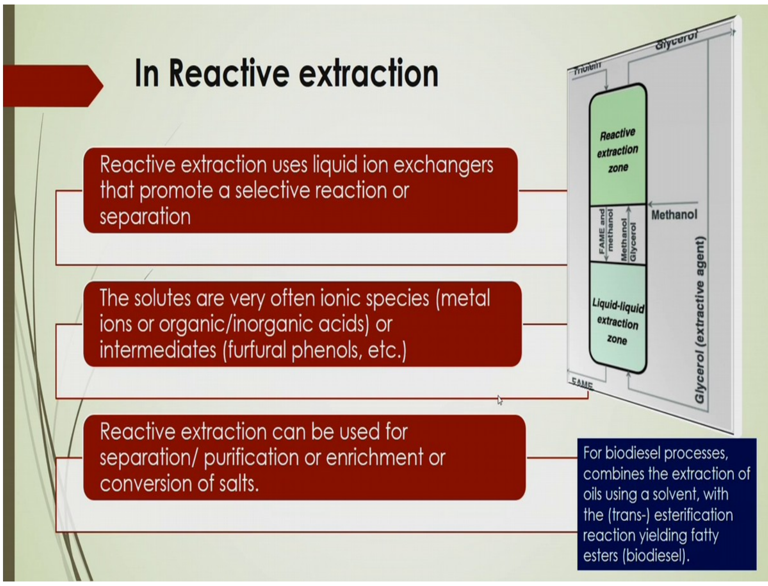

Now in reactive extraction, in that case, reaction as well as extraction both will happen and this reactive extraction uses liquid ion exchangers that promote a selective reaction or separation. And the solutes are very often ionic species like metal ions or some organic or inorganic species or you can say some intermediates like furfural phenols etc. This can be used for separation and purification or you can say that enhancement of the conversion of units, for the conversion of salts in the units there.

Like for biodiesel processes their combination of extraction of oils using a solvent with the esterification reaction that will give you yield of fatty esters, it is called biodiesel. So, the reactive extraction is the process intensification by which you can produce the biodiesel there.

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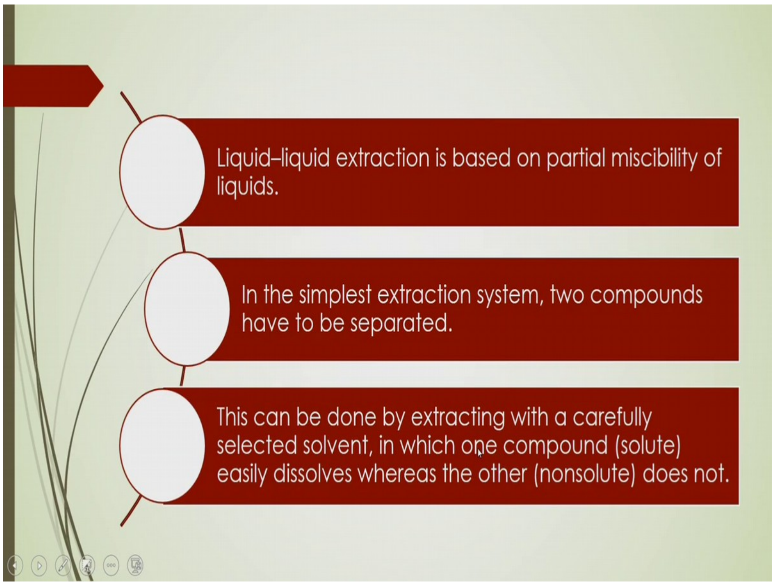

And liquid-liquid extraction is sometimes based on the partial miscibility of the liquid so you have to derive some liquids where that immiscibility will be there but separability, capability of that liquids will be enhanced there. So, both the way you can increase. So, immiscibility as well as that, you know that, you know that absorbance of the contaminants in that particular liquid should be increased.

In the simplest extraction system two compounds have to be separated there and this can be done by extracting with a carefully selected solvent in which one compound that is called solute easily dissolves where as the other does not.

Like as an example you can say that like propionic acid to be actually separated from the liquid water or you can say waste water in a, you know that paraffin or like octanol or Decanol like organic compounds. In that case Decanol and this water is immiscible and propionic acid is miscible with water. So, from the water, this mixed propionic acid to be separated by that Decanol and so this Decanol and water should be immiscible.

And also, there should be selectivity based on the boiling point also. You have to use the organic compounds which have the boiling points which are higher difference with the, you know that propionic acid so that after, you know that extraction of that propionic acid in a Decanol as an example here which is to be separated by just distillation

So, in that case, you have to select the organic solvent in such way that where this compound or contaminant in the liquid can be easily, you know that, transferred to the liquid medium which will be immiscible in the, you know that continuous phases.

So based on which this immiscibility, these two liquids will be, or organic liquids will be produced as a droplet form so that you can get the more interfacial area through that mass transfer or here in this case, as an example, that propionic acid to be transferred through the interface of this liquid-liquid to the, you know that Decanol or paraffin, some other organic liquid.

