Multiphase Flows
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Lecture – 20
Packed Bed Reactor

Welcome back. Yesterday whatever we were discussing is about the diameter of the bubble, that how the diameter of bubble is being calculated. And what we have done we have said that there is different forces which are critical and those forces was buoyancy force, momentum flux of the gas, the surface tension force, drag force and inertial force.

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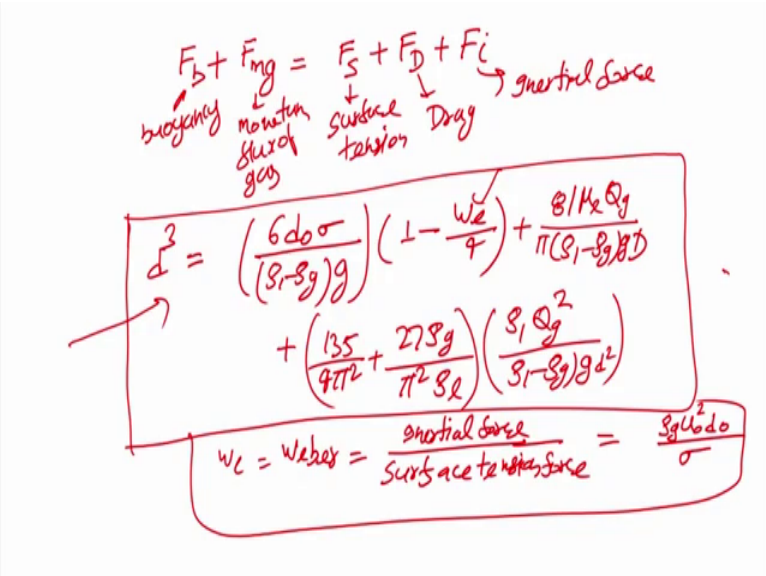

And we said that if we do the combined balance, we will get a diameter equation that what will be the diameter of the bubble which will be formed and, it will be detached from the surface ok. And we have taken a simple C plate holes where the small holes were there. And, that is going to be the function of the hole velocity, the flow rate, Weber number, and surface tension and all.

So, all this we have done we have also derived the formula for the simpler case where the buoyancy and surface tension is already playing a role, and the surface and this bubble size generated because of that. So, if you see this formula whatever we have developed if you see the such a first term Weber number term, only the first term of this which will be multiplied by 1. So, it will be the first term that will be the only formula for the diameter of the bubble once only buoyancy and surface tension is playing a role. If all other forces are also playing the role, then you will have a different formula and which you can use to calculate the bubble diameter ok. And if you see this is the function of Weber number, and Weber number is defined as the ratio of inertial force to the surface tension force, ok.

And which is critical to determine the bubble diameter. Now several researcher have put their own correlation or different correlation to calculate the bubble diameter depending upon the different cases the properties of the system, or different type of the systems. So, I am not going to discuss all those correlations, but what I am going to see what I have discussed already is about the basics how these correlations are derived. Now you can say that for certain system some forces are important, some forces are not important and, you can modify the equations or the diameter of the bubble, but the basics remains same.

The next question in the bubble column design, if you go for bubble column design or if you want to understand the bubble column is; what is the shape of the bubble? So, what we have done we have found that what will be the diameter of the bubble. As I said that I am interested in the mass transfer, I am interested in the heat transfer, I want to do the reaction. So, I have to first see that what will be the shape of the bubble depending on my flow rate.

Again I am quoting that I am not taking coalescence into that account, if the coalescence will take place a bubble break, will take place this story may be little bit different and you have to model the bubble size distribution and all that can be done with the advanced model, I will give the glimpse of that, but if you have interest we can go and discuss, we can discuss it further. You can write it to me.

This is the next problem is the bubble shape that what will be the shape of the bubble once it will be formed.

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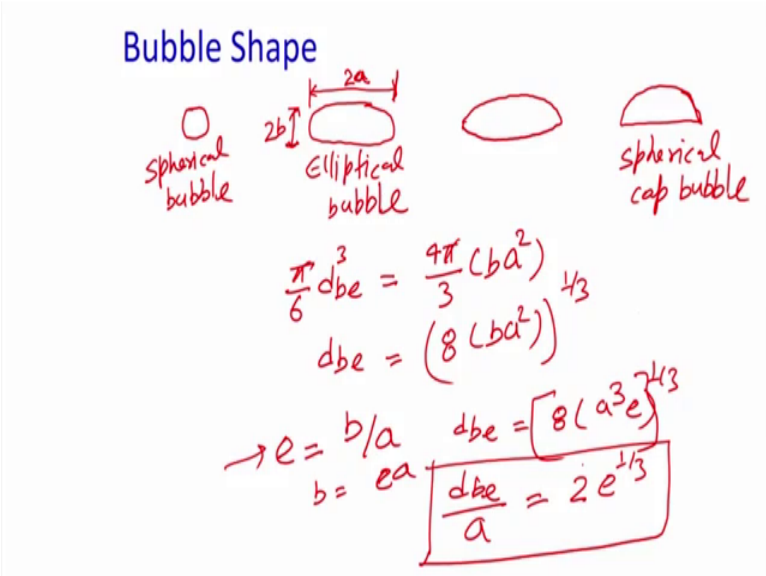

So, generally the bubble 4 type of bubble shape is being reported in the literature and, the first shape is if the bubble is very small in diameter it will be cynical in nature. So, you will see a very pretty much spherical bubble. So, if the bubble is small you will see the spherical size bubble, but if you put more gas then what will happen before detachment bubble size will increase.

Now once the bubble size will increase it will go to elliptical bubble when you see a ellipse nature. So, this is elliptical bubble, now if you further increase the velocity or the bubble size it means the bubble size what will happen, you will see the bubble which will be kind of elliptical, but the upper surface will be more towards this silicon and the bottom surface you will see some (Refer Time: 04:02) elliptical portion ok.

But it will not be perfectly ellipse the upper top surface will start swelling up and it will be going towards the spherical shape. And if you further increase the velocity then you will get that a spherical cap bubble, it means this bottom will get flattened up the bottom will go up, it, will be flatten up and the top will becomes more and more spherical you will see this kind of a shape. Now this bubbles will start bubbling well if you keep on increasing it you will get the spherical cap bubble. So, this is called a spherical cap bubble spherical cap ok. So, this kind of 4 type of bubble is being formed depending on that velocity and the orphans diameter which you use for the bubble gas injection.

Now, we know that if suppose the spherical bubble is forming you can calculate the diameter of the bubble very simply that it will be what it will be the volume of the bubble you can calculate and that will be pi by 6 D p cube and, if you know the volume of the bubble you can calculate the diameter of the bubble. Now if suppose this is not a spherical, then the problem comes that how you will define the size of the bubble because, suppose is a elliptical then what you are going to do how you are going to decide the size of the bubble. Now to bubble size or bubble shape are actually going to be different and what we will decide, we will decide based on the equivalent diameter ok. Now equivalent diameter how you will say that for elliptical thing, then we have to find the equivalent diameter based on that elliptical volume.

So, we will take the volume of the ellip elliptical bubble and we will say that this would be equivalent to whatever the volume of the spherical bubble. So, this volume will be fitted in which diameter of a spherical bubble which have the same volume as the of the elliptical bubble. So, you have to do the volume balance and based on that you can find it out the de correlation that what will be the equivalent diameter equivalent to c a diameter for the different shaped bubble. So, we define it that way.

So, say for elliptical bubble if this isif the major axis is say a, and I am using a notation which you might have used widely in the mathematics classes. So, this is say a and if this is b, or let us make it the mathematic little bit simpler let us say it is 2 a and this is 2 b. So, that from the axis it is a one side, and from the axis the height is b. So, if it is 2 a and 2 b and I want to find it out for this elliptical bubble which major axis is 2 a the minor 1 is 2 b, then what will be the diameter of the spherical bubble which will have a equivalent volume as of the this elliptical bubble.

