Chemical Reaction Engineering 2 (Heterogeneous Reactors)
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Lecture 14
Design Equation for MF of Solids, Mixture of Particles for different size but unchanging size, Uniform Gas Composition, SCM.

Yeah, in the last class, we have developed the equations for the design of mixed flow of solids but single size, okay. What we do in this class is that, again, we extend the same analysis for mixture of particles. We have mixed flow of solids and most of the time mixed flow of solids, the excellent example is, fluidized bed - very how perfect mixing of solids! And I hope you know what is fluidization, right?

So, that is why, only based on that we are moving and all chemical engineers must know what is fluidization and I am sure most of you would have done the experiments even in fluid mechanics laboratory, but your experiments at that time probably would have been liquid solid fluidization. You are not done? You are done, yeah. Anurag, you have done? Fluidization liquid solid. Yeah, Renita, done it. Yeah, gas solid is most widely used in industry. So, what we are talking here is gas solid where perfect mixing assumption is always very well valid, okay.

So, now, what we are going to do is, if you have two or three types of particles that means, you know, sizes like 1 mm, 5 mm particle, 10 mm particle. So, how do you get fluidization is a totally different matter, but we assume that we have uniform fluidization for all these three size of the particles and then can you also develop design expressions for this mixture of particles, right. So, that is the one, but in general the realistic situation in fluidized bed is when you have 1 mm particle and then 10 mm particle, I have just exaggerated there 10 mm particle will never fluidized and 1 mm particle may elutriate, it may go out, okay.

So, that is why, the realistic situation is that, even if we have very narrow sized particles and particularly when you have gas-solid fluidization you will have lot of attrition. Because, the solid particles are moving vigorously in the bed, so one particle will go and hit the other particle. If the there are edges for this particle, so they are not perfectly spherical particles. You never get perfectly spherical particles except on the board when you draw or in the textbook, okay.

In industry you never get that, so, always you will have some kind of edges, rough edges for any particle. And, if you want to remove those edges then go to fluidized bed, fluidize all the corners will be cleared then you will get almost spherical particle, okay. And during that time, what is happening is, the lot of powder is generated that powder comes out in the cyclone. And, sometimes, if it is catalyst particles, so, this powder again they take make particles and again they may send it, okay.

So, that is why, gas solid fluidized bed so you have this attrition that means small particles may get generated, but on the other hand to start with the process contains small particles and large particles. Small particles will go out of this terminal velocity, that is why, I have been asking, you know, tell me one use of terminal velocity in industry? This is one of the uses. You will calculate and then find out at what velocities these particles will go out, right. So elutriation is a normal phenomena in fluidization.

Now, in the next after finishing the distribution of solids, next one is extending the same thing to elutriation. If I have elutriation, can I design the fluidized bed reactor? This is more complicated, but, you know, as a teacher I have to take you from simple to complicated, right. This is complicated design the other one. So, that is what, what we do in this class, right. So, the problems that may, you may face now is that, the residence time of the particles may not be uniform in the bed, right. So, the first case is single particles, uniform gas composition and they are not changing with time that is the assumption, right. So, that is why, you do not have attrition powder coming and all that is not their ideal situation. So that, we can easily understand what is going on in the bed, okay. So that one we have derived already.

So, now, the second situation is, I have mixture of particles may be 1 mm, 2 mm, 3 mm particles, right. So, now, first we have to prove that, this 1 mm, 2 mm, 3 mm particle will have the same residence time or if they do not have how do you take that into account that is the problem.

And next one if you go elutriation, definitely, you will not have, yeah, the uniform residence time for all the particles. Why? Because, when you are continuously feeding to the fluidized bed, the light particles elutriation we are taking into account. That means, some of the fine particles will definitely go, maybe, if you have 200 micron particles, 500 micron particles and may be 800 micron particles, okay, fluidizing.