So, this is the mechanism by which that liquid-liquid extraction being happened, and in that case most important that you have to select the suitable solvent where that you can produce the droplet and you can easily separate those compounds after, you know that extraction of that contaminant.

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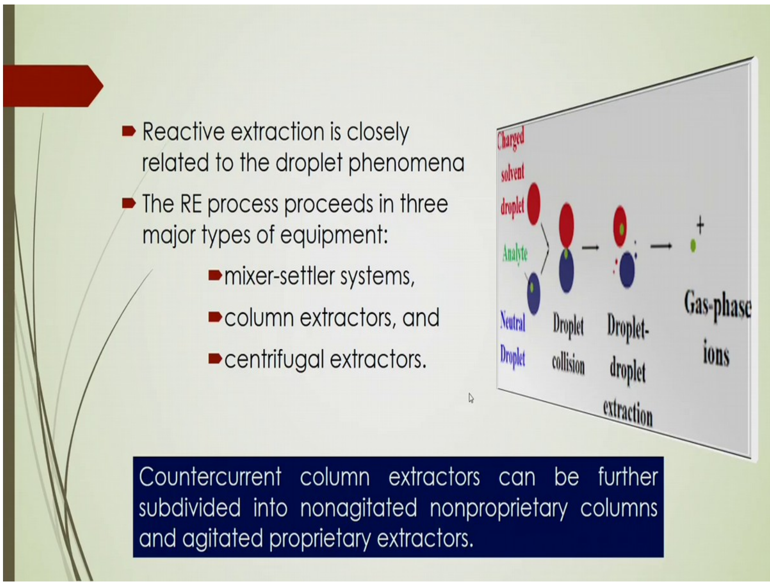

And also, it is related to the droplet phenomena that I told that if you produce that droplet, if you are producing more finer droplets you can get more interfacial area so that, you know that your extraction will be more and process efficiency will be more. More mass transfer will be there.

So that is why this reactive extraction process that depends on your, you know that design and how it can be designed, how to produce that more finer droplet, how to select that solvent, so for that, to produce the more finer droplet there, you have to design some unit like mixer settler systems.

You have to use some mechanical provision so that, that more turbulence will be there, more interfacial area to be produced by producing droplet. Column extractions to get the more interfacial area between the liquid and liquid so that you can have more extraction.

Even sometimes centrifugal extractors also are being developed for process intensification for this extraction. In that case, centrifugal action, centrifugal force will be applied to separate those liquid contaminants into another liquid by just action of gyration, and also making a thin film of that liquid, immiscible liquid so that through that thin film that mass transfer will be more efficient.

Counter current column extractors can be further subdivided into, you know that non-agitated, non-proprietary columns and agitated proprietary extractors. In that case you will see sometimes that counter current operations are being used there to actually design economically so that, that without making a droplet how you can increase the, you know that efficiency of the extraction.

So, in that case you can save some energy and also, you know that easier to handle those operations. That is why counter current column extractors are also one of the important intensifications of this extraction process.

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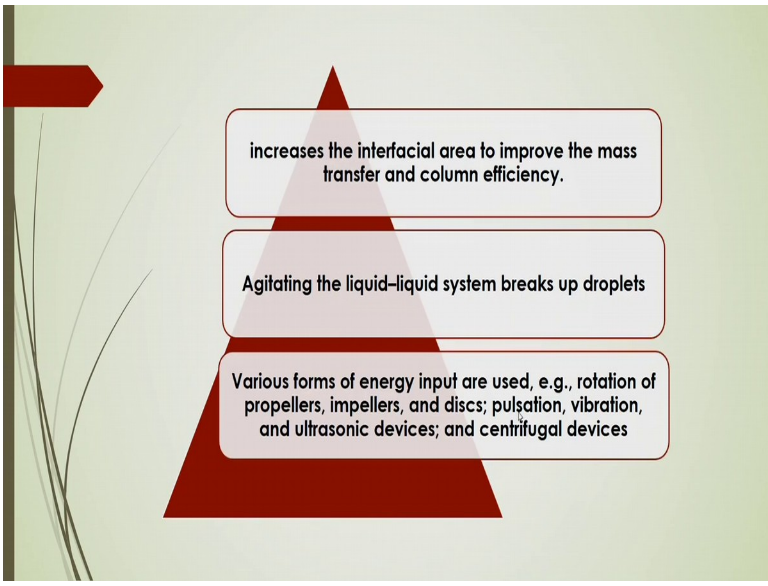

So, the extraction process you can say that, various forms of energy inputs are required like rotation of propellers, impellers, disk propulsion and also that pulsation process, even you know vibration and ultrasonic devices and centrifugal devices. So, to run those equipments for this process intensification of extraction you need various forms of energy.

And agitating the liquid-liquid system that breaks into droplets, to use this energy you can increase the droplets, you can increase the interfacial area so that you can get the better mass transfer of extraction. And also, if you increase the droplets by this energy you can increase the interfacial area to improve the mass transfer and column efficiency.