So, to do that there is a very simple mathematics we know that volume of the bubble for the spherical bubble that will be pi by 6 say D p cube I will write it D p e cube, or say let us write it d b e let us give a notation which is d b e, it means the bubble volume diameter which is equivalent bubble diameter in terms of the spherical if this volume is equal to the spherical bubble volume. So, I will write it d b e, and that will be equal to that what will be the volume it of this. Now this volume will be pi by 4 3 and then b into a square. So, that will be the volume of the ellipse and that is equivalent to this volume. So, you can find it out what is d b e. So, d b e if you calculate from this place that will be what d b e will be equal to this pi pi will be cancelled out this 6 so, you will get 8 into b a square whole raised to the power 1 by 3.

So, you will get this will be what will be the d b e for the elliptical bubble. Now this d b e can be used further to do the calculation because, we know the calculation whatever the we did the calculation till now in the multi phase flow, we did it for the spherical particles. So, now you can use this d b e 2 and use your equations whatever we have discussed the momentum equation the continuity equations and, then you can solve these problem by using d b e to get that does you can solve the momentum equation.

So, that will make your life little bit easier and that is why for all the bubbles we define it in this way the diameter we define for this way in this way. Now how it will be generated what will be the diameter that you will be generate whatever I have said in the previous, but if suppose the bubble shape has generated that diameter will be further modified and, you have to use this kind of a d b e this d b e can be used in your momentum equation in your continuity equation if needed or any other equation which we have discussed till now. So, you can use this to do the calculation ok.

Similarly, you can do it for the other shape also what you need to do you have to just find the volume of that shape and that should be equivalent to the volume of equivalent volume of the sphere which represent the same volume. So, that is the way you calculate the d b e in this way. Now for wobbling bubble, or a elliptical bubble, different people have given different kind of a correlation to calculate that what will be the d e what will be the d b e why because, it is difficult to measure the 2 a and 2 b how you will measure that. So, what you need to do if you want to measure the 2 a and 2 b, then you have to depend on measurement techniques you have to take a high speed camera, you have to take the photograph of the bubble send off.

So, what people have done people have tried to correlate it with the for the different condition different system and many people many researcher has given different correlation to predict that what will be the d b e ok, and d b e instead of d b e they have defined it in a parameter, in another parameter, for say elliptical bubble they have parameter the parameter they have defined is small e and, that is small is nothing, but it is equal to b upon a. So, they have defined a parameter e which is b upon a what is the smaller to the maximum angle. So, e value is going to be less than 1 so, this way they have defined that whatever the e value, they have tried to correlate this e value with the different correlation.

Now, once you have this e value what you can do you can convert this in terms of the e, you can say that in terms of the e and you can get the d b e correlation that what will be the d b e correlation. So, suppose if you want to calculate in terms of the e what you can do you can replace say b with the e, if you do that then b will be equal to e into a. So, if I replace it here it will be d b e will be equal to 8 into a and cube, this will be a cube and that will be multiplied by e 1 by 3. Now sorry whole raise to the power 1 by 3, now if I do that then it will be d b e upon a will be equal to 2 e raised to the power 1 by 3. So, I can develop this correlation.

So, now if I know this d b e upon a if I know this e value. So, people have what they have done they have calculated this e value given the different correlation in terms of the e, for the different flow rates for the different surface tension to the gravity to the surface tension ratio based on that, and they have for depending upon the different flow rate, different fluid property and all this e value will keep on changing and the correlation has been developed, in which you can see that how the e will be correlated for the different system.

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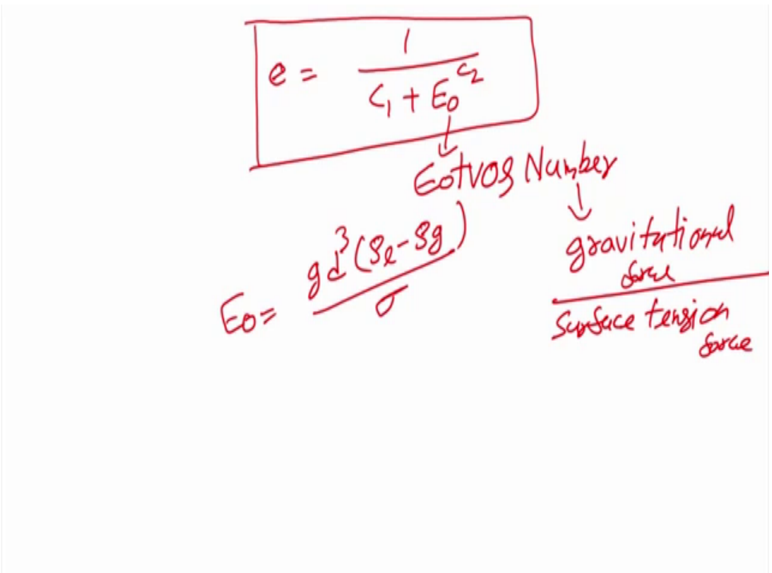

So, several such correlation is available, but most of those correlation again is being available in the form of e say if I want to find this e e is equal to 1 upon c 1 plus Eotvos number raised to the power c 2.

So, most of this correlation is in this form e is equal to 1 upon c 1 plus E naught E o raised to the power c 2. Now this E o is what it is Eotvos number. So, this E o is a Eotvos number and which says the ratio of gravitational to the surface tension force. So, this Eotvos number is actually gives the ratio of gravitational force to surface tension force ok, that is going to determine that what will be the shape of the bubble. So, this is this correlation is there now many researcher have used most of this correlation has formed at it in this way, the value of the constant c 1 and c 2 are the constant depends on your semi specific. And if you change your system, you change your property, you change your conditions this value of c 1 and c 2 will change.

But most of this correlation of the e is validated in this way for elliptical and wobbling bubbles ok. Now what is the Eotvos number actually you correlate in terms of the Eotvos number and if you write the Eotvos number for this case it will be g d cube and it will be rho of liquid minus rho of gas upon sigma. So, this is the way Eotvos number is being defined. So, you can say that this is going to be the gravitational forces what is the gravitational forces there and what is going to be the your surface tension force ok. So, this is the ratio of this most of this correlation is being developed it in this way. So, you can find that what will be the shape of the bubble and, if you find the shape you can also find the e value if you know the e value you can find in the d b e value ok. So, all these correlation all these things you can find it out ok.

Now, this d b e can be used in the momentum equation, or any other equation which you want to understand the flow. So, that is the way we discuss about the shape and definitely there is mainly 4 type of shape is available as I said it is spherical, if the velocity is very less, bubble diameter is very less, most of the bubbles are spherical in nature if the diameter is very less. So, if the diameter is less it will be spherical bubble if you increase the diameter further it will be elliptical, if you further increase the diameter flow rate from which the diameter is increasing the bottom portion will start shrinking, the top portion will be becomes like a sphere. And then further increase velocity you will see that a spherical cap bubble where the bottom will be flat and the top will be the spherical shape a spherical cap kind of a behaviour. So, this kind of a force shape of the bubble is being formed.

Now, next is what will be the bubble velocity how to calculate the bubble velocity. Now if I know the velocity, I know the diameter, I know the shape, I can calculate about the mass transfer provided, if I know the volume fraction ok.

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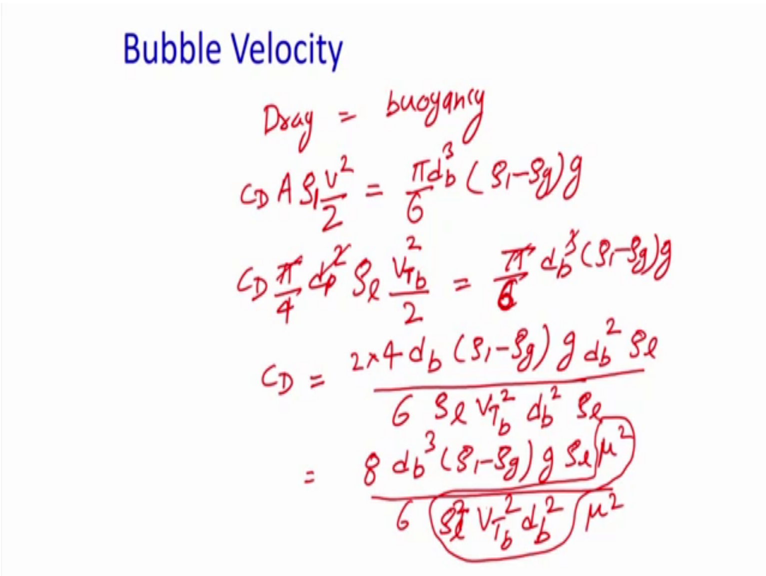

So, for volume fraction again several correlations are available most are those correlation are empirically fitted correlation based on the experimental data. Again I am not interested to do all those things here because, that will be a dedicated work on the bubble column reactor, what we are trying to see is that how the basics force balance equations can be used to understand or to solve the these kind of a reactor problem.

