Heterogeneous Catalysis and Catalytic Processes
Prof. K. K. Pant
Department of Chemical Engineering
Indian Institute of Technology, Delhi

Lecture – 36

Good afternoon, so in the last lecture I was talking about various catalytic reactor, say two phase system and multi phase system like three phase system. Let us continue the same today also and different kind of three phase or two phase reactor, which I was discussing last time.

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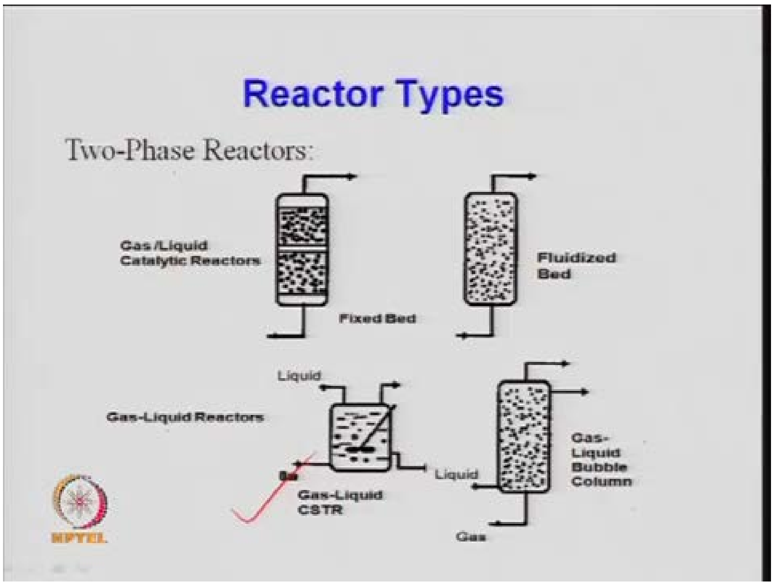

If you look at their schematic, these are different kind of two phase reactor, where you have a gas or a liquid in the presence of some solid, so catalytic reactor. So, when you have a just like a gas, liquid or solid, it is a three phase. But, when you have a gas solid or gas liquid, so it is a kind of what I told a simple packed bed reactor when you have gas from the top or bottom and liquid or the catalytic in the reactor. So, you have lesser number of resistance, so design becomes little bit simpler.

But, these can again be a kind of a CSTR like this kind of system, a tank type of reactor, it can be a kind of bubble column reactor, which is very common nowadays. Especially, when the heat transfer is an issue and it can be a kind of just mainly for the gas solid reaction, a packed bed reactor or a fluidized bed reactor. So, you can see here the gas which passed from the bottom and the product, and the unreacted reactant comes from the top and the catalyst is placed in this bed like this.

So, distribution of this is very important, how the catalyst particles are distributed in presence of some inert ((Refer Time: 01:59)) to have the heat dissipations, so regeneration of the catalyst is difficult in these kind of reactor. The another one again I said that, you have a good contact between the gas and solid. So, reactions is little in terms of back mixing if you look at, that will be more here in degree of back mixing, because it behaves like a CSTR as I discussed in my last lecture.

These are again a kind of CSTR time type reactor, where when the mixing is the problem or mass translation issue then, we prefer a gas liquid reactors in the form of something like CSTR. So, you have a well agitated tank creator here. It can be a kind of slurry bubble column reactor also then, it becomes three phase system. So, right now these are the simple a gas liquid reaction, where you have the gas and liquid, so these can be known catalytic type of reactors also.

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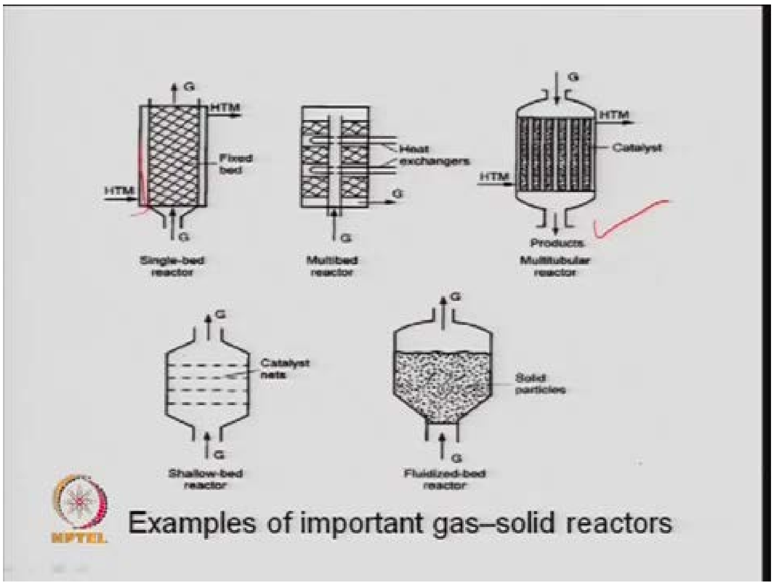

So, the different types of systems when I was talking yesterday that heat transfer, when the reaction is exothermic or endothermic, so we put a multi tubular multi bed reactor. So, this is a kind of multi tubular reactor here, if you can see here and this is single bed reactor, so again the type of it can be a heat transfer. So, you can see a jacketed here outside, so this is just some heat transfer of fluid, which is passing through the jacket or agitated, it is not agitated, but it is a jacketed.

So, it is kind of cell and tube type of heat exchanger, so continuously the cooling can be done here when the heat is generating throughout the system. It can be multi bed reactor, which I was talking just for sulphur dioxide oxidation, so one bed, second bed and third bed and in between we have the heat exchanger. So, this is just a geometrical picture of that what I was discussing yesterday. It can be shallow bed type reactor, where you have just the layers in the form of thin layer and it may be metals, a catalytic net.

So, just like in this case of automotive adjots, you have a small tube and that gas or the adjots gas pass through these kinds of the platinum wire gauge or all. So, this can be just a channels here or a nets here and the gas passes through that and this is again a kind of fluidized bed reactor and which is again a important kind of gas solid reactor here in the two phase system.

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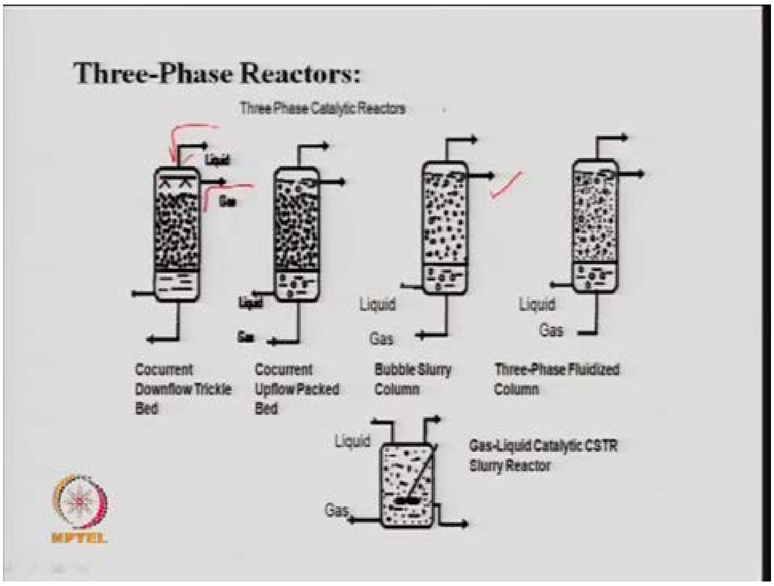

Three phase system is more complicated, so I will just discuss this part today, here you can see that, you have a solid inside the reactor, back. And then, that flow can be concurrent or counter current, so that also it depends on the concentration, difference which is required or the kind of the contact between gas liquid and solid, which is desired. So, both type of combination may be used, so here you can see the liquid comes from the top, so we need a distributor here.

So, distributor design itself is a complicated job and one needs to identify a good kind of distributor, the number of holes required and diameter of those hole, so to avoid the mild distribution inside the reactor. So, different kind of distributors are available and then, you need how to place the catalyst or packing inability, may be also kept along with the catalyst. And this is what you can see here, so you have a gas from one side, so this is just a kind of cocurrent operation. Both liquid and gas comes from the top like this, here the liquid and this is the gas, so how to get a good contact between gas, liquid and solid.

So, it can be a low flow rate of the gas, low flow rate of the liquid or it can be a high flow rate of gas and liquid, so this a kind of a down flow trickle bed reactor and I will talk on that little later. This is again a cocurrent type of up flow pack bed, because the flow can be downward side or up flow, so this a kind of up flow. So, you can have a good contact between gas and solid and liquid compare to this, so because the channeling flooding problems can be minimized in this kind of system.

This is a slide bubble column, so one is bubble column reactor when you have a gas liquid with no solid, here you have a solid which is in the form of basically catalyst, fine powder of the catalyst and kept in the form of slurry. So, already a liquid is here, so you need a kind of agitator also to make them in suspension and the gas which pass from the bottom and liquid is also the product which comes, that is taken continuously from here. So, it is a kind of continuously reactor and a bubble column or slurry bubble column reactor.

Same thing here, this is a kind of three phase fluidized bed reactor, so you have that solid inside the bed, you have the liquid, it can be in the form of suspension and the gas is being passed from the bottom continuously. So, gas comes out, liquid goes in, liquid comes out along with the product and that is, you have to decide what level or how much liquid product is to be collected accordingly. Just like in the case of Fischer-Tropsch reactions, this slurry bubble column reactor are very common.

Same thing, in the case of three phase fluidic bed reactor, the various heterogeneous catalytic reaction we have the fluidic type of system also, where the hydrogenation reaction say nickel catalyst ((Refer Time: 07:37)). So, that the hydrogenation of oil basically is done in these kind of reactors, slurry type of reactors and this is again a type of tank creator, which is a CSTR type of creator in the form of slurry.

