Multiphase Flows
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Lecture – 21
Fluidized Bed Reactor

Welcome, back. In the last class we were discussing about the packed bed reactor and what we have discussed is that what is the basic principle of the operation in the packed bed reactor, what is the major advantage of the packed bed reactor, what is the drawback of the packed bed reactor, what are the equations used to calculate the first principle like a pressure drop and pressure drop in the packed bed reactor and we have discussed about the Ergun equation we have derived the Ergun equation from the basic force balance.

So, now what we have found that packed bed reactor is actually very good, why it is good because it is very simple in construction and very easy to operate. What you need to just take care is that the velocity should be less than the minimum fluidization velocity. But, as we discussed about the packed bed reactor we found that the packed bed reactor that the pressure drop is a problem. Why it is a problem, because what we want if we think about as a reaction engineering person or as a chemical engineer and I want to do the reaction.

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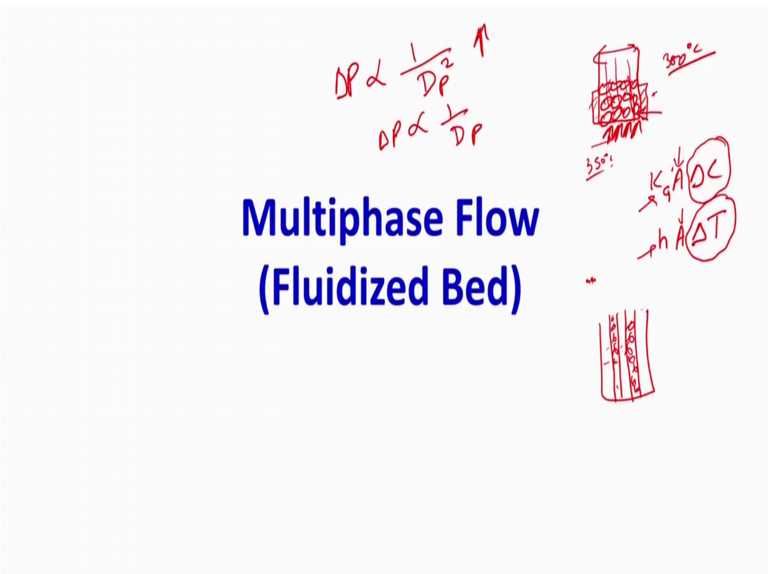

So, the problem is if suppose if I have a packed bed reactor in which solids are packed and we are passing a gas from the bottom of the column say and this is in a packed bed condition and suppose the reaction is exothermic or endothermic anything. So, what will happen, what we have to do to maintain the temperature if suppose, it is a endothermic reaction.

I want to maintain a particular temperature say around 300 degree centigrade inside the bed, what I need to do, how I will maintain this temperature. So, I have several options one of the option is that you pass this gasses as 300 degree centigrade. Now, in the gas solid bed increasing the temperature of the gases up to 300 sometimes becomes tricky.

Another way is to kind of you put a furnace at the outer periphery and you try to heat it, but this will be a problem or you put a signed off emos furnace kind of a structure and you heat it through this. Now, every structure has certain issues and major problem is that suppose if you are heating from the outside or through the gases then the uniform temperature distribution inside the bed is a major concern.

Why it is a concern? Suppose, if I am putting hot gas inside say the gases are coming at 300 or 350. So, if I have to maintain a temperature and they are heating the particle so, what will happen, these particles will see the maximum temperature they will absorb some temperature and gases temperature will lower down slowly what you will see, you will see a temperature distribution inside the bed. Secondly, what will happen most of the gases will try to pass through the centre of the column because it will have less pressure drop due to the frictional effect. The wall friction will also be acting.

So, in that case what will happen the central bed will have a different temperature near the wall the bed temperature will be different and then if there is some channelling or bypass problem then it will further severe the issues and if you make heat it from the wall then what will happen that if your diameter of the column is less then you will able to maintain a proper transition, temperature condition, but if think about a commercially scale packed bed reactor where the diameter of the column may be of 2 to 3 meters or even higher and then if you are putting a furnace at the outside then what will happen, the wall particle will have higher temperature compared to the central particle.

So, maintaining a proper heat transfer and similarly, the proper mass transfer is a very difficult and how what makes the life further difficult is that how we can increase the mass transfer if you think about it, then we know that to increase the heat transfer and mass transfer I have to increase the surface area. So, I can do it in two ways say mass transfer it will be say K G A into say delta C and heat transfer it is h A into delta T. So, if I fix the system this K G and H is fixed, let us assume and what you can play if you are fixing your gradient of concentration or gradient of temperature then these two are also fixed because you know that at what temperature you want to do that. So, if you fix the gradient this is also fixed what you can play is with the A.

So, if I keep on reducing the particle if I think about one particle the heat transfer or mass transfer across the one particle then if I keep on reducing the particle size my surface area will keep on increasing surface to volume ratio will be increased, overall surface area will increase and that will enhance my heat transfer as well as mass transfer ok.

So, in your scenario might have done with the packed one solid how the Thiele modulus or effectiveness factor will be varying and you will see that also those are the reaction quantities which is a strongly a function of the surface area. So, what I can do I can keep on increasing the particle diameter. So, if I keep on decreasing the particle diameter then what will happen my heat and mass transfer will increase.

But, at the same time what will happen your void fraction because we are keeping the particle we are making very very small, your tortuosity will increase, and that will enhance your pressure drop ok. So, the problem is the pressure drop is that if you will increase we know that the delta P in the pressure drop as we did in the Ergun equation is proportional to 1 upon D P square if your velocities are low and delta P is proportional to 1 upon D P if your velocity is high. So, it means what if you keep on reducing the particle size then, your delta P will be keep on increasing it will increase and if you are operating at a lower velocity the increase will be of the square order.

So, it will be drastically increase in the delta P if you are operating at a very high velocity then your Blake Plummer equation will be activated and in case of the Blake Plummer equation activated you this D P will be inversely proportional to the D P. So, it means what that if you keep on reducing the particle size then your pressure drop will keep on increasing. So, it is kind of a play between a trade off between the delta P and heat transfer and mass transfer, ok. So, if you go and try to increase the heat and mass transfer coefficient to delta P will go up, if you will try to balance your delta P your heat and mass transfer coefficients will go down and you will see the poor heat and mass transfer coefficient.

And, it means if you are operating a packed bed reactor you have to do some trade off and the trade off will be between the delta P and heat and mass transfer ok. So, that is the major problem and particularly the problem which the reaction is very temperature sensitive, or the concentration sensitive it means where you may be under the mass transfer control regime not in the kinetic control regime.

So, if you are operating a reactor in which you are under the mass transfer control regime you are going to be in trouble particularly in a packed bed reactor type and that is the region that once we started the petroleum cracking process initially we started with the packed bed reactor, but we face all this problem because reaction being very fast the cracking reactions being very fast the overall resistance lie in the heat and mass transfer coefficient. So, it is heat and mass transfer limiting reactor compared to the kinetic control reactor or kinetically limiting reactor.

So, if it is heat and mass transfer limiting reaction you are going to face a problem in a packed bed reactor particularly the problem will come to overcome delta P and heat and mass transfer coefficient you have to do the trade off. Now, this is the major region that why the fluidized bed invention has taken place because we want to overcome this heat and mass transfer limitations,. So, that was the major region that why the fluidized bed is being operated.

Given a problem if heat and mass transfer is not a major issues I would never like to operate a fluidized bed. I would like to operate a packed bed. Why, because there is no moving particles it is very simple construction, I do not need to take care of anything and particles are also stationary.

So, the erosion problem this all those problem is very very low, particle iteration, particle agglomeration all those issues will face in the fluidized bed reactor. But, all these things are not there if you are operating a packed bed reactor and that is why people have tried to improve it through the trickle bed and other type of packed bed reactor. The packed bed reactor in with multiple tubes are being put inside so that you can control the temperature in a better way.

Even people have tried to use a pipe plug flow kind of a packed bed reactor in which several pipes were there which was filled with the particles and there outside the hot or cold fluid was there. So, that you can have a better heat and mass transfer coefficient for doing all if your reaction is very very fast you are going to face a problem with the heat and mass transfer versus delta P. So, if you keep on reducing the particle diameter your delta P will be keep on increasing and you will face the problem with the better heat and mass transfer control.

So, that is the region that why the whole fluidized bed is being formed and why the whole fluidized bed is become so important in industry and why it find so much application in the industrial processes and the region behind that most of the industrial processes. We operate once, we go for the scale up, we are mainly controlled by the mass transfer or you can say the flow dynamics is going to controlled it or hydro dynamics is going to control the reactor compared to the kinetics and that is the major region that fluidized bed found a wide spectrum of the application because it tried to overcome this issue delta P and heat and mass transfer trade off and how it does is we will discuss it in this course or in this class.

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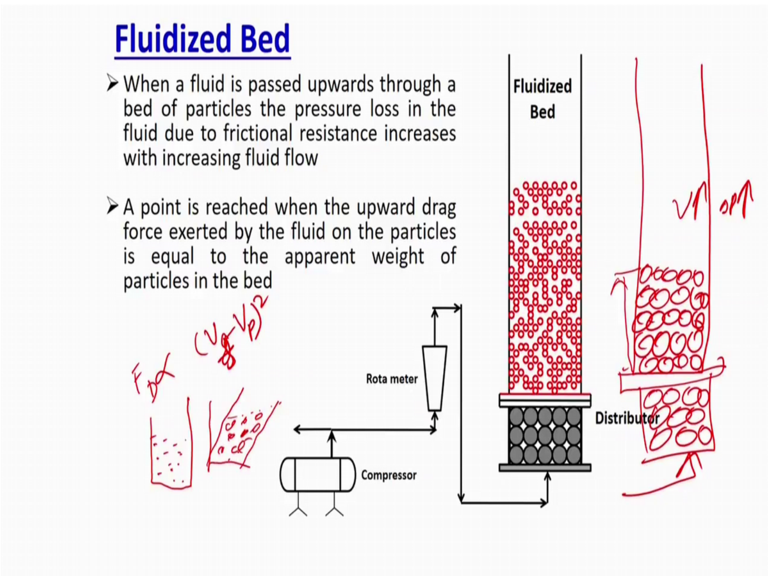

So, what is fluidized bed? The fluidized bed is nothing, but which is like a packed bed what we do there is a column in which we packed the solids, initially and then we pass the solid this gas or liquid or fluid I will say. The fluid is passed from the bottom towards the upward. Now, what will happen that if you will keep if you pack the solids, so, say this is a packed bed initially, ok. I packed it with the solids and say distributed assemblies then I put some of the solids here at the bottom bigger particles. So, that I can have a better gas distribution and then I pass the gas.

So, what will happen that if you will keep you will pass the gas from this then what will happen that initially due to the frictional losses as you keep on increasing the velocity your delta P will keep on increasing as we have seen that. So, you keep on increasing the velocity will increase your delta P will keep on increasing.

And, then at a point once you will keep on increasing the velocity because of the frictional losses your delta P is going to increase as we discussed in the Ergun equation also and depending upon the velocity whether it is smaller velocity or lower velocity or higher velocity it means you are in the Kozeny–Carman regime or Blake – Plummer regime of the Ergun equation you will see one of the pressure drop and that increase will be there.

Now, a moment will come up if you keep on increasing slowly increasing the velocity a condition will come were the upward force which is exerted on the particle in form of the drag because there is some drag is going to act on this particle because particle is stationary fluid has certain velocity. So, it will act put some drag on the particles, it will try to also that move the particle along with it and particle we try to reduce the motion. So, that relative motion because of this relative motion there was drag will be exerted on these particles or on each particles or you can say across the bed.

So, what will happen that the drag will be exerted on the particle and apparently at a particular velocity because we know that drag is also going to be the function of velocity and which is going to be a function of slip velocity square and initially if the particle is not moving the slip velocity this is going to be the function of the velocity of the gas. So, it will be V square.

So, F D is also proportional to V of say gas minus V or I will say V a fluid minus V of particle square. So, if I am keep on increasing the velocity and also increasing the drag force. So, at a particular point it will come that the drag force is actually balanced by the apparent weight of the particle. Now, why I am saying apparent weight of the particle or apparent weight of the bed instead of one particle I will say the bed the reason is that there will be some buoyancy also acting on it,.

So, the apparent bed of the once at a particular velocity when the weight of the bed or apparent weight of the bed is balanced by the drag force if you increase the velocity further beyond it then what will happen, the particle now the forces were balanced. If you further increase in the velocity the bed will start moving or the particle will start moving and the condition at which it is happens or when it is happen it is called the minimum fluidization velocity and the bed is called fluidized bed. Now, why it is called fluidized bed because as it is named, it is fluidized it means it works like a fluid.