So, in the bubble column again if you want to find the velocity, then we know that how the velocity if the bubble will move upward, once it will achieve its terminal velocity then what will happen, that the forces acting on it will be equal. Now what will be the forces acting on it will be buoyancy force, it will be gravity force and it will be the drag force, they are going to be equal. Once they are going to be equal the bubble will achieve its terminal velocity and it will rise with its terminal velocity.

And that is going to happen because, when the bubble will start then after certain time it will achieve its terminal velocity, it will achieve where all the forces will be balanced, and then it will be achieving its terminal velocity. So, if you want to calculate that what will be the bubble terminal velocity, then what we can do again we can use the force balance equation which we have done. We can say that drag will be equal to whatever the drag will be equal to the buoyancy minus the gravity because, this bubble will be lifting upward. So, what will happening that gravity will be going to be balanced with the drag and this ok.

So, drag and the buoyancy so, in that case if I write the equation I will say that the drag force is going to be equal and we calculated the drag force. So, drag and buoyancy will be equal and once I say buoyancy interact will be equal I am taking the gravity in part of the buoyancy. So, if you do that you can write it as a C D the drag force equation is C D into area into rho into V square upon 2. So, that will be the bubble this and, then buoyancy will be pi by 6 or you can say pi by 6 d bubble cube and that will be rho l minus rho g into g. So, that will be your overall the buoyancy force which will be acting buoyancy of this because of that it will be this kind of forcing it.

So, drag and buoyancy is going to be equal the buoyancy will be pulling it upward drag will be pulling it downward ok. So, in that thing if you do it then what will happen that your this forces will be equal so, if you do that you can write it in terms of C D, if you know that area what will be the area if I am taking again a spherical bubble the area projected area will be pi by 4 d b square, this will be the row of fluid or it means it will be if I am taking liquid, this will be flow of liquid into velocity of the bubble.

Now say if velocity of the bubble, we are getting it the terminal velocity to I will state V T b square terminal velocity of the bubble divide by 2 it will be pi by 6 d b cube into rho l minus rho g into g. So, you can simplify it further we can write it in terms of the Reynold number. So, if we try to write it in terms of their internal number. So, that we can easily do it we can write it in the non dimensional form I can say that C D will be equal to I will writing in I am trying to write it in terms of the Reynolds number.

So, this pi and this pi will be cancelled out it will be this 4 D p and this D p will be cancelled out. So, you will get d b ok, then you will say rho l minus rho g you will see g and then it will be once you will divide it you will see that pi by 6 naught d. So, this will be 6 and this will be rho into l rho l.

So, you will get something like this now what we need to find, there will be this V T b square also V T b square. Now this 2 will be also multiplied so, this will be the 2. So, you will get this kind of equation for the C D which we have already developed. So, if you see that C D will be equal to this 2 pi pi will be cancelled out d b cube if you go out so it will be only d b. So, this will be 4 into 2 8, then it will be d b rho l minus rho g into g upon rho l into V T b square.

Now we can write it in terms of the Reynolds number, if you want to write it in terms of the Reynolds number what we have to do, we know that what is Reynold number I have to multiply it here by it is V square. So, I want to write it in terms of the Reynold number a square function so, that my velocity will be accommodated. So, what I am going to do if I want to write it in this way, I will write it d b square, I will multiply up d b square down, I will multiply 1 rho l up I am multiplying with 1 rho l up and 1 rho l up 1 rho l down.

So, what will happen now this equation will be 8 into d b cube rho l minus rho g into g into rho l upon 6 rho l square so, rho l square into V T b square into d b square. Now what we need we need mu square up and, then 1 mu square will be multiplied with the down. Now if you see this is what this is nothing but Reynold number.

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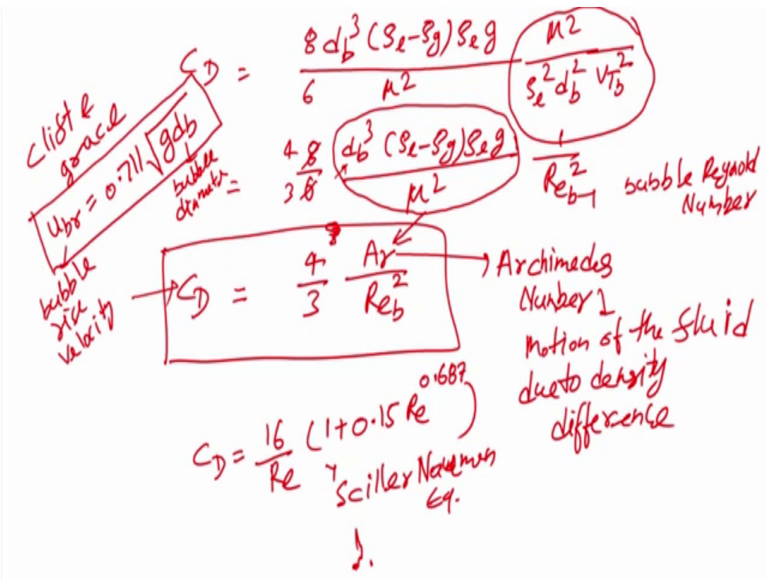

So, I can write this equation as C D will be equal to 8 upon 6 8 d b cube rho l minus rho g into rho l into g upon you say mu square 6 into mu square and, then this value you can write it as mu square upon rho l square into d b square into V T b square. Now this function is nothing, but 1 upon Reynold number square. So, I can write it as 8 upon 6 this will be 8 upon 6 d b cube rho l minus rho g into rho l into g upon mu square, and this will be 1 upon Reynold number square, so, we find that Reynold number and because this is based on that. So, I will say Reynold number of the bubble, so bubble Reynold number square. So, this is bubble Reynold number.

Now, this function whatever we are saying that this is nothing, but are called Archimedes number. So, this function is called as Archimedes number and this will be if you write it here then it is 8 by 6 or you write 4 by 3 better. So, you will write 4 by 3 Archimedes number upon Reynold number square Reynold number of bubble square that will be the C D value.

Now, Archimedes number this is nothing, but Archimede number and which defined the motion of the fluid basically due to the density difference. So, this is the Archimede number defines the motion of the fluid of the fluid due to density difference. So, why the bubble is rising bubble is rising mainly because, of buoyancy and the buoyancy is being generated mainly because of the density difference. So, Archimedes numbers shows that the motion of the fluid of motion of the bubble, because of the density difference it is being characterized by the Archimedes number and the Archimedes number is being defined by this value which is d b cube rho l minus rho g into rho l g upon mu square.

So, that is nothing but the Archimedes number; and Archimedes number actually characterize, the motion of the fluid due to density difference. So, if I do the force balance again I will get the correlation between C D and A r e. Now what if you want to find the bubble terminal velocity you have the formula available, that what will be the bubble terminal velocity. Now the only question is what will be the value of C D.

Now again we have discussed several correlation while discussing the drag force, you can use depending upon the system, depending upon what is your Reynolds number as we discussed that several correlation is there we are valid for a particular range, you can find the C D value. Now most important or most oftenly used or widely used correlation for the C D for the bubble column is Sciller Nauman which is 1 upon sixteen upon R e into 0.15 into R e raised to the power 0.687 this is nothing, but the Sciller Nauman equation. So, Sciller Nauman equation is being used widely to do this C D.