So, the design complications furry, depending upon the type of reaction, depending upon the catalyst which is used in the process, so one need to identify, it definite process or up flow, down flow or a combination of the reactor systems depending upon the process.

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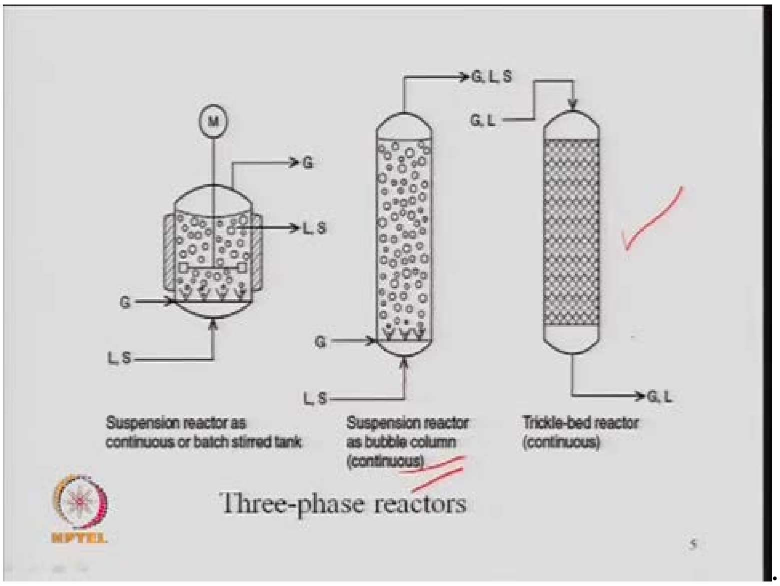

This is just a details of that, what I was talking a suspension reactor, where you have the solid particles are in suspension, suspended form, so you need a fine kind of agitator to have a well mixing. So, basically the mass transfer problems are minimize by using this kind of reactors, so gas is continuously pass through the sparger. So, good kind of a sparger is required, the size of the catalyst practical becomes very important, the bubble size liquid in the form of gas bubble.

So, this size are important, how can you make a good contact between gas, liquid and solid, because where all these resistance may be important and how to enhance the kinetics of the reaction. So, all these factors becomes important when you select the overall rate of the reaction and accordingly, the reactor design is required or it is important to select a prototype of a reactor. This is a kind similar, but this is a continuous type, a pluck flow type that is, a combination of CSTR and pluck flow.

So, suspension reactor which I was discussing, I just talk on little later again on this, so suspension reactors which is similar to a bubble column reactor, a continuous type of reactor. So, gas is being passed through the sparger, solid is already there and liquid is pass from this, so that is eslary here and the particles are kept in suspended form. So, again you need to decide, what is the particle size, what is the type of liquid and just like in the fluidized bed column, the similar slurry in hydro dynamic conditions are also required to be studied.

This is very important, especially in the hydro treatment reaction in refinery or petro chemical industry or advanced air oxidation process, the trickle bed reactors are used. So, here again you have a gas and liquid coming from top and then, it is coming down from the bottom. So, gas hold up, liquid hold up then, contact between the gas, solid, wetting, wet ability, so there are many factors involved, in which decides the or decide the efficiency of the process.

So, we need a good kind of contact between gas, liquid and solid, we need a definite kind of wet ability, because wetting and wet ability both are very important in these kind of multi phase reactor. So, that zones which may come, because of the inefficient type of catalyst or inefficient wetting during the reaction. So, there can be different kind of say pressure, depending upon pressure depending upon the flow rate of gas and liquid, the flow or hydro dynamic may be a factor.

And because of that, the pressure drop may be an a issue, energy consumption, how to minimize the pressure drops and drag force between the gas and solid or liquid gas, liquid solid, so interficial time are becomes important. So, there are many factors where interficial science and engineering also involved, reaction in engineering involved, hydro dynamics, fluid mechanics involved. So, a combination of all these need to be studied in order to design these kind of reactor. So, compare to packed bed reactor, the design of multi phase reactor becomes or three phase system becomes much more complicated.

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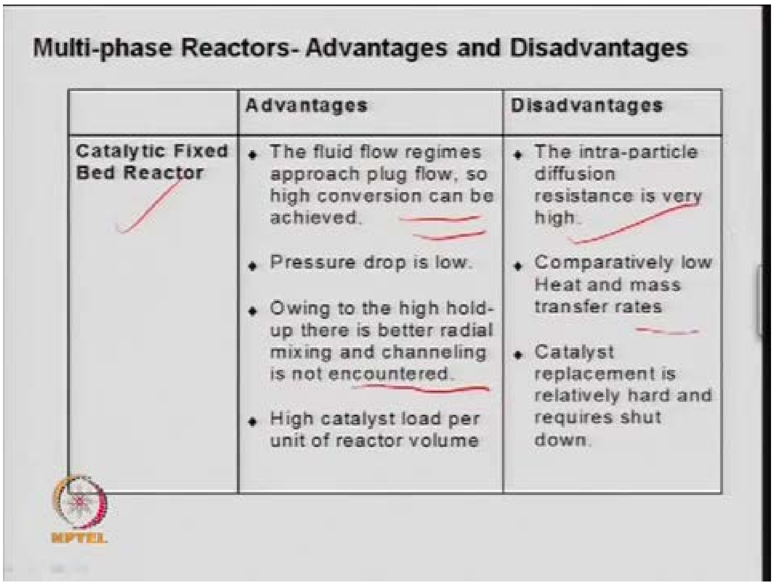

But, if you look at the compression, a catalytic fixed bed reactor just and a multi phase reactor, so catalytic fixed bed reactor it has some advantage, but disadvantage also. So, these kind of reactor system will have some advantage and some disadvantage also, one has to do all these exercise in order to find like dust reactor for the given process in the presence of the catalyst. So, here the catalytic fixed bed reactor, the fluid flow region approaches to the plug flow.

Because, most of the time I say that, the dispersion is to be minimized, so axial, regal dispersion which contributes a kind of non ideal flow, so that is to be avoided. And when you have a kind of fixed bed reactor, one can select the proper design conditions in terms of the height of the rector, diameter of the reactor, size of the catalyst particle and can approach to a plug flow condition. So, you get when you have a plug flow conditions, I told you that the, because the conversion down the length of the reactor will be higher, if you do not have any kind of non ideality in the reactor.

So, this is one advantage here, you get high conversion, pressure drop is low because it is a fixed bed reactor, one can decide the particle size. So, depending upon the particle size, the pressure drop can be minimized or reduced and since the holdup is high, owing to the high holdup, there is a better radial mixing and channeling is not encountered. So, this is what I was talking in the case of a fixed bed reactor or when you compare two phase, so the liquid flow, so what happen, the liquid bypass the catalyst. It just comes from the side of the wall or it comes from the voids space between the particle.

So, here you can have a better design and flow conditions are different, so one can look at the hydrodynamics to evaluate the RTD and try to find out the conditions when the reactor resembles like a plug flow reactor. So, that becomes a very important in the terms of the design of reactor or selecting a best kind of reactor and working under ideal conditions or making it ideal for the conversion. So, this is what that, channeling is avoided or minimized in the case of the fixed bed reactor.

And catalyst loading is high per unit volume of the reactor volume, so that is again important, because when you calculate the overall productivity, that depends on the mass of the catalyst in the reactor. So, per unit volume if you look at, you can have high mass of the catalyst in this case, compare to CSTR as I said that, the mass of the catalytic format will be low for the same conversion. So, this is the advantage of the fixed bed reactor, but disadvantage wise I told intraparticle diffusion resistance will be very high.

Because, use how to select a definite particle size, you cannot take very fine powder, because pressure drop will very high, so that is an important aspect. Again when you look at a reactor design, you have to look at the hydrodynamics and d p by d z, pressure drop, particular length of the reactor and that is to be minimized. So, that is one thing that, if you take the larger particle size, your pressure drop will be low, but the problem will be intraparticle diffusion resistance.

Because, effectness factor which I discuss in my last lecture, that depends on the particle size also. So, intraparticle diffusion resistance is one of the issue, which will decrease the overall rate of reaction just like, if you have a ammonia reformer or ammonia productions, where you have a reformer and if the catalyst effectness factors is very very low, 0.001. So, it means, the rate of reaction will be very low, so either that is why the new kind of reactor design is required, where you look at a monolith type of reactor, which are the kind of channel type of reactor.

So, micro reformer concepts, that is what used or being used to have higher conversion or higher rate, where the diffusion resistance is an issue, especially when microporous catalyst or non porous type of material so then, these resistance will becomes more and more dominating, so that is one issue. Second thing is the heat and mass transfer, because heat remover or concentration gradient, that may generate in the case of packed bed reactor, because you do not have any kind of exterior there.

So, there will always be kind of concentration gradient from bulk to the center of the catalyst and down the length as well as radically also, there will be these kind of concentration gradient. So, heat removal is an issue in the case of the fixed bed reactor and same thing, catalyst replacement is difficult. So, that why I told, the fixed bed reactor should be recommended when the deactivation of the catalyst is very very low or catalyst life is high, something like say a minimum of 1 year, 1 to 3 years just like in the case of hydro desulfisation reaction or in the case of your ammonia production, the life of the fertilization industry, the life of the catalyst upto 3 year.

So, there these kind of reactor can be used, provided the other problems are solved, so that is one disadvantage of the fixed bed reactor. Same thing, in the case of fluidized bed reactor, because when the deactivation is an issue, we prefer a fluidized bed reactor.

