Chemical Reaction Engineering 2 (Heterogeneous Reactors)
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Lecture 42
Continued (Kunii Levenspiel Model)

Good yes. Clearly written there Kunii Levenspiel model for fluidized bed. I think in the last class we have discussed what is the background for this model? Okay, the bubbles, two important things because the bubbles when they are going up in the bed they have the clouds and also the have the wake, right? And second greatest thing is to find out how many solids are there in the wake, okay. Even though sometimes upside values we will get for the measurements but these are the two important things.

So that means we have bubbles with very less number of solids. Then we have clouds and wakes around the bubble with a different solid concentration around that. Then we have away from the bubbles the emulsion. Emulsion is always at u m f with epsilon m f equal to voidage corresponding to minimum fluidization voidage, okay. So these are the important things. Now we can imagine how the reaction is taking place, right? That means the most of the gas is entering in the bubbles and there are some solids in the bubbles, okay.

There are some solids in the bubbles so first is reaction of gas in the presence because the catalytic reaction. Unless that catalyst is there it will not react because there are some solid particles in the bubbles so gas will contact them, some reaction will take place there. So that means some amount of gas is converted in the bubble itself. Then because of the concentration difference it will go to the clouds and wakes because those are the nearest particles and concentration is more definitely in this clouds and wakes.

Then there will be some more reaction. So whatever is left after the reaction in clouds and wakes, then that goes to emulsion. So beyond emulsion it cannot go anywhere. So under steady state conditions all the gas which has gone to emulsion should react. So the reaction and also transfer of all these steps we will see at the end of the reactor. Very easy to imagine, I think in very simple manner I am telling you. So now that is what you have to predict now using equations.

So you have to write equation now. What is the reaction in the bubble and what is transferred to the clouds and wakes? And whatever is transferred to clouds and wakes, there is reaction.

Again transfer to emulsion. Once it got to emulsion there is nowhere it can go because there are walls so then it has to react there and the combination of all these steps is the conversion which you will see at the end of the reactor when you measure your concentration of reactant, okay.

So that is the overall picture of this bubbling bed model and what the Davidson and Harrison that model what they did was all the solids are there only in the emulsion but they did not identified this clouds and wakes. Even though they know that they are there, okay. So all the solids are in the emulsion and gas goes in the bubbles. There is transfer between bubble and emulsion and then using those two steps only they have developed another model.

That is called two phase model and this is called three phase model because we have bubbles phase, clouds and wake phase and emulsion phase, right? So that we are not actually discussing. In fact that will be special case of three phase model if you remove clouds and wakes, okay. Yes, it is not so simple the way we tell but I think you know you can imagine that more easily. But more predictions very well accepted one till now is Kunii Levenspiel bubbling bed model.

That is why we are now discussing because that is the famous model where it can be used for not only for reactions, it can be used for mass transfer. That means you know for removing gases adsorption, you can use adsorbent gas in your fluidized bed, solid okay, as adsorbent solids and then gas you send. Let us say S O 2 is a pollutant. You want to adsorb that S O 2 on the solid phase. No reaction, physical adsorption.

Now you fluidize with the fluent gas okay wherever you have S O 2, this S O 2 when it is fluidizing this adsorbent, right? So it will go and stick to the surface because of the adsorption characteristics and even for that same bubbling bed model can be used, okay. Not only that, even heat transfer. When you want to heat the solids for example, you have high temperature in the gas and low temperature in the solids, you are heating the solids, even bubbling because bubbles you cannot avoid.

So again how heat is transferred, most of the heat is coming in the form of bubbles because you are sending gas to fluidize and our assumption is that most of the gas is going in the form of bubbles. That heat is transferred to clouds and wake and after that that heat is transferred to emulsion. It is very easy when compared to the reactions. So it is a very famous model used for many cases. So that is why let us discuss this one and before that as usual we should have some assumptions.

And there will be many serious assumptions like the first one itself is assume all spherical bubbles. And most of the time we draw. Experimentally we also so that bubble will be something like this, okay like heart, okay. So that is how the bubbles actually when you measure it looks. So that is why let us take the assumptions. The first one is bubbles are all sperical, all of the same size d B. This is another assumption you just see. D B, d subscript B diameter of the bubble, and all follow Davidson model.

Thus bed contain bubbles surrounded by thin clouds rising through emulsion. Another continue the same Para, we ignore the up flow of gas through the cloud because the cloud volume is small compared to that of bubble. This is the rising where u b is far greater than u e. U b is the bubble rise velocity. This is the rising where u b far greater than u e. U e is emulsion velocity. That I think already we have told. U b is the bubble rise velocity, okay.

That is one. Second assumption is, inside that there are many assumptions. Second point is the emulsion stays at minimum fluidization conditions, thus the relative gas solid velocity stays constant in the emulsion, good. I mean all these things are given in the paper which I have given you the last class, okay. These are given in the (for) formula wise also. So next assumption is each bubble drags up a wake of solids behind it.

This generates a circulation of solids in the bed, up flow behind the bubbles, and down flow everywhere else in the bed, okay. This is also good point. Already I discussed that but I think it should be in your notes also. Next one is full stop there. If the down flow of solid is rapid enough then gas up flow in the emulsion is impeded, can actually stop, and even reverse itself. That means gas can come down and reverse it, okay.

Such down flow of gas has been observed experimentally and recorded, and occurs when, this is very important again, u 0 greater than 3 u m f to 11 u m f, okay. And all our industrial reactors will definitely operate in this region. So that is why justification for bubbling bed model. We ignore any up flow or down flow of gas in the emulsion, okay. I have given all this information in the sheet. Hopefully you have not thrown this sheet right? Okay.

So if you have that sheet you can see that in fact figure 7 and 8. That will give all the information about what I have told you till now. Of course the spherical bubbles we are assuming and each of them are having uniform d B. You see that you know particularly figure

7 we have divided that entire thing into three regions and left hand side what we have the fluidized bed where all the things are given. Arrows where we have cloud, bubble, wake and all that for one bubble and three zones have been identified.

So then gas is going up in the bubble phase with delta the fraction and clouds and wake is the next region. I am talking about figure 7. Figure 8 also of course it is given. And then 1 minus delta is the total fraction of clouds and wakes plus emulsion together. Delta is the bubble fraction. I will tell you all that a little bit later, okay. So that is the essential picture which we would like to draw once because I think if it is there on that book itself I do not know whether you will really get it or not.

So let us see the simple fluidized bed. This is u 0, then we have the bubble, cloud, we have this wake also. So then one more bubble somewhere here, one more bubble somewhere here, rest are solids. Yes, so then here please write once this is cloud, this is bubble. So this will be emulsion and maybe this one I do not know if I write here, okay. This is wake, excellent good.

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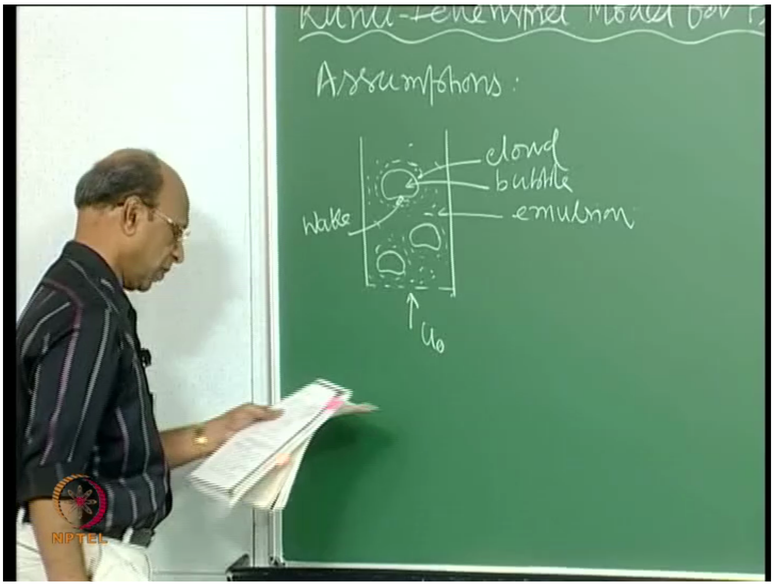

So solids may come down. They have to come down anyway, not may come down. These are the solids coming down and mostly gas is going up. This velocity you can write as all the bubbles together as u b and there is emulsion gas also coming down or up. This we cannot say how it goes that is why this is plus or minus, emulsion gas. These are the solids, all that. Very nice good. So then we also have one single very large bubble, yes. That is the cloud.

So then now we will have this kind of hatchback. Just to exaggerate and tell you that is the wake, okay. So here I have the solids. And if I mark approximately you know like we do, one bubble we take out and we have written. Even the last class or last but one or two classes we can still connect this one with the first class what we have done, okay. One particle taking out and writing balance and one bubble taking out, one drop taking out the same thing. So all this is emulsion, this is clear boundary of cloud, okay.

These are the solids, okay. This is emulsion, right? So this one bubble first we have to draw the picture of how the concentration is going. And you may have one or two few particles inside the bubble also, right? So that was experimentally found again. So you will have first the transfer between these two. This is the transfer arrows, okay.