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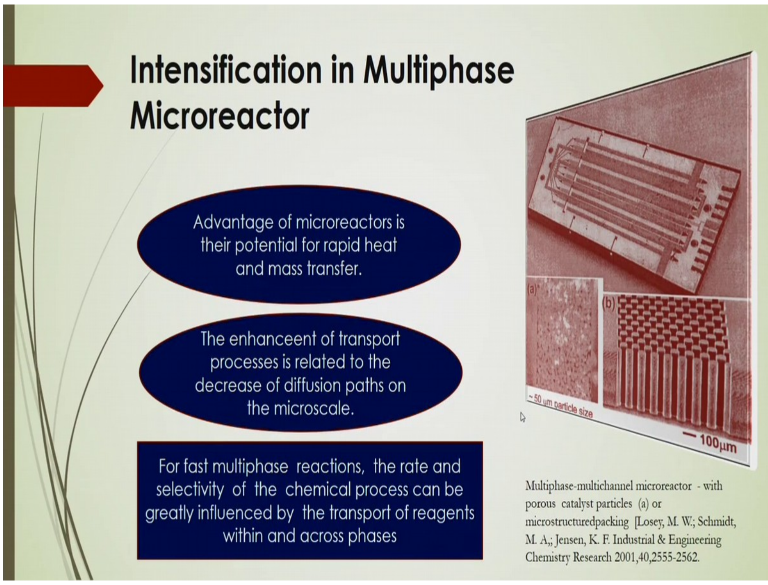

Other important intensification processes of multiphase systems are development of, you know the microreactor, microchannel based heat exchanger. In the case of microreactor, multiphase based micro reactor, in that case they have some potential for the rapid heat and mass transfer.

The enhancement of this transport processes is related to the, you know that decrease of diffusion paths on the micro scale phenomena. For first multiphase reactions, these are very important and the rate and selectivity of the chemical process, that can be greatly influenced by the transport of this reagents within the, you know that phases.

And here as shown in figure, some microchannel based reactor where you know the porous catalysts are being used and the microstructure packing, in that case, through that packing there will be reactions as well as mass transfer and heat transfer will be there. So to increase that interfacial area, these microstructure reactors are being developed and which, you know that enhancement of the transport processes are taking place.

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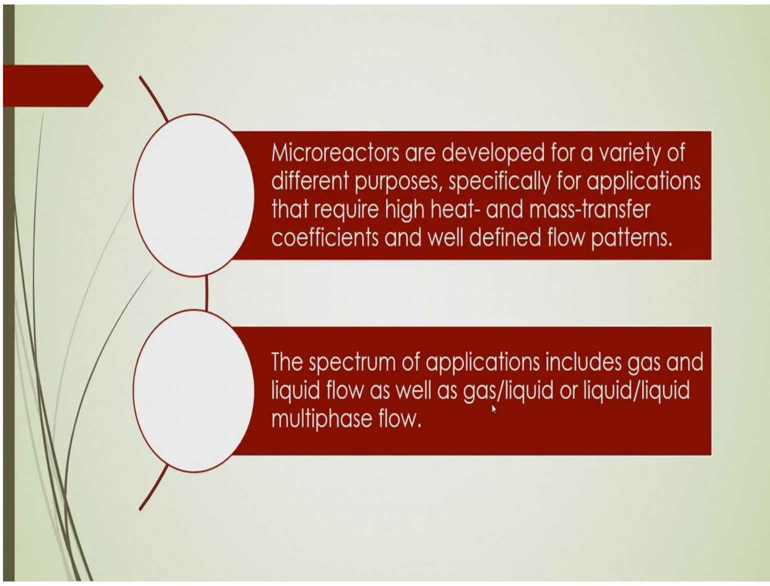

And variety of different purposes also are, you know that fulfilled based on this, you know the application and requirement of high heat and mass transfer coefficients in the microreactors and also in the microreactors we are getting that well-defined flow patterns and because you know that heterogeneous flow patterns sometimes, there back mixing are being used or actually seen in the column reactors.

There to avoid those back mixing, so microchannel based, you know slag flow pattern or plug flow patterns are, you know that devices. So that mechanisms are being used for process intensification. The spectrum of the applications includes gas and liquid flow as well as gas liquid or liquid-liquid multiphase flow systems in this microreactor system.