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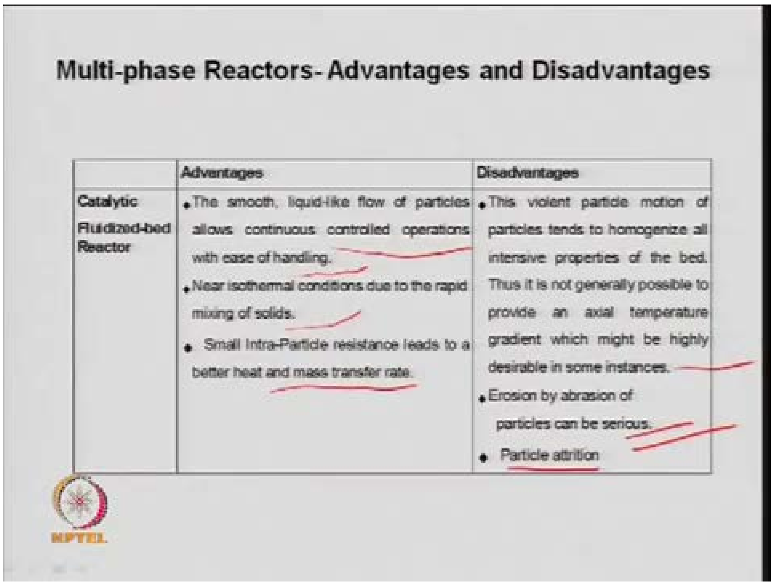

So, it has again some advantage, but simultaneously some disadvantage, so one thing is that, smooth liquid like flow , because it is a fluidized bed, so you just the particles are flowing just like a fluid. Only thing that you need to have some high fluid rate or superficial gas velocity, all these hydrodynamic studies need to be done in order to make the bed or particle fluidized at all the time. So, this allow a continuous control operation with ease of handling.

So, particles can be removed from the system and they are well in contact with the reactor, so rate transfer or heat transfer, mass transfer, these problems can be solved to some extent. So, near isothermal conditions can be obtained due to rapid mixing of solid, so this is the another advantage here that, the isothermal condition can be maintained. Intrapartical resistance is low, because the particles are now smaller here of the order of 100 micron, 200 micron.

So, the intrapartical resistance are lower and that will be again an advantage in terms of heat and mass transfer, because surface area per volume of the catalyst is very high, because the particles are now smaller. So, heat transfer and mass transfer problems are solved to some extent, but again there are some disadvantage. So, first the particles are moving up and down, so there is up flow and down flow, up and down. So, that is one violent particle motion, a particle and it tends to homogenize all internship properties of the bed.

So, that is what I just like a CSTR I said complete back mixing, there is degree of back mixing. So, because of this, thus it is not generally possible to provide an axial temperature gradient, which might be highly desirable in some extent say. So, in some cases, where you need some kind of temperature gradient then, it is difficult, because this is not a very big issue. Not in all cases the temperature gradient is desired, in most of the cases, the gradient is not desired. So, this is one problem, because of the well mixture like in CSTR, you cannot get the gradient of temperature.

So, in this case also, the temperature gradient is not generated, second erosion by abrasion of particle is serious issue. So, this is what the loss or attrition of the particle, because they are moving like this, there is a kind of partition between the particle and the particle is, they are soft. If they are not stable mechanically then, they will crumble during the reaction and then, they will leave the reactor bed. So, there will always be a loss of catalyst during the operation, so that is an important issue.

So, how to make the catalyst stable that is important here, so this is the second and third again the particle attrition. So, these are some issue, which are associated with the fluidized bed reactor.

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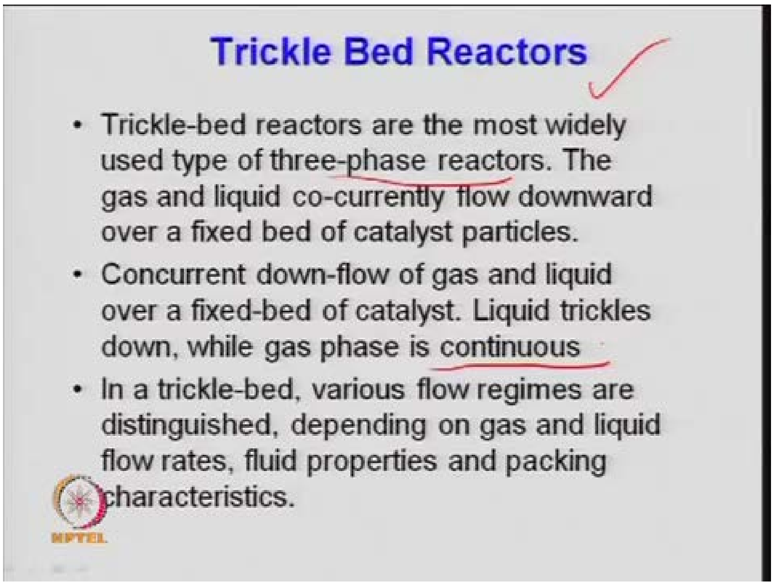

I was just talking about trickle bed reactor, so trickle bed reactor again as I said that, hydro dynamic is very important and to decide the gas flow, liquid flow rate or superficial gas velocity and then, the holdup gas liquid. But, the trickle bed reactors are a type of multi phase reactor and widely used in the process industry. So, especially when the mass transfer or the solubility is an issue, the hydrogen say difficult to dissolve in the kerosene or so, these kind of reaction, you need a kind of pressure.

High pressure is required to make it soluble and then, depending upon the concentration, depending upon the solubility and the solid, type of solid which is your catalyst. So, you will have a kind of gradient, concentration gradient, temperature gradient and if this gradient exist then, there will be mass transfer resistance, heat transfer resistance. So, these are some issues, which need to be addressed when you look at the trickle bed type of reactor.

So, let us talk about tickle bed reactor, because this is one of the important reactor used in the refinery and petrochemical industry and also for the advance oxidation or waste water treatment. So, trickle bed reactor is one of the common type of three phase reactor and here the gas and liquid, they flow concurrently downward over a fixed bed of catalyst particles. So, most of the time it is from upper side to lower side, downward flow, but nowadays counter current trickle bed reactors are also being practiced or tested or at R and D level, so to have the more and more concentration difference.

So, cocurrent down flow of the gas and liquid over a fixed bed of catalyst, this is what trickle bed reactor and liquid trickles down while gas phase is continuous. So, what does it mean, generally the liquid flow rate is low, relatively lower liquid flow rate although the gas and liquid both flow rates are low, but still it at a low flow rate, what will happens.

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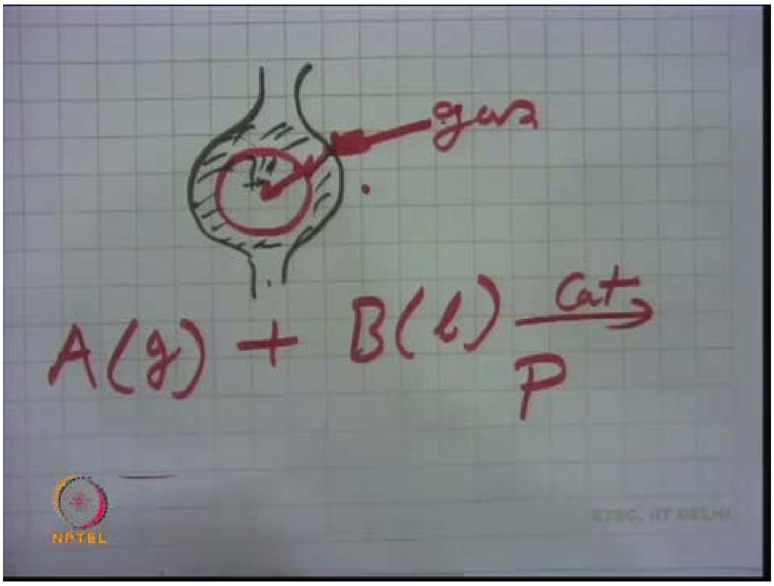

Suppose, you have a solid catalyst particle like this, which is porous material, so it may saturated with some liquid. So, when the liquid comes, so but at a low flow rate what will happens, it will come like this, it will trickle over the surface of the solid like this. So, this comes like in the form of rivulets or droplets and then, it comes like this, there is thin film of the liquid on the surface of the solid and this liquid is already saturated by the liquid, this liquid is already there in the pore of this catalyst.

And now, when you have a gas, so gas will be somewhere here, this gas is diffusing through this liquid film, which is a bulk of liquid and again a liquid surrounded by a solid, so I will talk on that. So, here will be a kind of resistance this, so there will be a constant, the gas has to penetrate this liquid fill and then, come to this surface of the solid and then, diffuse inside for that reacts. So, active metal is there or catalytic active sides are inside, but we have discussed earlier in the gas solid reaction also.

So, on the surface of the solid, the reactant where the liquid is already present in the pore, the gas reach there and then, it reacts. So, if I write the reaction something like this, so it is a gas A reacts with some liquid, which is B, in the presence of the solid which is the catalyst and then, it transforms it to some product P, which may be a gas or liquid and whatever that and that product P comes out of the pore. So, this is what we have to look at that, what are the resistance is offered, because it is a mass transfer dominating.

Because, the solubility of the gas is important here, this is something like kerosene hydrogenation or removal of sulphur from the kerosene, diesel hydrodesulfisation. So, we need to look at that, where the solubility of hydrogen in diesel and then, the transfer of this hydrogen gas from the diesel liquid, liquid which is there and through that, to the surface of the solid and then, come to the pore of a catalyst, where already some diesel is present.

And then, these two react like this and the sulphur which I am talking here, so when I said that gas, gas is your hydrogen, when I say this B liquid, so it is some sulphur compound, benzothiophene, dibenzothiophene or mercator. And then, it converts it into a sulphur compound or hydrogen sulphide basically and that comes out of the pore, so which is a gas basically, so this is what we look here. So, generally in trickle bed reactor, the various flow regions, they will be here what I discussed, depending upon gas, liquid flow rates, fluid property and packing crackers.

