Multiphase Flows
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Lecture – 02
Fundamental definitions and terminology used in Multiphase-I

So, we were discussing about the scale of issues and what we have discussed is that, in the scale up in multi-phase flow is actually the major problem and the region behind the problem is the flow pattern actually which changes from the laboratory scale to the pilot plant scale.

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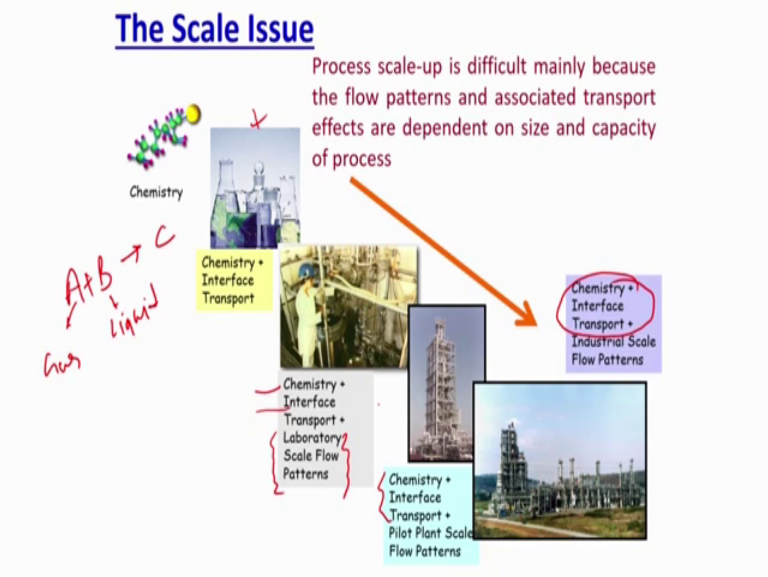

The Scale Issue

Process scale-up is difficult mainly because the flow patterns and associated transport effects are dependent on size and capacity of process

Chemistry

Chemistry + Interface Transport

Chemistry + Interface Transport + Laboratory Scale Flow Patterns

Chemistry + Interface Transport + Pilot Plant Scale Flow Patterns

Chemistry + Interface Transport + Industrial Scale Flow Patterns

And the major problem is that, even to understand the laboratory scale flow patterns, we do not have measurement tools or sophisticated measurement tools available which can accurately predict the slow behavior at laboratory scale. But that we will discuss separately. But the problem in the scale up is that, you have a problem, once you start flowing the things and you flow pattern which is actually going to be dependent on the size of the system as well as on the capacity. So, you change the size of the system or you change the capacity of the system, your flow pattern may change and that is the major problem or in the multi-phase flow reactors and to understand the multi-phase flow reactor and the scale up of the multi-phase flow reactors.

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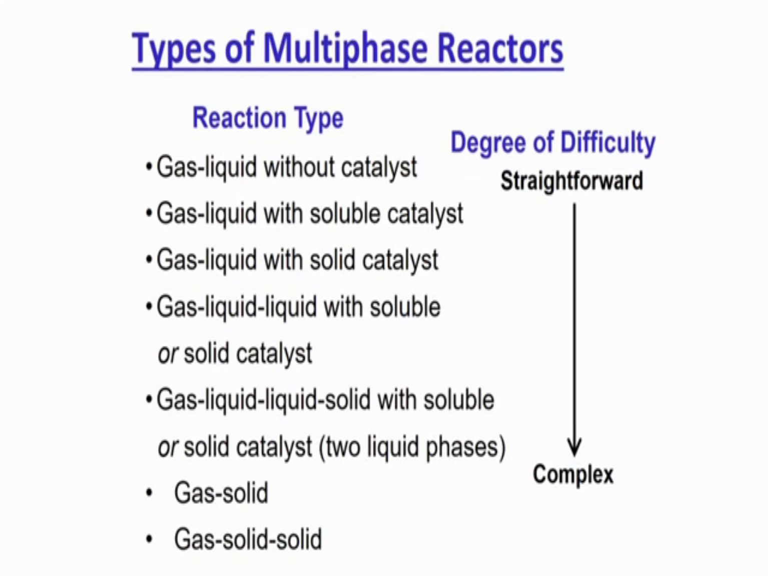

Types of Multiphase Reactors

Reaction Type

- Gas-liquid without catalyst
- Gas-liquid with soluble catalyst
- Gas-liquid with solid catalyst
- Gas-liquid-liquid with soluble *or* solid catalyst
- Gas-liquid-liquid-solid with soluble *or* solid catalyst (two liquid phases)
- Gas-solid
- Gas-solid-solid

Degree of Difficulty

Straightforward

Complex

So, there are different type of multi-phase flow reactors available depending on the requirement and I this is just my version that degree of difficulty. If you go from the top to the bottom in this list, you will see the system becomes more and more complex. But, that is actually person to person. This is my version. Someone can have a different version altogether depending on the application. So, like, if we about the multi-phase flow reactors, there can be a gas liquid reaction in which there is no catalyst available. I will consider it as a simpler. Again, I am that this is my version this may not be a universal version. So, the gas liquid reactor without catalyst then we can have a gas liquid reactor in which the catalyst is there, but that is in the homogeneous form. It means the catalyst is soluble in one of the phases..

So, that is gas liquid with soluble catalyst then gas liquid with the solid catalyst inside that makes us in 3 phase reactors which we call generally as a slurry column, but the velocities involved is not very high. So, I will still consider it as a relatively simpler column. Then, they can be a gas liquid liquid which soluble or insoluble catalyst or solid catalyst. So, this again becomes actually the number of phases has increased; one is gas to liquid phases are available and one solid catalyst.

So, number of phases you are increasing. So, the becomes more and more complex. Then, it can be gas liquid liquid solid with soluble or insoluble catalyst. So, 2 phase liquids and then again, the solid if you are having the catalyst as well as well one solid present may it have a 2 phase solids too. So, that is actually increasing the complexity. But, the most complicated systems are we will consider I will consider it as a gas solid or gas solid solids. It means there is a gas solid in the other solid, either it serves catalyst or there is a distribution of the solid available. So, I am taking it as only 2 solids, but it can have a polynomial distribution. So, it can have a poly dispersed solid phase in which different sizes are available.

So, increase the number of phases, the different solid sizes is considered as a different phase. So, if you have a complete distribution, you will have actually n number of phases available if you have n number of bins in the solid distribution. So, that becomes even more complicated. So, what I said that, we have different type of multi-phase reactor also available for the different kind of application.