Now, if you have the C D you can correlate, it you can find it out the bubble velocity, it will be also the function of Reynold number, you can get the bubble velocity. So, Archimedes number if you if you see the Archimedes number, if you know the bubble diameter, if you know the system, you know the system viscosity, you know the density of the liquid. you know the density of the gas and if you can calculate that what will be the d b what will be a bubble diameter.

Then what will happen Archimedes number will be calculated, now bubble diameter will be fixed the moment you fix you distribute your plate, your gas velocity, we have already discussed that how to calculate the bubble diameter. We have already discussed that how D p will be modified if the bubble diameter is of different shape, you can do that you can calculate the d b, if you know the d b you can calculate the Archimedes number, if you know the Archimedes number ideally speaking, you can calculate the terminal velocity of the bubble. So, we will also get that what will be the bubble terminal velocity.

And if you get all this phenomenon you can actually model all the things you can understand that how the velocity of the bubble is there, what will be the velocity of the bubble you can develop the correlation, for the mass transfer for the heat transfer and all and you can analyze the system. So, this is the basic force balance we are doing, again we have neglected many of the part like we have not included the shear that which will be caused and, which may change the bubble shape, bubble size.

We have neglected that if the bubbles are having coalescence or their changing the shape over the time, or if they are having the coalescence they are forming a bigger bubble they or they again they break into the smaller bubble, we have not taken in to the account any distribution the bubble death, or bubble generation, or any shear migration, or any because of the shear or any other forces the breakage of the bubble, all those things we have not generated, we have not done.

Because if you do that then you cannot solve it the analytical solution and, I said in the beginning itself that the motivation of all this course is to have a analytical solution a simpler solution to analyze the flow, if you want to have a kind of a detailed solution whatever I said, then we have to go for the numerical modelling approach which we have already discussed in the previous cases.

So, this is all about the bubble column force balances, now as I said that different type shape of the bubble is being formed different regimes is being there, and because of the bubble coalescence bubble death and all.

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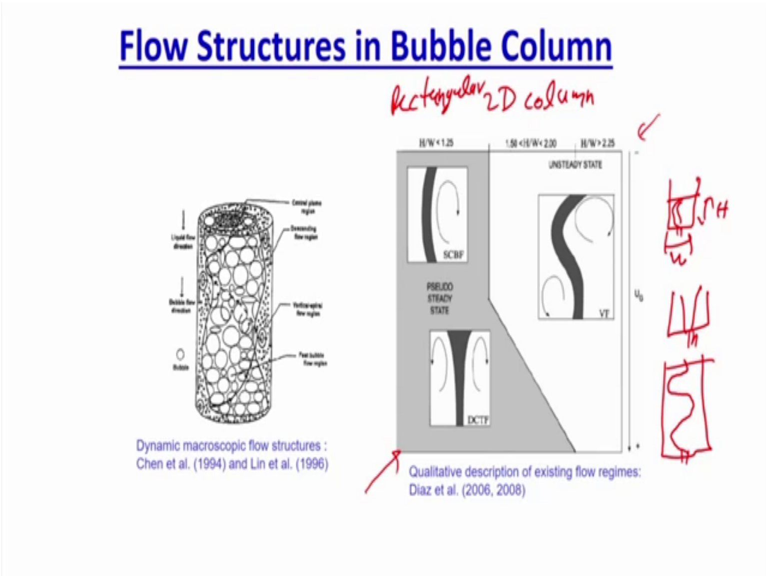

The typical flow structure there are several flow structures has been found in the bubble column, but different flow structures depend again on the column geometry, column dimensions, your velocities properties of the fluids all these actually play a role in determining these structures. Now these are the 2 graphs where the Diaz et al in 2006 and 2008 and followed by some of my own work which we have published in as a thesis, and some chemical engineering science paper, we have observed that there is different regimes you can get different kind of flow structures, you can get and that flow structure in 2 D column this is for the 2 D column and I will not say 2 D column I will say it a rectangular column.

So, in the rectangular column these are the flow regimes is being observed, that if your velocity if you are increasing on this side what will happen, if your now velocity is their low H by W ratio H by W ratio means height to width ratio of the liquid say this is the width and, this is the height of the liquid inside. So, if the height to width ratio is lower say around 1 you get that what happen if you inject the plume, you will see a single plume which moves towards 1 wall, if you have higher velocity for H by d ratio 1 H by W ratio less, than 1 then you will see what will happen that whatever the gas you will inject it will form like a jet and it will move outside. If you have even higher height, then what will happen you see the unstructured behaviour and you observe certain plume. So, if suppose the height of the liquid is there, and you inject the bubble. So, I inject the gas it form certain plume you will see this sneak kind of a plume behaviour is there.

So, these works are being done again these are the detailed analysis of the bubble column, but I am just trying to show you that the regimes are there in the bubble column even, if you operate the bubble column there are different regimes and that regimes again, if you see these things it is going in the rectangular column, it is going to be the function of the dimensions of the column, or the liquid height inside the column, it is going to be the function of the velocity at which you are operating the column ok. And if you make it inclined or something it would be also the function of inclination.

Similarly, Chen et al and Lin et al as in 1994 and 1996 has given the dynamic macroscopic structure, and they said that their different structures are being formed. And if you want to analyze those structures, you cannot use the single model which can predict all the structural which can cover all the structure and the multi scale nature of the bubble column has been showed, it means you have to use the different scale model or you have to use the model which can be used at the different length scales, which can predict at different length scale, or which is accurate or equally valid at different length of scale, then only you can found all the structures inside.

So, this is about the glimpse of the bubble column whatever is available industry, you can do the simple calculations, if you want to find that what will be the shape of the bubble, what will be the velocity terminal velocity of the bubble, what will be the diameter of the bubble, or you can have a numerical methods again you can have a detailed analysis.

So, you can do the simple force balance and you will get a clear cut idea, or not even the very clear cut idea, but at least you will get a fair idea that how your system is going to behave, what will be the bubble size. At least the bubble size you will calculate definitely to be very close to the mean bubble size, which you will be found in your system. So, what will be the bubble size what would be the diameter of the bubble, or what will be the bubble size, what type of shape you will get if you are getting this shape how the bubble diameter will change, what will be the velocity of the bubble which you will through which it will be moving upward.

So, different correlations is also being developed again I saying that while telling the velocities this you can find the velocity here, different researcher have, different given different correlation lot of correlation is there one of the important correlation which I missed here is actually given by the Clift and grace. To find that what will be the bubble rise velocity and, they said that bubble rise velocity U b r which is the bubble rise velocity it will be equal to 0.711 under root of g into d b, where d b is the bubble diameter, and g is the gravitational fault. So, this will be there.

So, similarly lot of people have done different correlation has been developed, you can calculate the bubble rise velocity, you can find the if you know the bubble rise velocity, you can find that what will be the residence time inside, that will be kind of you can be discuss, you can if you know the bubble this now, you can calculate the Reynolds number you can use your mass transfer equations, to calculate that mass transfer whatever it is happening. You can use the film theory, you can use the penetration theory, you can use the surface renewal theory, all those theories whatever you feel is valid or is valid for your case, you can do that you can do the analysis of the bubble column, you can see that how much reaction is going to happen what will be the conversion, what will be the residence time. So, all those studies can be done.