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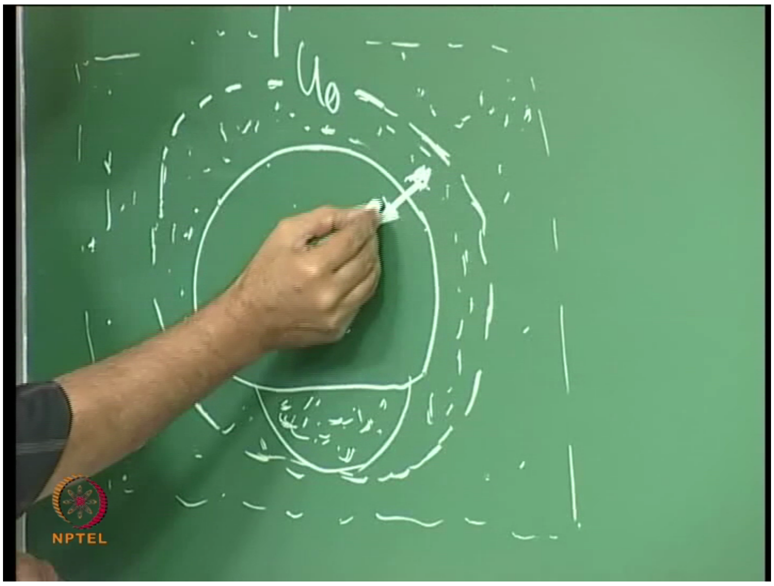

So this we call it as K b c. I hope K b c has a different meaning but here between bubble and cloud, okay. Yes, so then you also have now cloud and emulsion. This is emulsion by the way. This is cloud, this is wake and emulsion cloud, yes. Of course this is bubble. Inside itself I can write, yes. So this is K b c and this one K c e.

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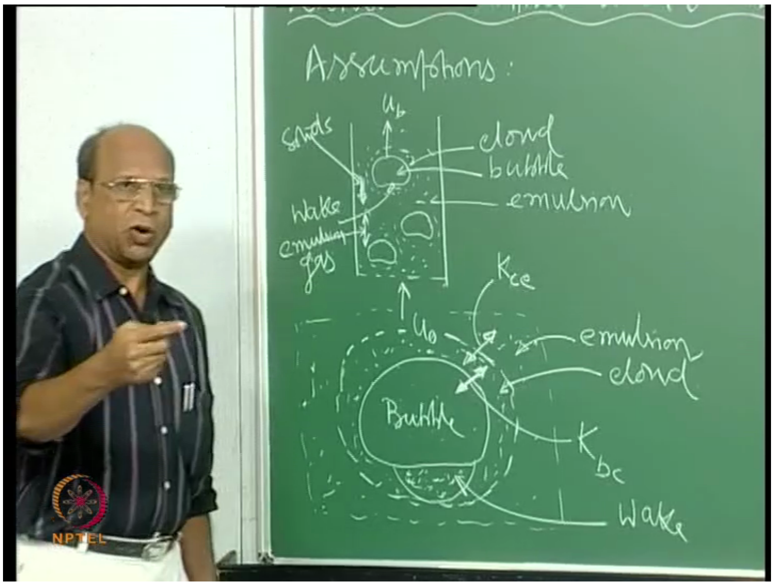

C means cloud, e means emulsion. Cloud to emulsion, b means bubble and c means cloud and wake together. Cloud and wake together we will put together, okay. So drawn in a different way once more, this is our imagination now for model writing. This is emulsion so this is cloud and wake and here we have imagination is that all the gas is trying to go through this but some of it will also go through this, okay. So this is the one. This is bubble phase and here we have cloud plus wakes and here we have emulsion.

Yes, all solid here, okay. So here also solids but of course here there are the very thin solids only, okay. Yes, so this is what is the transfer we have been telling. So this will be K b c, this will be K c e, good. So what we are trying to do now is we take a thin yes, okay. Another beautiful assumption here is that this gas which is going through the bubbles is it in plug flow or mixed flow? Plug flow, okay. Very obviously plug flow. That is one assumption but Kunii Levenspiel they have not done that.

But in the earlier model Davidson and Harrison model, so they have cried all possibilities, right? So that tried that, okay let me also try the n number of tanks in series and also perfectly mixing in the bubble phase and dispersion in the bubble phase, all kinds of things they have tried, okay.

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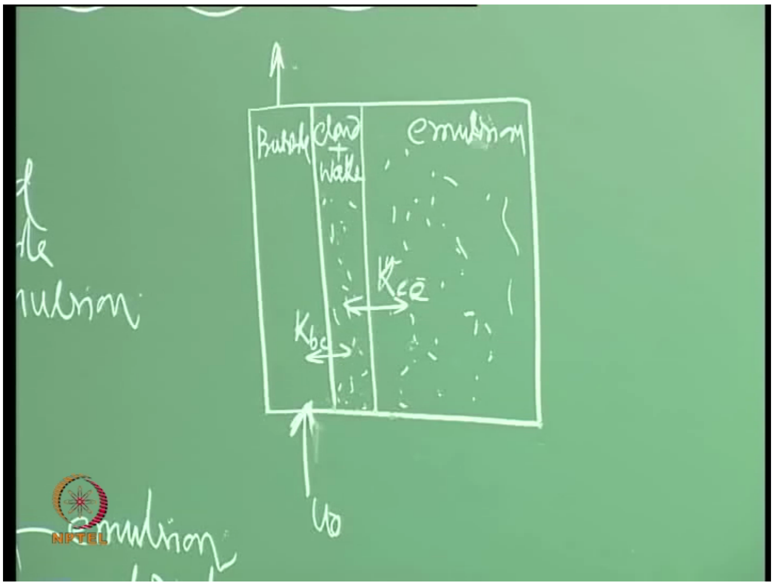

That was the first model. So here we take a small balance delta z here. This is z, this is z plus d z so the thickness will be d z. And here, okay this is moving with u b bubbles , right? And then we have the transfer to cloud and wake. Then transfer to emulsion. Cloud and wake to emulsion, right?

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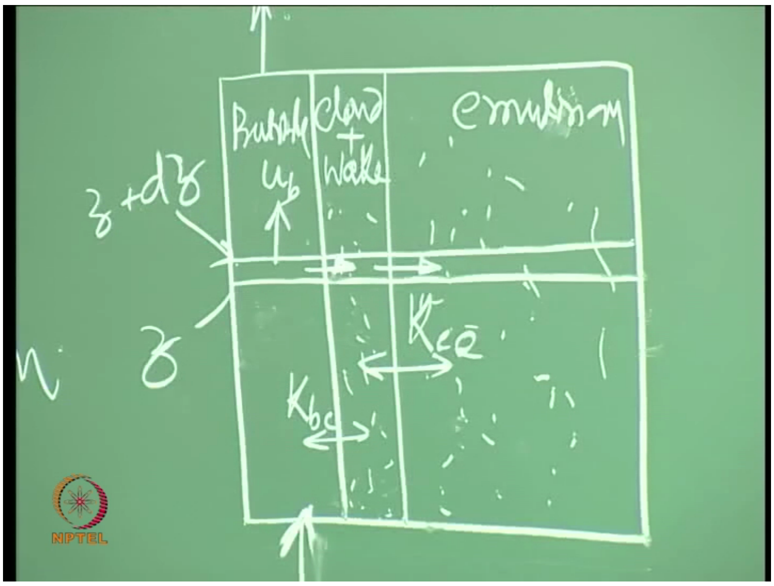

So what we do is we try to write in terms of words first what is happening, how the reaction is taking place? Then we try to write that in terms of steps. Then we get the equation, okay. For example minus r a, what would be you have to get right? Yes, so that is written slightly because it is a plug flow model where you have already derived this kind of thing. So this is delta z, okay. I think maybe I will write here d z. Yes good.

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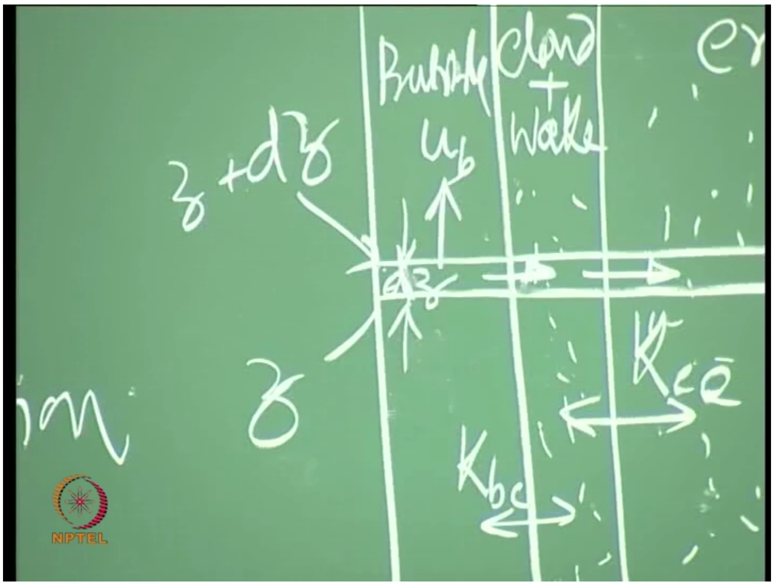

You see now that you know here whatever gas is going into this it has to come back and then join in the bubbles and then come out, okay. Yes, but overall picture what I see here this is the real one. That is the real one. Then this is what I imagine between any bubble. So I am now combining all the bubbles as this fraction and then we are trying to write this. Exactly same thing what we have discussed in the first class, right? Okay good. So now Anurag anything, no, okay good.

So now let us write the balance equation for this that is the mass balance of a. Yes and isothermal conditions, okay. That somewhere you have to write definitely isothermal conditions. Yes, so correspondingly here I can also just show you when you have z here you have concentration, okay. This is C A not, this is C A at the end because we are now writing for the reaction rate, right? Okay. So then this is correspondingly here I have C A and here C A plus d C A, correct.