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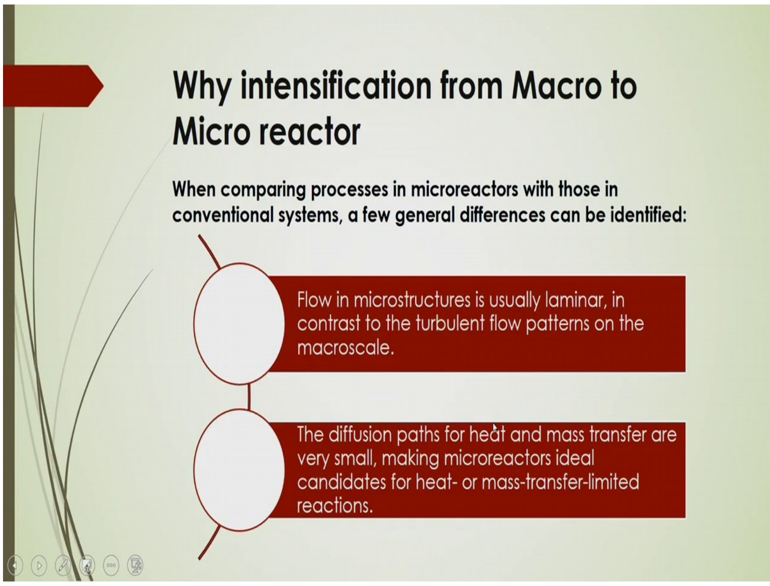

So why this intensification from macro to micro reactor? So, when comparing the process in microreactors with those in conventional systems, a few general differences can be identified. Like flow in microstructure is usually laminar in contrast to the turbulent flow patterns on the macro scale and the diffusion paths for heat and mass transfer are very small making microreactors ideal. And you can say that for heat and mass transfer limited reactions which are very, you know convenient in these particular microreactors.

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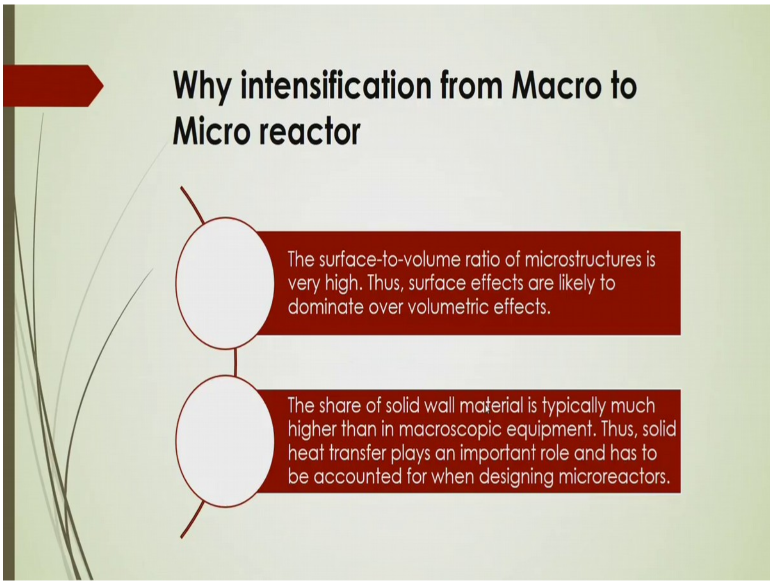

The surface to volume ratios ofcourse in this microstructure reactors are very high and thus surface effects are likely to dominate over the volumetric effects. The share of solid wall material is typically much higher in macroscopic equipment, thus the solid heat transfer plays an important role and has to be accounted for, when designing that microreactors.

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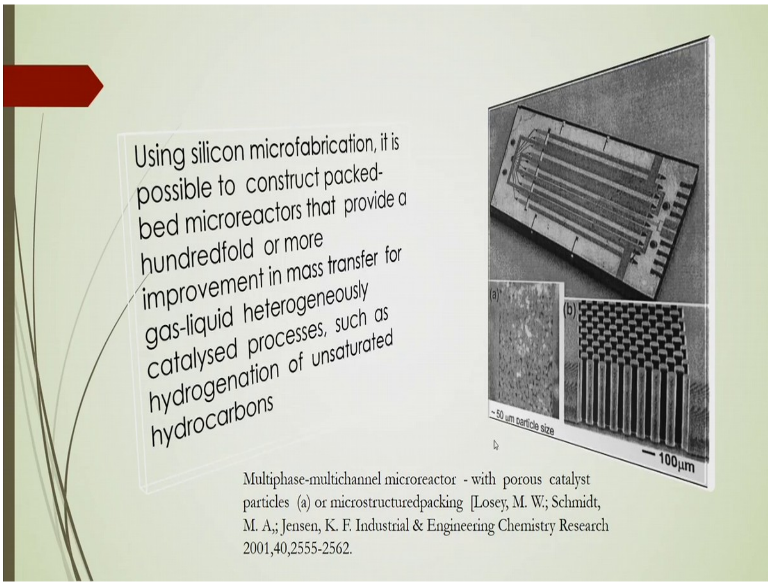

And using, like silicon micro fabrication it is possible to construct packed bed microreactors that provide a hundred-fold or more improvement in mass transfer for gas liquid heterogeneously catalyzed processes such as hydrogenation of unsaturated hydrocarbons, that is actually reported by Losey et al in 2007. They have done this, you know hydrogenation of unsaturated hydrocarbons in multiscale, multichannel, you know microreactor.