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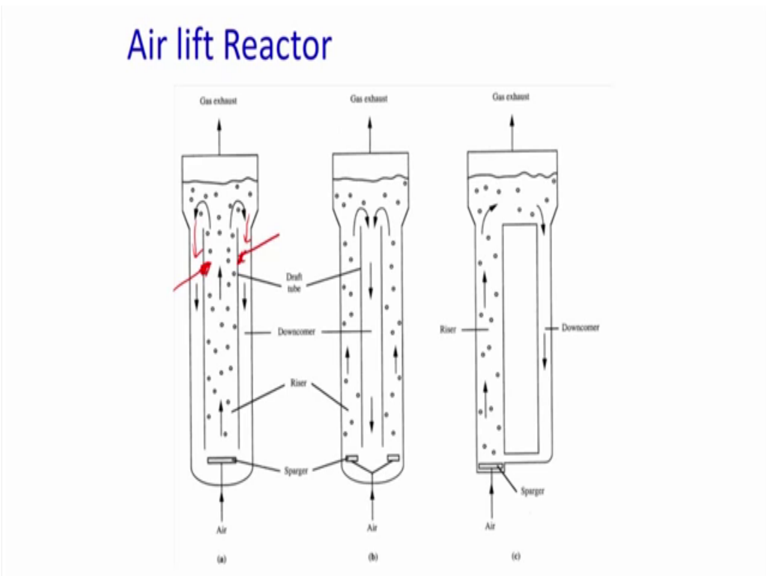

Similarly, the another class of the bubble column you can say is air lift rector. Now this is again a gas liquid system what we do we give the guided path to the gas. So, what we put we put some 1 riser and downer this. So, we put some draft tube these are the draft tubes sorry, this is the draft tube and this is the draft tube and what we happen we inject the bubbles, or we inject the air only and that the riser section, why we call it riser because here the bubble is moving upward, and with the bubble liquid will also move upward.

Now what will happen on the disengagement section, the bubble will go outside of the system while the liquid, which is coming here because most of the bubble is coming from this place on this place. The liquid will have only 1 path to go down from this place which is called downer, and again it will come back and do the riser. So, you get a directed flow this kind of a system is widely used, there are different geometries possible the riser can be centered, of the column the riser can be near the wall, or it can be on the one side it can be riser, other side can be downer.

So, different type of structures are available, these kind of flow reactors are widely used for the biological application, rest water treatment or any (Refer Time: 32:23) kind of a generation of biological application this kind of air lift reactors are widely used, all the principles are going to remain same, the force balances are going to remain same, as we have discussed earlier ok. The only thing will be the structure will be different and if you want to solve the 3 dimensional simulations, the way we did the modelling then the models will be little bit different the flow profiles will be different, but the basic force balance for the bubble size, for the bubble velocity for the shape, this these are going to be the same as whatever we have discussed till now.

So, with this gas liquids column or gas liquid systems, we have covered which is the main class is the bubble column and air lift reactor ok. So, I am not going to discuss air lift reactor in detail, if you have any problem or if you have certain interest please write to me on forum and, we will try to discuss it further ok, but that will be the offline discussion.

So, with this we will move now towards the gas solid reactors. So, gas liquid reactor we have already covered, the next class of the reaction, or next class of the reactor is gas solid reactor.

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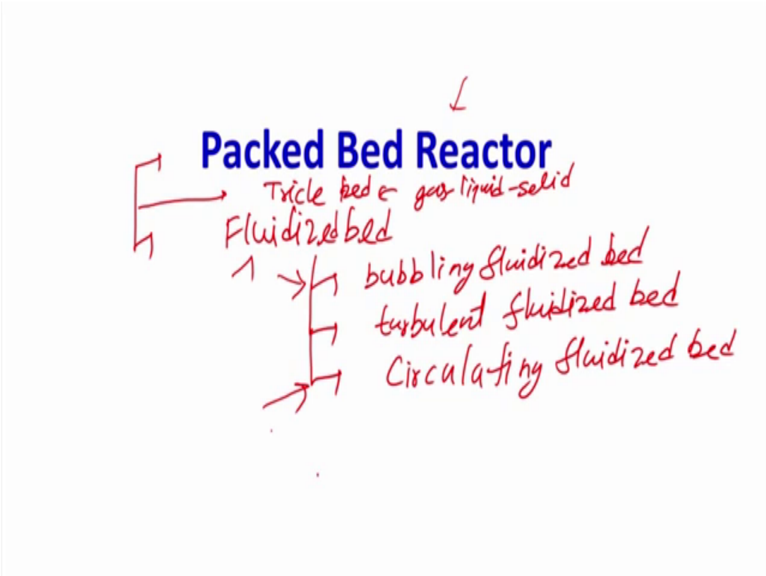

Now in the gas solid reactor actually there are different type of reactor available, now those are packed bed reactor is 1 of them, then fluidized bed reactor actually before fluidized bed there will be 1 more thing will come which is called tricle bed, but that is mostly tricle bed are gas liquid solid, most of the time it is being operated as a gas liquid solid not most of the time the tricle bed reactors are gas liquid solid reactor, then fluidized bed reactor, then fluidized bed has a certain class, now it can be bubbling fluidized bed ok, it can be turbulent fluidized bed, fluidize or it can be circulating fluidized bed. There are several other class, we will discuss about the regimes, but mainly this is divided in this 3 part bubbling, turbulent and the circulating fluidized bed.

So, what we are going to do now, we are going to discuss briefly about all these beds we will discuss mainly about the packed bed tricle bed is approximately same again all the force balance will be going to be the same, only the liquid part will be increased, then we will discuss about the fluidized bed and in the fluidized bed we will try to discuss mainly about the bubbling bed and briefly about the circulating fluidized bed, again we will try to see some force balances here.

So, let us start with the packed bed I will briefly cover it most of you might have done it thoroughly, but I just want to show that how the force balances which we have learnt can be used to do the force balance in the packed bed and to derive the some of the equations, which is widely used in the packed bed reactor.

So, now what is packed bed or fixed bed, it is also referred to as a fixed plate what we do we dump the solids inside the column, inside the reactor say this is my reactor vessel, we dump the solid though I sold a very systematic bed, but generally the bed is not being. So, that was symmetric. You dump the solids and it forms a certain shape inside. The only thing is you operate it at a velocity that the bed will not move it is lower than the fluidization velocity, or minimum fluidization velocity, the solid will be in the packed form ok, and it means what it will be packed and they will not move in the time frame of reference.

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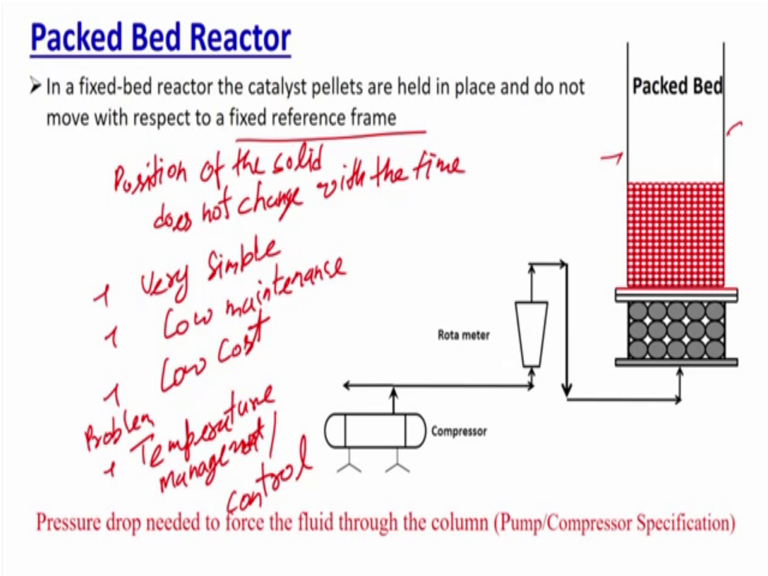

If you talk about the with the time the particle movement will be 0 they will not be moving so that this kind of a bed where the particle is being dumped, or catalysts are being dumped and, they held at a certain place and their place or their position does not change with the time it is called as a packed bed. So, the position of the solid they move certain things, but not much position of the solid they can vibrate, but they cannot move solid change with the time.

So, such frame of reference is called packed bed reactors, now this is 1 of the simplest gas solid reactor ok, very simple the advantage is low maintenance, low cost, because there is nothing available here ok. So, this is all is there the only problem is the heat management, the problem is temperature management or heat management slash control. So, this is the only problem neither generally this reactors are very calm, very simple what you need to do very simple to operate also and, there is no maintenance cost almost only the cost of the catalyst you need to change, but the column wise the reactor wise there will be no maintenance it will be available. So, it is and it is very low cost because you just have to dump the solid inside.