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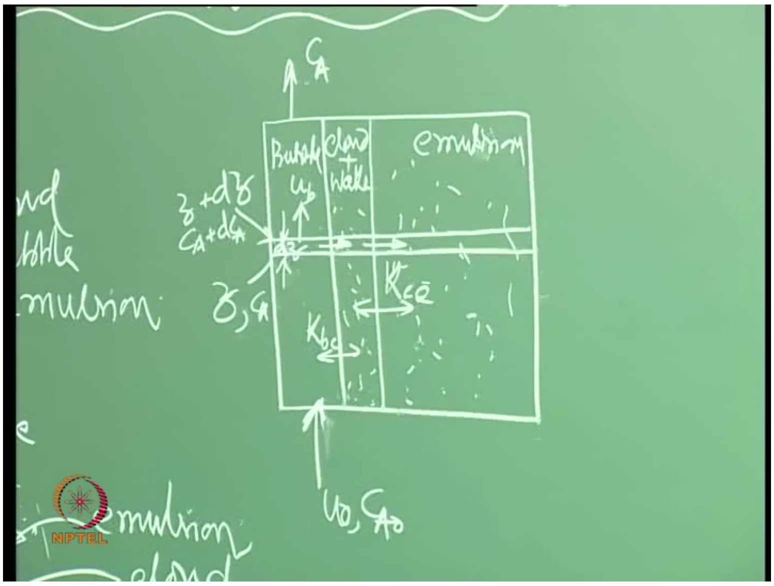

That small change, like exactly when you are writing plug flow, first time when we wrote the balance f A equal to f A plus d f A, okay into rate and volume, similar thing. It is not given in any book but I thought I will write that once to you so that you would be happy to know that thing what is really happening one balance at here. And of course the problem with these things is you know in the earlier book he has given this solids fraction. Solids available in the bubble phase per unit volume of bubbles.

And in cloud and wake per unit volume of bubbles and in emulsion also based on per unit volume of bubbles. That is what his basis earlier. But now we have changed that and written solids per unit volume of bed and again cloud and wake solids per unit volume of bed. That means entire bed. So that is changed a little bit but I think if you are having edition 3 Levenspiel book then I think this and what I am going to write will be tallying that, okay good.

So that is one and where do I write? I think I have to go here. So the material balance for M B for A, okay. So before that I have to also write here the rate what we have is minus r a into k C A, first order rate, no volume expansion. You see how many simplified things, okay. So that we will learn, we will not be lost totally. So that is the reason. So where this is given as rate in terms of, so this is moles metre cubed solids per second.

M dot s in the bracket means metre cubed of solids. So what will be the units of k? K units are metre cubed gas that is you know mole, okay. And you have metre cubed solid per second. Those are the units of k, okay, for heterogeneous system.

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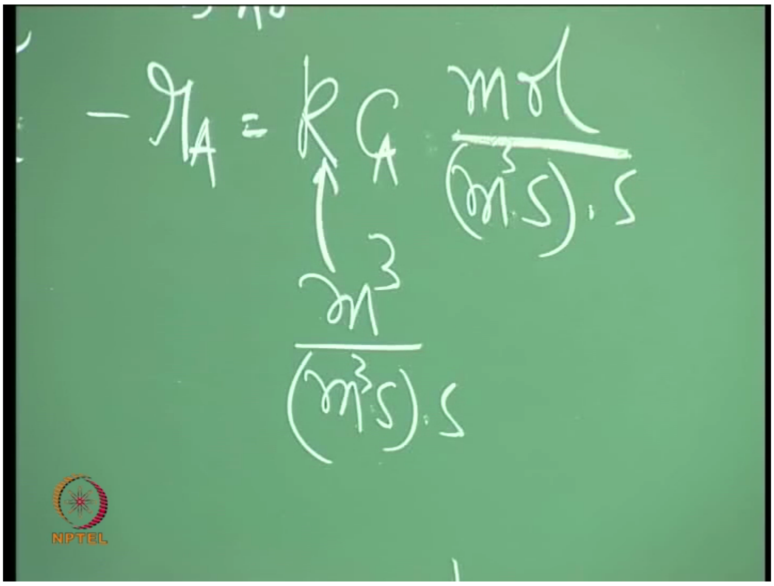

In a fact we know because there is no volume expansion it is a first order rate. If you dimensionally cancel out metre cubed metre cubed what you get? Time inverse, okay. But I think you know it is metre cubed gas metre cubed solid per time, right? Okay good. So that is the one. This is also very important for us. Now what you write is the balance. Overall rate of A must be equal to reaction in bubbles plus transfer to cloud and wake, okay. So what is the next one now?

Next step is transfer to cloud and wake equal to, that is all. Reaction, in clouds and wake there must be reaction first then transfer. So, reaction in cloud and wake plus transfer to emulsion. Next one Lachit now you tell me. Transfer to emulsion must be only reaction in emulsion. So now we have to write the corresponding equations for this, okay.

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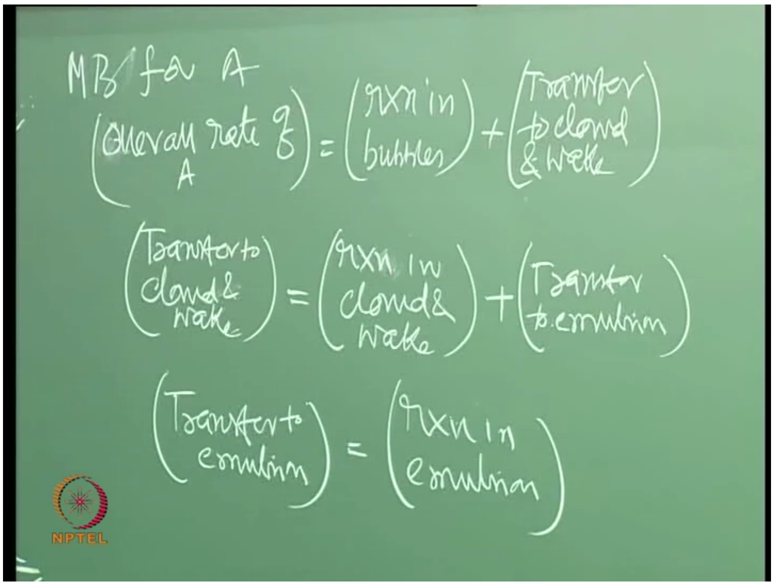

So when I want to write for this one first so again I think I will take this strip, okay. So now we have to write here you know this is molar balance what you write there. So if I write I think it may be sufficient, okay. I will first write that, okay. So entering into this A is u C A at z. What are the units of that? It is flux, okay. So moles of A per metre square bubble because these are flux, okay. So here we are talking about only the bubbles, right? So metre square bubbles, second that is the time flux.

And now multiplied by metre square bubbles because finally this balance is in terms of moles per second. So what is the fraction of bubbles here? It is if the total cross sectional area is a C, d is the delta fraction of bubbles per unit volume of the bed so this will be delta into A C. A C is the cross sectional area, okay.

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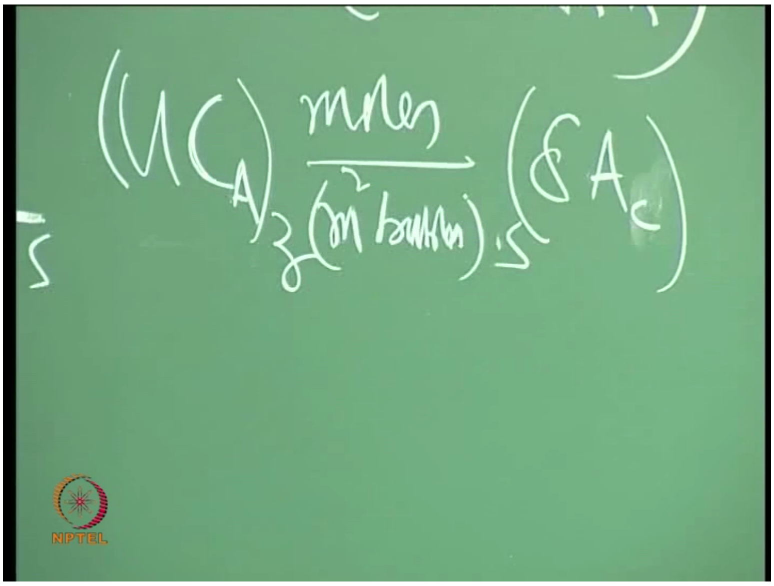

So now this will be in fact metre square bubble , okay. So when I cancel out this plus this you will get only that one. So now this is equal to exactly the same thing at z equal to, this is very easy, yes d z. And I have delta A C. All that at z plus d z. Now plus you have reaction in bubbles. Plus I will write here. Reaction in bubble is minus r a. I think maybe it will take some time. So plus minus r a, what are the units? Moles per metre cubed solids per second, right?

So that multiplied by a factor called f b. F b is metre cubed solids per metre cubed bed, okay. That is the second term you know. That is the reaction term. Yes, so multiplied by volume of the entire bed because metre cubed of the bed, okay. So what is volume? A C into d z, excellent. This is metre cubed of the bed. Yes but unfortunately I have to go to that side. That is still plus. Plus here what is the next one? Transport, right?

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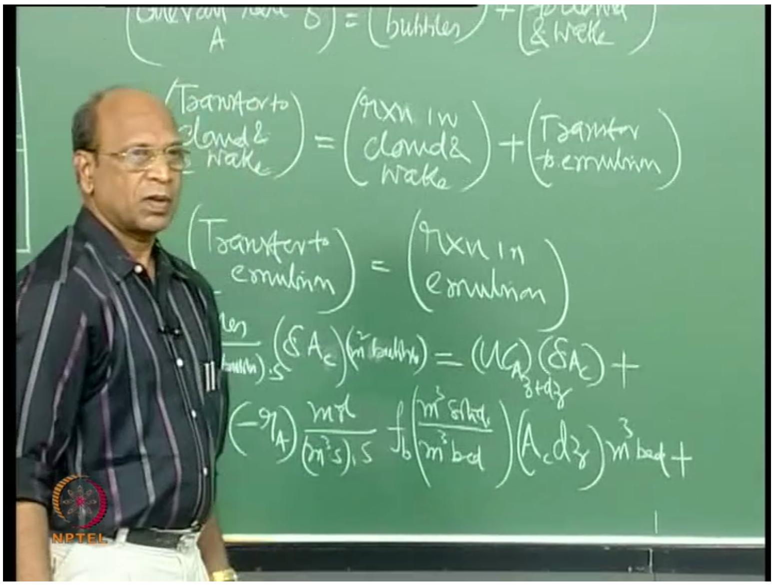

So the transport is K b c. K b c is defined as volume of metre cubed gas per metre cubed bubbles per second. In fact this will be if you see now K b c is nothing but again metre cubed metre cubed if I get cancelled you will get again seconds inverse, okay. So that is the one and into concentration. Concentration is C A b minus C A c. That is one important, okay. So here please write there. This is C A b and here also you can write C A b. This is C A c, here I have C A c and here I have C A e.