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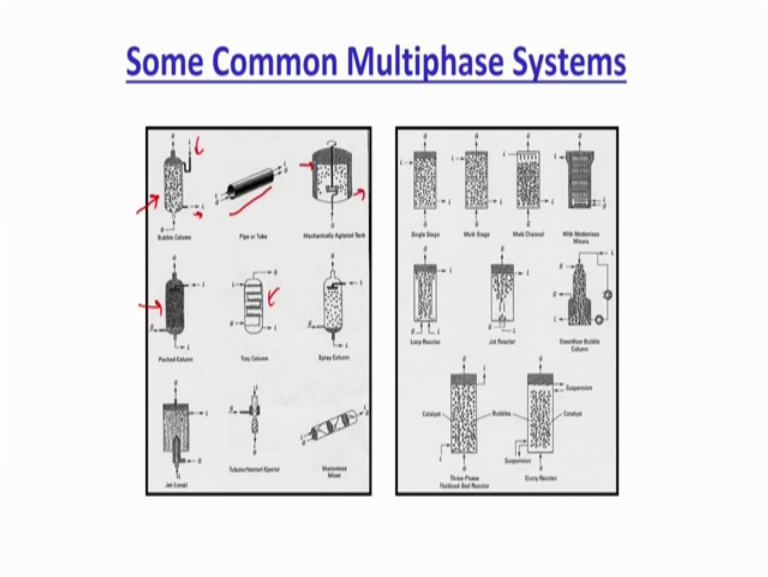

Some Common Multiphase Systems

And, I will say that, a whole supermarket is available in front of you to think about a reaction and I will give you a supermarket. So, I will give you a different variety of the multi-phase reactors which can do the same reaction.

So, what is needed in out of the supermarket, you have to choose a multi-phase reactor which is important for your own application or which can gives the best performance as per your own application. Now, once I say best performance; it means better conversion, better selectivity, it should be environmental friendly. So, a lot of multi-phase flow reactors is available, say if I think about the gas liquid reactor, which I said that is less complicated, I have a variety of application reactors available. So, like one of the reactor here, if you think, there is a liquid which is in the batch gas is passing through the bottom of the column, it is being bubbled and it moves upward. And, even though if the liquid is continuous liquid can be fed from the top and it will go out from the bottom of the column. So, that can be a simple column arrangement in which you can have the reaction.

The other arrangement can be a simple plug flow reactor kind in which gas and liquid is actually simultaneously flowing inside within a tube. So, ideally if the length of the tube is sufficiently long compared to the diameter, then it can be treated as a plug flow reactor. So, one can have the reaction in that one can also use the CSTR kind of arrangement in which liquid will be either in batch or continuous. If you want to make the continuous liquid, you can put it up from the up and pull it down from the bottom or pull it out from the bottom. They can be agitated and you can inject the gas. So, what will happen? There will be a combined mixing effect of the agitator as well as the because of the gas dispersion.

So, you will have the CSTR kind of the structure. You can have the reaction in the packed column in which this packing material can be used as a contactors. Hence, the contacting or can be used as also a catalyst. So, gas liquid solid reactions can also be done in a packed bed in which you fill the solid will pack the solids and you pass the gas from the bottom and liquid from the top or you can pass both the gas and liquid from the bottom itself ah. So, so, co current and counter current arrangement, you can have you can have a different C plate kind of arrangement, in which the liquid can be passed from the top to the bottom gas can be passed from the bottom to the top and you can have a contacting.

So, what I need to say that, you have a whole supermarket available or a whole spectrum available. So, we are not short of the reactors. What we are short of is, the understanding of these reactors that what each reactors can do. So, that is what we need to understand. And to understand that, it is important to see that how these contacting is going to change with changing the geometry, with changing the patterns, with changing the dimensions of the system or with changing the velocity of the phases. So, a whole spectrum is available. Similarly, if you see there, the (Refer Time: 06:47) spectrum which will be packed bit, you can have a structured bed, you can have a packing inside which is a structured packing inside rashing ring, you can put you can put the cata pack, mella pack inside the column and you can have a flow.

So, you can have all the kind of arrangement to find a suitable reacted combination for gas or liquid contacting. Now, the again I am (Refer Time: 07:14) we are not sort of the reactor we are short of the understanding to develop.

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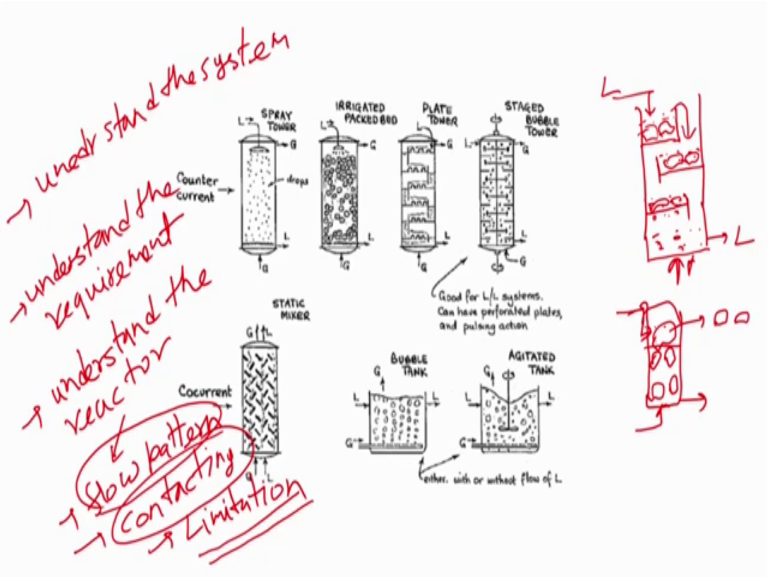

Now, similarly, we can have the arrangement. These are some more arrangement. There, we can spray the liquid or we can spray the gas into the column and we can pass the liquid from the bottom or we can spray the liquid from the top and we can pass the gas from the bottom of the column and we can have a contacting. Then, we can have a packing. So, we can have a solid which is suspended, you can spray the liquid on the solid and the gases can be passed or there can be a plate kind of a tray arrangement where the liquid will be like a simple. If you think about the distillation column, AC plate distillation column that is also a gas liquid contactors.

So, you will have a column in which there is a plate. So, this kind of arrangement is there. And suppose, I am passing the gas from the bottom and liquid is coming from the top, so what will happen? The liquid will fill here. Once the label will be higher, liquid will go down ok. And it will store on this plate. Then again, it will store on this plate, then it will store here and then it will go out. If you spars the gases here, then what will happen? Gas will pass. Now, this plate can have a holes and because of that, you will see a bubbles; gas bubbles on these platelet. So, it can have a stepwise contacting and multiple steps can be formed depending upon what level of mass transfer or contacting you need.

Similarly, you can have an impeller inside also the tray and the impeller together so that, you can mix the gases properly inside the vessel. So, that you can have a bitter is the dispersion of the gases inside the liquid. So, what we can do? We can have a tray or we can have a multiple layer's this agitators and we can have a tray where, we will pass the gas. Now, the gas will pass through the kind of sieves. Once it will pass through the sieves, it will form a bubble. Now, why we need these kind of arrangements? The major reason is, if I take a simple column and if I pass the gas from the bottom and if I feel, say, liquid from the top, if I inject the liquid from the top and pull it down from the water, what will happen? The gas will form a bubble.

Now, as we move up, this bubble actually will coalesce and form a bigger bubble. The moment the bubble size will increase, we know that the surface area will decrease and your heat and mass transfer efficiency will also decrease. So, to improve the heat and mass transfer, what we do? There are different methods have been taught and people can put up tray. So, if suppose, I if I put a tray here, then what will happen? In which there is a particular size holes this bubbles will actually break again and they will form a too smaller instead of one bigger bubble. Now, they will again form a smaller bubble.