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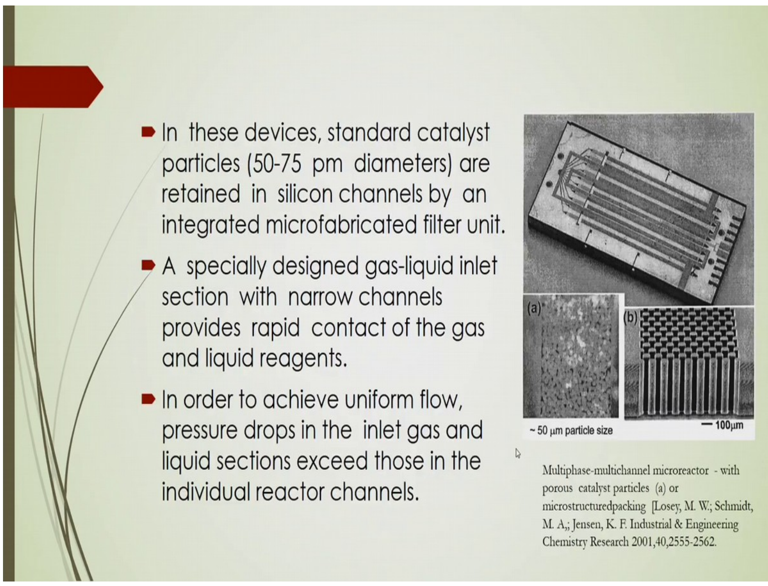

And in these devices, standard catalyst particles, 50 to 75 picometer diameters are retained in silicon channels by an integrated microfabricated filter unit, a specially designed gas liquid inlet section with narrow channels provides that rapid contact of the gas and liquid reagents. And now in order to achieve those uniform flow in that microreactors you will see that pressure drop in the inlet gas and liquid sections that will be higher than those in the individual reactor channels. So, though it has the higher pressures, still it has some advantages to get the more efficient reactions.

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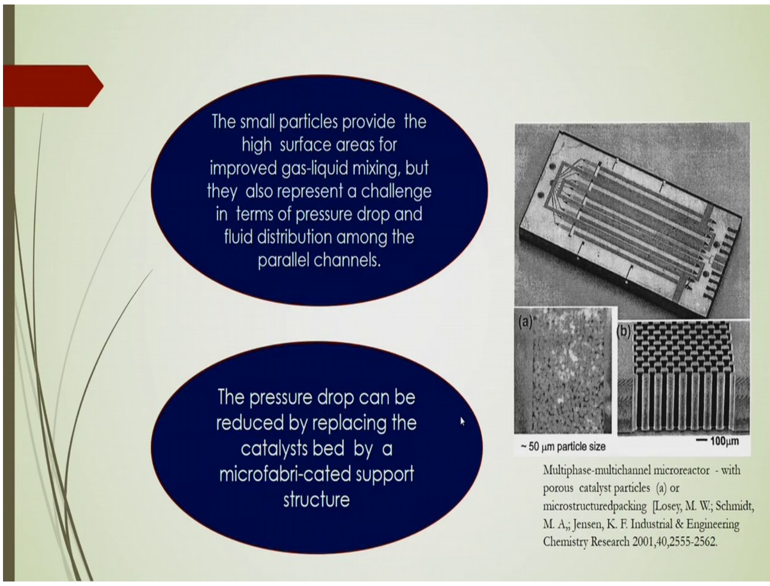

The small particles provide the high surface area for improved gas liquid mixing but they also represent a challenge in terms of pressure drop and fluid distribution among the parallel channels. And the pressure drop can be reduced by replacing catalyst bed by a microfabricated support structures there.

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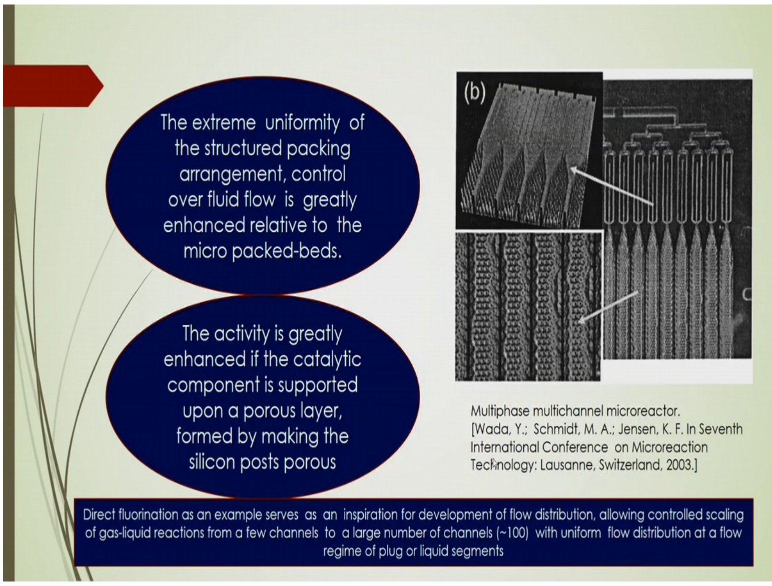

And uniformity of the structured packing arrangement also important in that case, you can control over the fluid flow, that is by this structure packing arrangement and that will give you the enhanced relative to the micropacked beds condition and the activity is greatly enhanced if the catalytic component which is supported upon a porous layer and formed by making the silicon posts porous.