So, it means, the viscosity of liquid is very important, gas properties are important, Reynolds number will be important. So, we have to just identify some dimensionless numbers or we have to correlate the flow property, pressure drop in the reactor and how to get a good contact between gas and solid. So, that will depend on mass transfer coefficient of the gas to liquid, mass transfer coefficient liquid to a gas in the liquid fill and then, from liquid to surface of the solid then, catalytic reaction kinetics, so all these factors need to be incorporated in this.

So, pressure will be important, pressure will inhale the solubilities, simultaneously temperature will be required, so one needs to look at all these.

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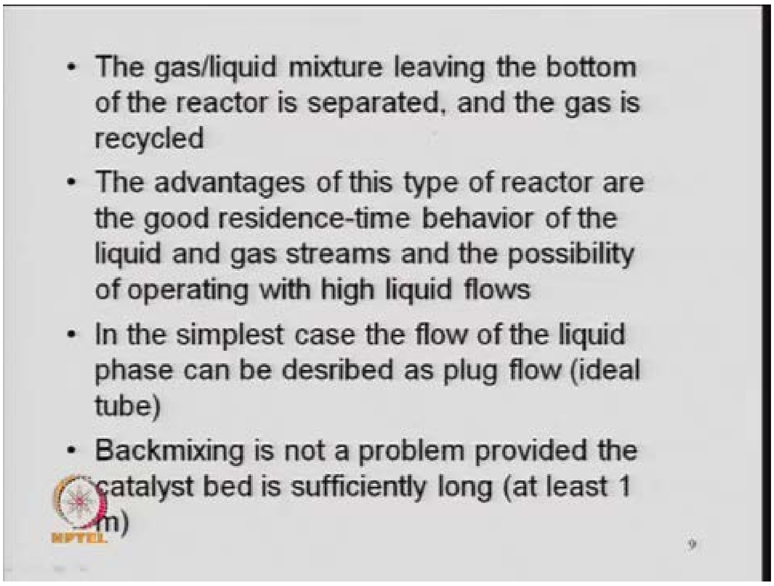

So, let us talk more about on this trickle bed reactor, so in this trickle bed reactor, the gas and liquid mixture leaving from the bottom of the reactor is separated. This is just like a packed bed reactor, otherwise it is similar to a packed bed reactor, the only think that, the liquid flow rate is very low. So, the liquid just trickles on the surface of the solid just like in a solid surface and one a ball, you put some water in a thin film, so water will spread like this.

So, that is here what the and that what about the product you get, you get separate and then, recycle the unreacted wall. So, advantage of this type of reactor is that, they have good residence time behavior of the liquid and gases stream and the possibility of operating even at high liquid flow rate. So, it can behave like a plug flow also, that what I was talking that, you have to just maintain the condition and then, under what condition, it resembles that is, RTD study can be done or flow rate of gas, flow rate of liquid on different shape and size.

So, here it is basically mass transfer control reaction as I said, so most of the time this kg or kl may be important that is, mass transfer coefficient of the gas wise, the mass transfer coefficient of in the liquid fill, these may be important. One has to look at, how these mass transfer coefficients can be enhanced, in order to minimize the resistances, so we will talk on that.

That mixing is not an issue, because it works like fixed bed reactor, so that height is very low. So, I told that, to avoid the back mixing generally the L by D ratio should be kept large, so high length of the rector is desired.

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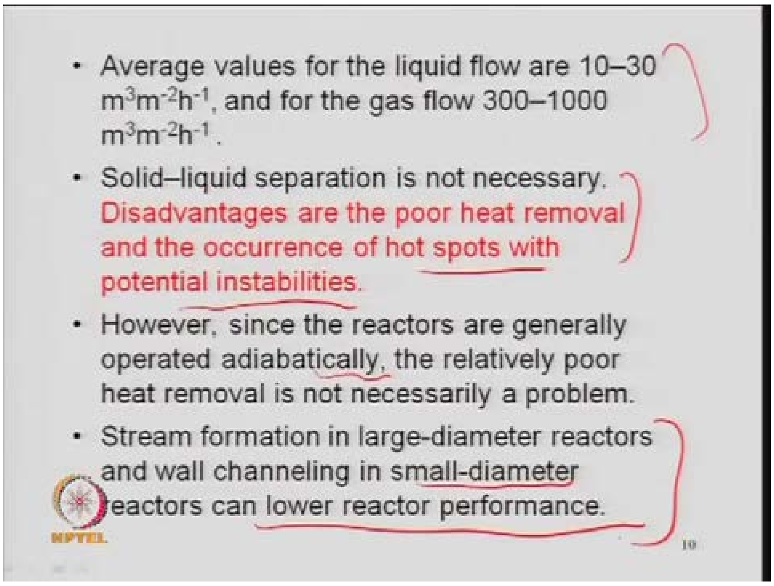

So, superficial lost is again important in the case of trickle bed reactor, because depending upon the liquid to gas or L by G ratio we call here in the case of super trickle bed reactor. So, this factor becomes important, what the liquid flow rate, what is the gas flow rate, so this L by G ratio, liquid to gas. So, depending upon that, you will have the pressure of the variation and then, also when the pressure of change then, you have the several other secondary problem inside the bed, so you need to look at all those.

So, here in this case, the liquid flow rate is roughly 10 to 30 meter cube per meter square per hour, which is in what you called the mass velocity or even can define in terms of the superficial gas velocity also. So, superficial gas velocity of gas, so u g divide by u l superficial gas velocity of the liquid, which is based on the tower diameter. So, 10 to 30 meter cube per meter square per hour is the flow rate of the liquid and flow rate of the gas is again 300 to 1000 meter cube per meter square per hour, it was a typical range of the data for the trickle bed.

So, solid liquid separation is not required, because they are already in the bed, so separation of solid and liquid is not required in the case of trickle bed reactor, so this is another advantage here. Disadvantage is that, heat removal, because it a packed bed reactor, basically it is a packed bed reactor, so heat removal is an issue. So, if the reaction is exothermic then, just so one needs to look at how to control the temperature and occurrence of hot spots within the potential instabilities.

So, when the heat removal is an issue and if reaction is exothermic then, the problem is something like hot spot formation. The temperature at a localized point may be very high, high temperature at particular point and that will damage the activity of the catalyst because of recrystalization, what I said sintering phenomena. So, this is an issue in the case of trickle bed reactor, because reaction hydrodesulphurization, hydrocracking, these are highly exothermic reactions.

However, since the reactors are generally operated adiabatically, so this is desired here, the relatively poor heat removal is not a necessary problem. So, one needs to look at these conditions for operation, how much it generates during the reaction or how that it can be removed as soon as it generates during the operation, so that is important, especially when the reaction is highly exothermic. Stream formation in large diameter reactors and wall channeling in small diameter reactor can lower the reactor performance.

So, this is what I told you the selection of the proper height that is, length of the reactor and the diameter of the reactor is an important aspect when you look at this. So, we need to look at, what is the height of the reactor, which we call length of the reactor, but it should be the diameter of the reactor. So, basically it is L by D that is one thing. Second thing is, what catalyst diameter should be selected, so that is again important.

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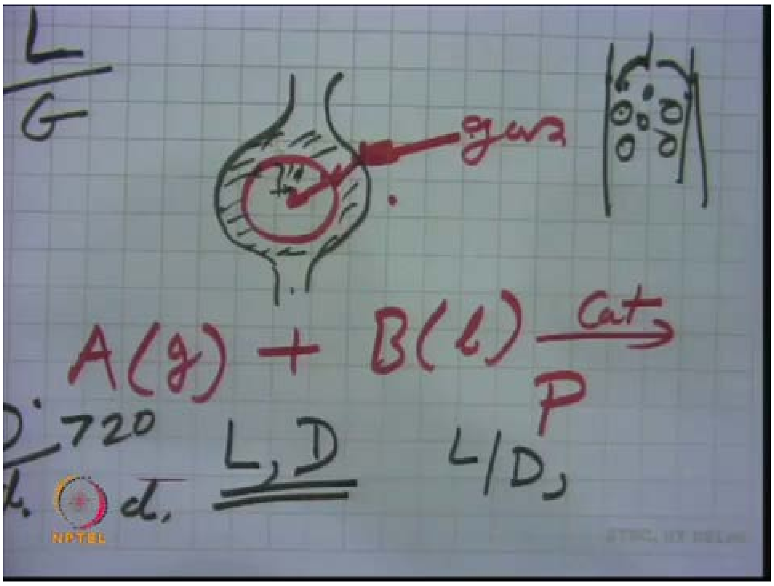

So, basically the wall flow, you have to select a D by D ratio that is, the diameter of the reactor to the diameter of the catalyst particle as high as possible, so roughly more than 20 if you keep on then, your wall flow are neglected. So, wall flow means, what I said that the fluid has the tendency when your particles are like this and you have a maldistribution. So, what will happen because of this maldistribution, your liquid will have the tendency to move towards wall. So, it will not go through the solid particles in between, so more and more liquid you will distribute towards the wall.

So, good kind of distributor is very important and again this diameter of the particle and reactor diameter becomes important. So, I told that, it should be kept higher and same thing, because you know the plug flow conditions if you want then, you need to have a L by D ratio, a larger L by D ratio. So, more than 30, more than 40, more than 50, so that kind of L by D ratio is desired, so this needs to be controlled.

So, again the issue with this trickle bed reactor or these kind of trickle bed reactor is the hydrophobicity and hydrophilicity. Because, suppose you have a solid material like alumina, so alumina catalyst they, if you put water onto that, so it will immediately take that water, so these are known as hydrophilic type material, when they wet the surface. So, that surface will be completely wetted, but suppose you have this same alumina, if you coat it with some plastic material like teflon, so what will happen.