So, if I have a smaller bubble, I will have better heat and mass transfer, I have a better mass transfer; particularly, if I have a better mass transfer, I can have a kinetic controlled regime. So, I want to always govern by the kinetic control. Again, the scale up issues that I want to repeat exactly same, whatever I have done at a flask scale, but because, if I am enhancing the size, my bubble size distribution is going to change because of the coalescence or breaking of the bubbles why want to normalize. All the time, I want to normalize and I want to get the same distribution which I was getting at the flask scale or at a very smaller scale.

So, all these arrangements has been taught has been practically implemented. Some has worked, some has not worked. But, whatever it has worked, it has worked only for a particular reaction or a particular system. It is not a universal solution which is available.

So, that is the reason that it makes the multi-phase flow more important as well as complicated to understand and to operate the system.

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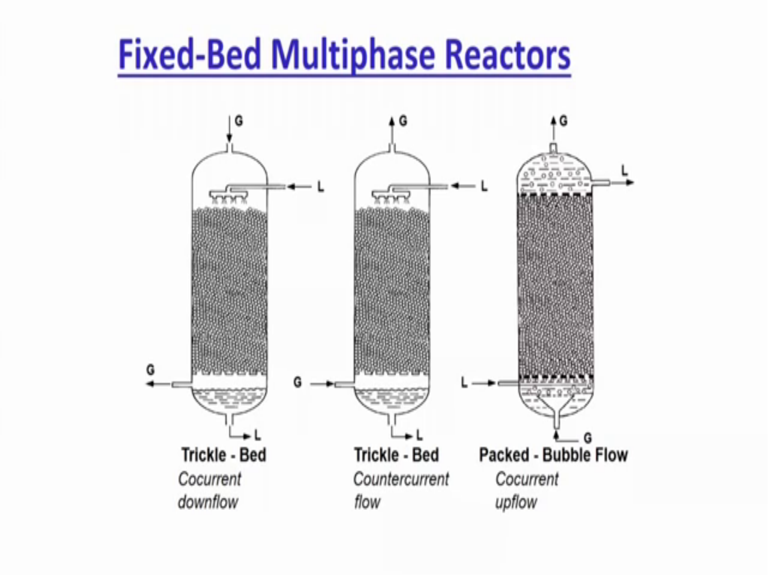

Fixed-Bed Multiphase Reactors

Trickle - Bed
Cocurrent downflow

Trickle - Bed
Countercurrent flow

Packed - Bubble Flow
Cocurrent upflow

So, and that again makes the multi-phase flow reactors choosing the multi-phase suitable multi-phase flow reactors for a particular application even challenging. So, do you need, you need to understand your system, you need to understand your requirement and based on the requirement, if you understand what is this requirement, if you understand your system, then a whole supermarket is available in front of you. You have to just go and choose one of them. So, what is needed? Need to understand the system, you need to understand the requirement and you need to understand the reactor.

Now, once I say the reactor, it means you understand the flow pattern and contacting and also the limitation. So, if you understand this the about the reactor, you understand about your system, you understand your requirement. We can try to match off so, but all these 3 need to be understand. And that is what we are going in this course. We are going to understand that, how to based on your requirement, based on the your kind of system requirement, based on your requirement, how what kind of a reactor can do the job and how this flow pattern and the contacting these 2 parameters is going to change with changing the dimensions of the system and we will also try to briefly understand what are the limitations of some of these systems which are available in the supermarket.

So, whatever I have discussed, similarly you have gas solid reactors, where you can have a reaction between the gas solid or gas liquid solid all 3. So, you can do it in the trickle bed, which is can be operated in the co current or counter current mode. You can do it in the packed bed all 3. So, what that means that, if suppose, I have a gas phase and liquid phase. I can pull the gas phase from the top liquid, also can be spread from the top and it will pass through the packing. So, it will have a typical gas liquid solid reactions which is all the gas and liquid is flowing in co current path. We can also inject the gas from the bottom and liquid from the top, then the contacting can be done or you can have a packed bed. Now, once I say the packed bed, the velocity will be relatively higher trickle bit the velocities are very low. So, you can have a contacting here also.

So, suppose, if I have a gas liquid solid reaction, I can have all these 3 choices minimum they are more. But, I am just going with the packed bed choices. So, we have all these 3 choices available. So, what will happen if you just change those contacting pattern? It means, once you spray the liquid from the top gas is also coherently downward, you will see a different mixing pattern, you will see a different contacting pattern and if you do it just opposite way around, if you just do the counter current, you will see a different contacting pattern.

Now, this both this contacting patterns or the flow patterns can result to an entirely different result. So, just a small change in the contacting will change the phenomenon, will change the overall your operating efficiency. So, that is the reason that, what we need to do we need to understand these contacting patterns. So, we have to understand the reactor, we have to understand the contacting pattern and by changing these 2, how my flow pattern inside will be differ like in this case, if both are flowing co currently downward, what will happen? Your liquid residence time will be reduced, but your gas resistance time will be very high because, the gases has a tendency to move upward. Now, we are pushing them down. So, it is going to have more stay for the more time.

While in the opposite way around, if you are doing the counter current, then what will happen? Now, the liquid residence time will actually decrease because, liquid has a tendency to move upward, but gasses are opposing the motion ok. But the gas resonance time will be reduced because, gases has anyway tendency to go upward. Because of the buoyancy, so they, so what is forces flying on? Here is the buoyancy which is favoring the motion of the gas as well as the momentum well be given. So, you have a motion upward and that is why, the gas resonance time will be low, liquid residence time will be high. Now, if you want a very low contacting time, so that, the gas and solid or gas liquid comes in contact with the solid. But, the contacting time can be reduced; you can do it in the packed bed in which you operate at a relatively higher velocities.

So, if you do all this pattern, you are going to change some of the parameter like the I will try to explain in terms of the residence time. But some other parameters can also be changed and based on that, you will see a different contacting patterns. Now, because you change the residence time from your basic series undergraduate studies, if you will see that if you change the residence time, what is going to happen? Your flow pattern is going to change; your conversion is going to be changed and it may possible that, your selectivity also changes depending on the reaction conditions.