And in that case, direct flourination as an example, that can be served as an inspiration for development of flow distribution allowing controlled scaling of gas liquid reactions from a few channels to a large number of channels like 100 micro channels with uniform flow distribution at a flow regime of plug or liquid segments.

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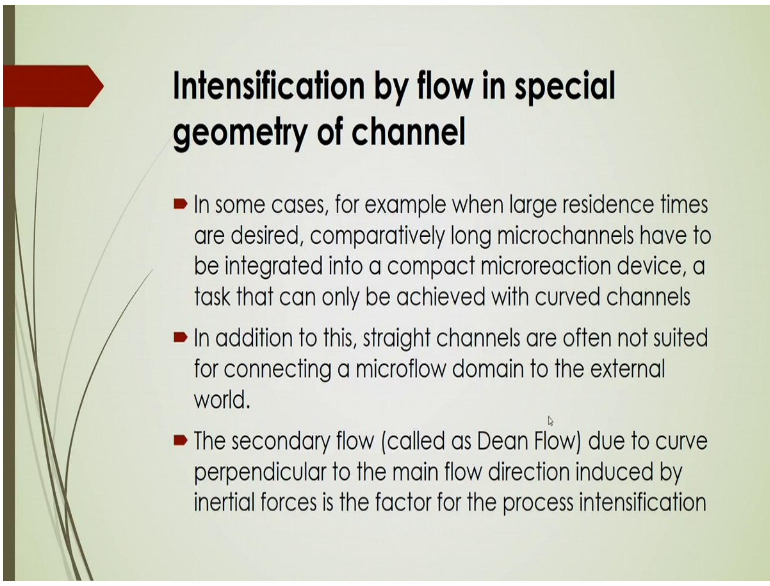

Another important intensification by changing the geometry of the channel, in some cases for example when large residence times are desired, in that case you will see the comparatively long microchannels are, you know have to be integrated in such way that it will be make a curve-shaped and it will be made curve channels.

And in addition to this, straight channels are often not suited for connecting a, you know microflow domain to the external world so that you are making that curved flow and also whenever you are making a curved flow there will be a creation of secondary flow that is called Dean flow due to the curve perpendicular to the main flow direction which will be induced by the inertial forces which is the main factor for the process intensification.

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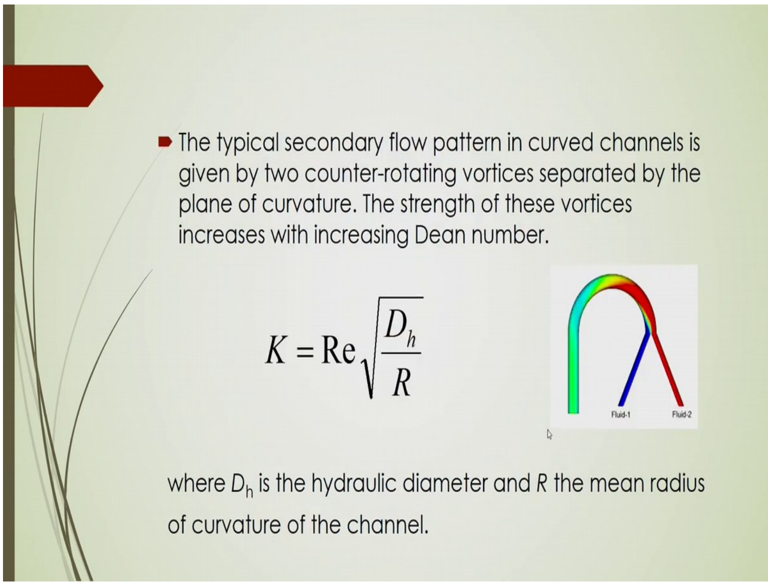

And the typical secondary flow pattern in curved channel is given by two counter rotating vertices separated by the plane of curvature. The strength of these vertices increases with increasing Dean number. For that this factor K, that is Dean number will be represented by the Reynolds number into root over of D h by R where D h is the hydraulic diameter of the curved channel and R is the mean radius of the curvature of the channel.