You take a vessel you dump the solid inside, you pass the gas or the liquid you can pass the gas or liquid, and you have to maintain it in such a way that the particle does not fluidize ok. So, you have to maintain a velocity which is lower than the minimum fluidization velocity. The only drawback of this column is you have a very high pressure drop, the pressure drop will increase and if you keep on increasing the bed length of bed height the pressure drop will be very high. So, what is the basic question which you have to encounter and once you are designing a packed bed reactor is that what will be the pressure drop, or what will be the pump specification of blower specification, or compressor specification, you need to pass the flow or pass the gas from this packed bed.

So, you have to give that much delta P that that should be operated at that delta P or that pressure then only the gas will pass through this bed. So, that is the only question is being asked or you should understand that this much is the pressure requirement is there. So, the delta P calculation in the packed bed is the major critical parameter ok, the bed has certain several advantages I discuss very simple geometry, low cost, low maintenance, it performs well only for very highly exothermic reaction, or endothermic reaction.

Whether the heat evolved from the system, or you supply the heat from outside of the system you are supplying the energy from the outside, what happened if the diameter of the column is very big, then you will not see they will proper temperature balance. So, you will see the temperature gradient across the radial and across the axis also if you are supplying the temperature, or hot air or something hot fluid. So, you will see the temperature gradient the temperature maintenance or temperature management of the bed is not that good, temperature control of the bed is not that good, and in case of very fast reaction a very highly exothermic reaction, you see some hot spot formation and it may also cause a runaway reaction.

So, these are the basic drawback of the packed bed reactors, but the major advantage is it is a simple you have to just dump the solid and then forget about it your job will be done.

So, it is very easy to operate very easy to handle, very easy to maintenance, and it is low cost and that is why that given a choice, if I have a choice I would never like to operate a fluidized bed, I will always try to go with the packed bed the fluidized bed we operate and we will discuss about the fluidized bed.

Once the conditions are such that we cannot live with a packed bed reactor ok, in the packed bed the calculations are very simple you just need to have 1 question in your mind that what will be the pressure drop needed, to force the fluid through the bed and based on that pressure drop calculation, you can calculate that what will be the pump specification, or compressor is specification, or blower specification, you require. So, what we are going to do we are going to see that what will be the force balance.

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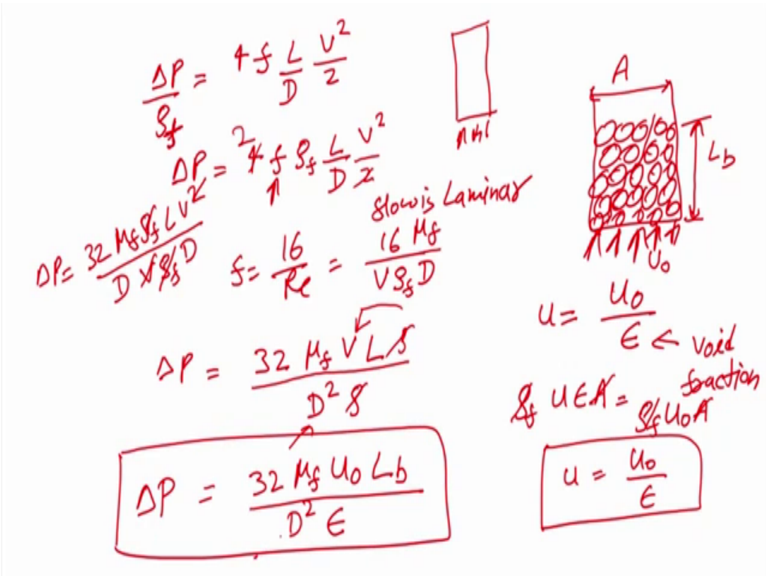

So, suppose this is a bed and certain solids are dumped inside of the bed as you eat, there is some you are seeing some force. So, the solids are being dumped, they are being kept inside. Now let us assume that the height of the bed is say L b this is the length of the bed and the area is a capital A is the area of this, or you can say the diameter I am writing in terms of the area, because the area will be cancelled out all the time. And this is the superficial velocity which is say U naught, which will be the superficial velocity of the gas, which is going inside the reactor. So, what we need to do we need to calculate that what will be the delta P.

Now, let us assume that we have already done that delta P calculation in the beginning of this multi phase flow courses. And I will take you a little bit back and we have also discussed it in this course that for single phase flow how you will calculate what will be the delta P equation, we have already done that we have seen that you can solve the Navier stoke equation or Bernoulli equation and, you can derive the delta P. So, the delta P equation for the single phase flow where the flow is taking place in a pipe is being kind of derived and that equation, if you remember this delta P will be equal to 4 delta P upon rho will be equal to 4 f, they should be friction factor L V square upon 2 this will be divided by D.

So, this is the delta P equation where f is the fanning friction factor. So, you will get this equation now this equation again can be modified actually you can see that how to calculate so, you know the delta P in a pipeline. So, this is the equation only if the single pipe line is there 1 pipe line is there empty pipe line, where the fluid is passing. So, what will be the delta P of the fluid you can calculate it with this equation.

I do not want to derive this equation we have done out already in the earlier class you can do it ok. So, this will be the equation we use for the delta P ok, delta P upon rho. So, I can write the equation for delta P. So, delta P equal to 4 f into rho, now rho of fluid or I said that say I will write it in terms of the fluid, why because it can be gas, or it can be liquid the basic force balance equation remains same. It will be L upon D into V square ok.

Now, that is what is the pressure drop in a pipeline, where there is no solid present. Now if there is a solid present what will happen your what the pressure drop equation will be modified. Why the pressure drop equation will be modified? Because now the gases or the liquid whatever you will flow across it or whatever you will pump or push through this bed, with go through the path available or the fractured path available between the solids.

So, suppose this is the path available it will go through this, it will never go through the solids till the solids are not porous, assume that solids are non porous, they it will not pass through the solids. So, it will go through the path which is available after the packing of the solids. So, which is the torturous path is there or the wide fraction which is present within the solid. So, it will go through that and because of that what will happen, your equation will get modified now how the equation will get modified will try to see that.

So, coming back to this equation what we are going to do we are going to take the delta P in empty column and, then will pack it with the solids and we will see that how this equation will be modified. Now we know that this equation actually the friction factor is a major problem that what will be the friction factor and, this friction factor is a function of Reynold number.

And we know that if the f Reynolds number is laminar or this flow is laminar, I will say not I will not write the Reynolds numbers number because, that is valid only for spherical pipe, I said that if flow is laminar, then f is equal to 16 upon R e Reynold number and R e is nothing, but 16 upon V into rho of the fluid into D upon mu of the fluid ok.

And this is the diameter of the pipe. So, I can modify this equation and this equation will be 32 into mu into mu of fluid into V into L upon D square into rho of fluid ok. So, that will be it would be modified now rho of fluid rho fluid will be cancelled out, actually of fluid is here also. So, this rho of fluid rho of fluid will be cancelled out, so, you can say that this will be the delta P equation this will be the delta P equation.

Now, what we need we need to know that what is the diameter, what is the diameter now the diameter will not be the diameter of the system because you are going to have a void. So, the exact diameter is not the diameter of the system, exact diameter will be the fraction where the voids are present wherever the void is there. So, you need to find this D value and you need to see that what will be this V value, earlier we can take a superficial velocity because the column was empty ok. So, we work on the superficial velocity ok, but now what will be the value of V what will be the value of D that is the major question, if you understand that we can calculate that what will be the pressure drop through the packed bed for laminar flow condition.

Now, we know that we have already derived it that what will be the correlation between the velocity inside and superficial velocity. So, we have already developed that correlation we have discussed it. So, inside velocity say u will be equal to u naught upon epsilon where epsilon is the void fraction. So, what you can do how you have derived it you can do it with the continuity. So, continuity says that mass in is going to be the mass or whatever the mass is going to be balanced at 2 different layer.