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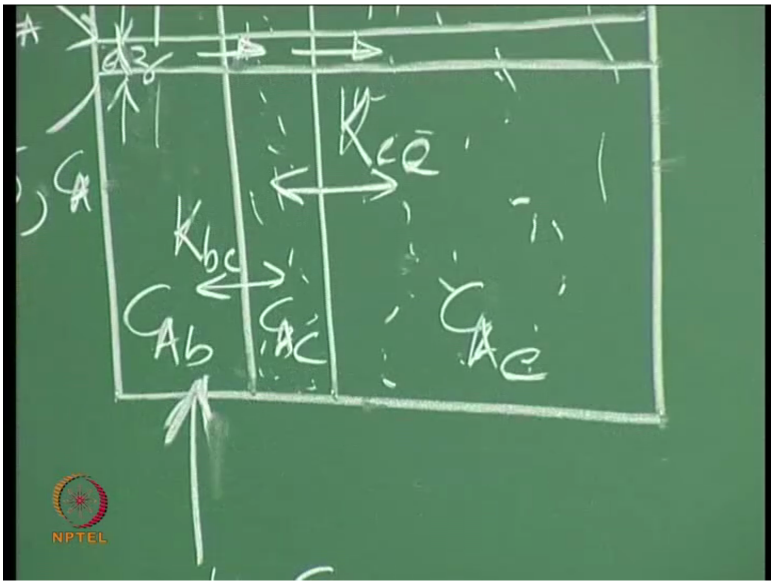

With that picture this thing should be very clear, good yes. So the units of this will be moles per metre cubed gas, right? Moles per metre cubed gas. That is concentration, okay. Now this multiplied by we have delta where delta is, volume will come later, (meta) metre cubed bubbles by metre cubed bed, right? Okay. Now this multiplied by A C d z where it is metre cubed bed. Now if we cancel out all that throughout you will get moles per second. I think this is clear.

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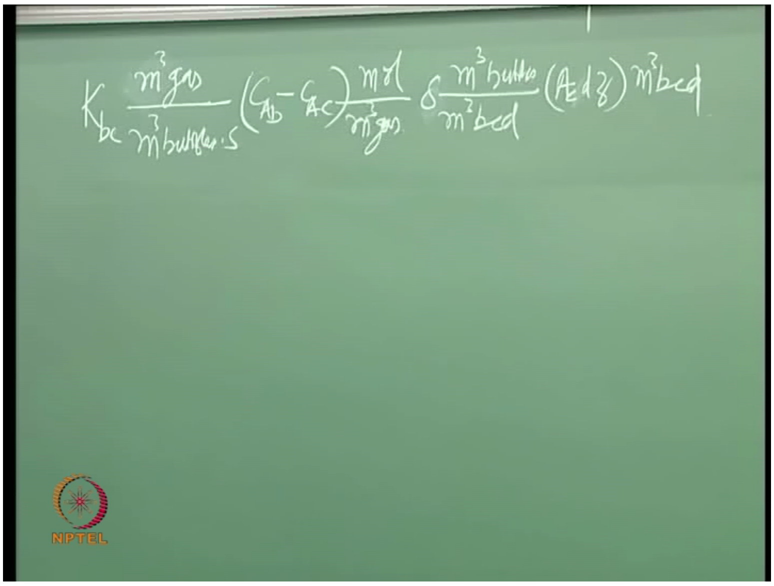

So the moment you cancel out terms like for example here, u C A delta A C, this side also you have u C A delta here. You will have C A plus corresponding to here this is C A plus d C A, correct. I think that I have to write I said. Yes here sorry. But I think if it is understood fine but otherwise this is plus d C A, the concentration at, okay. I think let me write that also. This is d C A, okay. Of course another, good.

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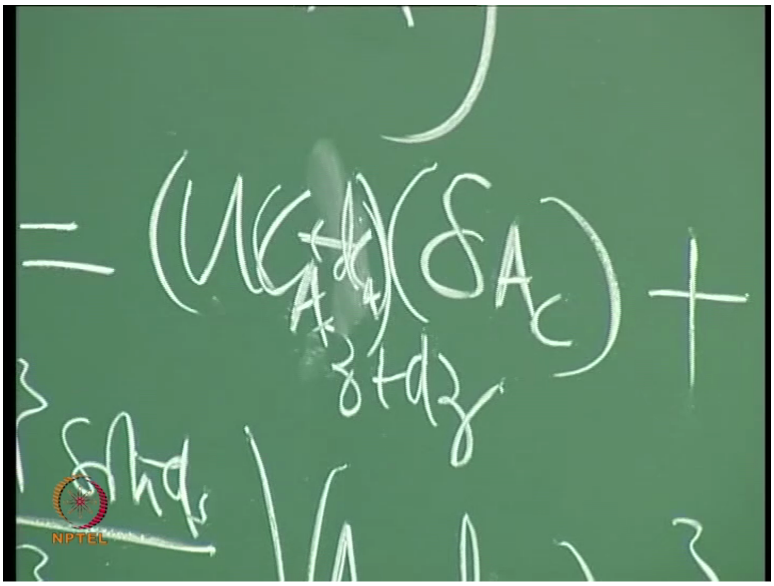

So correspondingly you cancel out that and also A is throughout common. A C is throughout common. Every term has A C. You cancel out, what do you get is minus u b delta d C A by d z. And of course if I bring that d z the other side then what you get here is equal to minus r a f b plus K b c delta C A b minus C A c, okay.

May be I think I will write first delta and then delta K b c, okay. So that is the equation what you get there. Yes so but what is minus r a? I have here let me write delta also here, u b d C A by d z equal to this is f b k C A first order. But C A b, correct, in the bubble.

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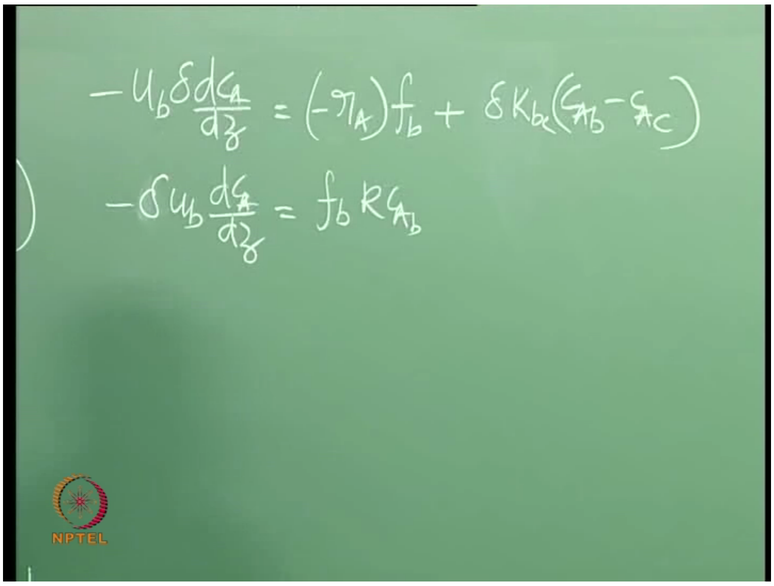

When I take a small value I have taken that. No I have written only here. I have written the first one. The other two is for you to write, okay. The other two are very simple no. Transfer already we have this. So that must be equal to reaction. That is equal and term is this, reaction term. So the third one is transfer term which is exactly same as that one but with C A c and C A e. So all that is simple, okay. So this is the one, plus this is first order reaction. Then I have, okay delta K b c, C A b, C A c. This is equation 1, good.

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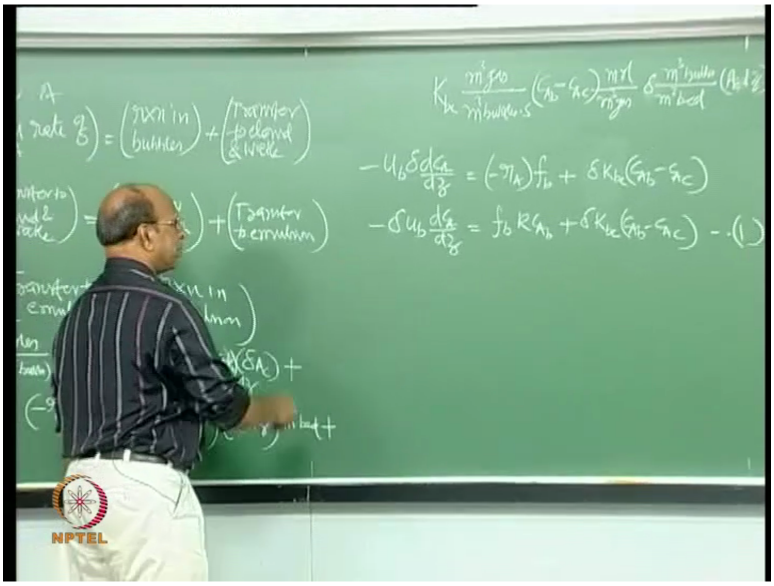

So if I write the same thing now that means for this step that will be delta K b c, same equation, C A b minus C A c equal to f c k C A c plus delta K C e second one, so into C A c minus C A e. That is equation 2, good yes, okay. What is the next one? Yes, so exactly delta K c, C A c, C A e equal to reaction. What is reaction? F e k C A e, this is the one.