So, start the solid to start working like a fluid and that is the region that this bed is called the fluidized bed and the phenomena occurs when the weight of the bed or apparent weight of the bed is balanced by the drag force or the pressure drop across the bed both are same because the particles are not moving. This is it means the frictional drag or frictional pressure is going to be dominating. So, both are the same actually.

So, that is the phase the fluidization occur and why it is called fluidization as I said in this case the particle start working like a or behaving like a fluid. So, what do you mean by the fluid? It means if suppose I tilt the column at a particular angle suppose if I take this if I take a glass and I fill the water in a particular level at a particular level and if suppose I tilt a glass, this glass say I tilt it now, at a particular angle. So, what will happen, the water level will also be tilted at the same angle, ok.

Similar thing, if you take a fluidized bed and if you tilt it at a certain angle then the top layer this whole solids will also move in the same way. So, the solid will also move it in this way. So, it is start behaving like a fluid, forget the nature of the solids, but it is start behaving like a fluid and that is the reason that it is called fluidized bed reactor or fluidized bed, and the condition at which is start happening or the velocity at which is start happening is called minimum fluidization velocity and at minimum fluidization velocity the pressure drop across the bed or the drag across the bed is going to be balanced by the apparent weight of the bed, ok. So, that is the condition at which it happens.

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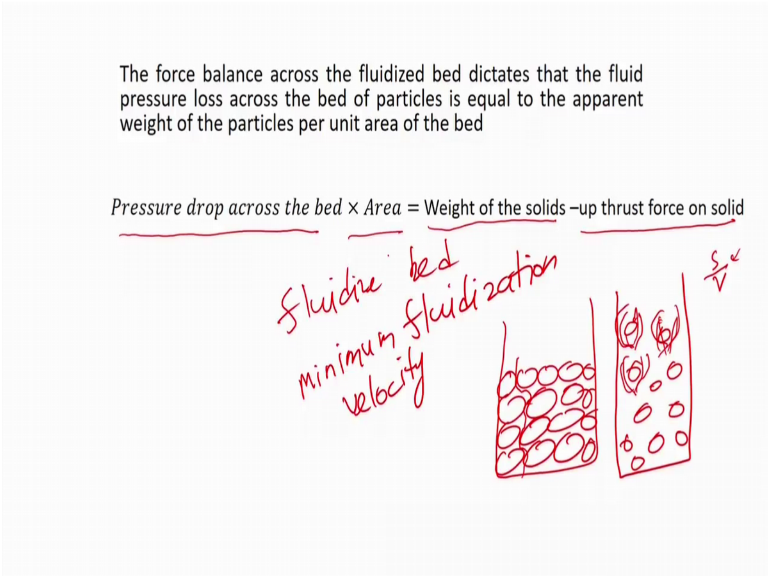

Now, as I said that the force balance across the bed actually states that the fluid pressure loss across the bed is equal to the apparent weight of the particle apparent weight of the bed and that is actually if per unit area if you will do if you do the force balance; then what you will happen you will see that that the pressure drop across the bed multiplied by the area.

It means the total force acting across the bed of the particle is going to be balanced by the apparent weight of the bed or apparent weight of the weight is weight of the solids minus up thrust force acting on the solids. So, there is weight of the bed whatever it is there and then what is the buoyancy acting on this the up thrust force is nothing, but the because of the buoyancy.

So, this is the thing which we balance and at the condition which it occurs or where when it comes the bed is called fluidized bed and the velocity condition for which these things happen it is called minimum fluidization velocity. Now, if you think about it what advantage it does? Now, you can ask that why we are we want to fluidize it because what it is going it is actually going to increase your heat and mass transfer, why? Because initially you solid work packed the solid was say packed.

So, your surface area was very very lower because the gases were not able to see. The gases were passing through this torturous path. So, you expose your area at the surface area was very very low. Now, what we are doing in the fluidized bed condition this solids will be now suspended if you think about this. So, this solid will be now like this. So, surface to volume ratio will be very very high now and this area as upon these so, surface to volume ratio will be increased very high. So, it means your a values will be very very high and it can be increased beyond like a single particle surface area.

Because, if you say increase the velocity a lot this particle will be further moving out it means the bed will be keep on expanding. So, if it will be keep on expanding this S upon V can be equal to a single particle suspended in the bed or so, single particle surface area and this is going to enhance your heat and mass transfer, because now the gases which are passing through is seeing the individual solids instead of the bed now they are seeing the individual solids.

So, this will be the way the gas will pass. So, it will see the enhanced individual solids and you will have a better control in the heat transfer and better mass transfer control and that is the region that why the fluidized bed is being used that it can give you a better control in heat transfer and mass transfer.

So, any reaction any gas solid or fluid solid reaction which is in the hydrodynamic controlled regime you can operate a fluidized bed reactor to balance or to kind of a control or to manage the heat and mass transfer and that is the region that why it is found a wide range of application is starting from cracking, gasification and drying granulation everywhere. So, if you think about this is the one of the widely used reactor for the gas solid or liquid solid contacting.

So, I have just given some of the example which is being widely used which also find the application in the mining, it is also find the application in gasification, in the petroleum industry, if you go the cracking all those things happens in the fluidized bed reactors.

Then if you go to the coal power plant you will see that the basic boiler is the fluidized bed boiler now and there is different regime of the boiling, but it is fluidized bed. If you go for drying most of the drying applications are now fluidized bed driers are being used, if you go for the granulation you will see the fluidized bed granular granulators are being used.

So, they have multiple application huge application is starting from any industry from petrochemical, food, if you in for the coating in the food for the coating things the fluidized bed are being used. So, you go for petroleum industry food industry pharmaceutical industry, bulk in chemical industry, fine chemical industries even for the treatment of the water or treatment of the gases you will find these kind of a fluidized bed applications a lot.

So, it is a found a wide range of a spectrum and that is why it is very interesting a very big topic of the research. Even now to design a better fluidized bed reactor now why it is a problem is still because there are many things which takes place and the thing is as I said that if you keep on increasing the velocity then your behaviour will keep on changing, ok.

But, is it possible that if I keep on increasing very high velocity can I keep on increasing the heat and mass transfer coefficient? The answer is, no. You will face some other problems also, and the problem will be your contacting time will reduce. We will discuss about that then we will discuss the different regime of the fluidized bed, but the idea is over the packed bed it is definitely gives you a advantage and the advantage is in terms of the better heat and mass transfer coefficient or better heat and mass transfer values.

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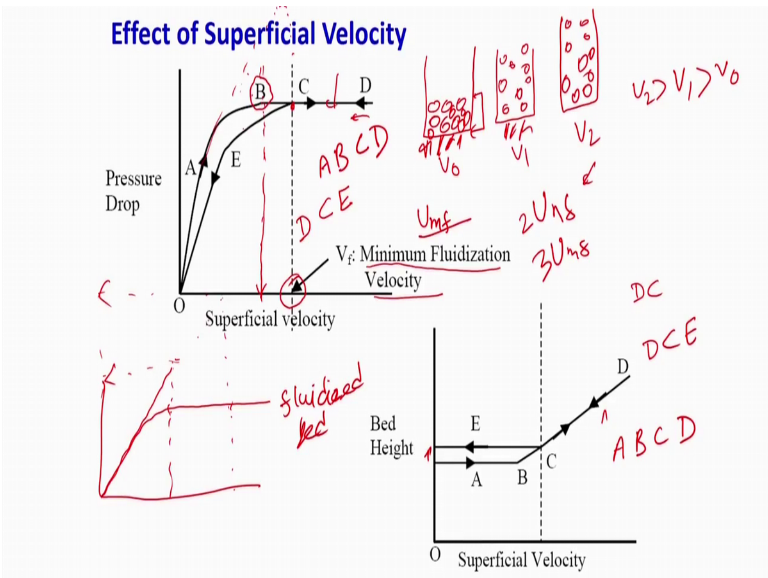

Now, the thing is as I said that if you keep on increasing the velocity what will happen in the packed bed reactor you will find some of this curve. So, this a curve. So, what will happen in the packed bed reactor if you keep on increasing the velocity the frictional losses is going to be increased and frictional pressure drop is going to increase. It means you keep on increasing the pressure drop.

Now, the moment it is start fluidizing then what will happen the pressure drop will be constant. Why it will be constant? So, this way the pressure drop is constant, why it is constant because now the moment you will increase the velocity say this was the packed bed initially you are putting a gas and you keep on increasing the velocity pressure drop was linearly increasing.

Now, once if you keep on increasing further once you fluidize then what will happen, the increase in the velocity will not result in terms of increase in the pressure drop, but it will be increase in the bed length. So, delta P upon l is going to be constant,. So, the pressure drop increases and the l increase will be proportional and you will get that delta P is actually becoming constant.

So, and what will increase is actually the bed height. So, it will be initially say smaller velocity it is this say this is V naught and V 1 it will be this and V 2 the particle will go even move further. So, the bed height will be further increased say V 2. So, V 2 is greater than V 1 is greater than V naught.

So, that is the way if you keep on increasing the velocity what will happen your bed will keep on increasing, ok, but your pressure drop will not increase and that is the major advantage. So, what you can do this gives you the advantage that you can now incorporate the bed at a higher Reynolds number because now you are not worried about this that if I keep on increasing the velocity to enhance my mass transfer, enhance my heat transfer which are both the function of the Reynolds number both either the Nusselt number or the Shearwood number both are the function are going to be the Reynolds number.

If you keep on increasing the Reynolds number or you keep on increasing the velocity then your pressure drop is not going to increase. So, ideally you are not only getting the benefit in terms of the surface area you can also operate at a higher velocity to enhance the heat and mass transfer further. So, that is the major advantage of this. Now, in this in case of this if suppose if I keep on operating a packed bed then what would be seen here the delta P if I extend this say length I will be seeing somewhere very high pressure. So, let us assume that it is cutting here.

So, what I am trying to say that suppose if this is the delta P or the fluidized bed if this is say minimum fluidization velocity after that it is becoming constant. If I keep on operating a packed bed reactor I might have seen this delta P. So, my delta P will be keep on increasing if I operate at this velocity say I would see a delta P of this. So, this will be your delta P, ok. Here this will be your delta P. So, you will be seeing a very high delta P if you want to operate a packed bed at a certain that velocity. So, it means what you will be limiting yourself, ok.

Because your delta P is keep on increasing here your delta P is constant, and that gives you the major advantage that why the fluidized bed reactors are preferred because you are able to operate at a higher velocity so that you can enhance the heat transfer and mass transfer coefficient further. Also you are not increasing your pressure drop even at a higher velocity because it is being balanced and the balance is coming because with increasing the velocity your bed height is keep on increasing.

Now, the question is that how to find the minimum fluidization velocity. So, minimum fluidization velocity can be found experimentally and we can do the force balance also to get the minimum fluidization velocities. Now, how you can find the minimum fluidization velocity experimentally? What we can do, we can keep on say we take a packed bed and we keep on increasing the velocity and we measure the delta P across the packed bed.

So, we measure the delta P then what will happen you will see that initially the particle velocity with increase in the velocity the pressure drop will keep on increasing then it will reach to a point where the increase in the pressure drop will be negligible and it will be you will see asymptotic kind of behaviour and then after a certain velocity it will becomes constant,. So, you will see the constant velocity actually it is not pretty much constant it is keep on reducing little bit, but for all the theoretical purpose you can assume it to be constant. So, it will be constant.

Now, to find the minimum fluidization velocity mini book says that this is your minimum fluidization velocity at which the pressure drop becomes constant, ok. So, at this point b where the pressure drop becomes constant, but this is not true actually. So, what you need to do if you want to find the minimum fluidization velocity experimentally then you are so have to de-fluidize. So, if suppose what I will do that I will take a bed I will measure the delta P across the bed and I will keep on increasing the velocity. What will happen initially, the velocity will increase then it becomes constant once it becomes constant I will keep on increasing the velocity is still, ok.

And, I will see that how my bed height is changing and what is happening with my delta P. So, it will be having a proper delta P say this way the delta P will be constant and. So, what you will be moving you will be moving while going up you will be moving with a line A B C and D this will be you will be following this once we know that the fluidization has been done the pressure drop is being constant bed height is keep on increasing. So, this is bed height it will be keep on increasing you are moving again the same path A B C D, what I will do we will start reducing the velocity.