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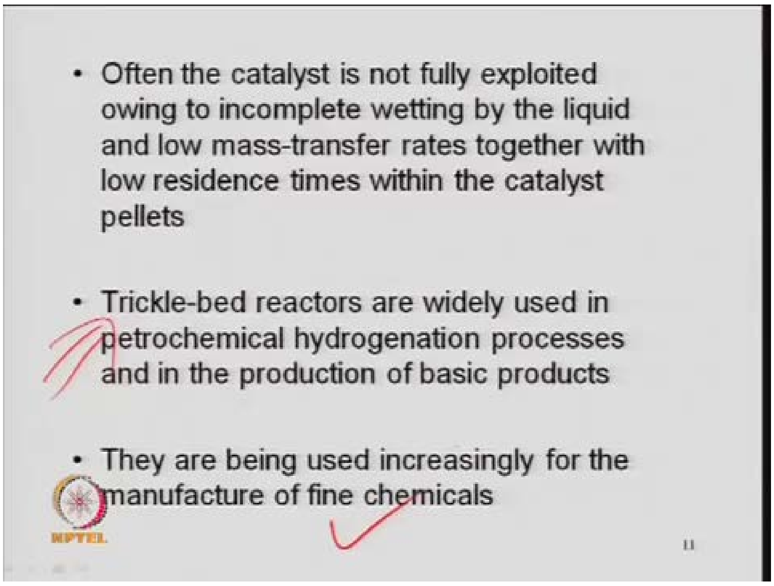

Now, this a polymer kind of material, so this polymer material will not accept the water, so this becomes the hydrophobic surface. So now, depending upon the hydrophobicity or hydrophilicity, there will be a kind of wetting phenomena. So, wetting practically you cannot mathematically identify, but it is a kind that, what fraction of the surface of the solid is being wetted by the liquid and that decides the efficiency of the process. So, some time 100 percent wetting may not be good and it complete hydrophobic substance is also not good.

So, you need a balance of that in terms of, to control the mass transfer resistance at the surface of the solid, because liquid and gas has to contact properly in the presence of solid for the transformation of these reactants into a product. So, that is again important that, how wetting should be correlated, wetting, wet ability and then, accordingly the pressure drop will also be affected because of this wetting and wet ability, viscosity and phenomena, so that will affect here.

So, everything is related here, so lot of R and D is still being done or required in order to study for the catalyst in a trickle bed reactor for different hydrocracking reaction, hydrotreatment reaction. So, this is what important issue, trickle bed reactors generally as I said, they are widely used in the petrochemical industries, hydrogenation process and production of the basic product, fine chemicals also they are now being tested.

So, or as I said advance oxidation process, say treatment of waste water, phenol oxidation or removal of oxidation of the organic compounds are being practiced in these kind of trickle bed reactor.

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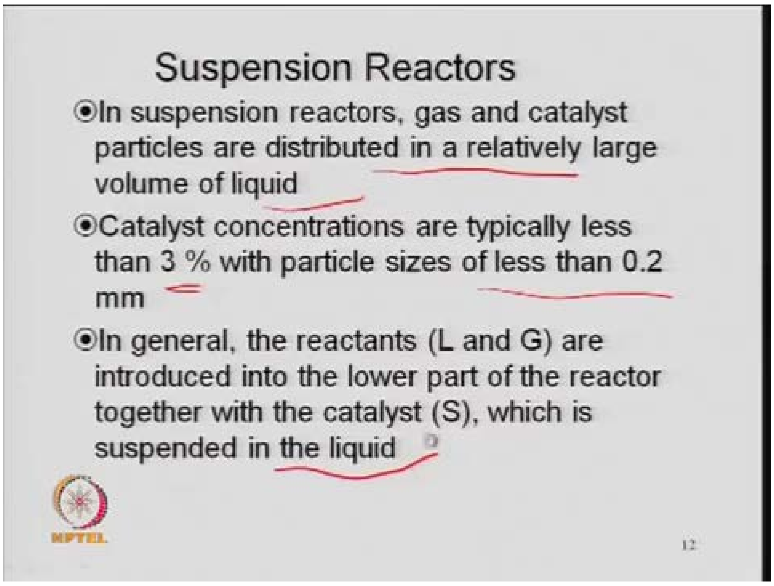

And just briefly before going in detail of trickle bed reactor, I will just talk on suspension reactor also. So, suspension reactor, it is a kind of again slurry type reactor, where the solid and liquid are together and some study is done to have a good contact between the liquid and solid. So, where the again it depends on the, diffusion is the problem, mass transfer is the problem then, these may be the better type of reactor. So, in suspension reactor, the gas and catalyst particles are distributed in a relatively large volume of liquid.

So, that is just differentiation between the trickle bed and a slurry or suspension reactor, your volume of liquid is relatively large right here, so liquid and solid are well mixed in the form of slurry. Catalyst concentration if you look at here, typically less than 3 percent and particle size is less than 0.2 minimum, the typical size can be a variation upto 0.2 to 0.5 millimeter particle size are used and same thing here, the concentration can be on a higher side also.

In general, the reactants liquid and gas are introduced into lower part of the reactor together with the catalyst, which is suspended in the liquid. So, generally gas is bubbled from the bottom just like in a slurry bubble column reactor. So, here the advantage is that, you have a good contact between the gas, liquid and solid, so your transport resistances can be minimized by using the stirrer.

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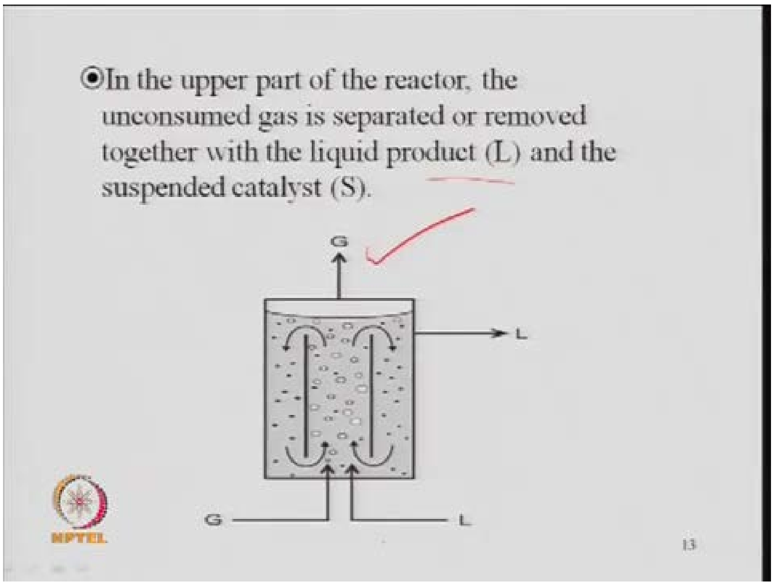

So, you can have the mass transfer resistances at it is lowest level, because you have a stirrer here or a kind of agitation of back mixing there. There is another type of reactor in this which I have not shown here, a bus loop type reactor which is generally you have a jet and from where the gas and liquid are infused or transport. So, and it can be external or internal mixing recirculating also, so different combinations of these kind of suspension reactant reactors are possible.

So, if you look at here in the upper part of the reactor, the unconsumed gas is separated, so which is here or removed together with the liquid product, so part of the liquid can be removed and this suspended solid catalyst. So, gas is separated and this is again a kind of, here the baffles and that gives a kind of recirculation within the system. You remove the product here, you remove the gas here and this is where the gas and liquid which is continuously recycled in the system.

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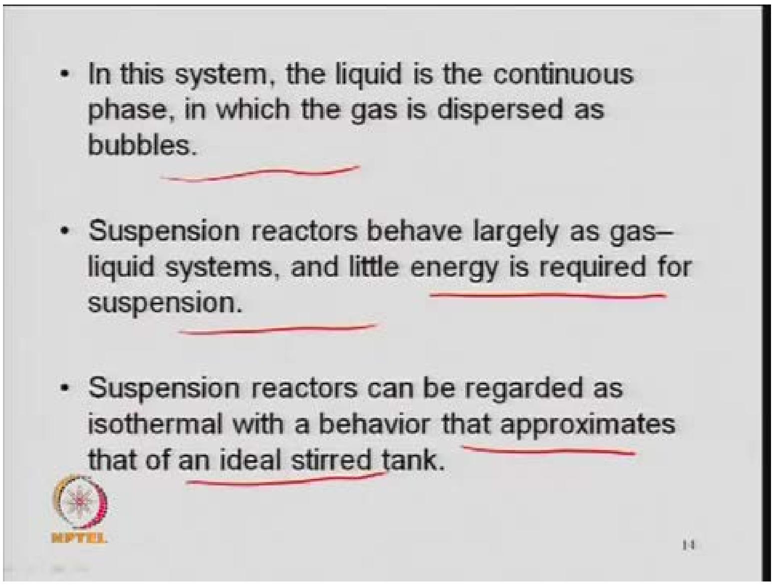

Some advantage if you will look at here in this system, the liquid is in continuous phase, in which the gas is dispersed as bubble. So, gas bubbles are coming from the bottom and liquid is already present along with the solid, so liquid is in continuous phase and gas is being dispersed in a form of bubble. So, even a small size particles, gas bubbles, so now you need to design a better spurger so that, the bubble size should be controlled, otherwise the mass transfer resistance will be an issue.

So, that is one thing here and the solubility of the gas, that is another issue that, whether gas is highly soluble or sparingly soluble. The small bubbles when there the, so it will be easier to dissolve in the liquid, so gas has to dissolve and then, it will be transferred into the liquids. So, some Henry law, which is related to pressure and concentration in the gas liquid, so one can use that. So, suspension reactor, they behave largely as a gas liquid system, so along with the solid and little energy required for suspension.

Because, catalyst concentration is low, so the energy requirement for suspension is low, but they behave like a CSTR ((Refer Time: 38:40)). So, conversion will be poor or productivity will be low in this kind of reactor, the suspension reactors can be regarded as isothermal with the behavior that approximates that of ideal CSTR tank that is, a stirred tank reactor what I said.