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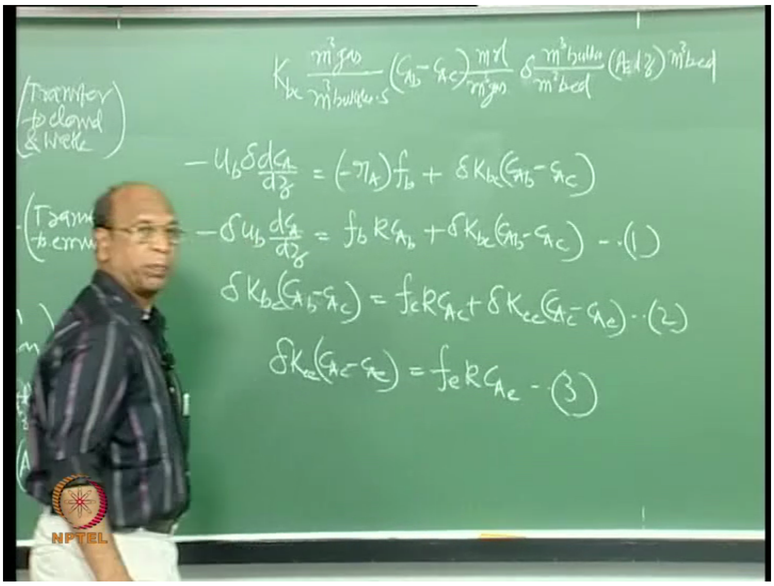

So now you will have a pleasure in the examination hall. So you have to eliminate C A e using this one, then you will get in C A c and go to this step, C A c you have to substitute there, okay. And so then you have C A e you get in terms of C A c. Then you will get this everything in terms of C A c. Of course C A b will be there and then finally C A c you substitute here in terms of C A b, finally you will get the equation. You know what kind of equation you will get? Very beautiful equation you will get. I have also done.

I have also done, you see so many pages all this, okay. So finally I have done but I do not give you this because you know you have to do it on your own then only you will enjoy it, okay good. So what you get here is this will be as it is. So when you solve equation 1, 2, 3 and eliminate unknown concentrations again class one, okay. So unknown concentrations you have to eliminate and express everything in terms of known thing.

Then what you get there after that is this kind of equation where minus delta u b d C A by d z equal to capital K o overall into C A b. So this is a question number 4 where K o, okay I think I have to write here, okay. Where K o equal to f b small k plus, I have to go till that point, 1. This will be delta K c e plus again all this, 1. F c k plus again all this, 1. Here 1 by delta K c e plus 1 by f e k. So this is K. Yes very nice equation.

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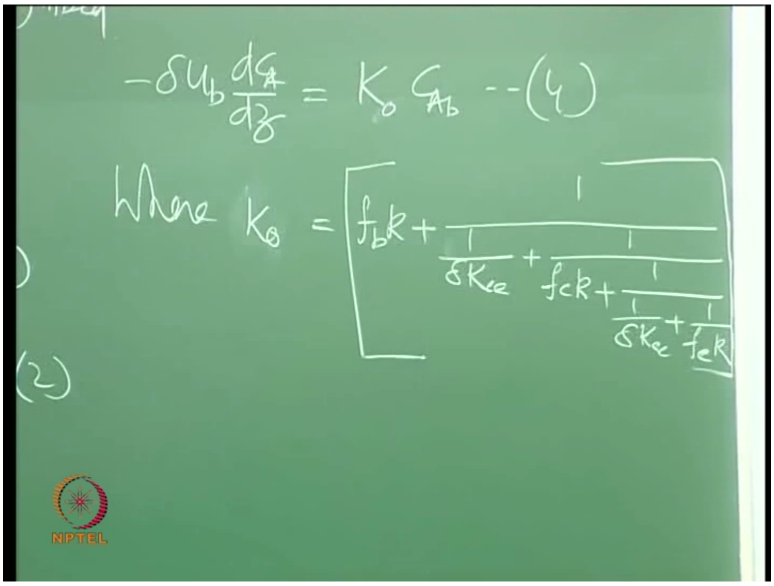

See this is series parallel problem. This is the first time I think you have come across series parallel even though I given the small problems in the examination. I think this one I gave parallel step, series and parallel, right? But I think this is the one and you can see this is the one. Yes f b you know the meaning, volume of solids divided by volume of bed. Like that f c is volume of solids in a cloud divided by volume of bed.

And f e is the again volume of solids divided by volume of bed. And all other things you know, okay right? K b c is the exchange coefficient between bubble and then cloud. This is K c e. This is K b c. Thank you. I think that is right. That is K b c. Then this is K c e, yes okay.

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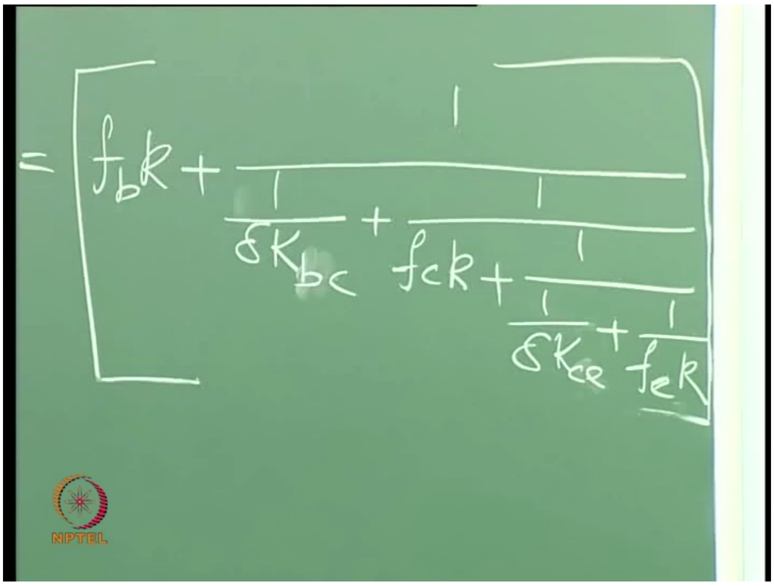

And now we can easily integrate this. Sorry this is C b. It is only bubble. Here also I have to write this yes, okay. What is the solution for that? Very simple. Integrating C A b by C A not equal to 1 minus X A equal to e power minus K not z by, because you know integrate between 0 and z. K not z by u b and that is at any z, okay. So if I say that my this z equal to H f, z equal to 0, correct.

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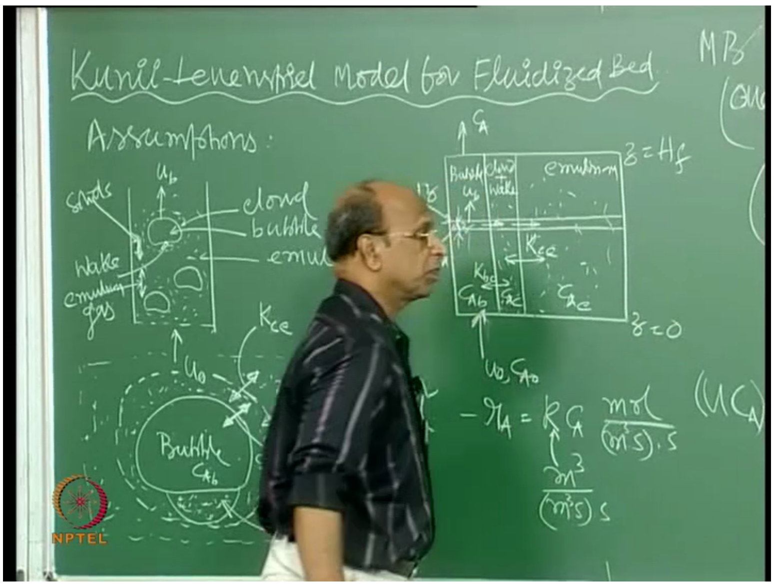

Delta is there sorry, delta u b yes. So K 0, this z equal to H f then we will have 1 minus X A equal to e power minus capital K not H f by delta u b. So this is the equation.

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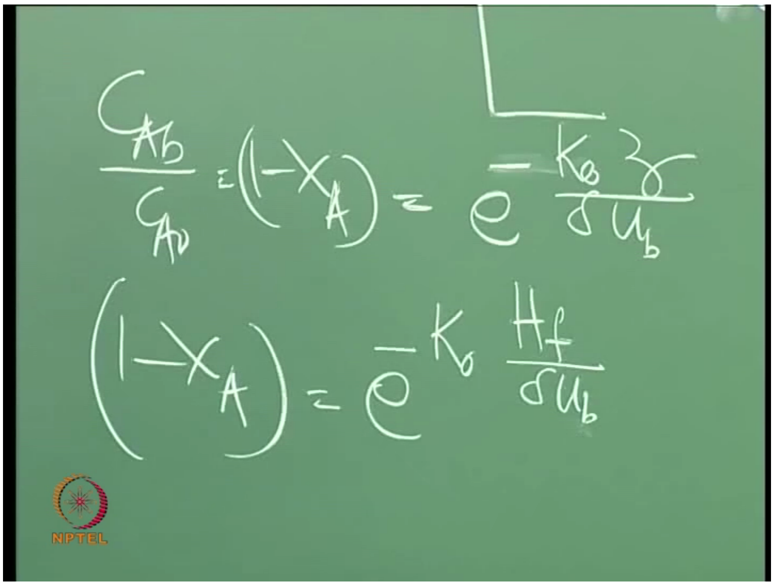

So now we have to find out equations for delta, f b, k will be given kinetics, right? So like that f c, K c e, K b c and f e. And also before that what is u b, okay. So these are the unknowns for us, right? So if I want to use this equation to calculate conversion for a given height or if conversion is given you have to find out the height of the bed, okay.

That height of the bed can be converted into the total weight of the solids because height if you know, bulk density if you know you can always calculate what is the total weight of the solids, so all that. So to calculate this I need all those parameters and let us know that now. So all my nice diagrams how do I do? But of course we have (relationsh) relationships like H f equal to W by rho S A c cross sectional area into 1 minus epsilon f because when you want to calculate that in terms of W, right?

So I do not know whether you get the point or not. This is very easy. If I write 1 minus epsilon f is the voidage of the bed, okay. 1 minus epsilon is the solid fraction, okay. So that is nothing but you have weight divided by, this is the volume of the bed, H f into and into the bulk density, okay. Here it comes two density, not bulk density because 1 minus epsilon f I have. Rho S into 1 minus epsilon is the bulk density, please remember that.