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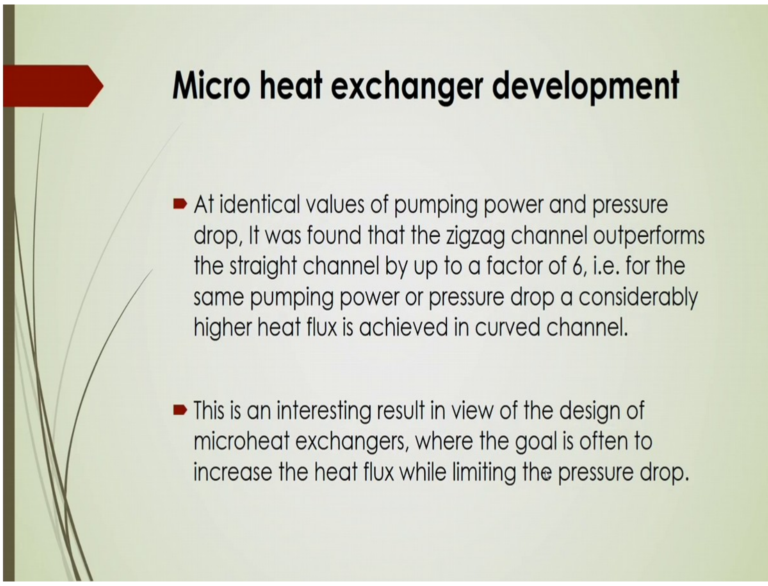

So, some other intensified unit like microheat exchanger development, in that case you will see that the design of microheat exchanger where the goal is often to increase the heat flux while limiting the pressure drop and also for that, you know for some pumping power or pressure drop, a considerably higher heat flux is achieved in the curved channel.

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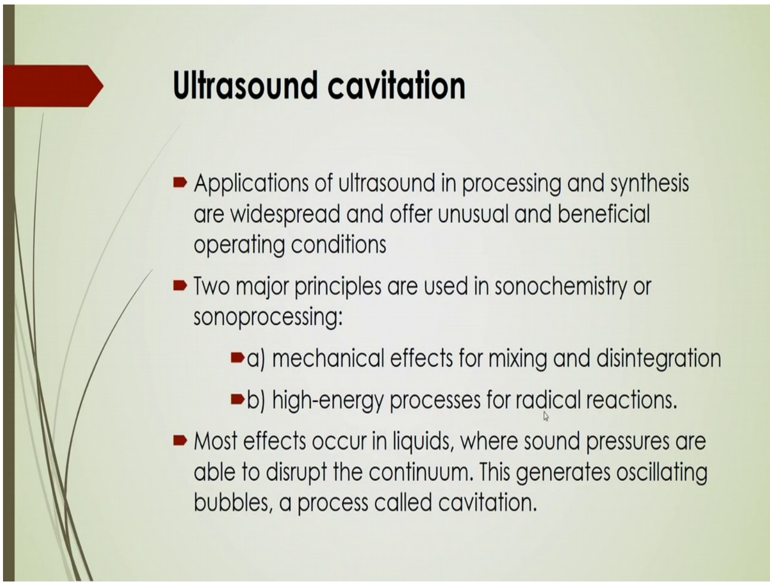

So, in that direction, the curved microchannel based heat exchanger are developed. And other intensifications like ultrasound cavitation, application of ultrasound processing and synthesis are widespread and offer unusual and beneficial operating conditions.

Two major principles are used in sonochemistry like; you know mechanical effects of mixing and disintegration, high energy process for, you know radial reactions. Most effective process like in that case, sound pressure sometimes developed to produce that cavitation to get the more interfacial area.

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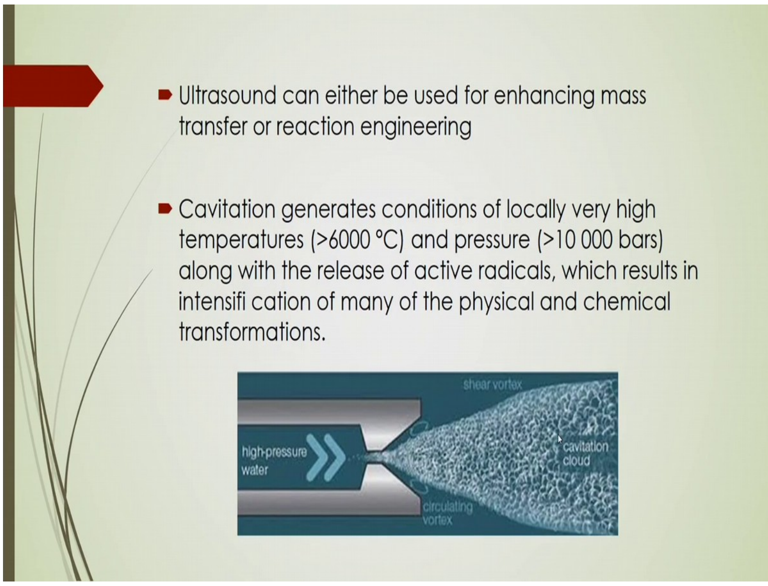

So, in that direction this ultrasound cavitation has produced to get more interfacial area and more mass transfer there.