So, then 200 particles may go to the top may not be all some of them, okay. Why? Because of this perfect mixing of all these solids. Some 200 micron particles may stay inside, some 200 particles which may got caught into this outlet gas then they may go out. So, that means, those particles are definitely not spending same residence time as other particles. That we have to bring into picture when you are designing this that is the only complication. If you are able to understand this story first then equations we will derive, okay. Mixture of particles, we have to prove that all the particles will stay same time or that means residence time is same. But, for elutriation, definitely, there will be residence time distribution or residence time changes for the small particles and large particles.

How do you take that into account and then try to design the reactor? What you mean by design again? Always, given the conversion find out the volume or the total holdup here, okay, or given the reactor find out conversion. That is all what do you mean by design, equation is same for both either this will be given or that will be given.

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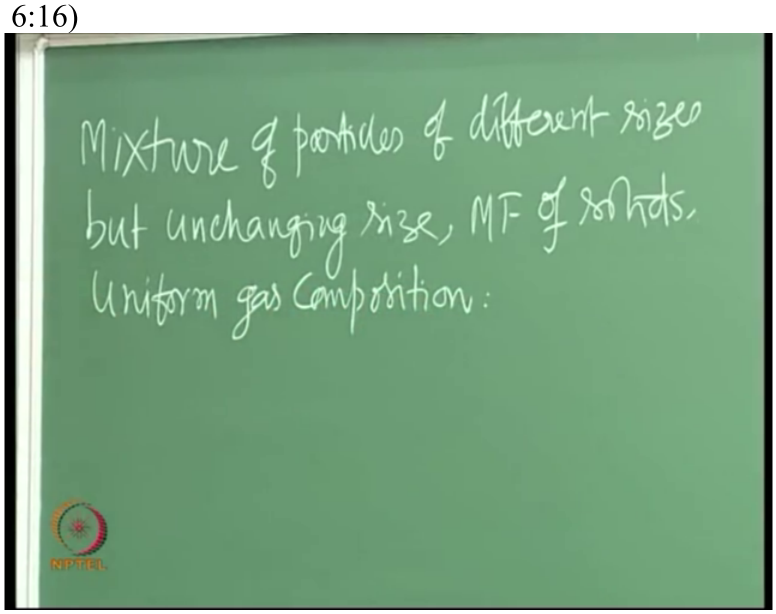

So, now, let us take that mixture of particles of different sizes, but unchanging size mixed flow of solids, okay, and other assumption is uniform gas composition, okay, good.

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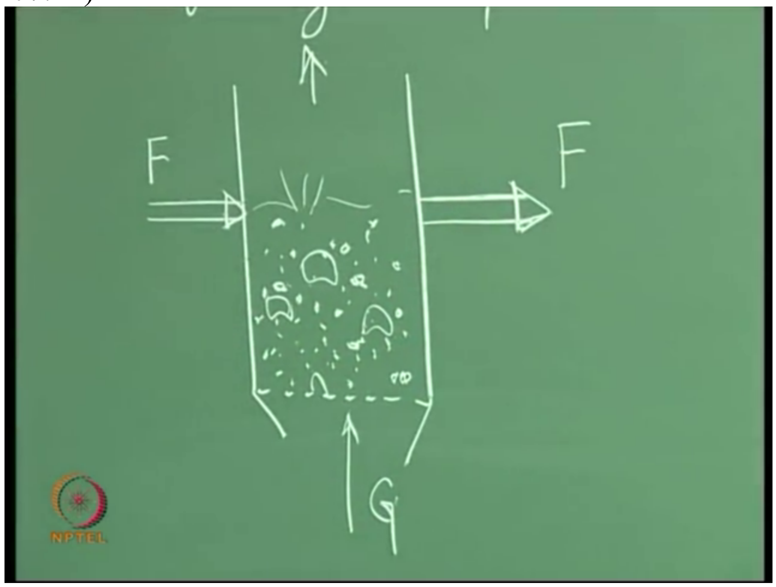

So, we will imagine our bed something like this we have the fluidized bed. This is gas, gas may come out there. Then we have the solids entering, okay. So these are the solid particles, I am putting something slightly bigger something slightly smaller. Yeah, they are not uniform size then we also have what are called bubbles. This bubble is breaking. Somewhere, here, we have bigger bubble maybe this side another bubble and solids also come out. So, if I take this one as F, F is coming out. So, then we have three particles, I know, three different size particles or maybe four different size particles or maybe two different size particles or three different size particles.