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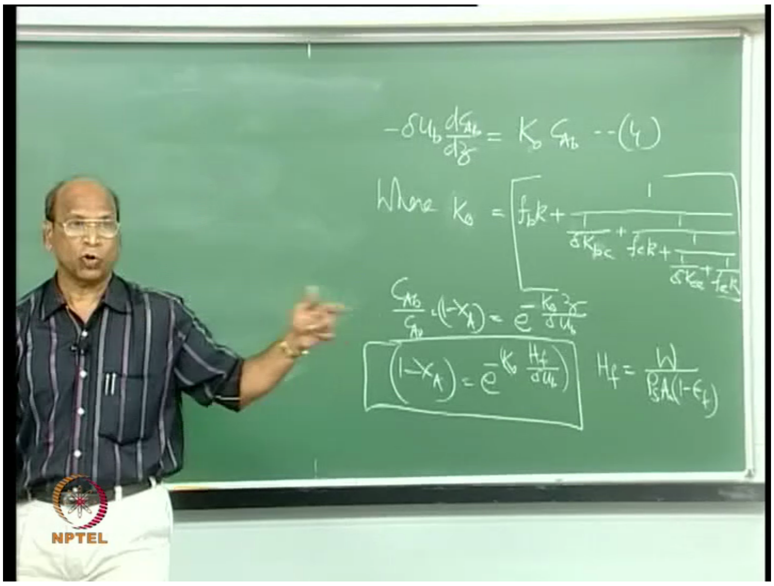

Do not make that mistake because you think that you have done correctly in the exam and you scold me, okay. Okay good. So now to find out the other parameters first we have to start with u b r you need you know because u b I have to find out. This is u b. U b is not I think here also I have to just explain that is why you know it takes lot of time for me. I think I have to take some extra class if you want to finish before Thursday, okay. So but that we will see. Yes u b is the bubble swarm velocity. That means all the bubbles how they are moving that is u b, okay.

U b r is one single individual bubble that is rising in the emulsion. So that is the starting point for us. So I will write here bubbling bed parameters. These are all parameters which we should know, okay. See, the beauty here is at the end that means when I substitute equations for corresponding f b, delta all that you will get an equation in terms of only d B, diameter of the bubble, epsilon m f, u m f and I think H m f because H m f is nothing but your H p, height of the packed bed.

Epsilon m f is nothing but your packed bed porosity again. And then d B is the only parameter which you have to measure. That is why sometimes it is called one parameter model but the main problem Abhinav there is that how do you estimate this d B very accurately? That is all. Entire thing goes to estimation of d B. Even now we do not have very good methods of estimation of d B in the fluidized bed. So if you are interested I told you know I can give you 110 problems in fluidization.

This is one of the biggest problems what we have, okay. And the other assumption like uniform bubble sizes can be extended with delta X because what we do is, okay in 1 metre what is the bubble size? So another one metre because you know bubbles grow. That is what we have shown. That is the reality. So you make this one as slices of the bed then, okay in first 0 to 1 metre I will have let us say 5 centimetres bubbles. Then next one, 10 centimetres bubbles. Then next one metre, 50 centimetres bubbles.

So I can measure that. Some measurements are there how the bubbles are growing. There are some empirical equations but even then they are not true representation because when it is particularly 3D bed we do not know what is happening inside the bed. At the centre you cannot see, okay. At the centre unless you again you know it goes to technology. It goes to sophisticated instrumentation which is nothing but you know sophisticated technology to measure.

I do not know whether you have seen a movie called Total Recall, long time back. Excellent, Arnold Schwarzenegger. He will get S grade now. Arnold Schwarzenegger. So they have a security system because you know they go from Mars to Earth and Earth to Mars like we go to our out gate and in gate, okay. So frequently they travel in that movie because that is highly sophisticated science fiction movie.

So then there is a security system where you know now if you go to airport or if you go to even this Coimbatore bus stand and all that they ask you to remove all your clothes, they ask you to remove all whatever you have in the bags. Recently they have also stripped Shahrukh Khan. Yes, so all kinds of things will happen. But here the thing is you can just move in the corridor, the corridors are just you know fitted with X rays. Every part of you will be seen by the security people, every part.

I think there is no secrecy at all. You cannot hide anything, okay. So then the moment you have gun or something that is extra thing you know. Easily they can find out. So probably similarly we should also develop that kind of instruments where the moment you put something between the bed, put the bed in between and these measurement techniques everything you should be able to see, every part of the bed. Then you can measure very accurately all the bubbles. What is happening at each and every point?

That is left to you for your future PhD, okay. And then your name will be like Levenspiel. Everyone will take Abhinav model, okay. Yes, so that kind of great name you can get provided you know you do all that. You know there are many things which you can really do in fluidized beds even now. Good. So the first one is bubble rise velocity. Bubble rise velocity u b r is point 711 g d p. Do you remember this equation?

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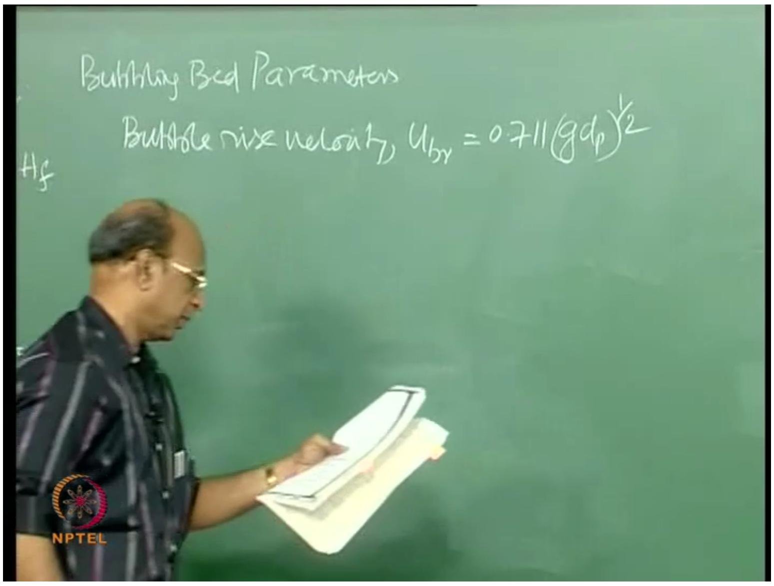

This is nothing but you know Taylor equation for bubble diameter when you have simple liquid and then gas going in, okay. That constant is different. This constant is adjusted to fluidized bed and that was derived by you know Davidson, okay. It is adjusted because I told you know he was excellent expert in gas liquid systems, bubble columns, Davidson, okay. So that is the one and because it is empirical constant we should mention definitely what are the units.

Please remember always when you have empirical constants, okay. That is why we are happy to convert them into dimensionless number so that we do not have to remember any constant. So this should be only in metres per second so that means this must be in S A units, this must be in S A units and of course this you will get automatically that constant point 77. My equation is gone. So this is 5, 6, 7, that is 8 so this will be 9, good.

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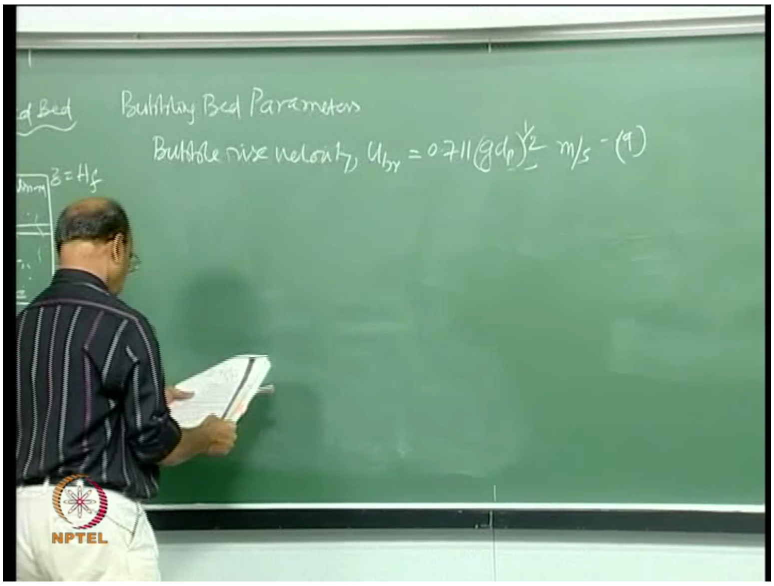

So then this is a single bubble. I can also write here, single bubble rise velocity, okay. Then swarm of bubble, okay. Bubble swarm velocity. Sometimes this bubble swarm velocity u b equal to u 0 minus u m f plus u b r. Yes, this also must be in metres per second because if you are using this equation. This is 10, right? So here the assumption is that you have the bubbles just rising, okay.

You have stationary bed and imagine that you have number of bubbles there just staying. Then you suddenly change the velocity from u m f to u 0. The difference of these two will give you so much amount of gas that it just pushing, okay. So, already u b r is having some velocity as a single bubble. Then the moment you increase that it will simply go. Like exactly you walk on the conveyor belt in the airports and all that, okay.

So initially conveyor belt velocity equal to zero, right? So but you are walking on that. So then suddenly someone came and then switched on conveyor belt. Then what will be your velocity with respect to solid coordinates? I mean you know stationary coordinates, okay. So that is the one, right? So that is why there is lot of derivations for this one again.