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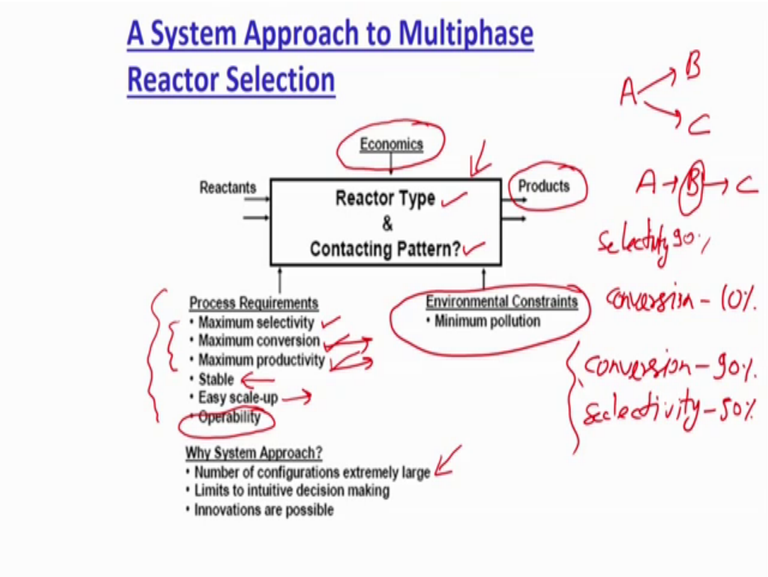

A System Approach to Multiphase Reactor Selection

Reactants

Reactor Type & Contacting Pattern?

Economics

Products

Process Requirements
- Maximum selectivity
- Maximum conversion
- Maximum productivity
- Stable
- Easy scale-up
- Operability

Environmental Constraints
- Minimum pollution

Why System Approach?
- Number of configurations extremely large
- Limits to intuitive decision making
- Innovations are possible

$A \to B$, $A \to C$

$A \to B \to C$

Selectivity 90%

Conversion - 10%

Conversion - 90%

Selectivity - 50%

So, you can have a different kind of pattern and the lot of multi-phase reactor available. We will discuss some of them in brief later on this course. But what we want to say is that, we need to choose a system approach. Now, what does it mean? The system approach that what you want first things; so, system approach means, we are going with the system requirements. Now, what are the system requirement? First system requirement is, so, what is the reactor? I already said reactor is nothing but a vessel in which you maintain a proper temperature and pressure to do your reaction. So, suppose, this is my system, a reactor type of where we want to do the reaction. What we are doing? We are injecting the reactant. So, first question you have to ask that, what should be the reactor type and what should be the contacting pattern inside.

Now, based on whatever the reactor type, you will choose a contacting pattern will be there. And, you need to understand whether this contacting pattern is going to suit your application. Now, on what basis this should be chosen? This should be chosen actually based on the economics that whether this reactor system or the whole system is going to be economical for the production or not. Then, we need to also see the environmental constraints. We definitely want to have a minimum. We do not want a reactive with pollute like anything because, the sustainability of that system is not good. So, you cannot run that system for the long run.

So, one important consideration also is the environmental concerns. So, we cannot operate with a very polluted reactor. So, we need to have economics, we need to balance the environmental constraints, we need to do the balance in between these 2, we definitely want a product which is very highly selective. So, what we need with the process requirement. Once I say that you should understand your process your requirement, I definitely want a maximum selectivity, maximum conversion, maximum productivity. So, these all 3 I want for sure as if I am developing a system, I definitely want that these 3 (Refer Time: 18:24) should be satisfied ok because, there what is the profitability is. So, I need a profit out of it.

So, for that, the term selectivity should be good. Selectivity means, was I say the production of the desired material is much higher compared to the undesired material. So, most of the reactions we do is always forms more than one product. So, one product can be desired another product can be undesired or they can be seen parallel reactions or a reaction in series and I want to just form a particular as suppose, A is reacting it is also forming B it is also forming C or I can say that is creating it is forming B and it is going to C. I want only the production of the B's.

The selectivity will be defined as that how much B has been produced to the how much C has been produced or how much B has been produced and how much total product has been produced the different way to define the selectivity. You can again go to your CRE books and you can see. So, based on whatever you decide, the way you selectivity you decide what it means that, it is the ratio of desired product to the total product or desired product to the undesired product. I want my desired product to be maximized because, there is the market for the desired product or the profitability is lies with the desired product. So, I definitely want higher maximum selectivity. Now, the maximum selectivity will be achieved and it will be profitable if I can do the maximum conversion.

So, say, if I am having a and I have a process which is very selective, but gives a very low conversion. So, say my selectivity is ninety percent, but my conversion selectivity is 90 percent, but my conversion is only 10 percent in a system and in another system where the conversion is 90 percent and selectivity, you say 50 percent , definitely I would like to go with this system though it is less selective. But I am having more product at the end of the day. My yield formation or my productivity for the desired product is maximum. So, these 2 need to be simultaneously optimized all this 3.

So, that is the process requirement, then definitely I want the process should be very stable. I do not want to operate a process which is very unstable and a small change in the process condition can go for a run variation or can pull it out completely. So, we will not be able to operate the reaction or we have to shut down the reaction reactor. So, we do not want to do that. So, stable operation is again is one of the very critical requirement then, definitely we want an easy scale up. It is not like, once we go for the scale up, we need to put the impeller. So, we need to put a lot of trays lot of baffles to have the conditions which can be replicated to the condition at the laboratory scale. So, definitely, easy scale up is one of the again requirement and then, operate ability definitely. We do not want a system which is very difficult to operate ok.

So, very difficult to operate means, suppose, if I want, if I design a system in which the temperature should be balanced between plus minus 1 degree centigrade, now we know that with the control it is very very difficult. We need a very highly sophisticated control system in which you can maintain the temperature within plus minus 1 degree centigrade. So, operate ability is also very critical issues. We do not want to operate say at minus 3 2 degree centigrade. We do not want to operate at say 600 bar pressure. So, operate ability of the systems should also be very very easy or it is very it is not like your operation itself is very very costly or very very dangerous to handle. So, these all are my process requirement. So, once I design a system, we do the system approach, we think about what kind of reactor and contacting pattern will be taking by considering my economics my productivity my environmental constraints and with the process requirement.

So, I make of wish list of the process requirement and then the system approach comes into the picture. So, I need all these 3. I can see that can I have a number of configurations extremely large. So, what will happen? I said that the whole supermarket is available and you can have a different choices. Now, whole configuration if I do that, if I do the permutation and combination and try to find it out that how many configuration I can make out of it, I can have a very large configuration you can handle actually. So, you have to understand out of this configuration. Whatever you can explore or you can get which one will be suitable for you, then it is a intuitive decisions making should be limited. So, it is not like, most of the time we do in the designing is the intuition that ok. We say that the based on the experience, we I will say not the intuition based on the experience we take a call. So, that should have a limit and innovations are possible.

So, we have lot of configuration is available. What we are choosing right now is not based on the science, but based on the art. why I am saying art because, it is more towards the experience, which is leading towards selection of a particular reactor. So, it means, still there is a lot of scope. If we want to work on the multi-phase system or multi-phase flow reactors, there are lot of scope to design a new system to design a new process, to design a new contacting pattern which may feed fed to the requirement. So, innovations are always possible or always welcomed and a pretty much scope is available in the field of multi-phase flow reactors to do the innovation to get a requirement a process requirement system requirement which you want.

Now, Krishna and Sai presented a paper in 1994 and it is a very classical paper in which they have said that there is a 3 strategies for selection of a reactor.