Now, so, I will try to come back with the same path and let us see that whether I am able to come back to the same path. So, I will keep on now reducing the velocity. So, if I will keep on reducing the velocity I will be moving I will be reducing my bed height. So, you will be moving line D C B let us stop at this place and they say D C not even B. So, let us see that we are moving with the line say D C here also D C we will be keep on reducing the velocity your pressure drop will be constant.

But, while coming back you will see that it will not follow the path of C B and A it will follow the path of C and E. So, it will follow ideally by reducing it will follow the path of D C E here is also it will follow the path of D C E. Now, why it is happening? Because now, the bed will not come to the initial packed bed structure; once we initially dump the solid what we do we make a dense packing while once you fluidize it and then try to de-fluidize then you will never come to the same packing structure what you have done while packing it because some of the gases will be now trapped inside which will not come outside automatically, ok. But, it will take long time with vapour it will come out. So, you never get that particle density.

So, your bed height will actually be little bit higher and because your bed height is now little bit higher it means you are now having more wired your pressure drop will actually reduce and you will not see go through the line this, but you will go through the line D C E you will come back and then you will come back to the o again if you will stop the velocity and there will be no flow, there will be no pressure drop.

And, the point where this two things cut each other and that is the point and that velocity at which it these two is called minimum fluidization velocity. So, this is your V or u m f. This is the velocity at this is called u m f or minimum fluidization velocity. So, this can be found both from the bed height versus the velocity graph or the pressure drop versus the velocity graph, and this is very critical because many books also and many people what they do they try to minimum fluidization velocity just by fluidizing it they do not de-fluidize. So, till you are not de-fluidizing it, actually you cannot get the minimum fluidization velocity.

So, you will be getting confused as well, you will be getting the minimum fluidization velocity as a B this point velocity you will say is a minimum fluidization velocity while your actual minimum fluidization velocity will be this. So, one need to be careful while measuring the minimum fluidization velocity in fluidized bed reactors. So, you have to start with a packed bed to keep on increasing the velocity and then again you have to de-fluidize it and follow this curve, ok. So, you have to mean these two curves to find it out that what will be the minimum fluidization velocity of the bed.

And, this is the very very critical phenomena because if you will go and see any literature any people on the fluidized bed they always talk in terms of the minimum fluidization velocity. So, no one talked about the superficial velocity people talk about that I am operating the bed say at 2 u m f or 3 u m f or say 4 u m f and so on. So, you keep on just you rescale everything, you rescale your velocity in terms of the u m f to get an idea that what velocity you are operating. So, if you are using the u m f you can find it out that if you calculate the u m f you can find it out that what is the velocity, ok.

So, in that way it is very needed and you should know while operating it that at what velocity you are operating and how much higher it is from the minimum fluidization velocity. So, that you can see about the system, this will be the bed height increase. So, this will be enhance in the mass transfer the surface area to volume ratio will be this. So, all those things you can calculate.

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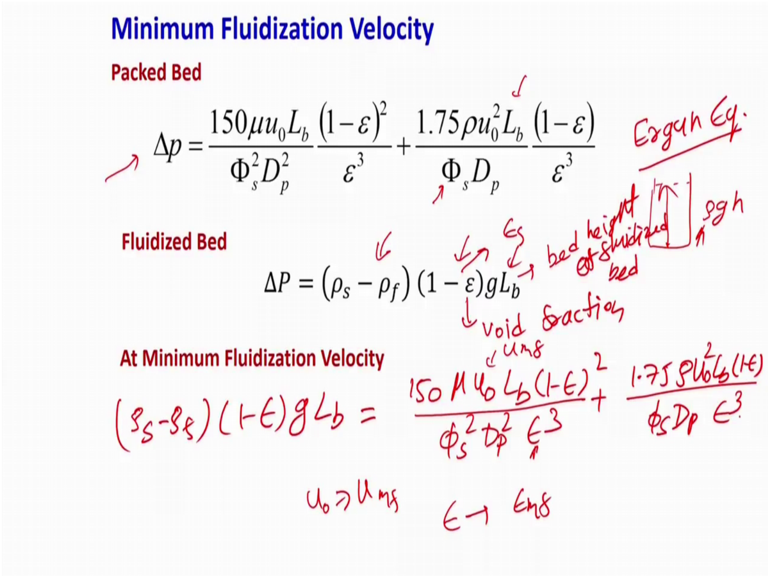

Now, how to calculate the minimum fluidization velocity by using the equations, we can do the force balance and the force balance equation this is the Ergun equation we have already discussed, in the last lecture and we have introduced the phi s density values that if the particle is not spherical then the phi s will also be introduced and it will be just the function of d s. So, what whereby it is D p it will become phi s there by it is D p square the phi s square value will come because now we are multiplying we are taking effective diameter of the sphere and we are multiplying it with those (Refer Time: 29:16).

So, D p is now replaced by say D p of exact particle is now replaced by the D p into phi s, where the D p is the equivalent diameter of the particle which is considered as a diameter of the sphere. So, same area if you maintained. So, that way you calculate it and phi s we have already discussed that so, I am not discussing in the detail.

So, this is what your packed bed equation is which is Ergun equation. Now, in the fluidized bed equation what will be the pressure drop in the fluidized bed it will be very simple the pressure drop in the fluidized bed is going to be balanced with the rho g h the way we do the pressure drop calculation because now it is going to behave like a fluid.

So, as I said that if it is behaving like a fluid in hydrostatic head whatever the fluid is there suppose the fluid is there till this point this height is filled in the glass or inner reacted then what will be the pressure the pressure will be rho g h. Exactly same thing we are going to follow we are going to because now fluidized bed behaves like a fluid the pressure drop will also be the rho g h.

Now, the question is which rho and what will be the value how we will take ways in the terms of the how much solid fraction is there. So, what we do, we say that the rho g h actually it is there, but the rho will be the apparent density and apparent density will be rho s minus rho f. So, this will be the density and you have to multiply by 1 minus epsilon.

So, 1 minus epsilon is the solid fraction. So, whatever the solid fraction is there epsilon is void fraction this is void fraction. So, 1 minus epsilon this hole is this solid fraction. So, it says that rho s minus rho f into epsilon s ok. So, this is what is the amount of the solid present into g into L b where L b is the bed height. So, if bed height at fluidized bed condition fluidized bed or bed height of fluidized bed, ok.

So, you can find it out with the rho g h that what will be the delta P now if you want to find the minimum fluidization velocity this we know that if I know that what is the minimum fluidization velocity the bed height will be at the minimum fluidization velocity and for all the practical application we can assume that the at the minimum fluidization velocity the increase in the bed height will be very very small. So, I can take it as a length at a minimum fluidization velocity it means I can say that these two L b's are same ok.

So, I can say that the minimum fluidization velocity the way the place where the minimum fluidization the velocity is equal to the minimum fluidization velocity, the height of the bed will be equal to the packed bed. If you see here you can assume that for all the practical purpose that at a minimum fluidization velocity the height of the bed will be equal to the packed bed reactor, ok. So, in that case if you do that we can do the force balance we can balance this both delta P and I can say that this will be if I balance this delta P.

So, this rho s minus rho f into 1 minus epsilon into g into L b will be equal to the Ergun equation delta P which will be mu u naught L b again I am saying that this both I am taking same for all the practical purpose we can assume it to be same one minus epsilon square upon phi s square into D p square into epsilon cube plus 1.75 rho u naught square L b 1 minus epsilon upon phi s D p into epsilon cube.

So, we can say that both are balanced and what we can do we can do the force balance to get that what will be the minimum fluidization velocity. So, this u naught will be actually replace with the minimum fluidization velocity u m f. So, at which minimum fluidization velocity this u naught will be equal to actually u m f and this L b will be L b m f or this both L b will be the same and this epsilon will be equal to the epsilon m f. So, u will be converted u naught will be converted to u m f epsilon will be converted to the epsilon m f rest of the things is going to remain same. So, only the epsilon m f this will be there.

So, you will do this substitution because what we are saying that at minimum fluidization velocity what will be the force balance. So, if you do the force balance the delta P of the pressure packed bed will be equal to the delta P of the fluidized bed ok, because you are now going to be the fluidized bed if you further increase the velocity it will be the fluidized bed.

So, the both the delta P should be the same that is what we are trying to do. So, we will do the force balance and if you do the force balance and do there is substitution as I said so, what we are done actually here we have taken the quantities common like rho u not square L b 1 minus epsilon upon epsilon cube we have taken phi s D p also we have taken common.

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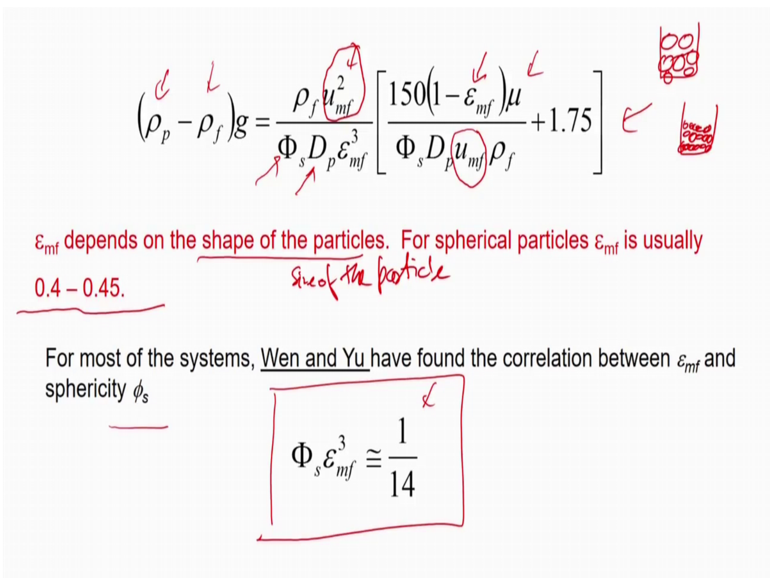

If you take the common then you will get this kind of equation and then we have divided it by rho p minus rho f 1 minus epsilon into g into L b. So, if you do that then we have just divided by 1 minus epsilon into L b. This we have divided if you do that if you do this substitution you will find this equation and this is the equation for the minimum fluidization velocity. So, you can calculate from this equation that what is the u m f this values can be calculated this is nothing, but the substitution you can do it it is just a one line. So, what we have done again we have taken all this as a common all this common and once we will do that and divide it by one minus epsilon into L b you will get to this equation.

So, this is the equation now the problem is you can calculate the u m f by using this equation by doing the basic force balance, the only problem you are going to face is that what is your epsilon m f, because you do not know this epsilon m f value and that epsilon m f actually depends on the shape of the particle and even on the size of the particle, ok.

So, it depends on the size of the particle for very fine particles this epsilon m f value will be different for very coarse particle the epsilon m f value will be different. Why, because we know that the void trapping will be say particles are very big and in one case the particles are very very, fine very very fine particles. We know that the epsilon m f value the void fraction in both the cases will be different in the packed bed condition. So, at minimum fluidization velocity condition also the void fraction will be different.

So, the only problem is to how to calculate this epsilon m f. If I know that epsilon m f I can easily calculate the u m f because I know the particle density I know the fluid density g value is, obviously, known if I know the particle shape and particle diameter I know the phi s value and D p value rest everything we know if I know the fluid then I know the fluid viscosity also.

So, what is unknown in this equation is the epsilon m f and that is the reason that what you need to do to calculate the minimum fluidization velocity you have to go and perform the experiments or you have to use some of the empirically developed correlation to calculate this epsilon m f. Like many of the literature report that for a spherical particles epsilon m f is usually found in the range of 0.4 to 0.45.

So, if we do that we can get the value of the u m f immediately. So, if I know this value we can put this value I can immediately get that what will be my u m f, but any wrong prediction in this values is going to seriously hamper your u m f velocity predictions, ok. So, that is the reason that several empirical correlations are developed actually to find that epsilon m f value at a minimum fluidization velocity and few people like Wen and Yu have said that for most of the system they have studied they found that the epsilon m f and historicity have a correlation which follow that phi s into epsilon m f cube will be equal to approximately equal to 1 by 14 and based on these assumptions several correlations has been developed which is will be find in the literature.

I am not going to discuss any those correlations because those are empirically developed correlation if you want you can see any open any fluidized bed book and you will see those correlations, but the idea is they all did the force balance and they try to develop some of this kind of a correlations and they replaced it to get a easier form of the fluid I mean minimum fluidized bed equation in terms of the Archimedes number or Reynolds number.