So, if you take at any place inside this what will be happening that u naught whatever the mass going is rho of fluid into u naught into area, and that will be equal to rho of fluid that is into u into your area and area will be now multiplied with the volume fraction. So, that you know that whatever the flow area is available. So, if you do that area will be cancelled out rho rho will be cancelled out you will get this value it means, if I write it I will say this will be u into void fraction into area into rho of fluid that will be equal to rho of fluid into u naught into area.

Now, you know that rho f and rho f is cancelled out overall area is same. So, you will get u will be equal to u naught upon epsilon, we have already done that just to revise it again. So, you will get this u value. So, we already know the u value now. Now what is about the D p what is about the diameter of the column. So this V will be modified with this value. So what will happen your equation will be changed I will just put it here so, it will be 32 mu of fluid it will be u naught into length now length will be the length of the bed.

So, I will replace it with the L b upon D square into rho of fluid. So, this will be into rho of fluid, so, that is the way it will be modified this equation will be modified, now what we are going to do we are going to put it here that how this things will be modified, I think rho will not be there I just forget to cut the rho because, this will be rho delta P will be equal to rho f, and if you write it in terms of the Reynolds number this will be 16 upon v rho and f and this rho rho will be cancelled out actually.

So, it will be only d I just did it. So, please do it is you will find it out this will 4 f rho f L D upon V square, if you will write it 16 upon V rho D upon mu f if you do it here, then what will happen this 2 and this 2 will be cancelled out this will be V square upon 2 also. So, this 2 and this will be cancelled out this will be 2, now if you put it here right let me do it actually so delta P will be equal to 32 this will be mu f into rho f into L V square upon D. Now Reynold number I am writing it in terms of the V rho of f into D. So, v rho of f into D into mu this rho f rho f will be cancelled out V this will be cancelled out this will be D square. So, what you will get thirty 2 mu f into V into L upon D square. So, that is what you will get.

So, now you will get this equation and this will be divided by epsilon. So, this will be the delta P equation. Now what you need you need that what will be the diameter because diameter is not going to change. So, we know that in case the diameter is not regular what we need to do we define a term which is called equivalent diameter.

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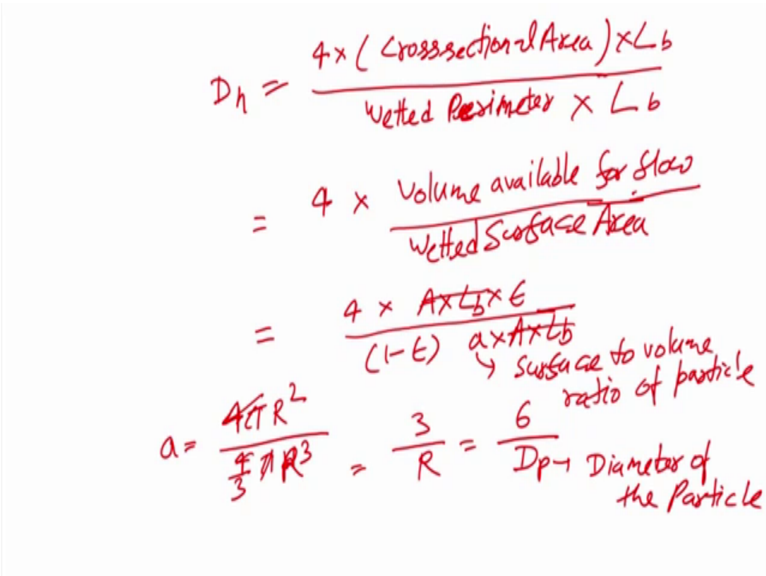

Now equivalent diameter is being defined or hydraulic diameter, or equivalent diameter or hydraulic radius it is being defined as D h since the hydraulic radius or hydraulic diameter is 4 times of the cross sectional area by wetted parameter ok. So, 4 times cross sectional area by wetted perimeter. Now if I am talking about the cylindrical column what we need to do, we need to find it in terms of the volume. So, I will multiply by the length top and bottom, if I just multiply with the length which is going to be the same.

So, that is the length if I multiply it will be say L b L b if I am multiplying this will be 4 into volume of reactor or volume of flow, of flow volume available divided by wetted surface area. So, volume of flow into 4 divided by weighted surface area. Now what you need to do we know that what we need to find it out that what will be the volume of the flow? So, volume of the flow will be what we know that what is the volume of this reactor that is if suppose this is there.

So, volume of this reactor will be area 4 cross area into length say L b that will be the volume, but volume available for the flow will be only the void portions. So, we will multiply with the epsilon which will say that what is the void fraction available. So, volume of flow or volume available for the flow I will write it in this way for more clarity, you can say volume available for flow a flow or fluid. So, this will be this now area will be what that will be the wetted area.

Now, that wetted area will be what that will be across the particle fraction that what will be the surface to volume ratio of the particle. So, that area will be defined as your length we have already multiplied up and down. So, that will be 1 minus epsilon and this area will be defined as area surface to area of this whatever the surface to particle volume ratio.

So, that will be the a small a I am defining it as the surface to volume ratio of the particle and because, you are multiplying with the volume of the particle you have to multiply with the volume it will be multiplied by capital A into L b. Where a is surface to volume ratio of the particle ratio of particle. So, what we are doing, we have to find the wetted area that what will be the wetted area. So, wetted area will be the area which will be wetted so this particle is there between these 2 particles say this is the flow. So, fluid will pass through say this line. Now a fluid will pass through this line what will happen that this areas are the wetted area.

So, for that what you need to find that what is the surface to volume ratio of the particle and, then that will be multiplied with the volume of the reactor whatever is available into 1 minus epsilon, why 1 minus epsilon because, 1 minus epsilon is the solid fraction. So, that will give you that what will be the wetted perimeter or what will be the wetted area that will be all the solids which will be wetted not only the walls, but the solids will be also be wetted that will be the wetted area.

So, in that way we write it in this way now this is small a is surface to volume ratio of the particle. Now surface to volume ratio for say if the particle is a spherical the surface area of the particle is 4 pi into D square. So, 4 pi R square you can say and the diameter this ways particle is 4 upon 3 pi R cube where R is the diameter of the solid. So, if you do that what will happen this 4 pi 4 pi will be cancelled out, it will be what it will be 3 upon R or you can write it 3 upon diameter of the particle.

So, I am writing D p which is the dia of the particle, and it will not be 3 because you are converting R to D p it will be 6. So, the a will be 6 upon D p. Now what will happen you can replace this a value here, and you can calculate the D h. So, now the D h will be I will just modify the D h here again, so if the D h I will say A and L b A and L b will be cancelled out, it will be 4 epsilon upon 1 minus epsilon into A.

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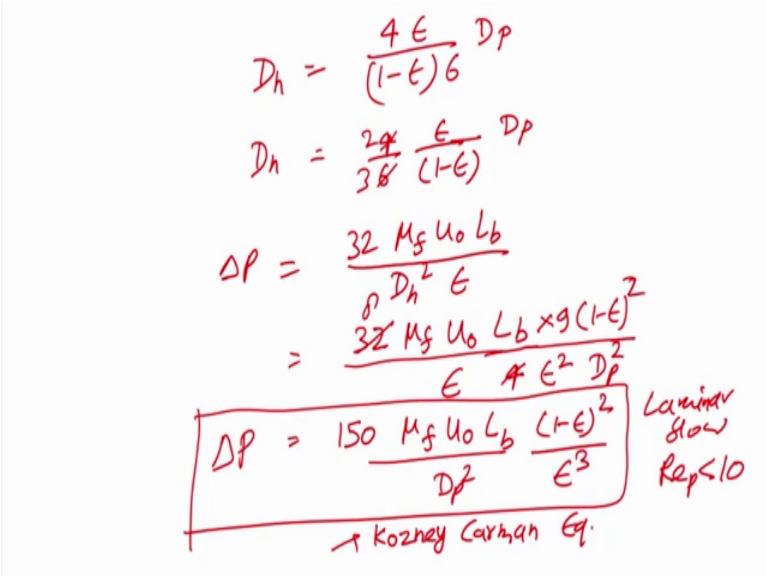

So, this will be 4 into epsilon upon 1 minus epsilon into a, and a is what it is 6 upon D p. So, this will be 6 upon D p so, it means you can write it as 4 upon 6 epsilon upon 1 minus epsilon into D p that will be the D h value.