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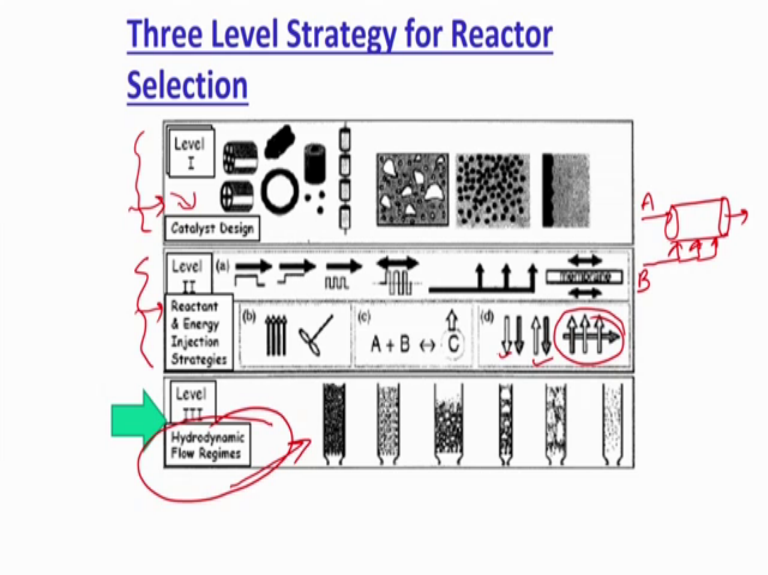
Three Level Strategy for Reactor Selection

So, you can devise the strategies on the 3 level. So, the first level strategy is definitely the catalyst design. The first part, which I say that, let us assume, I have a better chemistry available. So, what you need to do to design, a new to better chemistry or fast chemistry or fast kinetics you need to design a catalyst. So, how you want to do? The reaction you want to do? The reaction in the gas phase you want to do the reaction in a liquid phase, you want to do the use a solid as a catalyst, you want to use a soluble catalyst. What kind of a catalyst you want? You want in a pellets form, you want in a tablet form, you want in the ring form, you want to use monoliths kind of a structure in which the solid is coated on the wall.

So, first, let us design the solid ok. So, you have a catalyst design which is the first label strategies that what kind of a catalyst design I should prepare which will be giving me the maximum selectivity, maximum conversion in a very low time. So, first level of a strategist should be the design of the catalyst. Then the second level of strategies. One should see is that; how we should do the contacting? So, injection; so, now, what I can mean by the contacting, I can pull, say there is a reactor like an use a plug flow kind of reactor and I can inject both the species A and B together and form the product.

So, there can be one contacting it in this way. Second is that, instead of doing this the B which we were injecting from this place can be injected at different location. So, this can be a second way of contacting that I am injecting the B in the different location. I can inject it in this way that there is a membrane which is in sight and within the presence of the membrane you are doing the reaction. So, you are separating some of the species or you are selectively passing one of these species which is coming in the contact with the others and that is having a reaction like PM fuel cells you said that we just allow hydrogen to be passed through. So, in that way, we can have a different strategies for the contacting pattern.

So, you want direct contacting, you want indirect contacting, you want the contacting at a different places, you want a particular phase to be contacted, you want to put a stirrer inside to mix it properly, you want to just mix it with the flow, you want co current operation, you want counter current operation, you want cross current operation. So, you can have a contacting strategies to that each contacting strategy is how it is going to play a role.

So, first level design; a suitable catalyst design your catalyst having a catalyst which what should be the design of the catalyst. You want to choose based on that you can have that what should be my system requirement or my reactor design you can find it out the contacting pattern whether you want a counter current even though you want co current cross current, you want to operate inject at a multiple location, you want to put a stirrer to break them .what you want you want to selectivity remove one of the compound. How you want to do the contacting. So, once you decide this and once you decide this, you will have a better understanding that what should be your reactor design typically. What are the design or what are the design available which you can use or typically how you should design your reactor. So, broader pictures will be clear.

Once the broader picture is clear, you can go to supermarket or you can design your own reactor and now, once you start designing your own reactor or you went to the supermarket to choose your reactor, you need to understand that, now in this reactor, if I do the job, how my hydrodynamic flow regime is going to play the role. So, there will be a flow regime which will be moving here now based on the contacting, you want co current operation, you want counter current operation, you want cross current operation, you want to a membrane inside to remove selectivity or selectively one of the compound, you want the catalyst should be in form of rushing ring, it should be in form of just a solid packed bed, it should be suspended, it should be in the form of monoliths, it should be quoted on the wall. Based on these 2 strategies, you will choose a reactor design. Once the reactor design has been finalized, now you need to understand how the flow dynamics inside is going to change with changing the scale. How the flow dynamics is going to happen, once we contact these 2 fluids together how this flow dynamics is going to result in terms of the final convergent and final selectivity.

So, what is needed is the hydrodynamics and the flow regimes of each of these reactors which you are trying to choose of the possibility the configuration possibilities which are available with you out of all those configuration possibilities as I said that there is no limit to the configuration their very large number of the configuration possibilities are available based on those large number of configurations for this for possibilities, you will try to understand the hydrodynamics of each of these reactors. And the hydrodynamics of the reactor which will be suited for your system requirement based on the profitability environmental concerns operate ability your selectivity convergent you should choose that reactor as a final choice of the reactor.

So, what we are going to do in this course? We are mostly going to focus on the label 3 that, how the flow regimes or the hydrodynamics inside the reactors can be decided, how it can be predicted so that, once I have this to label prepared label 1, strategies is ready the label 2 strategies ready with 3 strategies we can combine it and get a suitable reactor for the choice.

So, this was the background of multi-phase flow systems. Why you want to understand the multi-phase flow systems? Why it is complex? Why it is very very critical and why is still after working since decade, after decade still lot of scopes available to do something innovative to do something new to have a concept to have a system which can give even the better performance and I said that these kind of reactors or heart of any industries particular petro chemical; chemical pharmaceuticals, all these industries and if you increase a profitability or if you increase the selectivity or productivity by 1 percent or 2 percent, it can give you a billion dollar profit in a month.

So, still lot of focus this is still going on, lot of research is still going on. It is a very hot cake. Your people are trying to work to get an improvement and now, getting the improvement is even more challenging because, say I already have achieved in 90 percent. Now I want to go from 90 percent to 95 percent or 95 percent to 98 percent or 98 percent to 99 percent. So, the delta available is very less and that is why the challenges is still becomes very very critical and will need to come up with the innovative ideas.

So, we will try to see all those things during the course of this new course of this course and we will try to understand that how the contacting pattern and how the mixing pattern inside the reactor is going to change the dynamics. But, let us start formally with these basic introduction about the course and before starting the course, will define some of the basic definitions which are very important and which we are frequently going to use. Some of these definition, you might be already knowing, but still to make everyone on the same platform. I would like to just briefly go through the important definition which is very critical in multi-phase flow and very frequently we are going to use all those definitions.