So, everyone have tried to find it out the correlation. Those correlations are widely used, but each correlations has certain limitations some correlations are valid only for fine particles, some correlations are valid only for the coarse particles, some correlations are valid for a particular size of type of the particles say group A particle or group B particles or group C particles and all. So, these correlations all these correlations are empirically developed and they have their own limitation, but is widely used in the literature to calculate the minimum fluidization velocity or to get an idea of the minimum fluidization velocity.

But, if you want to calculate the minimum fluidization velocity exactly what you need to do you have to go back and do the experiments you have to fluidize the bed you have to de-fluidize the bed you have to measure that the pressure drop at which the condition the C point where this both the pressure drop this curves you have to form and that the C point will be the minimum fluidization velocity.

So, this is the exact way to measure the minimum fluidization velocity, but if you do not want to do the this you can use all any of these correlation which is available like one of the correlation I have given you with Wen and Yu say that phi s epsilon cube is equal to approximately equal to 1 upon 14.

So, now if you know the phi s you can calculate the epsilon m f you can put it here you can calculate the minimum fluidization velocity or you can use the correlation developed by many people like correlation of Wen and Yu for the very fine particles with a very high flip velocities you can get the minimum fluidization velocity there for coarse particles they are correlation by the (Refer Time: 39:01) grace. So, several correlations are there in the literature which can be used to calculate the minimum fluidization velocity, but this is the basic principle.

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Now, what it happens that once you inject the particle now this is very critical pictures. So, what happens once you inject the particle this is a single point injection where what you do you inject the gas inside the solids the bubble start growing. So, you will see this kind of a growth in the bubble and at a certain when this grows at a certain level there the buoyancy is sufficient to lift the particle to overcome the surface tension force it lift the surface and then the bed start moving.

So, initially if you see this was the packed bed condition, but then once the bubble is started moving you see a particular shape and this height is increased and you keep on increasing the velocity what will happen once it will further move up initially it was a mushroom shaped bubble, then it becomes a completely spherical bubble. So, this kind of a bubble will be formed this is the 2D column where the bubble photograph has been taken place to see that how the bubble formation take place how it lifts up and how it moves.

So, you can see a bubble which is moving inside and based on this bubble movement the bubble shapes several theory has been given for the fluidized bed this theory for the given by the Kunii and Levenspiel that how the mass transfer take place how the bubble movement take place the theory is given by the Davidson all these scientist has given. Again, I am not going in detail of those theories because that is not the scope of this course what we are going to see that how the basic force balance is going to (Refer Time: 40:30) or is going to tell you about the fluidized bed behaviour.

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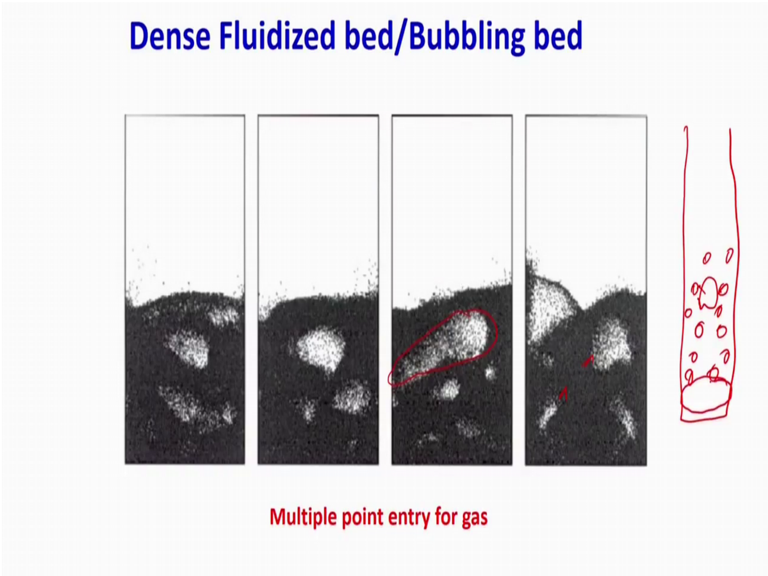

So, people have done the single point injection you can do the multi point injection. If you do the multiple point injection you will see the several bubbles. Those bubbles will be moving together. Now, what will happen if they are moving together, they will coalesce. They will form even a bigger bubble as you see here.

So, initially the bubble single bubble they form a bigger bubble they will again break they may form a two smaller bubble. So, these phenomena is continuously going on as it goes on in the bubble column reactor, where the bubble coalescence, bubble breakage plays a major role.

Here also the problem is the dynamics of the bubbles is actually governs the dynamics of the fluidized bed and that makes the process more complicated. So, what you need to do? Now, you need to understand the bubble dynamics. If you want to understand the fluidized bed you have to understand the bubble dynamics.

So, as I said several models has been given each model have their own applicability and that makes your process more complicated for that the particles are moving. So, if your particles are very sensitive to iteration they will iterate actually because they will go to the wall and they will change the particle size.

Then it can also agglomerate because of the charge develop on the particles, ok. It will also create the erosion problem because the particles are moving they will hitting the walls. So, slowly the ball will be get eroded. So, you will have several other issues, and that is why I said in the beginning also that if heat and mass transfer is not a limitation then I would always like to operate a packed bed because that is very easy the phenomena is not very complicated, ok.

We know that if this is the velocity that is going to be the pressure drop, but here there are many rules are going to be played. Your bubble dynamics can change your heat and mass transfer if suppose though you form such a big bubbles then what will happen gas to solid mass transfer coefficient will decrease drastically. So, all those things start playing the role and you need to now understand the bubble dynamics you need to understand how this bubble dynamics is going to change your solid velocities.

So, you need to depend on the experimental technique which we have discussed whether it is a LDA, PIV or RPT or any other intrusive technique like optical fibre probe hot wire anemometer anything depending upon what you want to measure what accuracy you want and what you want to look for.

So, you can use these techniques you can also use the high speed camera to find the bubble dynamics and all we can do the PIV experiments a lot of work has been done in the literature to understand the hydrodynamics. Now, why it is complicated because now, they have bubbles of different size your particles is going to behave in a different way depending on what is your bubble diameter, what is your bubble size what is your bubble shape, ok, how the bubble are getting agglomerated or coalescence, how the bubble are death how the bubble death rate is taking place, how they are dividing to the smaller bubble, how they are collapsing to a big bubble.

So, all those things is going to play a spotted role, a very critical role and that makes the hydrodynamics very very complicated and to study these hydrodynamics you need to use whatever method we have developed. So, we have to we have discussed till now you can use the experimental method you can use the numerical method you can do the basic model and that makes the whole reactor very challenging.

And what is further challenging that this further word dynamics whatever I am talking about is going to be the function of the operating condition that how you are operating. So, you keep on increasing the velocity of the gas you will form bigger and bigger bubble. Now, what will happen if whatever we have discussed is about the better heat and mass transfer if suppose, we were discussing once we said that we discuss it in this way that it is the continuous fluid the particle is being settled, but now the fluid is no more continuous it is also being form of the bubbles.

So, what is going to happen that your contact area will reduce we will see the mass transfer where the gases solid will come into contact with each other. So, if your particle say bubble diameter is very very big say this is your bubble diameter what is going to happen because your bubble diameter is very big the heat transfer and mass transfer throw the bubble to the solids relatives and then you will not see that much increase in the heat transfer that much increase in the mass transfer and that is why several regimes has been operated several velocities people have operated this to overcome these limitations.

So, now if you operate a fluidized bed your hydrodynamics becomes very very critical you need to understand thoroughly, and that is the major topic of research.

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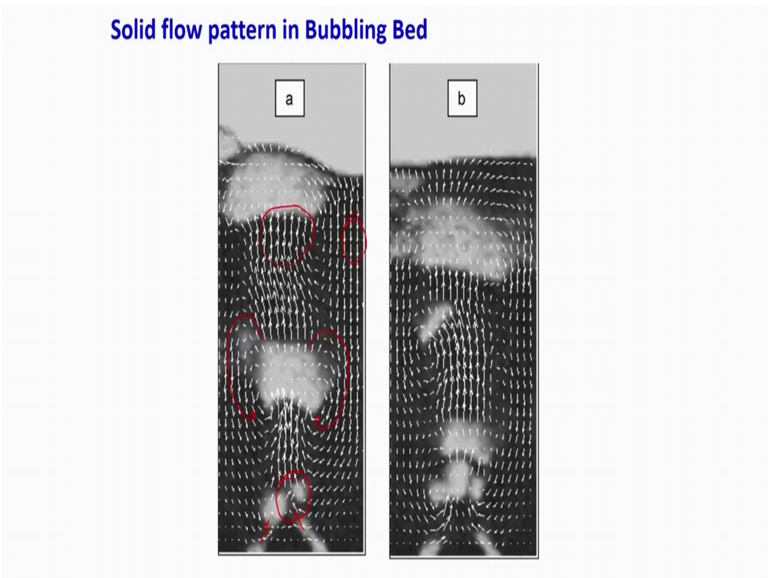

As I said that your particle will be moving with the bubbles. So, wherever your particles bubbles will be going up your particle will be going up wherever there is no solid though no bubbles or no gas your solid will be coming down. And, you can see that the pictorial representation here this is the photograph taken from the literature that initially the bubble size is small they coalesce, actually they coalesce form a bigger bubble and in the week of the bubble you see that this is a weight formation is there.

So, there is some local recirculation also taking place if you will see here where the particle is coming inside then as it moves up more bubble actually comes and coalesce with it the big bubbles and form a bigger bubble and you see the bigger bubble also. And, if you see the magnitude of the velocity you see that it is keep on increasing it is not same. So, the magnitude of the velocity at the bottom it was low now as the bubble size is increasing definitely a magnitude of the velocity will increase and you see that here the magnitude of the velocity is very very high and then it is coming downwards.

So, you are now not seeing a single velocity which was being assumed while designing a fluidized bed reactor you are again seeing a distribution of the velocity. It means what you are going to have a distribution in the mass transfer we will you see the distribution of the mass transfer. So, a mass transfer everywhere will not be the same and then if that is not the same definitely your reaction will not be same across the whole cross section it is going to depend that where is the bubble, what is the velocity received.

So, if you want to do that reactor design you need to understand the hydrodynamics well and if you want to understand the hydrodynamics well we need to do the force balance, we need to do the simulations, we need to do the develop a model, we need to use the experimental method to validate those models all those things you need to do, ok.

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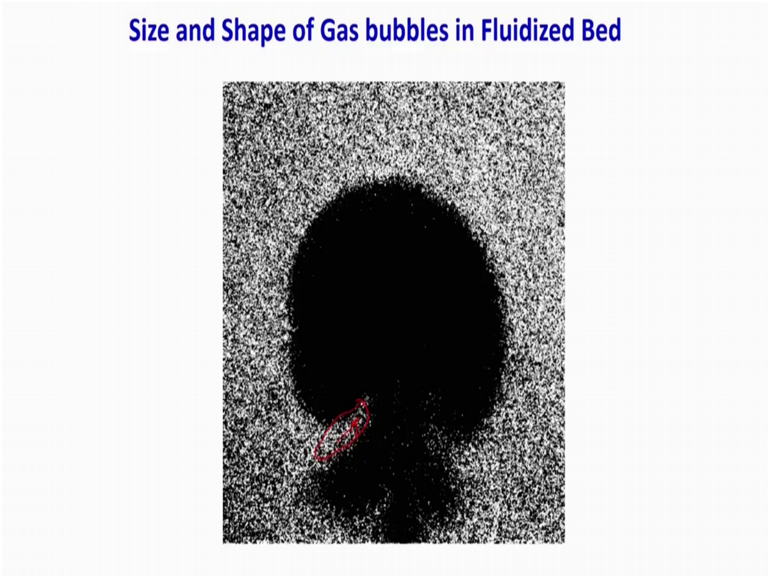

And, that makes the life complicated. This is one of the shape that was I said that the bubble forms in the mushroom shape and you can see the in the wake of the bubble you see a very high solid fraction. So, what happens there are some (Refer Time: 46:34) theory is there that bubble moves up it generate a week at the bottom at the backside and the solid is being actually comes in this way and moves upward. So, that is the way and the weight will be higher for the bigger bubbles compared to the smaller bubble and that is why the velocity here is higher compared to this smaller bubble case.

So, there are several mechanism again I am saying that I am not I do not want to go in detail of this because this is the content of the whole full course where we can do the fluidization studies, we can see the bubble dynamics model and all it cannot be covered in one lecture or two lecture. So, I am just introducing that these all are the things. So, you can have to do the force balance again across a bubble that how the bubble is moving you can do the force balance to see that how the particles will come across it. So, all those things you need to do to find it out the dynamics in the fluidized bed.