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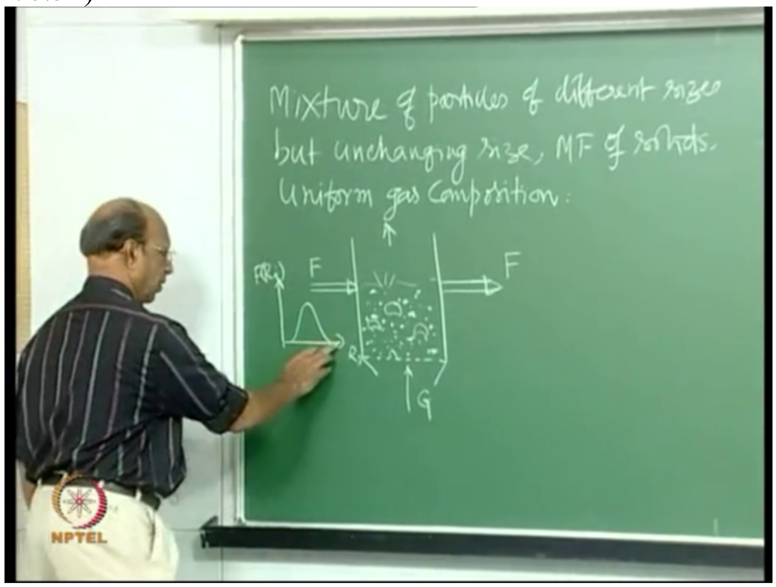

So, if I just show the distribution of the particles, so, this is F of Ri verses Ri, Ri is the particle, F of Ri, you know, the flow rates, okay. So that, distribution maybe if it is something like this, this is very nice distribution, okay.

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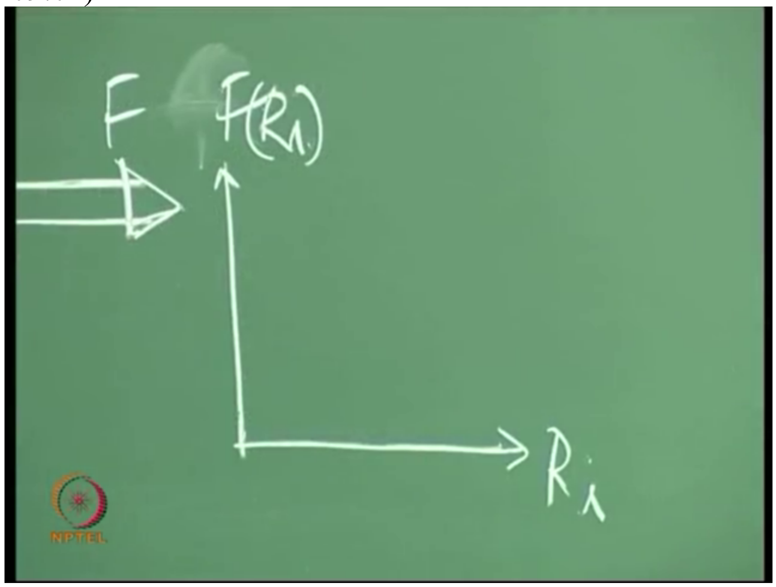

And this side, also, we can show that distribution. This is again F of Ri versus Ri, okay. Yeah, so will this distribution really change? Because, all the particles are coming in. They are not changing in size and getting reacted coming out. Will the distribution, this distribution will it change here? Just think, I say. Will it change? You know, normally, this is what is the problem with all of us the moment we say distribution our mind will block. We cannot imagine.

Why you are thinking so much time to answer this question? Yeah, (())(09:56) must be same, but, why are you keeping quiet sleeping time? Yeah, okay, so this must be the same, okay. Because, there is nothing no change is happening. Those are the assumptions very clearly, right. So, this distribution will be exactly, yeah, same, good. This is one thing.