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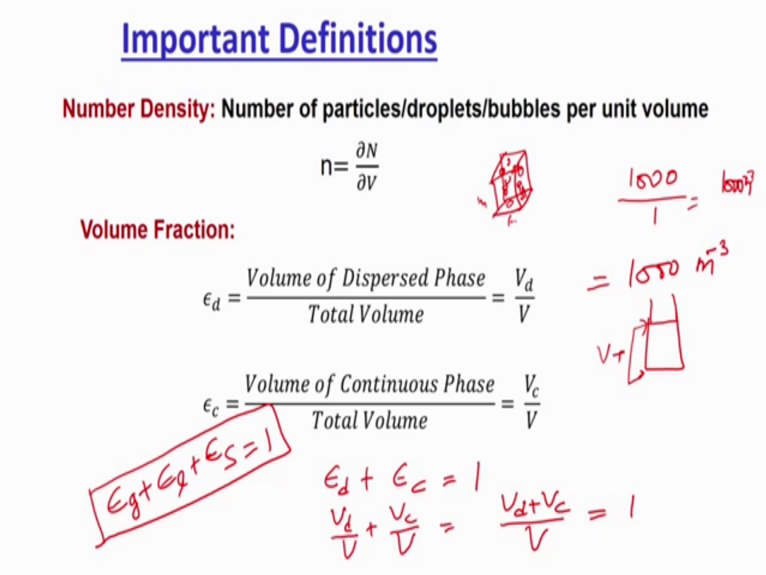

Important Definitions

Number Density: Number of particles/droplets/bubbles per unit volume

$$n = \frac{\partial N}{\partial V}$$

$$\frac{1000}{1} = 1000 m^3$$

$$= 1000\ m^{-3}$$

V_T

Volume Fraction:

$$\epsilon_d = \frac{\text{Volume of Dispersed Phase}}{\text{Total Volume}} = \frac{V_d}{V}$$

$$\epsilon_c = \frac{\text{Volume of Continuous Phase}}{\text{Total Volume}} = \frac{V_c}{V}$$

$$\boxed{\epsilon_g + \epsilon_l + \epsilon_s = 1}$$

$$\epsilon_d + \epsilon_c = 1$$

$$\frac{V_d}{V} + \frac{V_c}{V} = \frac{V_d + V_c}{V} = 1$$

So, first definition is the number density. You know what does the number density means? Now, I am going to define the class by 2, I will say on discrete phase or particle phase and 1 continuous phase. So, once I say the discrete phase or particle phase or droplets phase, it means that is a discrete phase like I we already discussed that in multi-phase flow like in the gas liquid or is a gas solid or is a liquid solid or it is a gas liquid solid some of the phases will be in the dispersed form.

So, once I say dispersed phase or discrete phase or droplet phase or the particle phase, it means I am talking about the phase which is dispersed and once I say continuous the phase which is continuous. So, that is what the way we are going to do the notation and I may interchangeably use these locations, but I will try to be consistent as much as I can, but to still if I sometime interchange, it actually all means the same thing.

So, what we first need is the number density. Now, number density is that number of particles or number of dispersed phase in that it can be practically droplet bubbles per unit volume that is called the number density. So, n which is denoted by the number density is nothing, but the dou N up dou V. So, it means what the number of particles water droplet per unit volume is number density now it can change if you change the volume why we have defined in terms of the dou because, if you change the volume, your number of particle will also change.

So, it is on the per unit volume delta V particular delta V a delta N, you will get it this number, you will get and that is called number density. So, suppose, you know 1-meter cube if I keep a cube which is of volume of 1-meter cube which means all the leg is of 1 meter 1 meter and 1 meter and suppose there are 1000 number of the droplets are available in this cube volume, then the number density will be 1000 divided by 1-meter cube. So, number density will be 1000-meter cube inverse ok. Write it more clearly say 1000-meter cube minus 3.

So, that is the number density and that is very important to understand that if we are thinking about a contacting, if you are thinking about reaction, I should understand how much of the discrete phase is available inside. So, that is the way number density has been defined, then there is one of the important parameter which we always say and I have used during the introduction also is volume fraction. Now, volume fraction can be designed for the discrete phase can be defined for the continuous phase and the definition is very simple it is a volume of the discrete phase is divided by the total volume. So, this total volume can be the volume of the reactor. It can be the volume where the gas and liquid. Say, there is a column in which gas and liquid is filled to the particular height though the reactor volume is higher. But the liquids will take and gas volume combined is lower well take this volume. So, it is a volume of this either V where the gas and liquid has been filled.

So, discrete phase volume fraction is the volume of discrete phase divided by the total volume continuous phase volume fraction is the volume of the continuous phase divided by the total volume in a 2 phase system termed as epsilon d plus epsilon c, it means should be equal to 1 and why it is because, if you do that it will be V d upon V plus V c upon [vocalized-noise], it means what it will be V d plus d c upon V then that is going to be the 1 because, the whole reactor volume will be filled either with the continuous phase all with the discrete phase we will see the summation.

So, we define the volume fraction that one whenever we call volume fraction. It means, what I am saying that total volume of that phase particular phase present inside the reactor divided by the total volume of the reactor or system. So, that will be the volume fraction and the volume fraction if suppose, is a 2-phase system, the volume fraction formation of the volume fraction of both the phases will be equal to 1 and why it is equal to 1? It is because of this when we are going to use it very frequently. Suppose, if it is a 3-phase system gas liquid and solid. So, I will say if epsilon gas plus epsilon liquid plus epsilon solid this will be equal to 1.

So, if you have 3 phase system, all the summation volume will be equal to 1 volume fraction will be equal to 1 and the reason is very simple as I said that finally, the reactor volume will be the summation of all the volume of the individual stages.

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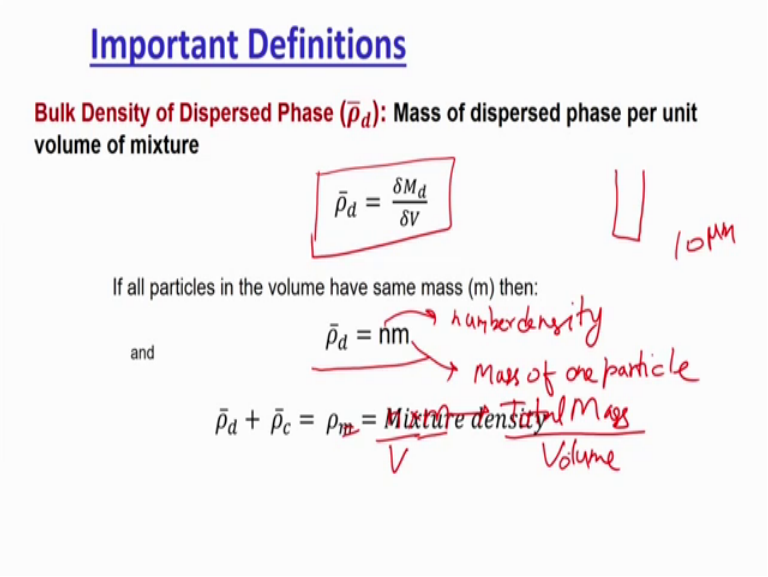

Important Definitions

Bulk Density of Dispersed Phase ($\bar{\rho}_d$): Mass of dispersed phase per unit volume of mixture

$$\boxed{\bar{\rho}_d = \frac{\delta M_d}{\delta V}}$$

10 μm

If all particles in the volume have same mass (m) then:

and

$$\bar{\rho}_d = \underline{nm}$$

n → number density

m → Mass of one particle

$$\bar{\rho}_d + \bar{\rho}_c = \rho_m = \frac{m}{V} = \text{~~Mixture density~~} \frac{\text{Total Mass}}{\text{Volume}}$$

So, that is also important definition then it comes to the bulk density. Now, many of the times finding the individual density itself is difficult and most of the time the bulk density is more important compared to the individual densities. Now, why the finding the bulk density or individual density is really difficult sometimes suppose, I have a bed, I have designed a catalyst in which the individual catalyst solid catalyst is of 10-micron size.