What I am trying to say again and again that the dynamics the hydrodynamics of the fluidized bed is very very critical and your performance of the fluidized bed is now going to depends on the hydrodynamics of the fluidized bed. So, you need to understand the flow behaviour, need to understand the mass transfer maybe you need to understand the heat transfer behaviour in detail and for do that whatever we have done till now you can do that, you can track a single particle motion, you can track a single bubble motion, you can write the equation the Euler, Euler frame same equation to model it you can write the Euler Lagrangian frame of the equation to model the solid motion and all or the gas motion.

So, you can do all this whatever we have done depending upon what is the accuracy level you want.

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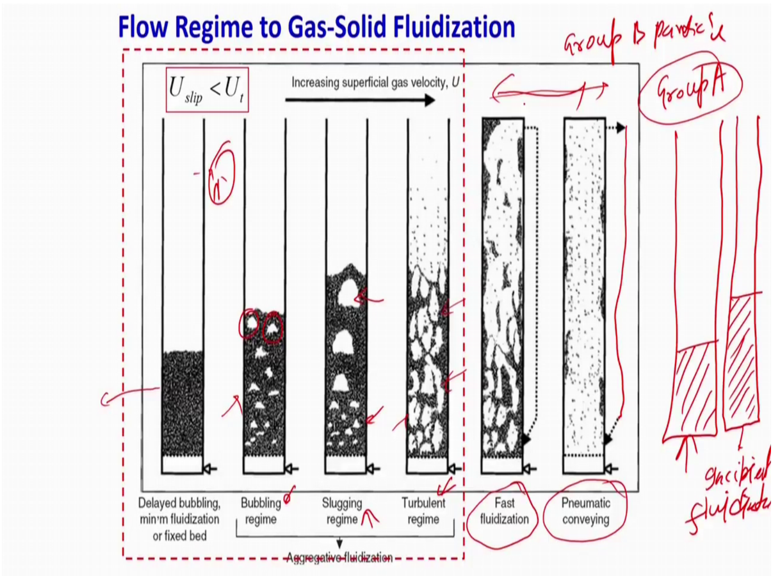

And, as I said that the phenomena becomes more and more complicated as because it depends on the velocity now. So, if you keep on increasing the velocity your bubble dynamics is going to change and if your bubble dynamics or gas dynamics is going to change then your whole behaviour performance or the bed performance is going to change it means your bed dynamics is also going to change, all your solid dynamics is also going to change. So, the performance of whole reactor will depend that at what velocity you are operating.

So, based on that several regime plots has been done and as they do the regime plots as we said that with increasing the velocity we plot the regime graph and we see that as we did earlier for the gas solid bed earlier also then because this is the vertical column most of the fluidized bed what will happen that if you do that increase the velocity initially it will be packed bed reactor. So, do not get confused with the transportation gas solid transportation once we have discussed.

Because, we have discussed mostly pneumatic conveying those map were there for mainly when where the motive was to convey the particle to throw the particle from one location to another location. We have discussed in the horizontal pipe and we had discussed the regime which is mostly in the pneumatic conveying regime. So, this is at the end of this. So, we have discussed mostly the things here.

But, now what happens in the packed bed reactor that a reactor in the gas solid reactor once you want to do the operation or the reaction what we do is we have a packed bed if you keep on increasing the velocity depending on the type of the particles, again that depends on the type of the particle.

This regime also depends on the type of the particle for the coarse particle or group B particle or above you will see this kind of a curve. So, what will happen we will pass a gas from the bottom you will see a bubbles, but if suppose there is a group a particle not very fine particle, but it is a smaller particle you will add one more regime that is called a incipient fluidization in which what will happen this will be next to this in between these two actually and say this regime and what will happen here that with increasing the velocity say this is initial packed bed.

If you keep on putting a gas from the bottom and for group A particle the incipient fluidization will take place and your bed height will smoothly increase which is the basic the concept of the fluidized bed whatever we have started that to keep on increasing the velocity your bed height will keep on increasing linearly. So, that will take place this is called incipient fluidization which occurs in the gas solid bed it occurs only with group A particle and it occurs mainly in the liquid solid bed where the homogeneous increase in the bed has been observed.

So, if you keep on increasing for the gas solid velocity then what will happen in the first if it is group A particle you will see the incipient fluidization where the bed will homogeneously expand and then you will start seeing the formation of the bubbles. So, you will see the bubble formation and gases will not be now continuous, it will be coming in form of the bubbles, and that regime where the gases are in form of the smaller bubbles is called the bubbling fluidized bed regimes ok.

Most of the fluidized bed where we do not want a continuous operation is being operated actually at this regime the bubbling fluidized bed regime.

But, what will happen now your hydrodynamics again I am saying is going to be controlled. If you are not able to maintain the proper velocity conditions you are putting more and more gas inside then what will happen this bubbles will start coalescing and they will form a bigger bubble. So, once the diameter of the bubble is in the range of the diameter of the column you call it as a slug flow regime, this is not desirable and this happens mainly for a very small diameter column.

If you have a bigger diameter column then you never come to the slug flow regime where the diameter of the bubble is balanced by is equal to the diameter of the column, but you will form the bigger bubble. Now, bigger the bubble lower the mass transfer, lower the heat transfer. So, you are now going back to the same problem that now you are limiting by the heat and mass transfer because we need the smaller bubble we need a smaller higher surface area; So, if you smaller the bubble, higher the heat and mass transfer coefficient.

But, if you increase the throughput you will see the bubble coalescence initially you see that we are seeing the smaller bubble, but because of the bubble coalescence now, they are becoming a bigger bubble they are growing and the growth will be higher. So, what will happen as the bubble size will increase your heat and mass transfer will keep on reducing. So, that regime where the sizes of the particle size of the bubble is equivalent to the diameter of the column that is called the slug flow regime. So, you will see the slug flow regime.

Now, if you further increase the velocity then what will happen this bubble coalescence will start much earlier and they will be kind of merging with each other at the formation place itself and we will see very elongated bubbles, very big and elongated bubbles. So, L by D of the bubble will be very high actually. So, you will see the elongated bubbles big bubbles and some bubbles maybe of the kind of a continuous regime. So, you can see that it may be a complete bypassing if you are not maintaining it properly.

So, what will happen you will see this regime where you will see the elongated bubble is called turbulent fluidized bed regimes. This is very unstable regime actually and you the particle because the velocity is very high the particle out of the system. So, that is actually particle entrainment may be a major issue in the turbulent fluidized bed and if you further increase the velocity then what will happen the particle entrainment rate will be very high particle will be moving out of the system and you do not left with any other option other than to catch the particle and re circulate it again to the bed and this kind of a bed is called circulating fluidized bed this different regime in the circulating fluidized bed. This is called where this particle again you increase the velocity you call it as the fast fluidization.

And, then if you further increase the velocity you come to the pneumatic conveying regime where the particle fraction inside will be very very small. You will mostly see the gases which suspended particles and the particle fraction will be less than 1 percent and most of the particle will be going out of the system and you have to again catch it and re circulate it back. So, you have to catch it and re circulate it back if you want to use it for the reaction purpose.

But, the solid fraction is so low in this case that it is practically not being used for any reaction purpose. So, pneumatic conveying is generally being used for the transportation of the solid, but not for doing any reaction because the particulate in the particle fraction. So, small that doing any reaction will be not very fruitful, because you are not having any gas solid contacting left because the solid fraction is very very low.

Now, if you see that I have put a smaller bracket. So, what will happen the U slip will be very less than the U terminal till the turbulent fluidized bed and after this in the fast fluidized bed and further the U slip will be more than the terminal velocity. So, it means if it is more than the terminal velocity then the particle will start moving out of the system, because now you are the slip velocity is higher than the terminal velocity.

So, it will go out of the system. So, this is called where the U slip will be equal to the U terminal and U terminal how to calculate we have already discussed in the classes that how to calculate the terminal velocity.

So, you can calculate the minimum fluidization velocity you can calculate the terminal velocity and this will be in between when U slip will be less than U terminal till that point you will see the batch (Refer Time: 54:58) kind of fluidized bed where the particle entrainment may take place in the turbulence fluidized bed, but the rate of entrainment will be much lower. If your U slip is higher than the terminal velocity the particle entrainment rate will be very high and you do not have any other option to catch the particle and circulate back and that is why this class of the bed is called circulating fluidized bed. This class of the bed is called circulating fluidized bed.

So, this is the whole regime and as we said that the regime is governed by the gas dynamics, how you are what is your gas velocity, what is your column diameter, what is the bubble size and all and that makes the life very complicated. But, it enhanced the your heat transfer it is reduce your pressure drop it enhance your mass transfer and that is the reason this kind of a bed is widely preferred, but very poorly understood even as of now.

So, we need to develop some mathematical model a better mathematical model with a good knowledge of the experimental measurement techniques so that we can understand the dynamics, we can measure the dynamics we can develop a model computational model or empirical model based on the data which is reliable data and to understand bed behaviour and what makes the life further complicated that as you see that it is also the function of diameter as we said in the earlier classes of the multi phase flow it will make your life further complicated once you go for this scale.

So, these are the major issues in the fluidized bed and this is the gas solid fluidized bed regimes.

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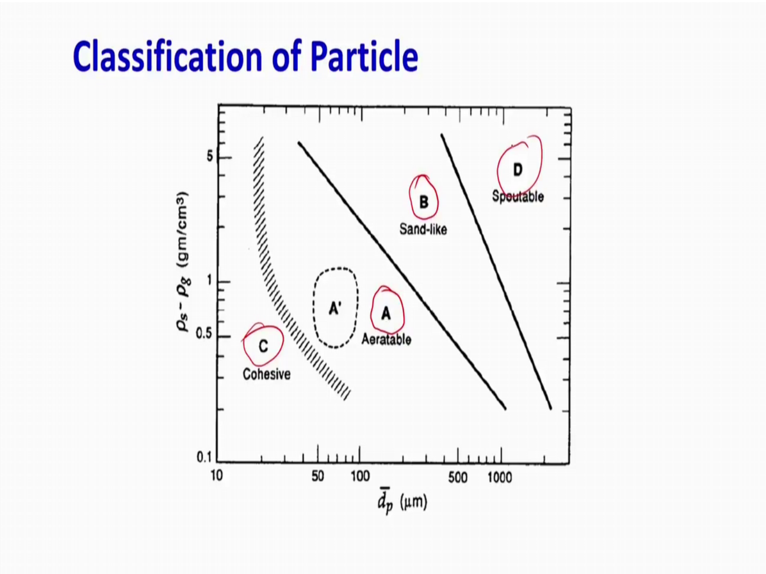

Now, as I said that this fluidized bed regime also depends on the classification of the particle that what type of particle you have we have already discussed this Geldart chart of the classification. So, this Geldart class of this Geldart classification of the particles heart for any fluidized bed operation.

So, once you start operating a fluidized bed first you need to see that what is my particle which regime I am which class of particle I am handling with, whether I am handling group A particle whether I am and group B particle C particle or D particle. Now, these three particles are very very cohesive in nature like and if you are trying to fluidize bed this group c particle it will be very very difficult to fluidize because the particular will collapse and from a bigger particular or chunk of the particles.

So, the fluidization of this kind of a particle is very very difficult. Group A and group B is very easy to fluidize, group A is very smooth fluidization you will find see the incipient fluidization also handling this kind of a particle for fluidized bed is very easy and that is why the most of the fast reaction where we want to operate a fluidized bed we generally try to have a group a particle.

The group B particle is also used for the fluidization when we want a bubbling fluidized bed we generally use a group B particles where you can increase the particle size and like gasification like the four combustion this fluidized bed combustors mostly comes in the group B particles and we operate a bubbling fluidized bed there. So, generally once we operate a bubbling fluidized bed we can go with the group B particles. Group D particles are very big and they are generally being a spoutable they do not fluidize they form a spouted bed.