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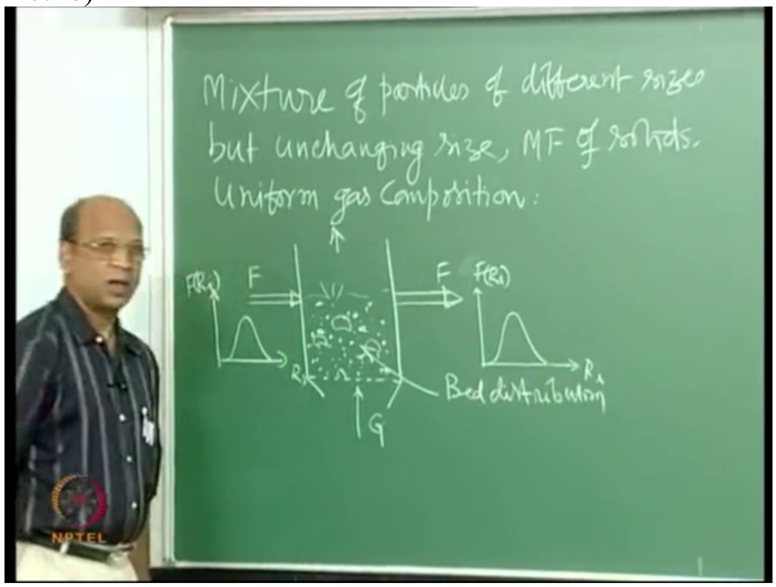

Now, I will ask another question.

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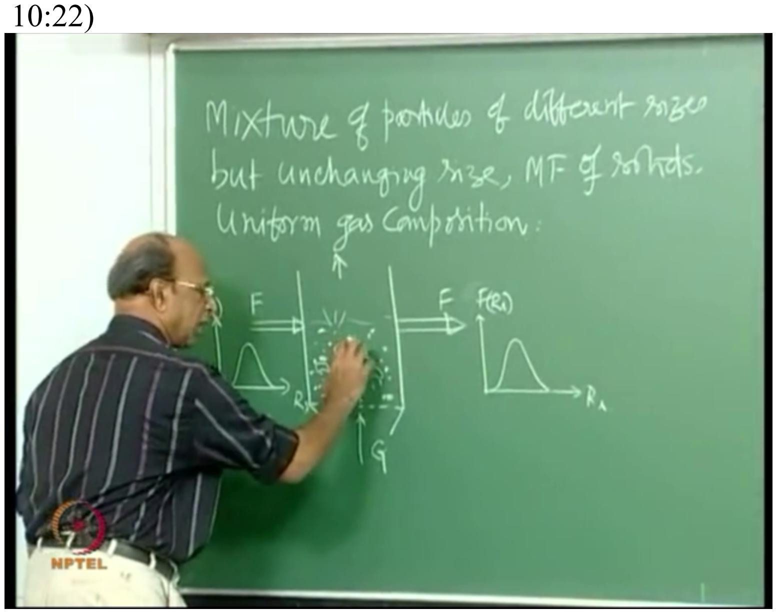

Now, I have this distribution of solids inside.

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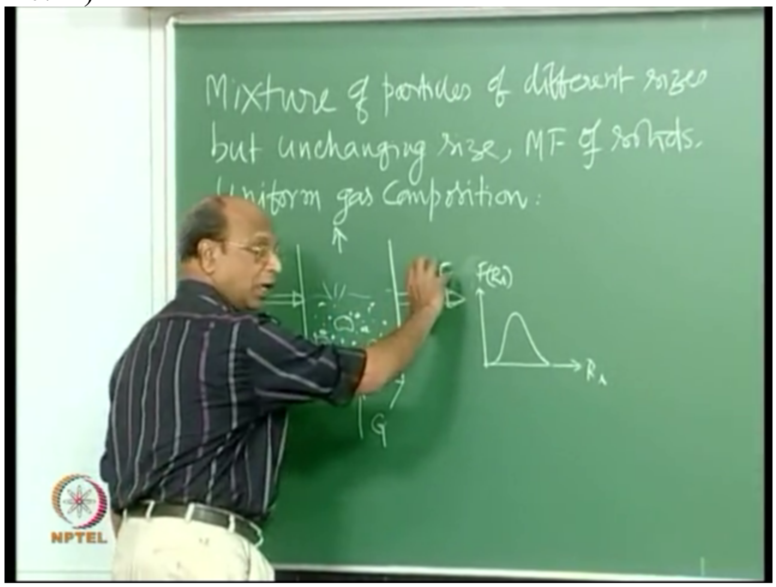