So, now again I can do this D h value put I can put it here and here, D is will be what it will be D h because, I will take the hydraulic diameter, instead of the pipe diameter, this will be again modified delta P will be equal to 32 it will be mu of fluid it will be the length of u naught L b u naught into L b upon D h square into epsilon. Now this D h square will be replaced here you will write it out D h square. So, this will be 32, now you can cancelled it out it will be 2 upon 3 again, you can write here mu f into u naught into L b upon epsilon this epsilon we can say right here.

Now I am doing D h square on the separate side, if you do that it will be epsilon square 4 it will be into 9 and then this will be 4 into 9 upon 1 minus epsilon square into D p square into D p square. So, you will get this value. Now if you solve this then this will be again further solved this will be 8. So, this will be 9 72. So, you will get 72 mu f u naught into L b upon D p square into 1 minus epsilon square upon epsilon cube, this will be the delta P ok, this will be the delta P value which will be mu f u naught and L b which is the length of the bed D p square 1 minus epsilon square upon epsilon cube that will be this. So, this is the delta P in the packed bed for the laminar flow.

Now, experimentally it has been observed that this equation actually the constant is not 72, but it is 150 that is the experimental observation why it is the more because, we are taking the straight path we have not taken the torturous nature, actually if you see this bubble column the path is not straight there is a torturous nature of this path and, we simplified that while doing our this force balance calculation.

And because of that the constant value get modified and instead of 72 we found that more resistance is there and that is why delta P will be higher, because of the torturous path. So, this 72 is being replaced with 150 and that has been found experimentally so, this is 150, and again I am telling why it is 150 do not worried all the force balance is correct we have not taken the torturous path into the account and that is why it is coming 150.

So, this is there and that is the class of the equation which is being used to calculate the delta P in a packed bed for the laminar flow. So, this is for the laminar flow. Now we know that the laminar flow concept for the particle flow when the particle is there, this is equation has been found to be experimentally valid till the R e p Reynolds number of the particle is less than 10. And the equation is very famous equation and it is known as Kozeny Carman equation Kozney Carman equation, which is valid for laminar flow of the packed bed reactor.

Similarly what we can do, we can derive the equation for the turbulent flow. Now if I divide the equation for the turbulent flow, we can do it very quickly you can also do it.

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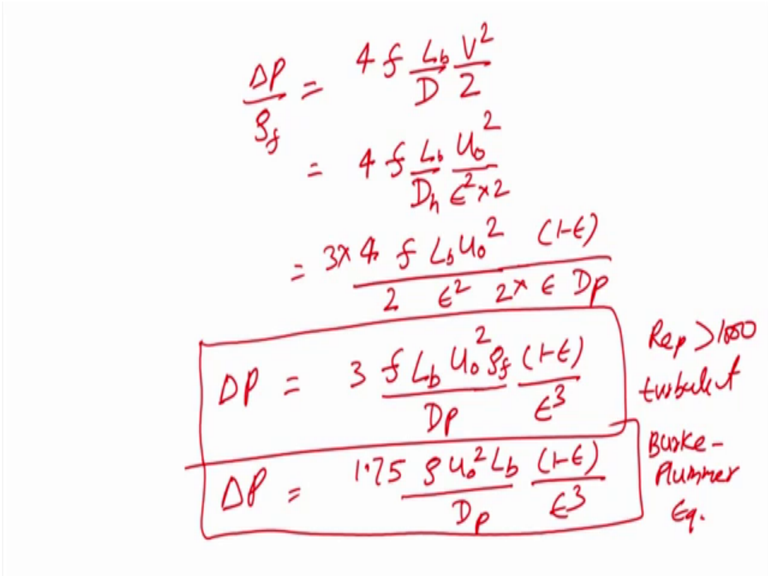

So, that will be again delta P upon rho is what will be equal to 4 f rho of fluid into L upon D into V square upon 2. Now V we have already defined that is u naught upon epsilon. So, we can say that this will be 4 into f L upon D into u naught square upon epsilon square into 2. And D will be equal to what D h. So, you can replace this D h value from there whatever the way we have defined and D h is what D h will be equal to 2 upon 3 epsilon upon 1 minus epsilon into D p.

So, you can use this so this will be D h will be replaced this will be 4 f L u naught square upon say 2 into epsilon square. Now D h I am again replacing with this it will be 2 into 3 this will be multiplied by say 3 into 2, then into it will be epsilon to 1 minus epsilon upon D p. If you simplify it then this 4 4 will be cancelled out you will get 3 f L u naught square into upon D p into 1 minus epsilon upon epsilon raised to the power 3, that will be delta P upon rho. Now if you want delta P you can also multiply it with the rho of fluid.

So, you will get this value and this is for the turbulent flow and that is valid for R e p greater than 1000. So, this is for the turbulent flow you can say and what you need to find you need to find the value of f. Now depending on the value of f it has been found that for Reynolds number f this value is 3 into f is being replaced with 1.75 rho into u naught square into L of bed, this will be the L of bed everywhere L of bed upon D p into 1 minus epsilon upon epsilon cube that is delta P. And that is again the experimental observation 3 f is being replaced with 1.75 and this is valid for the turbulent flow

Reynolds number of particle is more than 1000, and again this is a class of equation which is called Burke Plummer equation Plummer equation, which says that delta P in the turbulent flow.

Then there is another class which is being there. So, these equations if you will see is valid for the 2 different zone due to different region, 1 is for Reynolds number less than 10 for Reynolds number greater than 1000. So, Ergun equation is there a scientist Ergun what he did he added both the equation together and say that.

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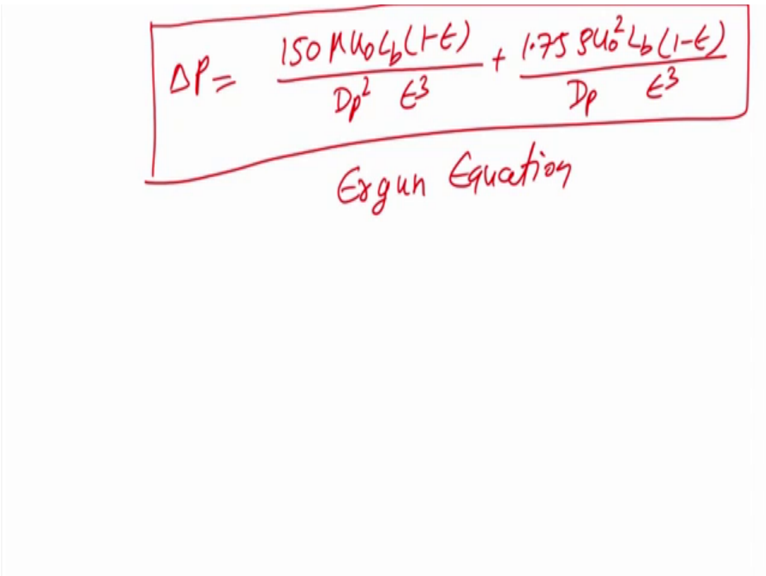

If you have to calculate the delta P in a packed bed, that will be the combination of Kozney Carmen and Burke Plummer equation. So, it will be what it will be 150 into mu into u naught into L b 1 minus epsilon upon D p square into epsilon cube plus 1.75 into rho into u naught square into L b into 1 minus epsilon upon D p into epsilon cube, and this is called Ergun equation which is used to calculate the delta P in a packed bed. And it has been derived from the basic force balance equation the way we have done.

So, if you know this delta P what you can do, you can calculate that now you know that what is the delta P is there. Now you can calculate that delta P you can use the Bernoulli equation, you can calculate that what will be the power required for the pump. So, you can find it out the pump power, you can find it throughout the compressor power, or blower power whatever you are using in the flow. So, this is the basic force balance we do in the packed bed reactor, again this reactors is widely used for many application the only drawback of this reactor is the temperature management and higher delta P.

So, next time what we are going to do we will discuss about the fluidized bed reactor.

Thank you.