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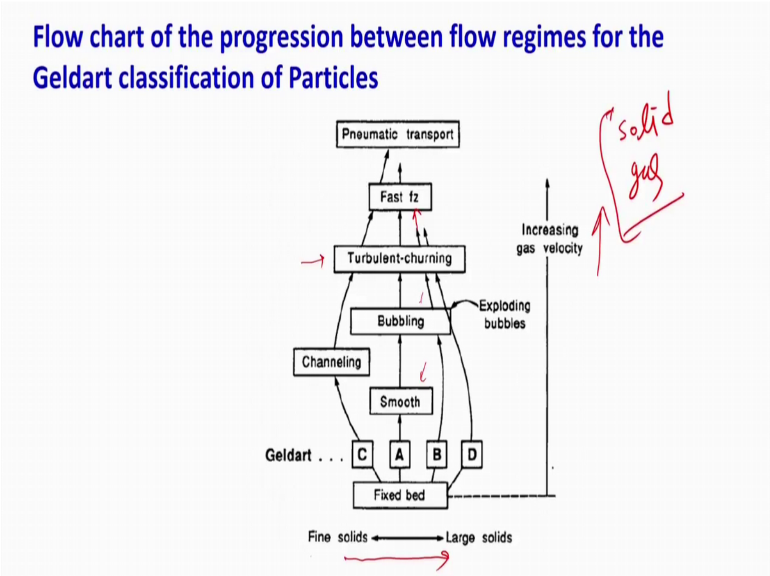

So, how the regime as I said that this the how your bed will behave depends on that what type of particles you have and then what is your velocity both. So, say if you are having a group C particle you will never see a smooth fluidization you will never see a bubbling fluidized bed you will see directly channelling you will see some channelling where you try to fluidize the group C particles the gases will pass from here because the particle will get agglomerates.

So, it will form a channel and it will escape then it can see the turbulent fluidization you can see that because once you keep on increasing the gas velocity or continuous elongated bubble will be formed and you will see the turbulent this velocity, you can also see the fast weight and pneumatic transport because if you keep on increasing the velocity further the particle will move out of the system.

But, a smooth fluoridation bubbling fluidization is completely ruled out for the group C particle. If you have group A particle you will see everything you will see the smooth fluidization you will see the bubbling fluidized bed you will see the churn turbulent fluidized bed you will see the fast fluidized bed and it will go to the pneumatic conveying also again I am saying that because pneumatic conveying I am not written there is a broke here why because we know that pneumatic conveying is not used for the reaction purpose.

For group B particle and group D particle a smooth ring is almost ruled out, you directly go to bubbling fluidized bed for group B particle then you go for turbulent fluidized bed and some of the group B particles now particularly is being used for the fast fluidized bed this literature is very old where the group B particles was not suggested for the fast fluidized bed.

But, now this line has been continuous and many group B particles are using for the fast fluidized bed the only thing is that your velocity requirement will be very high because group B particle size is bigger. So, your minimum fluidization velocity is going to be higher. So, if you are operating a fast bed you will have to have a very high velocity. So, now, many people like coal combustion gasification and all people are trying to use the group B particles and they are using the fast fluidized bed also.

Group D particle again you do not see the smoothening fluidized bed very small you will see the bubbling fluidized bed actually you know see the bubbling fluidized bed it is this floating bubbles which is called actually the spouted bed. So, you can see the touch up on the bubbling fluidized bed you can have a turbulent fluidized bed again group d particle because velocity requirement will be very very high. So, even now no one use it for the fast fluidized bed.

So, this is the map and if you go from the bottom to the top you keep on increasing the velocity and if you move from the left to right you keep on increasing the particle diameter size of the particles keep on increasing. So, this is the map that what how the progression of the fluidized bed or the regime take place for the different Geldart type particles.

So, what is going to depend on your fluidized bed characteristics it is going to depend on the solid and it is going to depend on the gas for the gas solid and for the liquid solids. So, will be going to depend on the solid and the liquid, but it makes this whole hydrodynamics picture.

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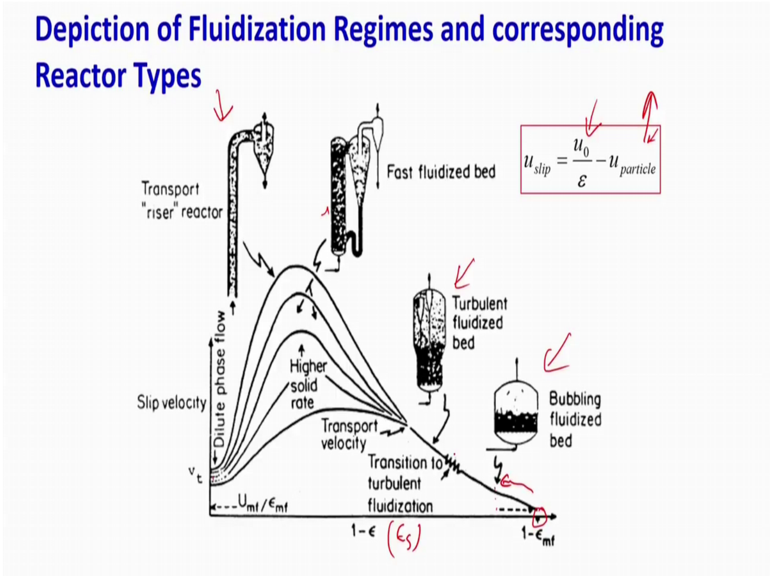

Now, how different type of reactor we have this is a very classical curve where you can think about that how my bed is going to be behave and why the pneumatic conveying is not being used. So, u slip is being defined as u naught upon epsilon which is the maximum say u naught upon epsilon u naught is the gas superficial velocity divided by the void fraction.

So, it will if you give the what is the gas inside velocity or interstitial velocity of the gas or local will not interstitial instantaneous velocity of the gas or the local velocity of the gas inside the column and u particle. So, what is the particle velocity inside so, that subtraction will be u slip.

Now, epsilon is the void fraction. So, if you are going from the left to right actually what you are going to do this is 1 minus epsilon is means epsilon s. So, it means if you are going from left to right you are increasing the solid fraction it means reducing the wide fraction. So, if I start from this place where you are having a packed bed 1 minus epsilon m f which was a packed bed it is just started.

If you further increase the velocity what will happen your void fraction will increase it means epsilon s will reduce you will move towards this side and you will see a bubbling fluidized bed which were the solid fraction will be in the range of forty to 45 percent or say yeah or 40 to 45 percent then if you further keep on increasing the velocity what will happen your solid fraction will reduce and you will see that the particles are moving at a relatively higher velocity.

So, now what will happen because you are increasing the gas velocity also your solid velocity is improving, but increase is not proportional. So, you will see a higher slip velocity compared to the bubbling fluidized bed.

So, bubbling fluidized bed gas velocity is lower, but the particle velocity is also lower so, the slip velocity is also low. In the turbulent fluidized bed your gas velocity is very high the solid velocity is not that much high and that is the reason that you see a turbulent fluidized bed, you will see the particle entrainment here for sure some of the particle will go out.

If you further increase the gas velocity it means you are reducing increasing the void fraction or reducing the solid fraction what you happen you see the circulating fluidized bed now the particle this entrainment will take place.

At the rate of entrainment of the particle or rate of recirculation of the particle which we are catching and moving back is going to depend govern your slip velocity that what will be your slip velocity ideally for better heat and mass transfer what I need I need a higher slip velocity ok. My Reynolds number is depends on the slip velocity. So, for better this heat transfer and mass transfer I need a very high slip velocities.

So, what we are saying that your slip velocity is definitely higher for lower for the packed bed. If you go to bubbling fluidized bed you increase your slip velocity we see a clearly see the advantage in terms of the heat and mass transfer, go for turbulent fluidized bed you are again clearly seeing the advantage for the heat and mass transfer. Then again you keep on increasing the velocity depending upon the solid transportation rate that where the transportation rate is higher or lower you will see a difference slip velocity pattern, but the pattern will remain same it will keep on increasing and then it will decrease.

Now, what is happening that if you further increase the velocity you will see the fast fluidized bed regime where the particle is kind of now coming out you are catching those particles with the cyclone or something and then you are moving back the particle again back to the system. So, what will happen your velocity is higher your slip velocity is further increased because you require a very high gas velocity. So, particle velocity is higher, but definitely the particle velocity is also keep on increasing, but the increase in the gas velocity is much higher. So, that is why you are increasing the slip velocity.

Now, after that what happened that you move to the transportation regime now what is the transportation regime there is also a riser here and then downer here also your slip velocity will see the fast fluidized bed regime and transportation regime or where the riser reactors are used you are operating approximately at the same slip velocities, but now you are on the other side. So, what happened you are not at the maximum? Now, what will happen your gas velocity is higher, but your particle velocity is also high, ok.

So, because why because your wide the solid fraction is increase decreasing your solid fraction is decreasing or you can say the void fraction has increased you see that your solid fraction has reduced your solid fraction has reduced the particle will try to approach now to the gas velocity because the losses is now reduced there a few number of the particles available and to the gas. So, gas will try to transfer it is momentum to the particle and the particle is moving at a much faster space. So, definitely you will have to increase the particle velocity gas velocity.

But, at the same time now the particle velocity will also be increased and you may see the same slip velocity with a dilute fraction of the solids. Now, this can be advantageous, why? I am not compromising with my slip velocity; my solid fraction has marginally decreased not very highly decreased. So, for any reaction which is really highly exothermic or endothermic I can have a better heat transfer and mass transfer because my slip velocity has remained same, but my solid fractions goes down. So, I can have a uniform distribution of the solids.

I can reduce the back mixing which is very critically there in the bubbling fluidized bed where the particles are in batch or turbulent fluidized bed even in the fast fluidized bed though the some of the particles are going out, but some of the particles are falling back from the wall. So, you will see the severe back mixing which may result say in the cracking reaction this kind of a back mixing can be caused a particle this deactivation of the catalyst which is actually used as a solid.

So, solids are nothing, but the catalyst and you are doing the cracking. So, some of the coke will be actually deposited on the solids and you need to actually regenerate the solids or heat the solids so that that coke can go out and you can generate the catalyst. So, that catalyst deactivation will be very fast which can be overcome in the rise reactor and that is why for the petroleum cracking the riser is being used widely across the whole world for the cracking for any fast reaction where the catalyst regeneration is required low back mixing is required the riser reactors are being used.

Then, if you further increase the velocity you see that we sharp decrease in the velocity the slip velocity why? Because, now you keep on increasing the velocity the solid fraction will goes down even further. So, what will happen the gas velocity and the particle velocity will come very close to each other say you are having only 1 percent or less than that the solid inside. So, the gas will transfer all its momentum to the solids because very few particles are there and they will try to move with the same velocity.

So, though you are operating at a very high gas velocity the particle velocity will also increase and your slip velocity will drastically decrease and that is called dilute phase transportation or you can say the pneumatic conveying and that is the reason that why the pneumatic conveying is not being used for the reaction purpose because ideally you will get the same slip velocity which you can get in the bubbling fluidized bed a little bit above than that.

So, if I am going to operate in terms of the heat and mass transfer exactly same as of the bubbling fluidized bed why I should waste much energy. So, that is why the pneumatic conveying is not being used for practically not being used for any reaction purpose because a slip velocity decreases drastically. So, this is the regime and how the heated mass transfer is going to change how your solid fraction is going to change you can find it out.

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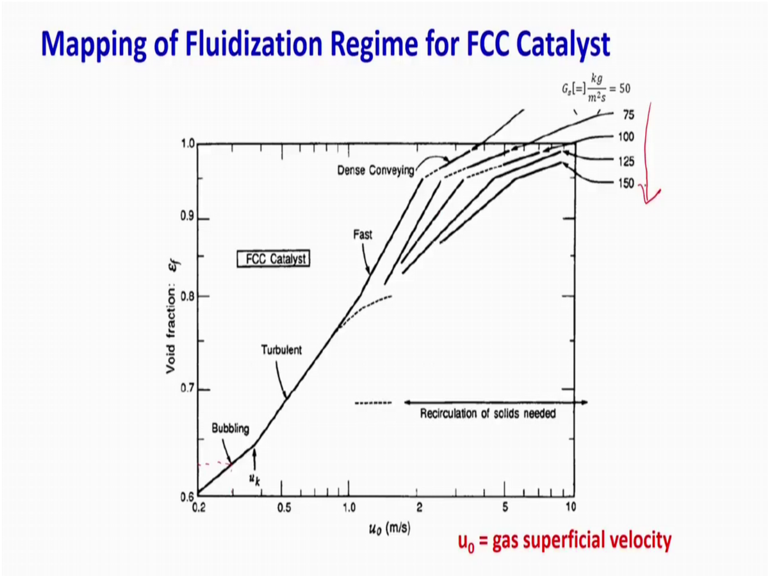

Then for FCC which is very critical actually people have plotted it again for the different velocity and the some numbers is given that if you keep on increasing the velocity. So, like you can see the bubbling fluidized bed occurs at a velocity of say 0.3 meter per second superficial gas velocity and at that case if you see that the bubble fraction or the void fraction is in the range of 0.65. So, it means you will have around 35 percent of the solids.