This is distribution in the outlet.

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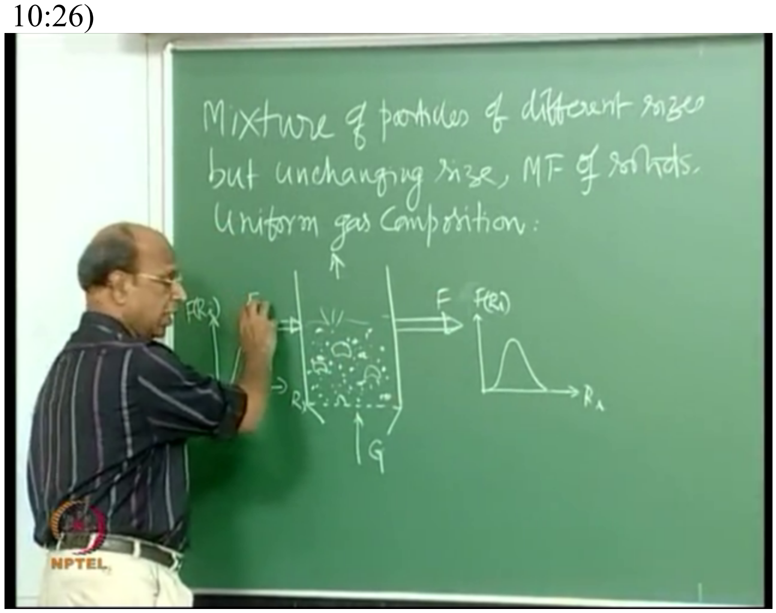

This is distribution in the inlet.

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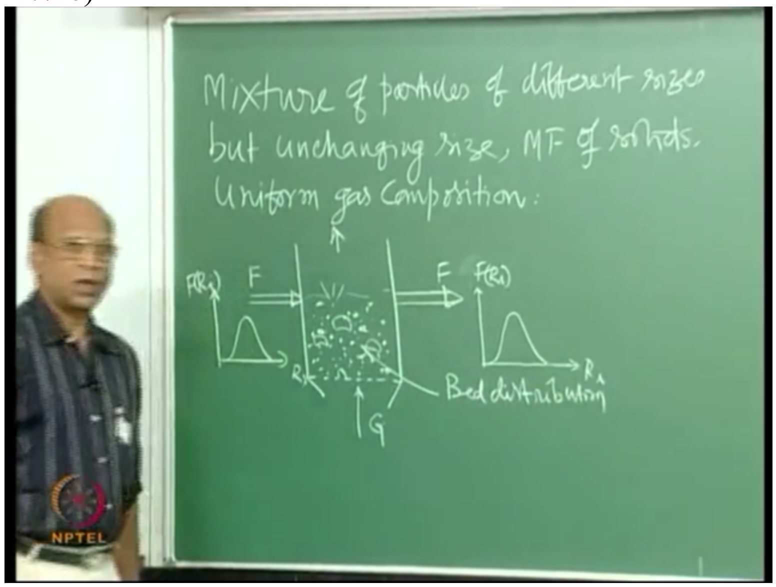

And, now, this is distribution in the bed, okay. Will the composition will be same there also? That means this is in the bed means it is W. W is the holdup, holdup of 1 mm particles, 2 mm particle, 3 mm particles.