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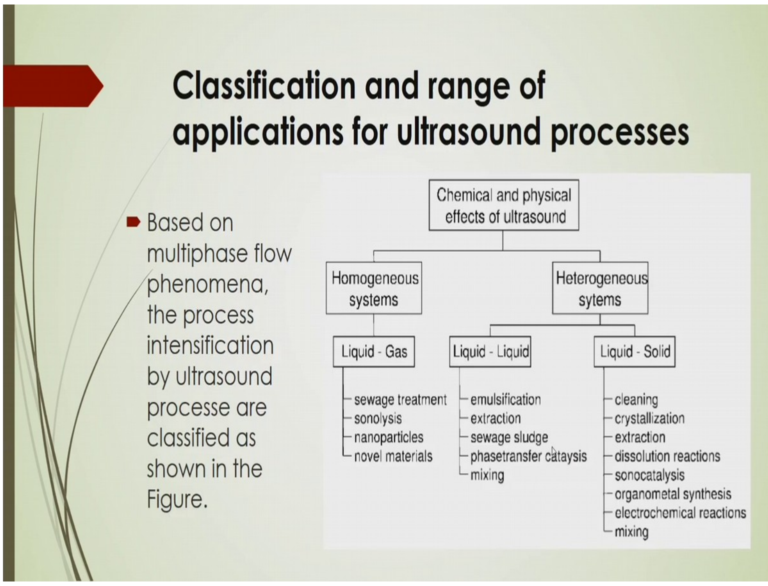

So, we can classify that range of applications of ultrasound process based on different multiphase systems like chemical and physical effects of ultrasound, here homogenous systems, liquid and gas systems, sewage treatments, sonolysis, nanoparticles, even novel materials, liquid-liquid systems like emulsification, extraction, sewage sludge even phase transfer catalysis, mixing etc, liquid solid like cleaning, crystallization, extraction, dissolution reactions etc.

So, in this lecture then we have gone through what actually that, what are the different mechanism of different process intensification of the chemical process which are being intensified for particular process systems and different mechanisms which are involved in this process. So, I think it will be helpful for, you know further understanding of the process intensification in chemical engineering processes.

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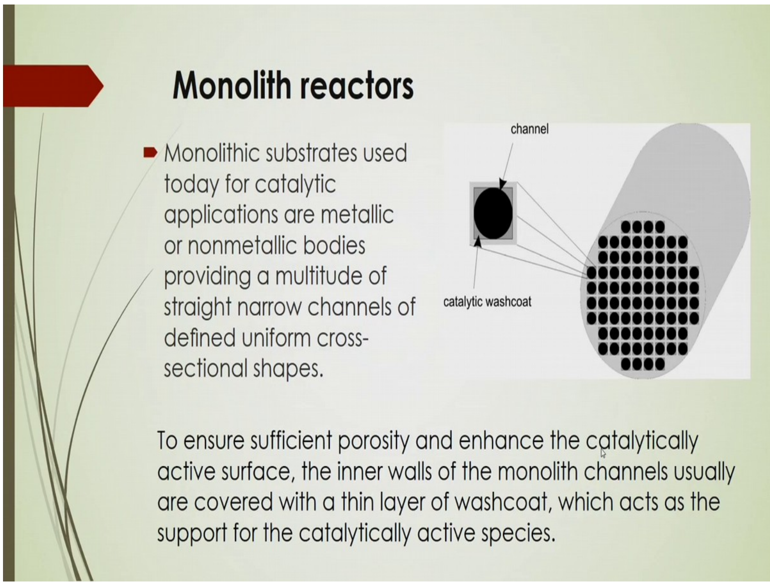

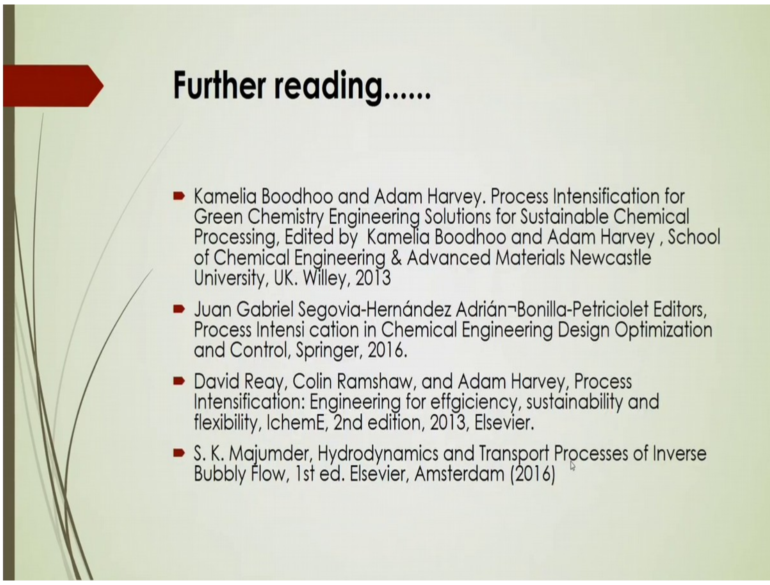

So, I would suggest you go further reading with this, you know that suggested books for this further understanding of process intensification mechanism for various application in chemical engineering process, thank you.