So, you keep on increasing the velocity you will move into the turbulent then fast then dense conveying and the solid fraction will keep on your bubble fraction will keep on increasing and then you see that you will see some decrease in this, you the graph will be flattening and it will be lower as you keep on increasing the solid circulation rate then your solid fraction the void fraction will be keep on reducing.

So, that is the same graph as we discussed we plotted for the FCC also.

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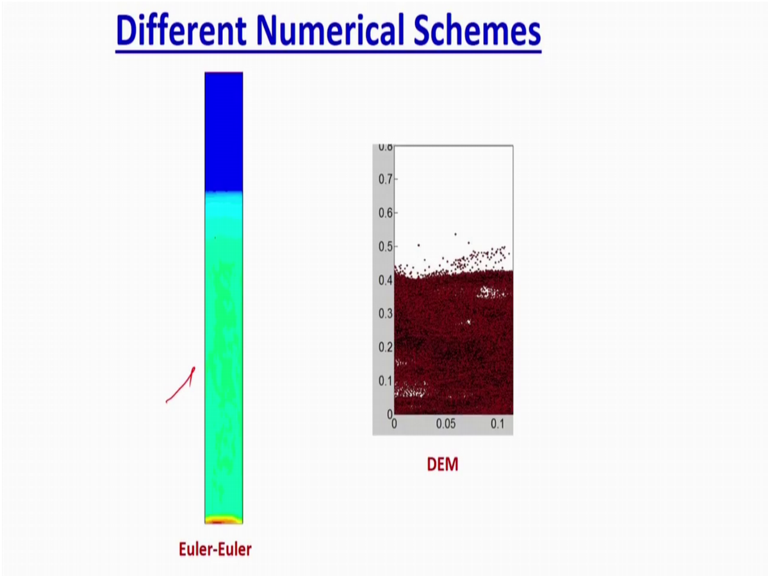

Then, different numerical schemes are being used as I said that because this is a dynamics governed this is depends on the bed behaviour is going to depend largely on the hydrodynamics in several kind of approach can be used to model this you can use different experimental method different modelling method you can use Euler-Euler in which you assume that both the fluid and the solids are in continuum.

So, what will happen you do the Euler-Euler simulation of the gas solid bed you will see something like this colour shows actually the control bar where the red colour shows the high solid fraction, blue colour shows low solid fraction and you can see that everywhere there is a solid and all.

You can use the Dem kind of simulation as we have discussed or Euler Lagrangium simulation you can see that how the solids are moving inside, you keep intact the particle nature of this you find that how the bubbles are forming how the particles are moving and also you can use different numerical approach to understand the technique different experimental approach to understand the method.

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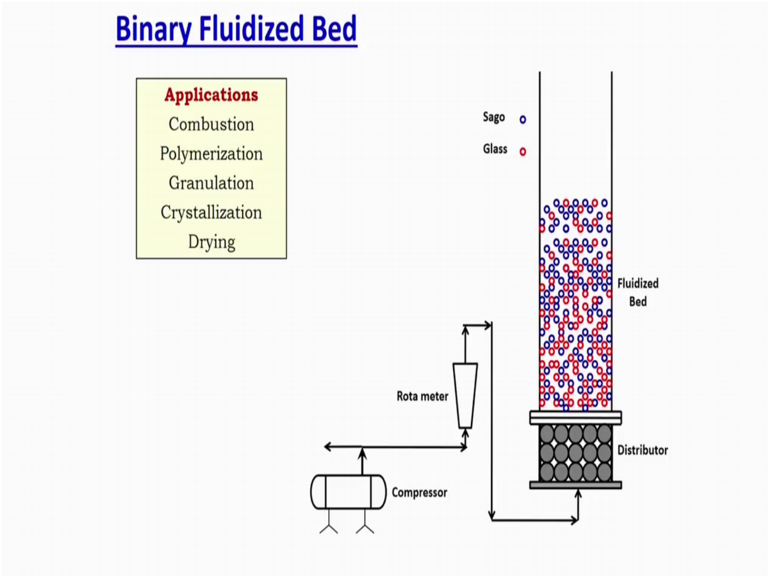

So, this is all about the fluidized bed, again there is another class of the fluidized bed is the binary fluidized bed. So, actually whatever we have discussed till now was for the mono particle mono fluidized bed. Now, mono fluidized bed is just a concept it never existed. Why? Because making a mono disperse particle, the particle which is having a same diameter is very very difficult ok. It is almost impossible to make a catalyst which is all the particles are in the same diameter.

So, we have a distribution of the particle and more rigorous case actually we say it a binary fluidized bed, but we have a poly dispersed nature. So, we have a distribution of the particle in terms of the size, in terms of the density or in terms of both, and that actually changes the dynamics of the bed. So, if you want to operate a fluidized bed you need to also understand that what is your particle size distribution because depending upon the distribution you see a different type of behaviour altogether, ok.

So, the binary bed I am saying binary bed because for all the practical application again to understand in the academia we operate a binary bed, but in industry level you never see a binary bed it is a poly disperse bed, where the particles are having distribution in the density or distribution in the size or distribution in both size and density. Have a many application like combustion; if a coal particle is there say it is burning then what will happen the size of the coal particle will keep on changing, density of the particle will also keep on changing.

So, depending on the burning rate you will see a distribution of the size distribution of the density. So, coal particle will form ash particle which have a different density different size. So, you will have a poly dispersed nature depending upon how much particle has been burned, the amount of ash will be formed the amount of, the size of the particle will be different the density of the particle will be different. So, you will see the poly dispersed nature. So, they are just giving an example.

Similarly, the polymerization if you are making a granule depending upon the granular size initially it will be smaller then it will be a bigger. So, you are going to see a distribution in the particle size and all. So, all these applications we see the poly dispersed nature of the bed now the poly dispersed nature of the bed further it changes the dynamics of the fluidized bed and you need to understand this that if you have a distribution poly dispersed bed how to handle that.

So, to do that in a academic world what we do we generally take a binary bed which is of having the different size or different density or both and try to analyze the system to understand the behaviour.

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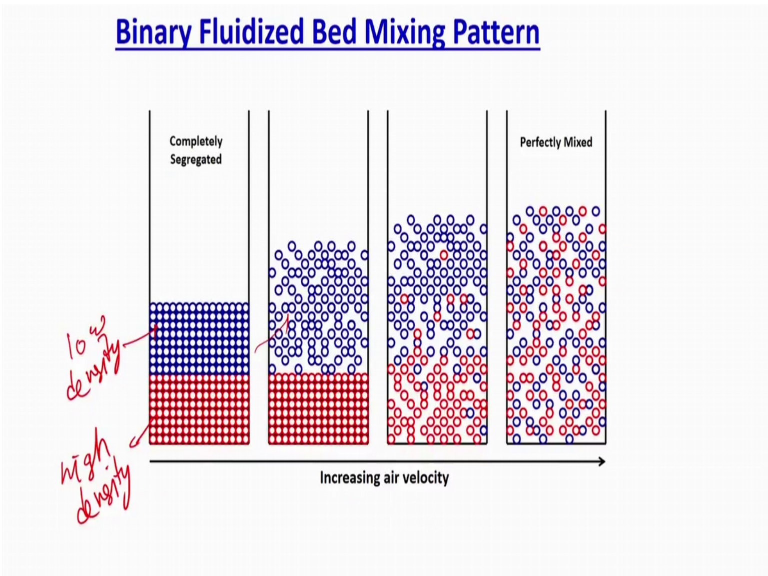

Now, what we see in the binary bed of the poly dispersed bed we see the further regime. So, any regime whatever you have you see a further subclass in the regime initially what will happen at a very low velocity it will be segregated. So, the bed was completely segregated. It means say this blue particle is say low density, this is high density. So, what will happen at a very low velocity, low density particle will be on top high density particle will be at the bottom. If you keep on increasing the velocity then what will happen the small low density particle will start fluidizing.

So, you will see a fluidized bed at the top. So, one part of the particle is fluidizing, but on the part of the particle is being packed bed because the minimum fluidization velocity is different why because the particle size is different or the density is different or both are different and we that know that minimum fluidization velocity depends on both particle size as well as the density.

So, one particle which have a lower minimum fluidization velocity will start fluidizing while other will be remaining same we will remaining as a packed bed. You further increase the velocity what you will see you will see that the particle has a start fluidizing and you will see a particular mixing and segregation pattern it means both the top particle will again operated or even higher velocities.

So, it will be fluidizing more a vigorously. So, increasing the bed height will be higher while for the smaller particle bigger particle or like denser particle the decrease in the bed height will be low. So, you will see a particular mixing and segregation pattern completely mixed bed regime where both the particles are mixed completely.

So, depending upon what you want in your system you want to operate in one of the regime. Say if I want to calculate separate the ash from the coal combustion I want to operate in the segregation regime. So, that I can ash I can easily segregate. In some of the cases we want a perfectly mixed regime like in the variant coal combustor be sometime use refractory's to maintain the constant bed temperature now in the refractory's and coal I want definitely this would be perfectly mix so that my heat transfer can be maintained.

So, depending upon the situation you may desire that the complete segregation you may desire a complete mixing, but there is a regime exist and you should know that what conditions you are operating and whether at that velocity whether you are going to see these kind of a behaviour or not.

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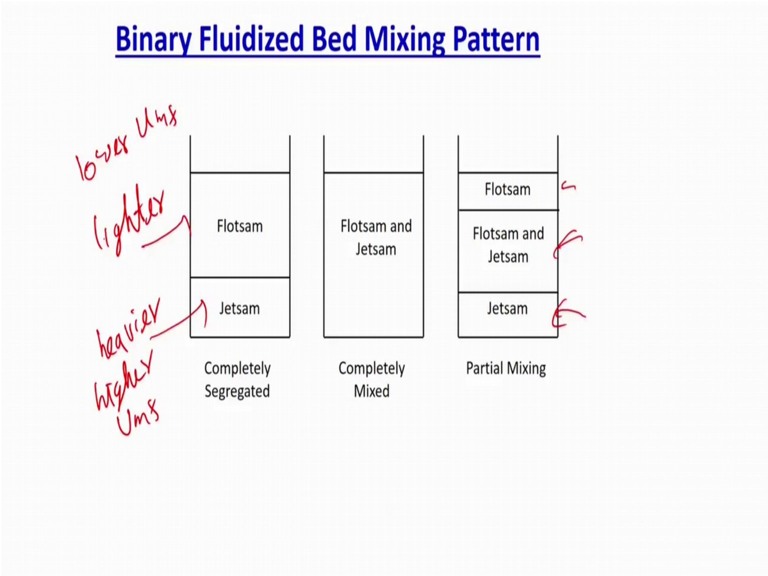

So, generally this has been characterized the higher density particle or bigger particle is called jetsam it means which is actually sink at the bottom the lighter particles are called flotsams. So, these are lighter or I will say lower u m f this is heavier or higher u m f. So, you will see the jetsam and flotsam and as I said that you will see a complete mix rate at a very high velocity or you will see the partially mixing bed in which the jetsam will be at lower some flotsam will be on the top and in between you will see the combination of the jetsam and flotsam like this is partially mixed bed.

So, again your bed behaviour is going to depend that what is the velocity of the bed and this kind of a bed again binary bed is very very critical as I said that most of the application you are going to see the poly disperse nature of the bed. So, the change then this can change your entire dynamics of the bed. So, you should understand if you want to analyze the fluidized bed you should understand what is your particle size, what is your particle density, what is your derive dynamics and you should also see that what is the distribution of the particle size.

So, I am just saying that what are the critical parameters which are going to change; the dynamics of the bed which you need to be careful.

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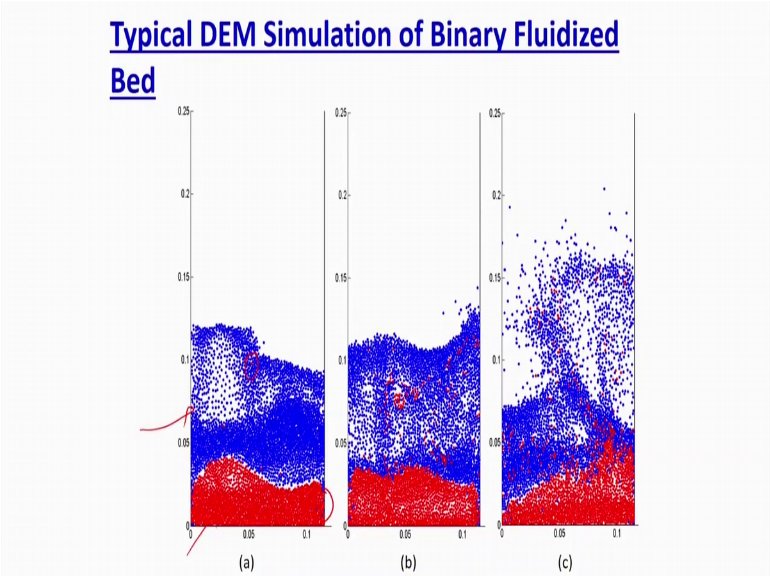

And, this is some typical DEM simulation we have performed in our lab and we have seen this is the red particle is heavier, blue particle is lighter you see initially the only both the particles are say fluidizing, but they are forming a clear cut interface, very small particles of the blue you can see inside here very small fraction of the solid you can see inside here if you keep on increasing the velocity some of the solid diffuses inside.