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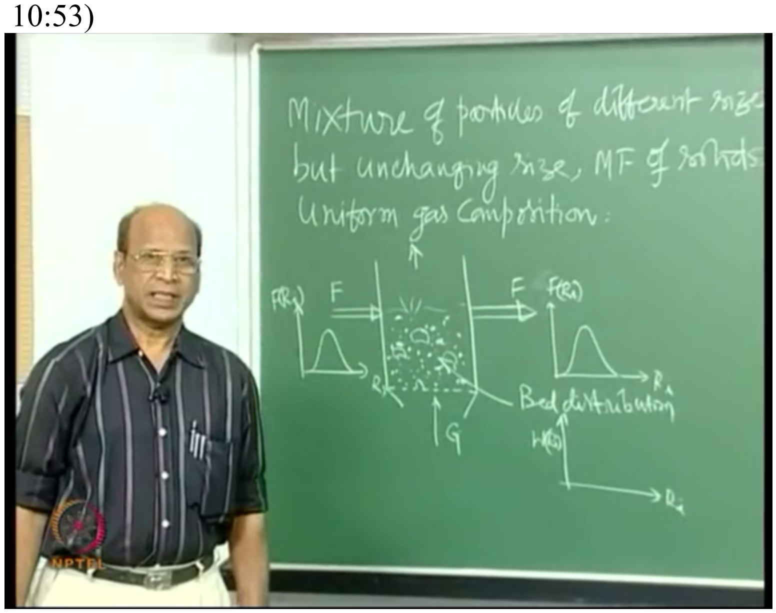

Will that distribution will be different than this and this? Will be it different?

Yes, Sir, why yes? It is elutriation. Is it we have taken that case, are you a chess player? Chess players think ten steps ahead. You are thinking about the next problem which I am going to tell you, okay. This is the present problem, where, we are only assuming that, you know, no elutriation nothing, right, I mean where did we say that particles are going out. It is the same size, uniform size nothing is happening. So, yeah, why it is say? Yeah, that is the again beauty of assuming perfect mixing ideal condition, okay. What is the meaning of this perfect mixing? The outlet conditions and also bed conditions are exactly same, okay. Otherwise, I told you know you cannot even write the material balance in the basic mixed flow reactor also. I have been repeating these things many times, but still it will not record. Because, simply, I think you come and sit and then enjoy the class and go. That is all, no? Yeah, not for learning.

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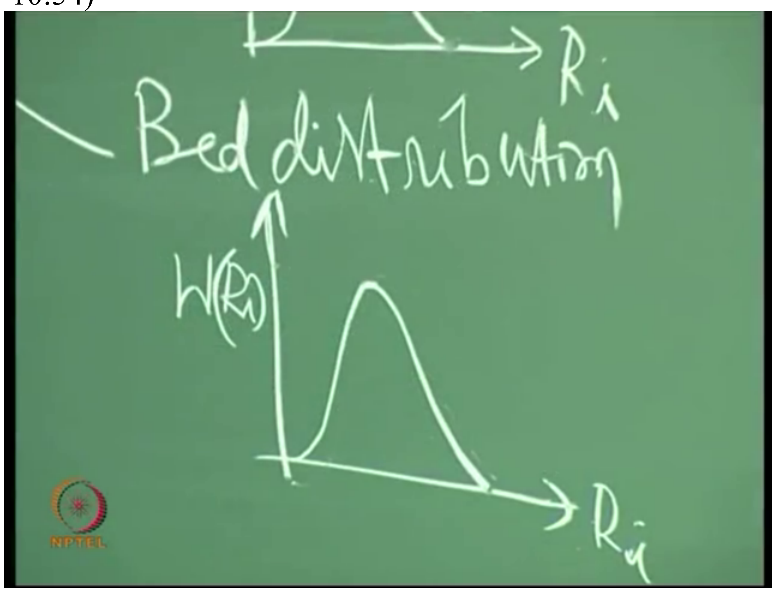

So, that is why, here also you will get exactly the same distribution, right. So, this bed distribution. So, now, this tells me that we do not have any change in the residence times, okay. But, anyway, mathematically also, we can prove that. Please take this, otherwise, you know, you do not understand I know that. At least, once in a before the examination at least you read it.