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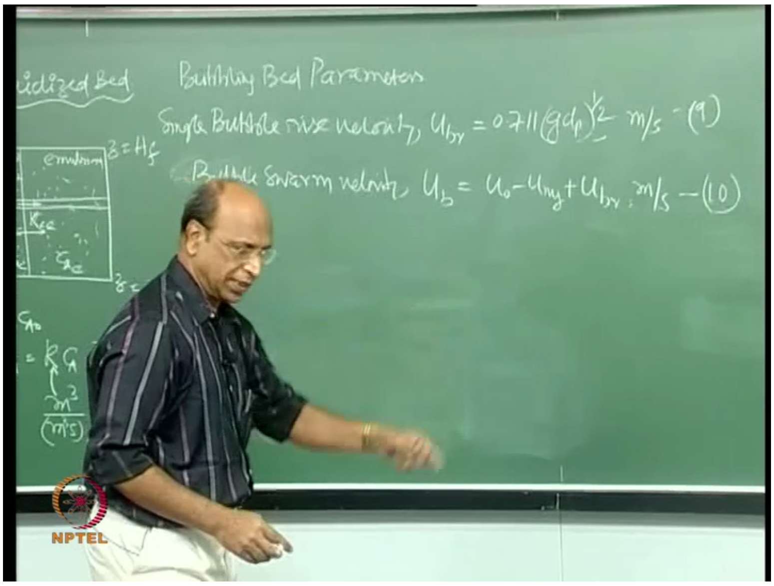

So this is another thing. Then we have bubble fraction delta equal to u 0 minus u m f. There are lot of equations for that but so many assumptions are there. Yes, so this is nothing but metre cubed bubbles by metre cubed bed. So this equation is 11. And this also can be written as you know if I substitute correspondingly u 0 minus u m f here, right? U 0 minus u m f if I write then I will have 1 minus u b r by u b, confusion. Yes, simply this u 0 minus u m f, u b minus u b r, okay good.

So this is the one and for u b the same equation delta if I have u b far greater than u m f, we can use from this equation simply delta equal to u 0 by u b. This has some but this is for very large values. So when you are going for very large values in fact you can see now delta u 0 u b. You now just see there in that equation delta u b equal to u 0.

But a lot of assumptions that cannot be better than that, that is all. Lot of assumptions are there. We cannot do anything else over there beyond this, okay good. So this is another equation for delta.

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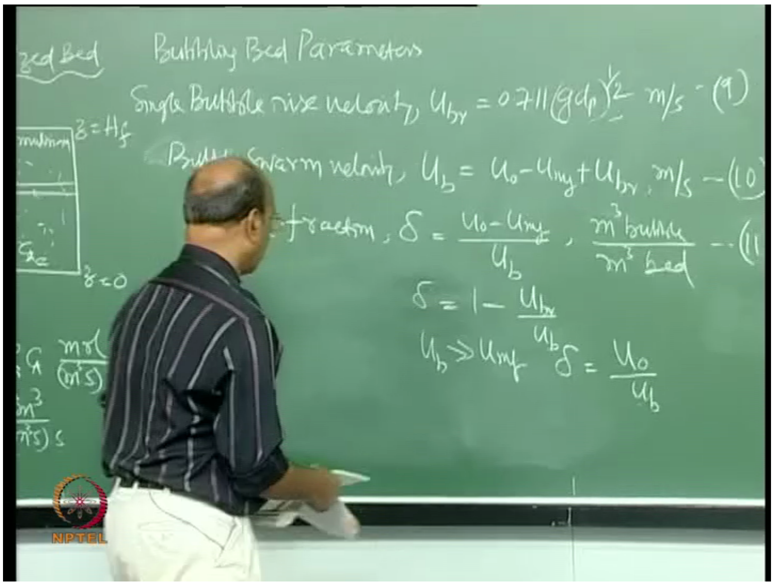

So now you have values for two parameters, u b you have value, delta you have values. You know how to calculate but everything is in terms of basic variables like u 0, the amount of gas you are sending. Even if it is not u 0 it is u 0 and u m f and u b is again in terms of u m f, right here. And u b r is the basic equation, okay, single rise bubble velocity. So all these things, good. So the next one is let us say K b c, okay. K b c is of course I will write the equation and then try to write , okay.

K b c equal to 4 point 50, u m f by d b plus 5 point 85. This is gas diffusivity D g. This is to the power of half. This is to the power of 1 by 4, 1 by 4, d b to the power of 5 by 4. So that is the equation we have to use to calculate K b c and K b c definition is interchanged volumes of gas between b and c or vice versa, okay, b and c divided by volume of bubbles into time.

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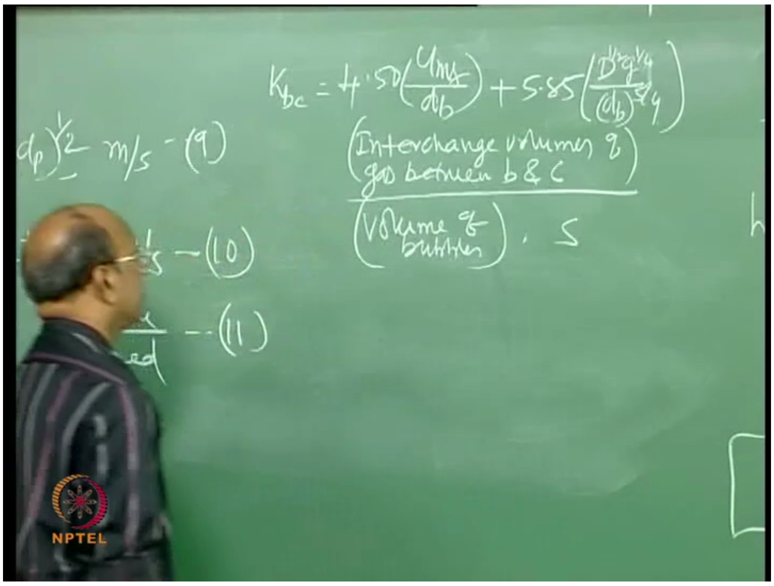

So in effect again interchange volume. Volume and volume will get cancelled, we will have only seconds inverse. Dimensionally strict dimensional if you apply, okay good. So then we have K c e. K c e is the simple equation. 6 point 77 epsilon m f. Again yes I think you have to write here. The d b you know, u m f you know, right? And D to the power of half, this D is molecular diffusivity of gas to gas, okay. And g is the acceleration due to gravity.

That is no problem, yes. So epsilon m f and here also same diffusivity D into u b r divided by d b cubed into d b cubed so equations. So this is another form. I think I do not have to give you equation. So this will be 12, this will be the 13, okay.

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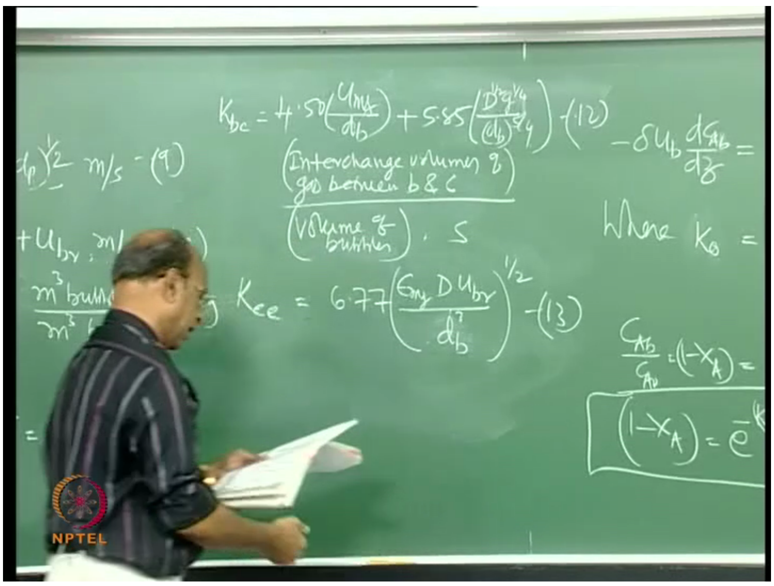

So what is K c e definition now? Volumes of gas exchanging between cloud and emulsion per unit volume of the bubbles per second, okay good. That is the one K c e. Then we have this parameter f b. It is generally given 001 to 01, volume of solid metre cube solids by metre cubed bed. This is estimate from experiment. This estimation is only from the experiment.

Experimentally they have measured and then they know what is the total volume of the solids in the bubbles, then that is expressed per unit volume of the bed, okay good. So then next one is you have f c. F c is delta into 1 minus epsilon m f and multiplied by 3 u m f by epsilon m f, that is one parameter, divided by u b r single rise bubble velocity minus u m f by epsilon m f again plus alpha. Yes, so this is equation number 14. You know do you remember alpha? Yes, that is what is that.

So that should be given to you. That is also experimentally measured value. In the problem definitely that will be given to you. I have already given. I think you have not thrown last time I have given you some assignment, okay. In that also it is mentioned. If you want to throw it you can come to my room and throw in my dustbin. I can take it and reuse it, okay good.

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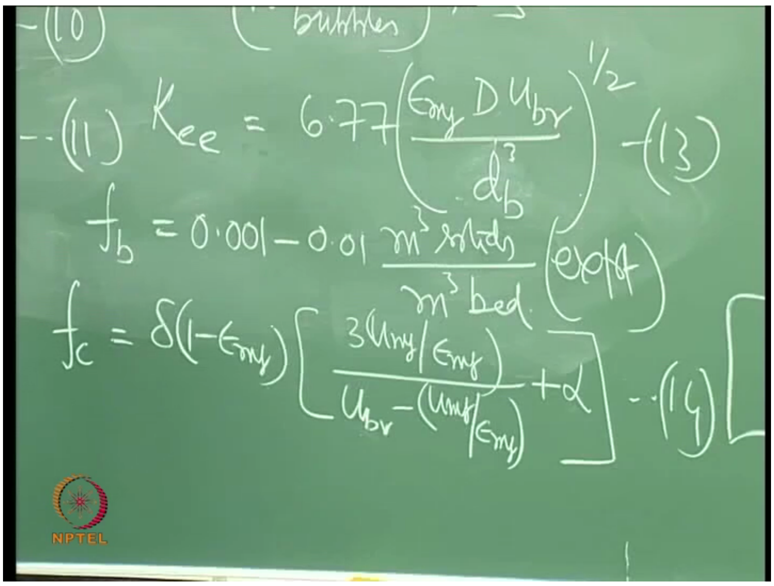

So this is f c. Then next one is f e. Oh my god, time. So next parameter is f e. F e again is volume of solids in emulsion divided by volume of the bed, right? That I think you have to write down somewhere. So this equation is very simple in the sense 1 minus epsilon m f into 1 minus delta minus f c minus f b. So this is the equation. And this one is nothing but 1 minus epsilon f, good. So this is also same.