But, even we have observed that even very high velocity getting a complete mixing bed is a very challenging actually in this kind of. So, if you want to operate a complete mix bed structure you need to understand that at what velocity you are going to see the complete mix bed.

Neither you will see this kind of a structure we will see the partially mixed bed always that jetsam particles will be at the bottom, flotsam particle will be on the top and in between you will see certain mixing in the segregation pattern. So, your whole dynamics will change your whole reactor performance will change.

So, again I am saying that these are very very critical because you should know that how your reactor performance in the fluidized bed is going to depend. It is going to depend on the solids again gas velocity you are going to depend on the column geometry also column diameter, it is also going to depend on your particle size distribution.

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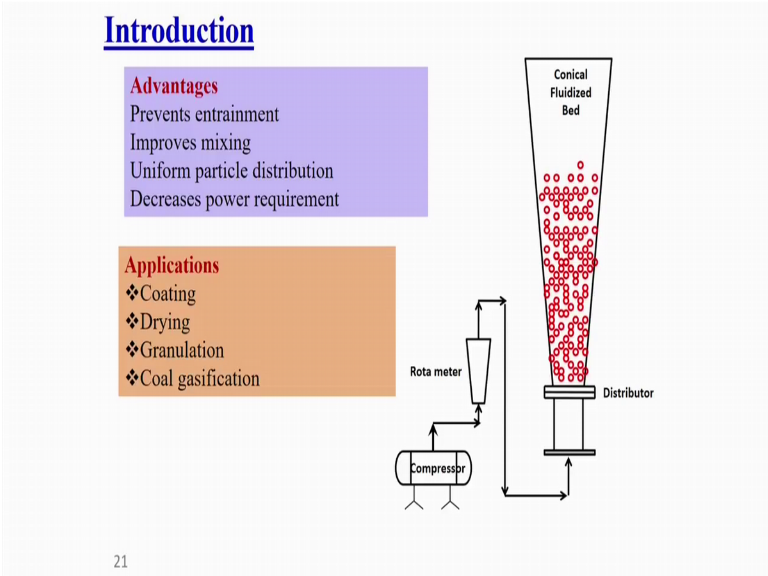

Now, another class of the fluidized bed which is being used widely in the industry is the conical fluidized bed. Now, this kind of a bed is being used for very coarse particles. If suppose I have a very coarse particle a particle say if I have to fluidize a tennis ball how to fluidize it we have minimum fluidization velocity will be very very high.

So, to reduce the minimum fluidization velocity or to enhance the fluidization what we do we reduce the column diameter at the bottom of the column. So, if you do that conical bed what will happen at the inlet the bottom the velocity will be very very high because your diameter is very low and which would be keep on reducing on the top.

So, it helps in two ways; it can fluidize your coarse particle at the bottom because your velocity at the bottom is very high and that you have gained because of reduction in the column diameters and will for the same flow rate you are getting now higher velocity. So, you fluidize your core particle.

Second thing it reduces your entrainment rate. So, it gives you the flexibility to operate at a higher velocity. Why? Because at the top you are increase the veloc[ity]- diameter. So, the velocity of the gas will reduce at the top. So, entrainment rate will be reduced. So, where the entrainment is a major critical issues we can use this kind of a bed, ok. Like it is being used highly in the granulation in the drying where the poly disperse nature is of the particle is there and there is a chances that the smaller particle or lighter particle may go out.

If suppose, you have a coarse particle and a smaller particle and you want to fluidize then if you are fluidizing in a higher velocity you can get a perfectly mixed bed condition at that condition what can happen the lighter particle because the velocity is very high can go out of the system ok, they can entrain. So, to reduce that you can increase the diameter at the top if you will keep on increasing the diameter the velocity of the gas will be reducing and you can reduce the entrainment rate.

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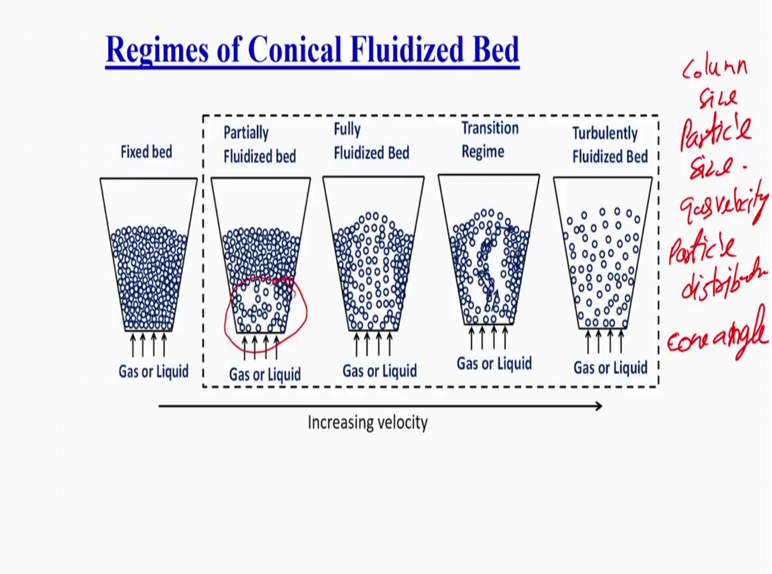

But, it comes at a cost and what is the cost? The cost is that again you will see a regime here that initially what will happen? The gas or liquid whatever you will pass, it will be a fixed bed condition then if you increase the gas or liquid velocity. You will see the fluidization is only happening at the bottom part; the top part is still is pretty much fixed bed then at a higher velocity. You will see that the fully fluidization happen, it means the whole column is being fluidized and then further increase in the velocity can cause the transition regime and turbulent fluidization regime when it is completely fluidized. So, the fluidization is there again a regime introduce into this.

So, if you do any modification what I am trying to say you will introduce a additional parameter. So, now, the column geometry also becomes a parameter. Earlier what was the parameter? Earlier the parameter was column size, particle size, gas velocity, particle distribution, now you have another parameter is the cone angle or the column angle.

So, you keep on modify anything you keep on adding one more parameter and it makes your life further complicated, but we need to do all this to have a better controlled in the hydrodynamics. So, hydrodynamics analyzing the hydrodynamics of the bed to understand the hydrodynamics of bed is still a major challenge and you do any change you add one more parameter which you need to understand,. So, that is the reason, but there is several advantage of this bed and that is why this bed is still preferred.

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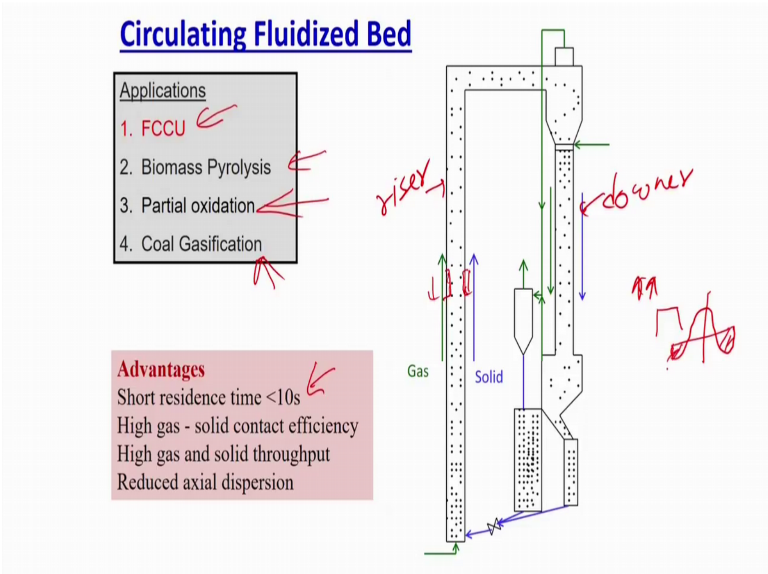

Then the last class is circulating fluidized bed where I said that what happen the particle entrainment rate is very high. So, it goes outside you have to catch the particle and put it back now this is very very important class of the rate can the fluidize bed and any fast reaction where the chances of the cooking is high where the kind of you want a properly controlled on the heat and mass transfer we use this kind of a bed.

So, this is if you see the important this is FCCU for the fluid catalytic cracking unit it is being used as a CFD biomass pyrolysis this kind of a CFD is used. Partial oxidation reaction again CFD is used, so that you can precisely control the mass transfer any partial oxidation if the contacting is very high then what will happen the complete oxidation will take place.

Similarly, gasification where you do not want a complete oxidation you want to use with the H2O you use the circulating fluidized bed. So, all the important class of the reaction is there and that is why this kind of a reaction hydrodynamics is very very difficult what happened in this case the both gas and solid or fluid and solid move upward in the riser part. This is called riser part, this is called downer part, the solid goes out the gas is being separated out from the cyclone the solid scratched back and sent back again to the system.

So, this is the bed which is called the circulating fluidized bed. The residence time is very very small it is only in 10 seconds. So, you have a very you should have a very efficient contacting very small residence time is there. So, part of the chances of the particle cooking or the catalyst cooking or the catalyst deactivation is low. The left of the part mostly the reaction is being done in the riser part where the reaction take place the downer part is being used to regenerate the solids and then again the phase catalyst or phase solid is being fed into the system.

Some of the reactors some of the distant studies have shown that this can be reversed, the riser can be used for the regeneration and downer can be used for the reaction part. So, there is a debate on this lot of work is going on. It is very difficult to conclude that which one is better or which one is not better because both have certain problem.

The riser has some major issue is that the particle recirculation or back mixing which we say. So, the what will happen that near the wall because the velocity of the gas will be very very small even if you operate at a very high velocity say turbulent flow and near the wall the velocity of the gas will be 0, because of the no slip boundary condition.

And, the solids whichever will come near the wall may started moving downwards. So, what you see you see a distribution in the residence time we want to operate a plug flow reactor. So, what we wanted we want that ok, if the solid fraction is very very high both will be moving coherently upward, and it will be kind of a perfectly kind of a plug flow reactor, but if the solid start moving downward then you will see something like this kind of a profile you see something like this kind of a profile.

So, at the wall you will see the negative velocity and that negative velocity will increase your residence time of the solid inside and that solid can have a coking, ok. So, your catalyst will deactivated or say you are doing the biomass pyrolysis you will now the solid will stay for the longer time. So, what will happen again you will come not do the pyrolysis you will move to the other regime. The gasification, same thing you want to gasify the coal, but if your resonance time will be very high you may go for the complete combustion.

So, you will kind of lost the things and that is why the solid recirculation is a major problem and that is why many people suggest to move towards the downer where the recirculation is come or solid back mixing, I will not say recirculation back mixing is completely ruled out because here both the forces are going downward. But, the problem is the gas contacting because gas has mutually tendency to go upwards. So, you have to push the gas downward. There are lot of debate going on lot of research work is also going on the downer and the riser comparison.

So, that is the circulating fluidized bed initially both the solid moves upward, very low solid fractions. So, better contacting, but that is the advantage and a disadvantage both because very low solid fraction if they were not in the very precisely want to control the heat and mass transfer this reactor will be very very costly to operate, ok.

So, need to be judicious by using the whether we need the circulating fluidized bed or not where you need to precisely control the heat and mass transfer of only there the circulating fluidized bed is being used, where the solid coking or solid deactivation rate is very very fast where you need to regenerate the solid very quickly this kind of bed is being used.

So, this is the complete classification of the different gas solid fluidized bed, we covered the packed bed, we covered the fluidized bed I will not say that gas solidified complete classification of the gas solid bed, we covered the packed bed, we covered the fluidized bed, we covered the different regime of the fluidized bed, we covered the different challenges which is being taken place in the fluidized bed and we say that whatever we have discussed in the mathematical model are in the experimental method how those can be used to analyze this kind of a bed.

With this our gas solid bed is also over and we come to the end of this course.

Thank you.