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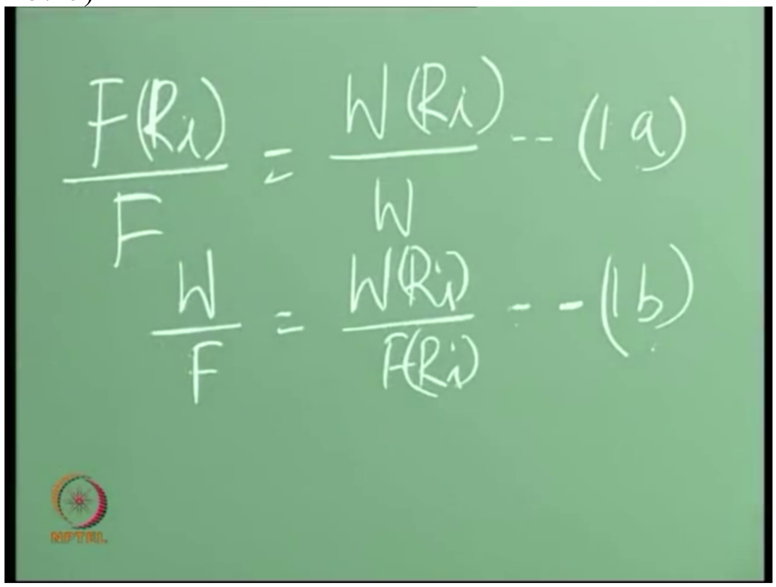

Yeah, please take this. Since, the system is assumed to be mixed flow of solids and the size particle is unchanging. The exit stream represents the bed conditions. We can also say that, the size distribution of the solids are, okay, the size distribution of the bed, feed and exit streams are all alike, okay, are mathematically F of Ri by F equal to W of Ri by W, okay. So, then which can be, this is 1 a. Which can be written as W by F equal to F of Ri, yeah, good.

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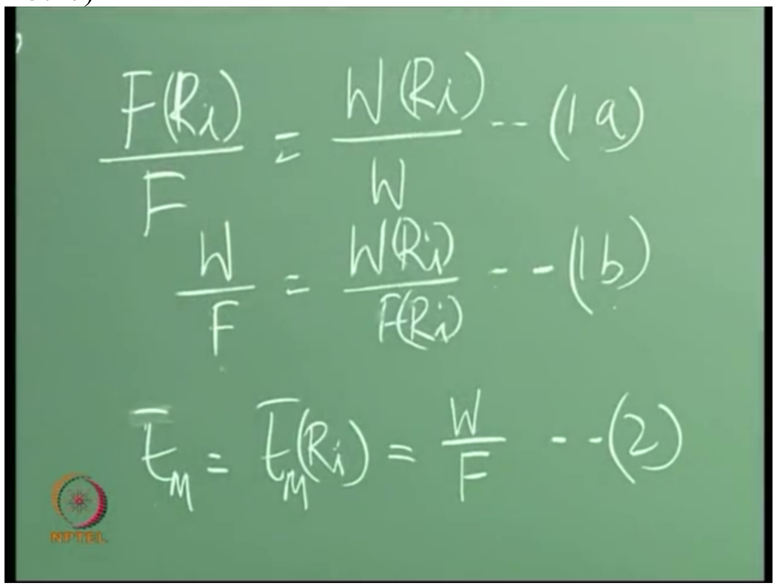

So our t bar M equal to t bar M of Ri, because, W by F is nothing but your t bar, right. Yeah, this, the since these two are same. We also have W by F, so this is equation two. This is holdup divided by mass flow rate, F is mass flow rate, good. So, now, once we know that the thing is same, okay, the residence time for each and every particle is same.