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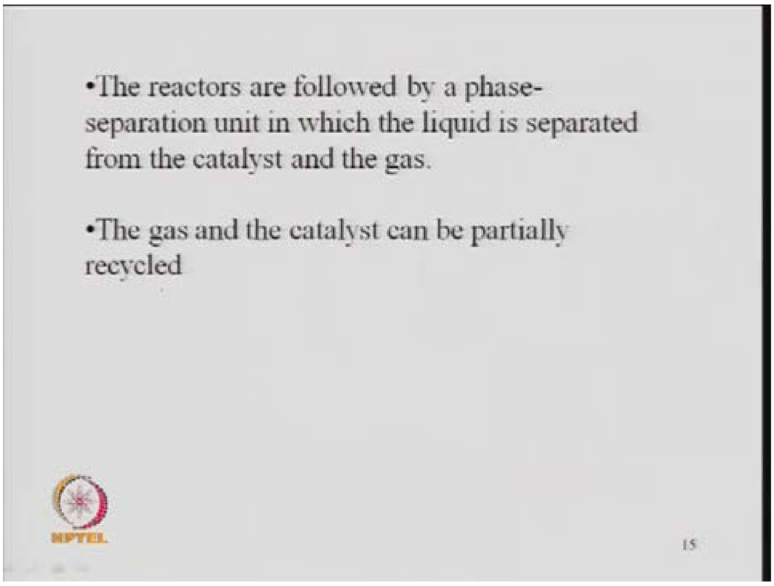

So, this is what I will just, the gas and liquid they can be recycled during the system, which I said in the case of this reactor here, you can have a possibility of a cycling this gas and the liquid in the system. So, external or internal recycle, both kind of possibilities are there and same thing in a bus loop reactor, where you have a jet and through that, you can pass the liquid and gas.

So, the reactants are followed by a phase separation, so you need to separate the gas and liquid, in which the liquid is separated from the catalyst and the gas and then, recycled back into the system.

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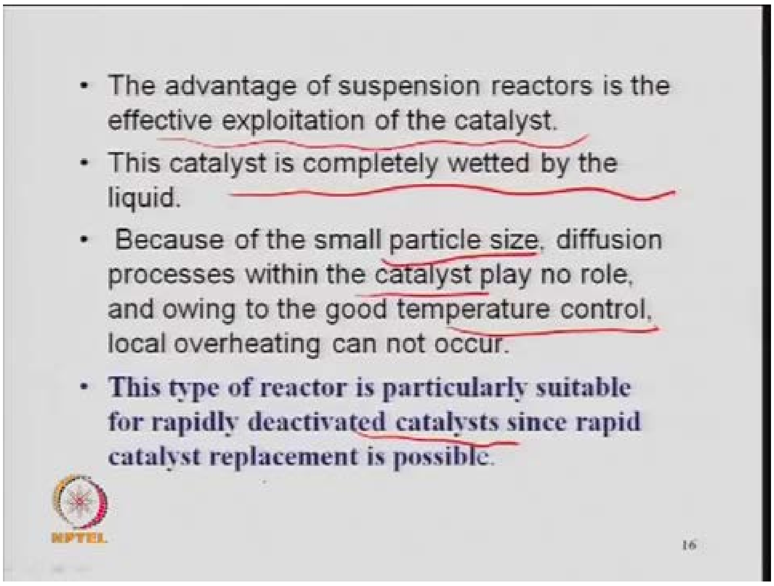

The advantage if you look at, but I discussed is that, the particles are smaller in size, so diffusion process within the catalyst will not play any role, because you have the Tiller modular, which is based on the particle size. So, the effectness factor in this case will approach to 1, so that is one advantage that, the diffusion issues are minimized, so you will have the complete rate or highest rate in these kind of reactor. So, this is one and that complete catalyst is being used here, because it is a fine low concentration of the catalyst and in a large volume of the liquid.

So, well dispersed fine powder or particles of the catalyst, they are well dispersed in the liquid, so the gas will have enough time to contact with these catalyst particles. So, that is another advantage compared to a packed bed reactor, where the most of the particle surface of the catalyst may not be utilized properly, so this is one advantage here and catalyst is completely wetted. So, when you need a complete wetting surface, so smaller the particles and they are in contact with the liquids, so catalyst has enough time to contact with the liquids.

So, all the time they are completely wetted, they are not partially wetted, so efficiency will be higher. So, this is and the important one what I already said that, because the smaller particle, the diffusion within the catalyst play no role. And if this is the case then, it will have good temperature control and local overheating can be avoided, because it is a stirrer you have, so you have well mixed reactor, so temperature gradient will not be an issue.

So, this type of reactors can be used when there is a rapid deactivation of the catalyst, because catalyst replacement is possible. So, you have a small concentration of the catalyst and continuously it is coming up and you separate the gas, solid and the liquid, and from the product and then, recycle it back. So, if you have a catalyst in the system, you separate it, if it is deactivating, regenerate it and recycle back again into the system or change the catalyst if it is poison. So, this possibility or this is the advantage in the case of a suspension reactant, but again there are some disadvantage.

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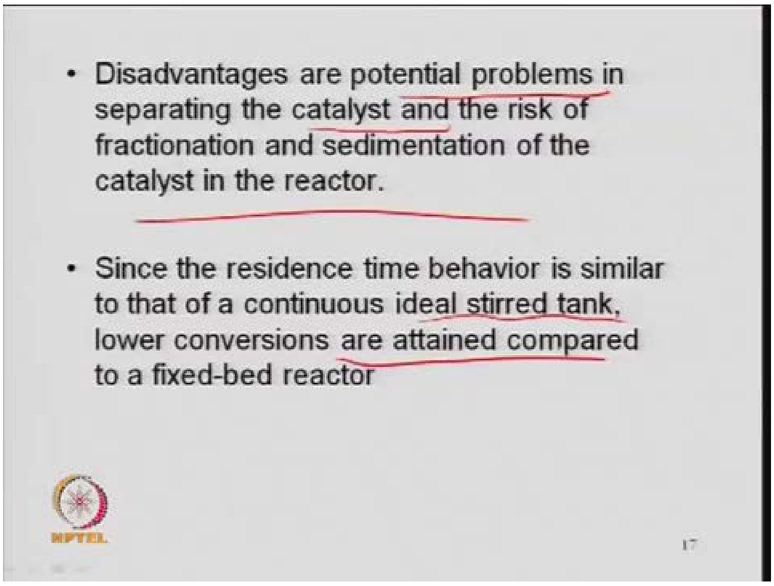

Because, this is what the separation of the catalyst, you have fine powder, smaller particle size, so separation of the catalyst and the risk of fractionation and sedimentation of the catalyst in the reactor. If the stirrer is not well designed or if the dusty of the catalyst is high then, there may be the chance that, some of the catalyst will get sedimented or some of the catalyst may, if it is very fine, it may get out along with the liquid.

So, all these problems, the separation may be an issue, so this is one problem basically in the case of suspension reactor, but that can be avoided by selecting a proper system for separation of liquid, solid and from the gas. Residence time behavior is again like a

CSTR, because I told that, all these reactor, bubble column reactor, suspension reactor, slurry bubble column, they are resembling towards a tank reactor, stirred tank reactor.

So, the conversion will be low, so if the conversion is low and you want the high productivity, you need a larger size of the reactor. So, large size of the reactor will be required compared to a fixed bed reactor, which works like a back flow.

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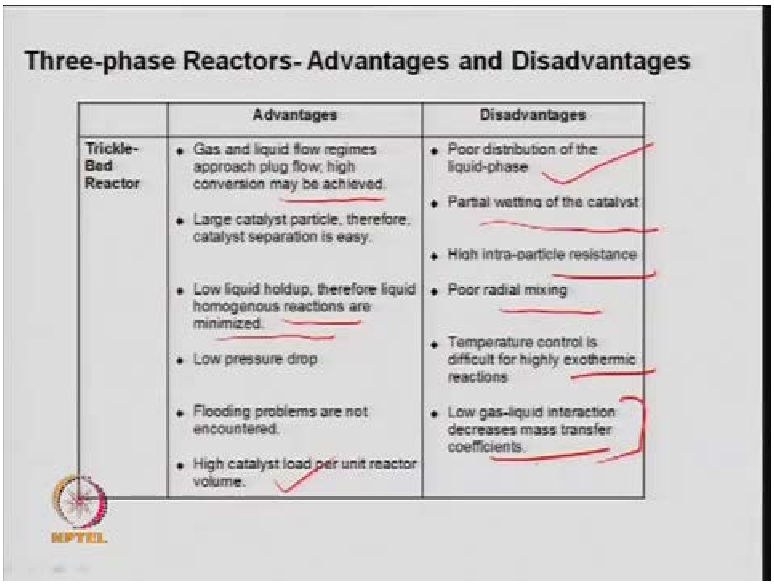

So, these are some advantage of a trickle bed reactant, so which I would like to explain here, because that is very important when these are widely used reactors in the process industry. So, the gas and liquid flow regime, it approach like a plug flow, so if you properly controlled, the gas flow rate, liquid flow rate and the type of the catalyst, size of the catalyst, particle shape then, one can approach to a plug flow. And when you are approach a plug flow, degree of back mixing is minimized, no axial dispersion, no radial dispersion, so definitely the conversion will be high.

So, that is the advantage that, high conversion can be achieved in the case of trickle bed reactor if properly designed. So, a well hydro dynamic study need to be done and properly the conditions are to be optimized and then, one can achieve a plug flow design conditions in a trickle bed reactor. So, distributor design is again important in order to achieve the high conversion over the maldistribution. Then, large catalyst particles can be used in the trickle bed reactor, so pressure drop will be low and simultaneously, the separation of the catalyst is easy.