Like for example if I bring f c and f b this side, what will happen? I have f c, f b and f e. What are that entire thing? Total solids. That is nothing 1 minus epsilon f because epsilon f is the voidage. 1 minus epsilon f is solid fraction. So that is what that balance is simple to understand. So this is another equation. This is 15, okay good.

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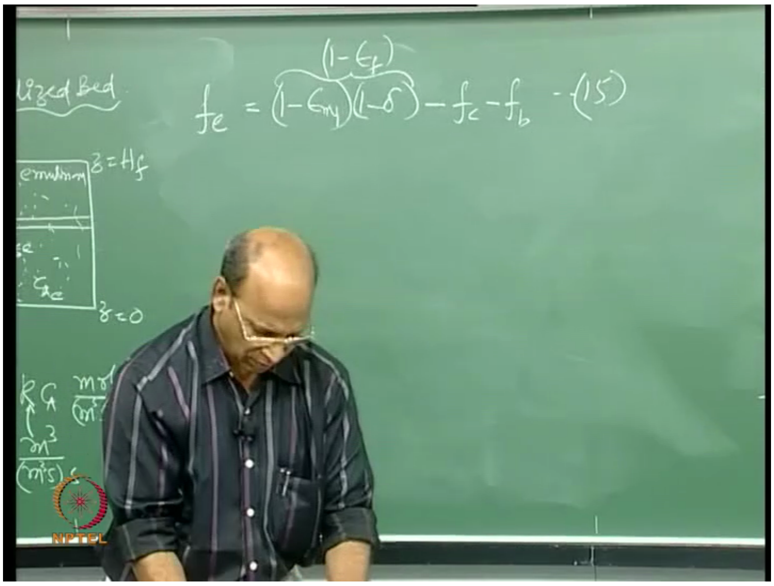

So other equations I have given, yes good. I think so this is the one. And now you have all the equations and you see for example f c. F c is again in terms of only u m f and epsilon m f and delta is in terms of again u m f, right? U 0 and u m f, right? So then what else. All this f c yes f e will also come in the same way. Yes, K b c is again in terms of u m f, right? All these things are known (())(01:00:46) to you. U m f will be known, epsilon m f will be known to you, right?

And of course the properties like diffusivities, acceleration due to gravity, all that you know. If you convert this entire equation in terms of only d b, right, so that d b you can vary so that you can also fit the data with your experiment. That is what exactly they have done in this figure 1, this corner is there figure, okay. So they have mentioned you know different diameters for intermediate large bubbles and all that. Sorry small particles d p and all that. Yes I think none of you have brought the Levenspiel book.

If you go to this is d p which is representation of what kind of bubbles you get. But if you go to Levenspiel figures and then see you will also see in terms of d b written. D b 10 centimetres, d b 5 centimetres, d b 30 centimetres. D b means diameter of the bubble. So that is why there is a single parameter d b which you have to use finally to calculate conversion in the bubbling fluidized bed. That is why Levenspiel model is very beautiful and very appreciated, Levenspiel and Kunii model, okay good.

So anything else equations? Savita, anything else missing for calculating that? First of all you have to calculate K 0. For K 0 you need f b, f c, f e all that you know, deltas you know, K b c K c e you know, no problems, right? And u b you know. So you can calculate very easily. Good. So like you know you have the delta equation, delta equal to u 0 minus u m f and all that but there is a very big derivation for that. But we are simply accepting that it is acceptable. I have that derivation.

It is this is the one for example you see. Cut across a cross section, imagine that all the gas is in the one bubble. That is delta. All the bubbles are in one bubble imagination. Then the rest is 1 minus delta, right? So now through delta, delta is the bubble phase, Davidson has already calculated through the bubbles how much gas is flowing, okay. So what he has calculated is delta into u 0.

Total u 0 is splitted into delta into u b plus 3 u m f. That is delta part, right? What is the other part? Other part is 1 minus. That is you know imagine this, okay. I think maybe if I have a cross section something like this and a bubble like this and the remaining is going down, okay. So this is delta, this is 1 minus delta.

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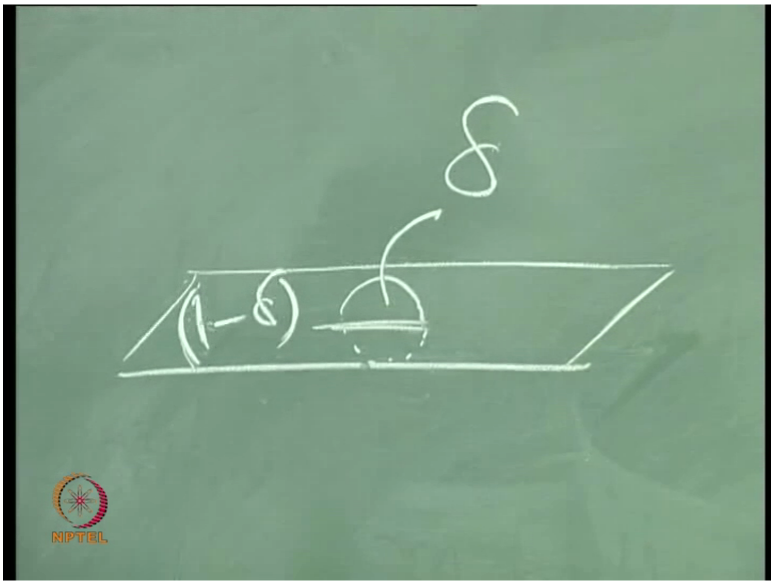

Davidson has given in this one what is the amount of gas that is going. This is nothing but your u b plus 3 u m f. He has derived that equation. And in the other one you have 1 minus delta. In this 1 minus delta how much gas is going? 1 minus delta is what first of all? Delta is the bubble fraction. Our imagination wise other thing is solids, okay. So solids are supposed to be at what velocity? U m f, that is all. This is nothing but 1 minus delta into u m f.

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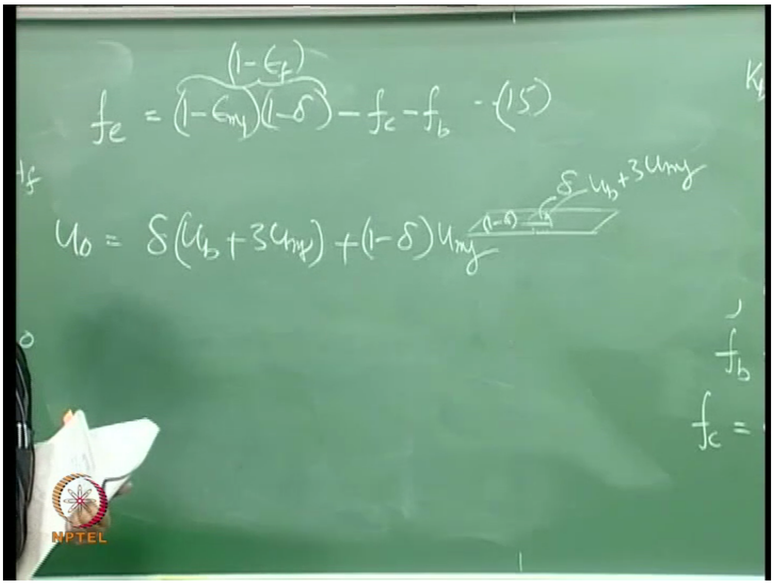

So now you can calculate delta here as u 0 minus u m f. If I solve for this, u b plus 3 u m f. That is the basic equation, okay. That is the basic equation where if u b is approximately equal to 5 u m f, yes then you will have delta equal to u 0 minus u m f by u b. Where 2 u m f?

Student: (())(01:05:30)

Professor: No, I mean see this is very approximate, right? This one, yes. 2 m f, thank you. Yes, so this is an approximate one where you get this kind of one. Then if you go for still very far then your delta is simply u 0 by u b.

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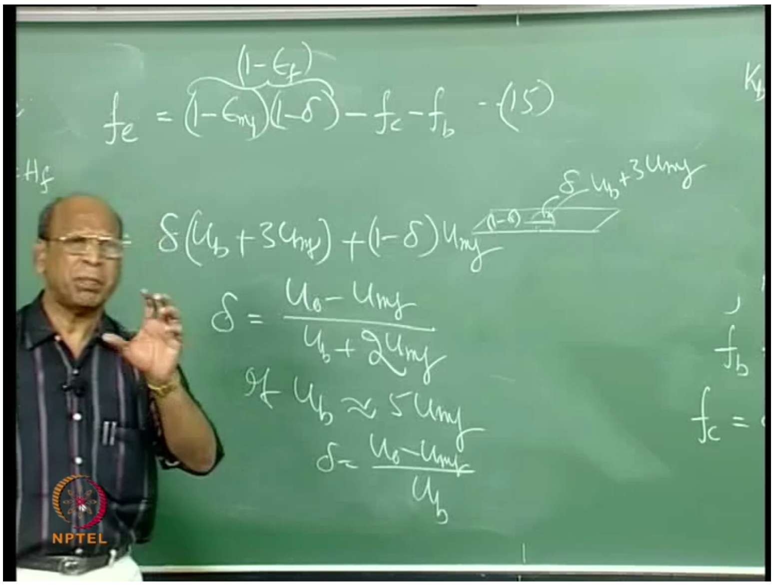

There are many approximations. That is why I want to tell you just one derivation. I just would like to tell you know what kind of things they have done. But now you see this one is also is a complete paper where they used (())(01:06:12) theory to get K c e equation that is the amount of gas that is going into the emulsion from clouds, okay. So like that for each and every one there is lot of theory behind.

But finally constants and all that adjusted with empiricism, with experiments and then finally this wonderful model has come. Good. I think we will stop here and tomorrow first hour we will meet.