Now, if I want to measure the density of the system, then I need to ideally do a settling experiment or I need to major the mass and, in the volume, divided by volume of the system. Now, because the particle diameter is very small, finding the exact volume is very very tough and it is very difficult to have a 10-micron particle which will be completely spherical. So, if it is not a spherical, if the shape is different getting the volume is making for the difficult. So, what will happen? You will not be able to get the exact volume and then change making or measuring the mass of a 10 micron particle or even lower micron particle is also difficult. So, majoring the density is very very tough individual density. So, what we do we do the bulk density measurement? So, we based on the Archimedes principle, we put a amount of the solid in a liquid and we say that how much volume has been displaced and based on that you can find it out the density.

So, the bulk density is nothing but, the mass of dispersed phase per unit volume of the mixture. So, that is the way the bulk density has been calculated. So, what I can do? I can have a mixture, I can see that how much mass of the dispersed phase, I have entered inside of multi-phase what should be the volume, what is the volume of the total phase. So, I can have the volume of the total reactor or where the whole dispersed phase is suppose is distributed or dispersed inside the reactor. I know the volume of the reactor, I know this much mass, I have been put in. So, I can find it out what is my bulk density of the dispersed phase.

So, based on that, we can have a bulk density which is being calculated and why it is important or critical is that sometimes measuring the individual density itself is very difficult and bulk density is more relevant because, at the end of the day, we are operating a multi-phase system. So, the bulk density definition is more critical. So, if suppose, I am operating a packed bed, I am not worried about the density of the solid, but I am worried about the bulk density of the bed because, that is going to me the more critical information. So, bulk density can also be calculated based on the number density by this formula which is nothing, but n is the number density and m is the mass of the 1 particle. So, number density is what number density is nothing, but total number of the particle divided by V and mass. If you multiply with the mass of one particle, you will get the total mass this is nothing but the total mass and this is the volume volume of the whole dispersed phase plus the continuous phase, you will get that what is the bulk density of the system.

So, that is also a very critical parameter the rho d can also be calculated with the number density or vice versa. If you have the rho d measurement, you can calculate the number density. If you have the mass of the individual phase available with you, so that is critical and that is being used widely both the things interchangeably used. If you know the number density, we calculate the bulk density. If you know the bulk density, we calculate the number density.

Then the mixture density rho m is nothing, but the summation of both the bulk densities. So, bulk density of the continuous phase plus the bulk density of the dispersed phase again it is the same what will be the mixture density is the mixture mass divided by the mixture volume. So, if you do the bulk density it will be the nothing, but the mass of the dispersed phase. So, this rho d is nothing, but m d upon v this will be mc upon v.

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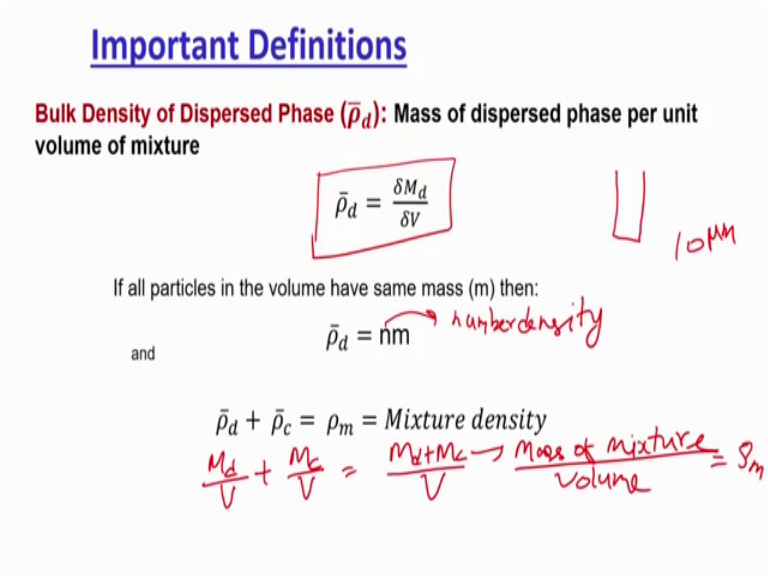

Important Definitions

Bulk Density of Dispersed Phase ($\bar{\rho}_d$): Mass of dispersed phase per unit volume of mixture

$$\boxed{\bar{\rho}_d = \frac{\delta M_d}{\delta V}}$$

$10 \mu m$

If all particles in the volume have same mass (m) then:

$$\bar{\rho}_d = \overset{\curvearrowright \text{number density}}{n}m$$

and

$$\bar{\rho}_d + \bar{\rho}_c = \rho_m = Mixture\ density$$

$$\frac{M_d}{V} + \frac{M_c}{V} = \frac{M_d + M_c}{V} \rightarrow \frac{\text{Mass of mixture}}{\text{volume}} = \rho_m$$

So, it means you will have Md plus Mc upon V and that is the total mass of mixture divided by the volume. So, that will give you the rho m because, this is lot of time will get confused and we say that why we are adding these 2 density to get the mixture density. So, if I have my individual bulk densities, I can just add both of them and I can get the mixture ok. So, this is what we are going to use very very it is very useful and we are very quickly going to use that to find the mixture density. So, do not get confused. If you add the 2 bulk densities to get the mixture density and this is confusing because, people in it can feel that why we can how we can add.

So, this is the way bulk density can be calculated. Now this, if you want, you can also correlate with the volume fraction. Now, what will be the bulk density? Again, the bulk density is what the bulk density is nothing, but your mass of the dispersed phase divided by the total volume.