Hold up, I will talk that little low, so liquid hold up that is, the volume or amount of liquid which is available in the reactor, it may be dynamic or static, we will talk on that. So, that is low in the case of trickle bed reactor, because trickle bed reactor is generally when you have high flow rate, hold up will be high and when you are low flow rate, hold up will be low. So, here in the trickle bed, generally it operates at a low flow rate as I said, it trickles on the surface, so low liquid hold up.

And therefore, liquid is homogeneous reactions are minimized, so that is one advantage, because the liquid, it is not large volume, so secondary reaction which may be possible that can be avoided in this case. And so, no liquid homogeneous reactions between the liquid phase itself then, pressure drop is low. As I said, flooding problems are avoided if the distributor is properly designed, proper size of particles have been taken, all these D by D, L by D issues have been adjusted and the high catalyst load per unit reactor volume is generally used in this case.

So, large catalyst mass, per unit volume of reactor is high in this case, so that depends on the size and diameter of the reactor, so one can have that advantage. Per unit volume of the reactor if you take calculate then, the mass of the catalyst is high compared to your suspension reactor. Disadvantage again if they are not properly designed, so poor distribution, this is a big issue in the case of trickle bed reactor that is, maldistribution of liquid, so that is one.

Then, partial wetting of the catalyst, because of the solubility of the gas, liquid and then, it is a surface of the solid, so pressure conditions. So, depending upon the pressure, so there may be that, some of the surface of the catalyst may not be properly utilized that is, the liquid is not in contact with that surface, so that is one problem here in the case of trickle bed reactor.

High intra particle resistance, these are the diffusion resistances, so liquid is diffusing into the pore and then, depending upon the resistance that is, I will just talk on that, but basically it is a kind of effectness factor, which is into the pore of the catalyst. So, liquid is already there and gas is diffusing through that, so there will be a kind of concentration gradient, so rate will be slowed down, because of this resistance. Then, radial mixing is, that is again an issue here in the case of trickle bed reactor.

So, there will be a poor radial mixing to there will be the concentration gradient more and more in the case of trickle bed reactor. Temperature control, you do not have any kind of controlling device inside the reactor and the particles are kept in a larger size. So, there will be a kind of temperature gradient within the pellet itself, in a catalyst pellet if the reaction is highly exothermic. So, temperature reaction is inside the catalyst pellet, so temperature may be higher, outside it is low.

So, there will be a kind of temperature gradient, thermal gradient or thermal stress may generated right here, so that is again an issue. And low gas liquid interaction decrease the mass transfer coefficient, so interaction between gas and liquid will depend on the several other factor, solubility, process condition and, but this is again a problem that, the interaction between gas and liquid is low. So, because of that, the mass transfer coefficient may be low, because it depends on the velocity, superficial gas velocity and other factor, so we will talk on that later.

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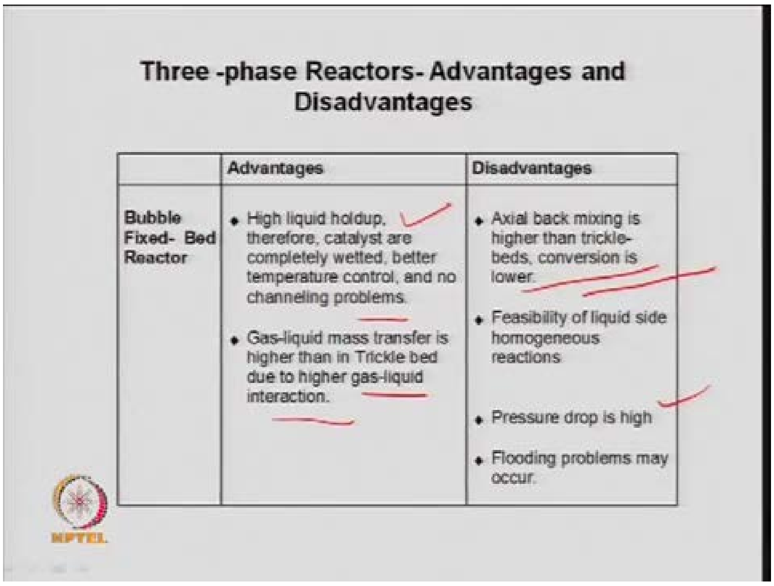

Bubble fixed bed reactor just I thought that, here also we should look at that compared to bubble, what is a bubble fixed bed reactor and then, what are their advantage. So, it is a fixed bed reactor basically, but we discuss earlier and gas is being bubbled or liquid is being bubbled. So, it is basically high liquid hold up here compared to your the earlier case in a trickle bed reactor. So, basically it is a packed bed and therefore, catalyst are completely wetted, wetted temperature control and no channeling problem.

You have a gas being bubbled and liquid is already there, it is a kind of slurry bubble column reactor. So, but instead of bubbling, you have a fixed bed reactor type, so you have a liquid, solid and gas may be bubbled from that. So, gas liquid mass transfer is higher compared to trickle bed reactor, because there the flow rate was low, liquid flow rate, here liquid flow rate is high. And so, in trickle bed due to higher gas liquid interaction, so interaction between gas and liquid in this kind of reactor will be high.

Again disadvantage in this is that, axial back mixing is higher than trickle bed reactor, it is a behaving like a CSTR here, so back mixing is will be an issue. So, because of the back mixing, because as I said, the convergence will be lower. Feasibility of liquid, side homogeneous reaction, so the mass of the liquid or volume of liquid in the bed is now higher. So, there may be a chance of homogeneous reaction between the liquid, so that is again a problem, liquid side homogeneous reaction.

Pressure drop is high, particles are smaller now, flooding problems may occur, because it is not a well designed. So, here you need here to minimize these problem, but compared to trickle bed reactor, the flooding problem may be severe here in this case.

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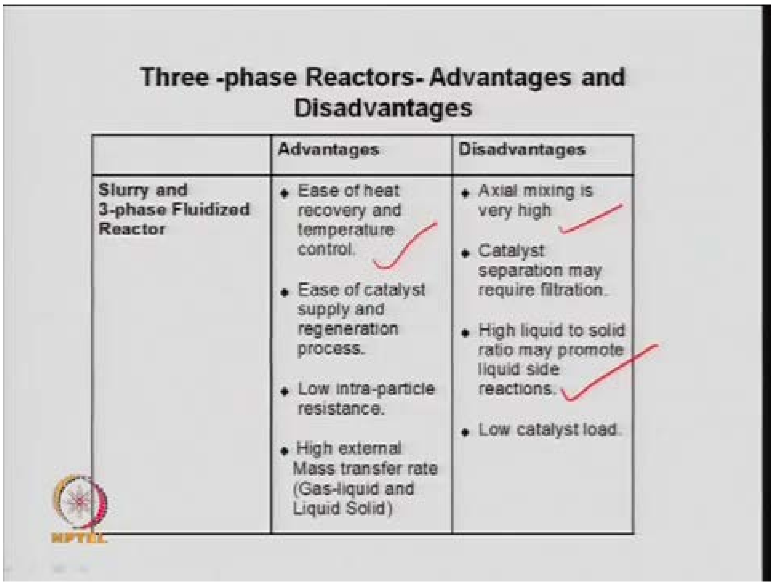

Then, again a slurry three phase fluidized reactor, so here again we have some advantage and disadvantage, so just I have tabulated them. So, slurry three phase fluidized bed reactor ease of heat recovery and temperature control, because you have a in the slurry phase, so particles are fine. So, as in the fluidized bed reactor, you know whatever the advantage, these will be here also, so ease of recovery and heat and temperature control is one.

Ease of catalyst supply and regeneration is possible, intraparticle resistance will be low, because particle size is smaller here, high external mass transfer rate, gas liquid and solid. So, mass transfer rate is high, because the superficial gas velocity is higher in the case of fluidized bed reactor. So, mass transfer coefficient depends on the particle size, so particle size is smaller here, velocity of the superficial velocity is high, so coefficient will be higher.

So, that is, but again here the disadvantage, the axial mixing is very high, catalyst separation may be a problem here, because it is a slurry, reactor particles are finer, you are fluidizing it. So, the separation may be filtration is required from the fine separation of the catalyst particle from the liquid. High liquid to solid ratio may promote liquid side reaction, so here liquid volume is high, so liquid to solid ratio is high.

So, it means, there may be kind of homogeneous reaction, side reactions, because the volume of liquid is high, secondary reaction which may happen in the presence of high volume of liquid. And catalyst loading is low if you look at finite volume, because so that is again an issue here.

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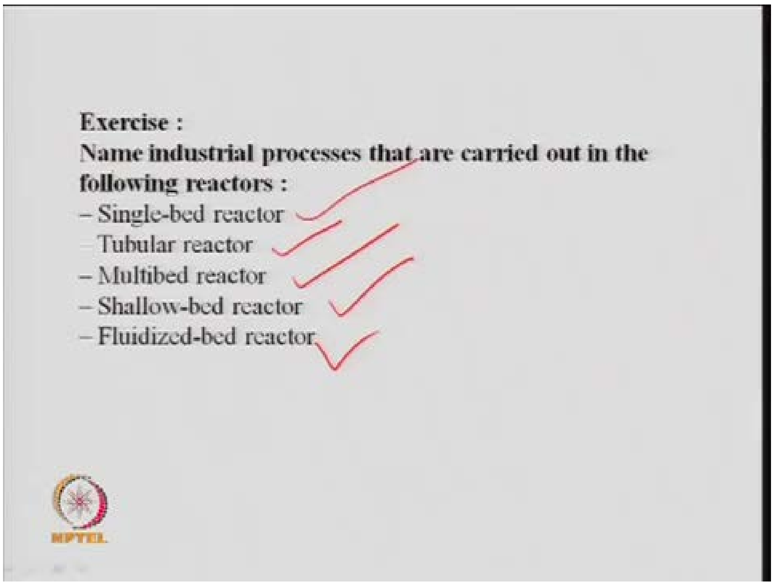

This is just an a exercise, I have left it for you, you have to name some industrial process based on literature review or right references. And then, identify the reactions or which can be carried out in this single bed reactor, in a tubular reactor, multi bed reactor, shallow bed reactor, fluidized bed. So, the same what I have discussed yesterday, now you have to just sight some industrial process, where these kind of reactors are generally used, just as a you have to just find it from literature or exercise it.

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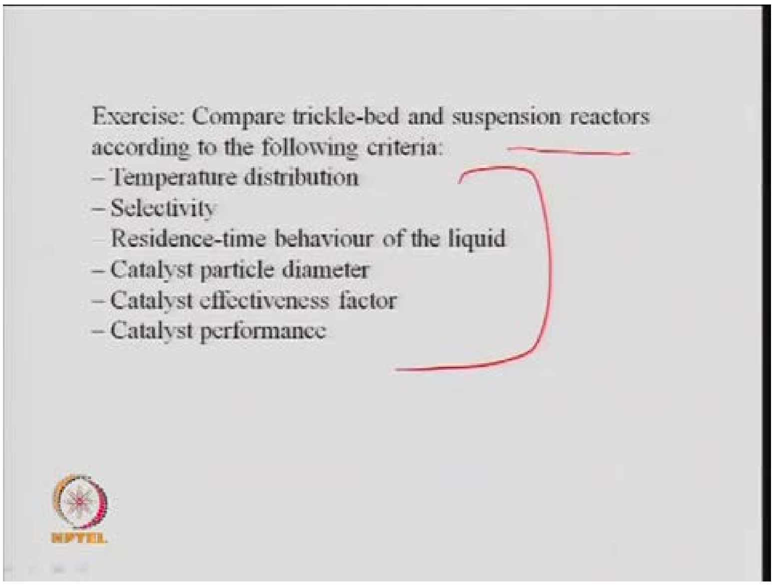

There is again a problem that compare the trickle bed and the suspension reactor depending upon the criteria. So, means, whether you will go with the trickle bed reactor or the suspension reactor, so just have some study on this and what you have understood so far. So, depending upon that, that for temperature distribution, selectivity terms, resistance time distribution, behavior of the liquid, catalyst particle diameter, effectness factor, performance.

So, you have to look at or compare these two reactors based on these parameters, so identify which will be higher in which case, but should we do or how to go with these to improve the selectivity, whether these or these, temperature distribution, resistance time distribution, behavior of liquid, which so, in each reactor, in each case you have to just talk on that.

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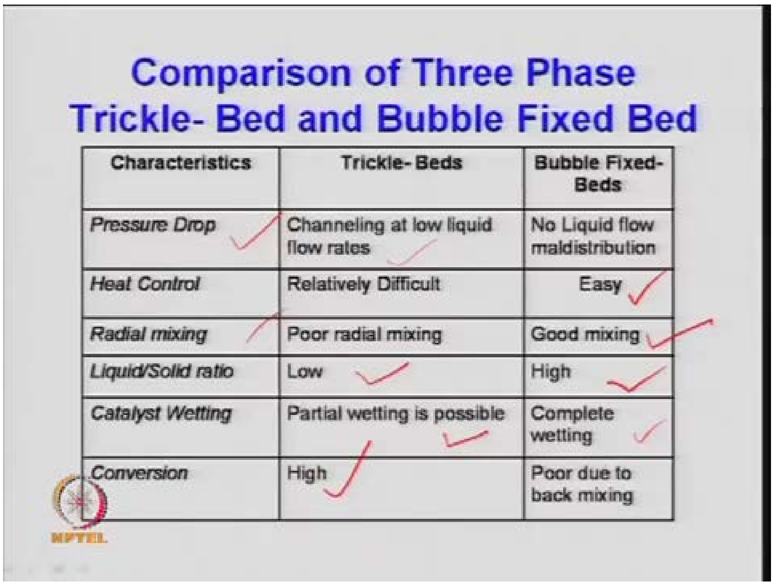

Comparison of Three Phase Trickle- Bed and Bubble Fixed Bed

Characteristics	Trickle- Beds	Bubble Fixed- Beds
Pressure Drop	Channeling at low liquid flow rates	No Liquid flow maldistribution
Heat Control	Relatively Difficult	Easy
Radial mixing	Poor radial mixing	Good mixing
Liquid/Solid ratio	Low	High
Catalyst Wetting	Partial wetting is possible	Complete wetting
Conversion	High	Poor due to back mixing

So, just in continuation of this advantage disadvantage, if you just compare the two three phase reactor or multi phase reactor system, so trickle bed and bubble fixed bed, which I was already I had discussed that advantage, but just very quickly I will go through that. The pressure drop which is the important parameter, which we study during hydrodynamics or when we just compare the two catalyst, so pressure drop is one. Then, heat control, radial degree of mixing, radial mixing, liquid to solid ratio, catalyst wetting and convergent.

So, all these aspects I have already discussed, but very quickly I will go then, in trickle bed reactor, the pressure drop characteristics, so channeling at low liquid flow rate, it comes. So, then the flow rate of liquid is low, so there will be chance of channeling and in the case of bubble fixed bed reactor, no liquid flow maldistribution. So, this is again in the case of bubble flow, the maldistribution avoided. So, characteristic in all case, the pressure drop, heat control, radial mixing, so all these aspects need to be looked into.

Heat control if you look at in the case of trickle bed reactor, I told that there are no stirrer and particles are larger in size. So, if the reaction is exothermic then, control of heat becomes difficult, so heat control is relatively difficult in this case. But, here in this case of bubble fixed bed reactor, the control because you have a bubbling gas is being bubbled and a kind of stirrer, so can be used or you can control the temperature, so this is easy here, particles are relatively smaller in size.

Radial mixing, in the case of trickle bed reactor, radial mixing is poor, poor radial mixing, but here you have a bubbles going up, smaller bubbles, so good mixing is obtained, it is behaving like a back mixer reactor. Liquid to solid ratio in trickle bed reactor, as I discussed is low, here it is high. Catalyst wetting, it is partial wetting is possible, here it is complete wetting is possible in the case of bubble fixed bed reactor. Conversion, it behaves like a plug flow, so high conversion is achieved, but here the conversion is poor, because degree of back mixing is higher.

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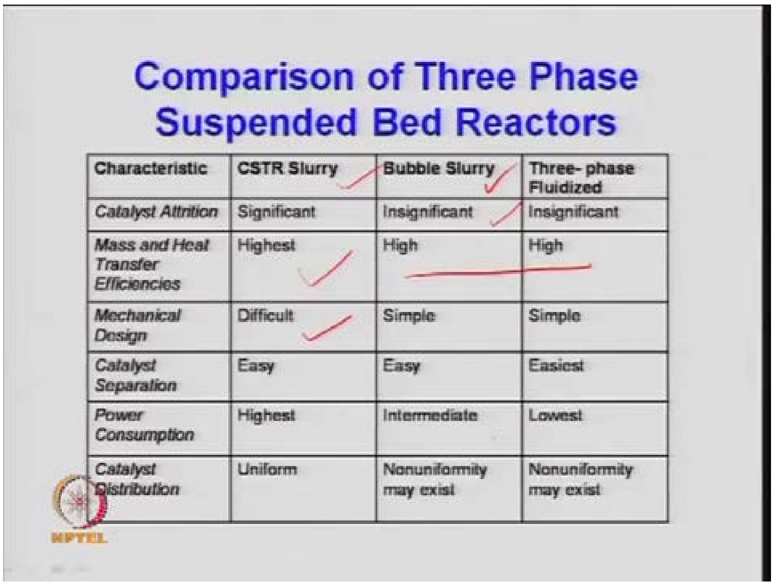
Comparison of Three Phase Suspended Bed Reactors

Characteristic	CSTR Slurry	Bubble Slurry	Three- phase Fluidized
Catalyst Attrition	Significant	Insignificant	Insignificant
Mass and Heat Transfer Efficiencies	Highest	High	High
Mechanical Design	Difficult	Simple	Simple
Catalyst Separation	Easy	Easy	Easiest
Power Consumption	Highest	Intermediate	Lowest
Catalyst Distribution	Uniform	Nonuniformity may exist	Nonuniformity may exist

Same thing, the suspended reactor if you look at, different type of reactor which we talk CSTR slurry, bubble slurry, three phase fluidized reactor, all these we have to discuss. So, here the attrition of catalyst may be an issue in the case of slurry reactor, because you have a stirrer there, so particles may scramble. So, here the particles may scramble, so if the catalyst is soft material then, you should not use a CSTR type of bed reactor. In bubble slurry, it does not matter, particles are smaller and they are in the suspension forms, so it does not matter, insignificant.

Same thing in the three phase fluidized, there is no attrition of the particle, catalyst attrition is insignificant. In the case of the mass and heat transfer efficiency, the CSTR slurry has highest efficiency. Bubble slurry has high and three phase fluidizer is ((Refer Time: 56:42)), so both are similar in one way. But, CSTR has high mass and heat transfer efficiency, because you have used an agitated there.

Mechanical design is difficult in the case of CSTR, but in the case of bubble slurry and three phased fluidized, it is simple, because no agitation, no moving parts are required, so this is a advantage here in one way. Catalyst separation is easy in CSTR, bubble slurry also it is easy, but in fluidized bed, it is much more easy, so one can take it out and separate. Power consumption is highest in the case of CSTR, because you need a agitation, here in the bubble it is intermediate, you need some sparger and bubble, the gas and in three phase fluidized, it is lowest.

Same thing for catalyst distribution is uniform in the case of slurry reactor, but it is bubble slurry and three phase fluidized, it may not be uniform. So, I stop here and I will continue again this chapter in the next lecture, the same module will be continued in next lecture, so thank you for today ((Refer Time: 57:50)).