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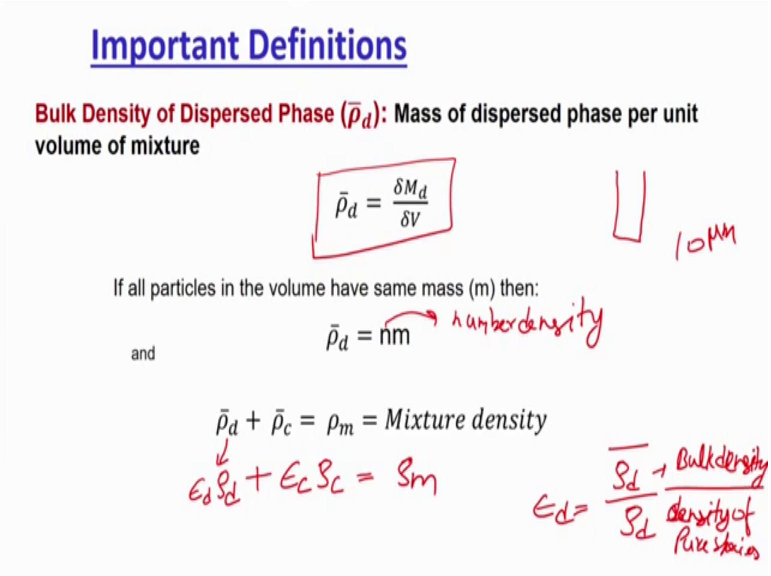

Important Definitions

Bulk Density of Dispersed Phase ($\bar{\rho}_d$): Mass of dispersed phase per unit volume of mixture

$$\boxed{\bar{\rho}_d = \frac{\delta M_d}{\delta V}}$$

10μm

If all particles in the volume have same mass (m) then:

$$\bar{\rho}_d = nm$$

n → number density

and

$$\bar{\rho}_d + \bar{\rho}_c = \rho_m = Mixture\ density$$

$$\epsilon_d \rho_d + \epsilon_c \rho_c = \rho_m$$

$$\epsilon_d = \frac{\bar{\rho}_d}{\rho_d}$$

$\bar{\rho}_d$ → Bulk density

ρ_d → density of Pure species

So, I can say, I can also write it out as rho d as a epsilon d into rho d. It means volume fraction of the dispersed phase multiplied by the density of the dispersed phase. So, suppose, if I know the density of the dispersed phase, if I know the volume fraction, I can find it out the rho d ok. Similarly, this will be epsilon c plus rho c and this will be equal to rho m.

So, the bulk density can also be represented in terms of the volume fraction. If I know suppose, the individual density, if I am using the particle solid and the solid field glass bits, I know the density of the glass bits. if I pat the glass bead inside a packed inside a bed or inside a reactor, I know the density of the glass beads. If I can measure the volume fraction, I can find it out what is the bulk density vice versa. If I know the bulk density, if I know the individual density, I can find it out what will be the fraction volume fraction of that phage inside the reactor. So, I can also write rho epsilon d is nothing but equal to rho d upon. So, do it means the bulk density divided by the solid density or density of pure.

So, I can find it out the epsilon d. So, that is the way bulk density can be defined and bulk density you can calculate the number density the bulk density, you can find the mixture density from bulk density, you can also find the volume fraction or if you have this individual density and volume fraction you can find the bulk density. So, interchangeably you can use all these definitions to find the one of the parameter inside.

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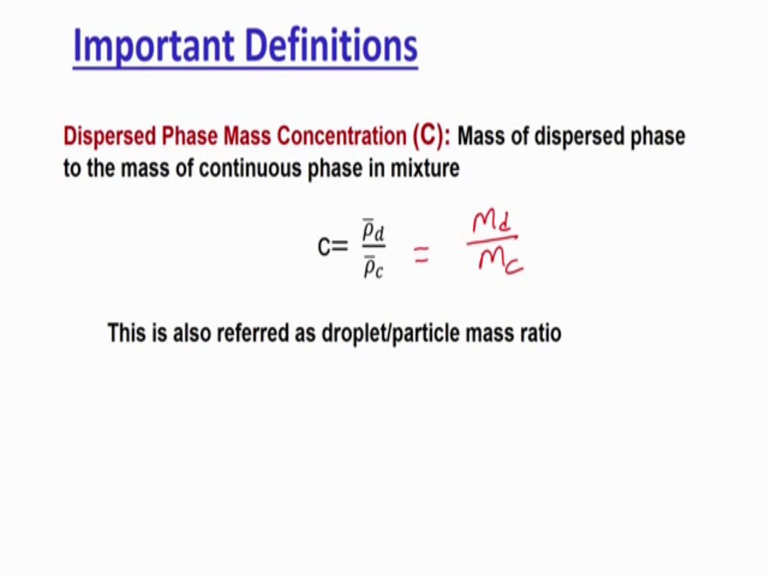

Important Definitions

Dispersed Phase Mass Concentration (C): Mass of dispersed phase to the mass of continuous phase in mixture

$$C = \frac{\bar{\rho}_d}{\bar{\rho}_c} = \frac{M_d}{M_c}$$

This is also referred as droplet/particle mass ratio

Then there is a dispersed phase mass concentration we will also find it out that what is the concentration of a particular phase or mass concentration the mass concentration of the particular phase can be find it out the ratio of the bulk density of the 2 phases. So, it means, suppose if I want to find the dispersed phase mass concentration, again I am saying is a dispersed phase mass concentration it is nothing but it will be the ratio of dispersed phase bulk density to the continuous phase bulk density.

So, rho d upon rho c you can find it out with the dispersed phase mass concentration. Many books also refer it as a particle mass ratio that, how much particle is available. So, if you do that how much particle mass ratio is available, you can say that what will be the mass of the dispersed phase divided by the mass of the continuous phase because, volume will be the same in the bulk density. It will be the mixture volume which will be canceled out. So, what you can get is that the mass ratio of the dispersed phase also. So, it can also be referred as the mass ratio of the dispersed phase and it can be found with the ratio of the bulk densities.

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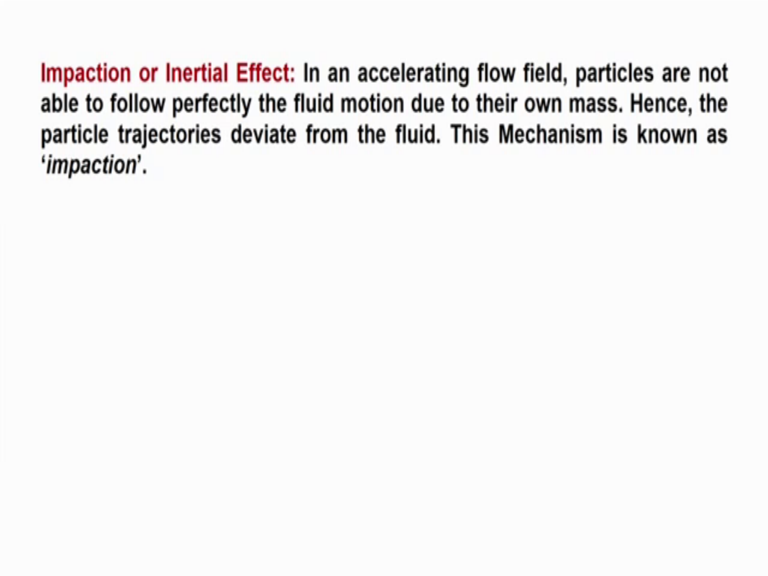

Impaction or Inertial Effect: In an accelerating flow field, particles are not able to follow perfectly the fluid motion due to their own mass. Hence, the particle trajectories deviate from the fluid. This Mechanism is known as '*impaction*'.

Now, another definition which is very very critical is called impaction or inertial effect, now, what is impaction or inertial stage? We will discuss in the next time.