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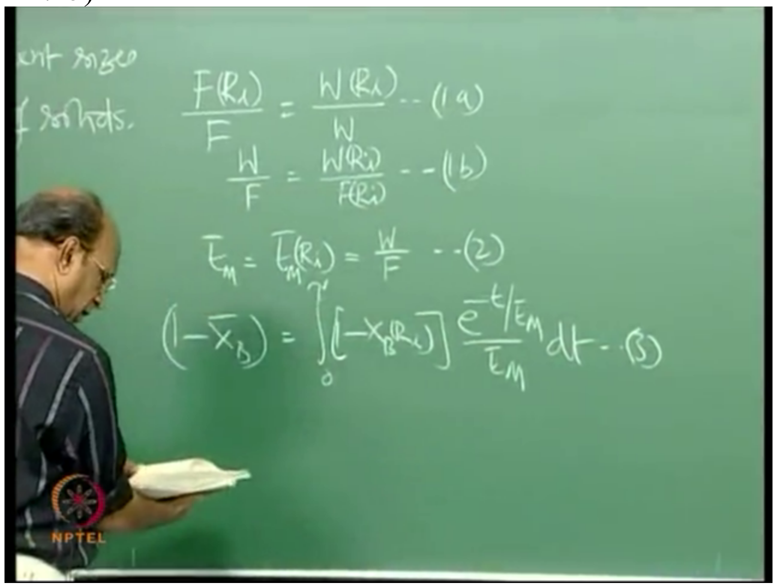

We have an equation for calculating conversion 1 minus X bar B equal to, yeah, what is that equation? 0 to Tau 1 minus XB of Ri into E power minus t by t bar M by t bar M dt, right. So, now, the procedure is same that means 1 minus XB Ri for each particle, I have to substitute and then add up all the particles. I mean, this is for a single sized particle. And because, you have, now, the distribution.

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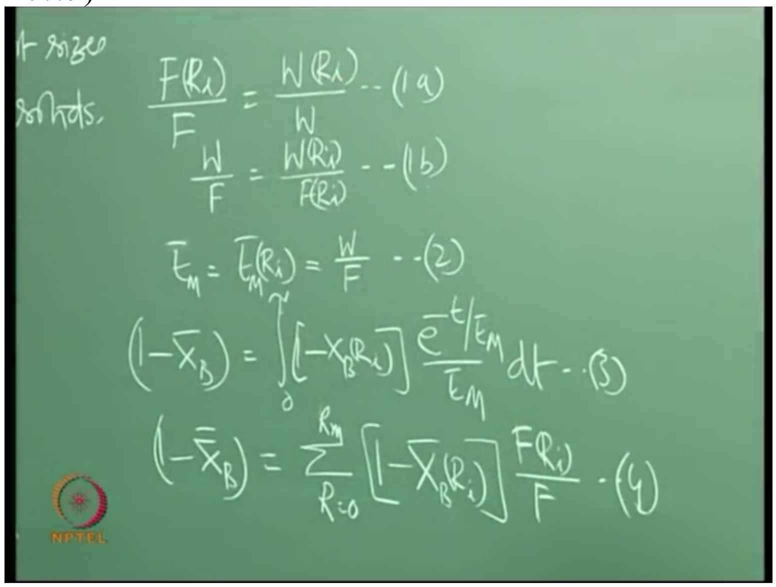

You will have, this is equation number 3. Since, you have distribution you will have, now, 1 minus X bar, the two bars sigma or equal to 0 to RM. Then we have F of Ri by F. So this is equation number 4, good. So, now, we already know what is the solution for this we have, but, again, you know, independent steps controlling film control, reaction control, diffusion control. We can substitute here and correspondingly write the equations. Let me write that those equations. And I think this is clear, no? There is no not much a, you know, it is very simple. You have done already for that integration and all that you have done for single sized particles. Yeah, individual rate controlling steps.

So, now, we have to just only take the weighted average, but the only thing you have to prove is that your residence times are same, so that, your t by t bar, here, which is coming in later, okay. You will get most of in all the equations you get t bar by Tau, no? t bar M by Tau. So that, t bar you will know for each and every size, okay. So, that is all, what you have to prove there. That is why, you are not learning anything extra, here, in terms of equations. Except that, you are only extending your knowledge of understanding, that is all, okay. Other than that we do not have anything new here, good.

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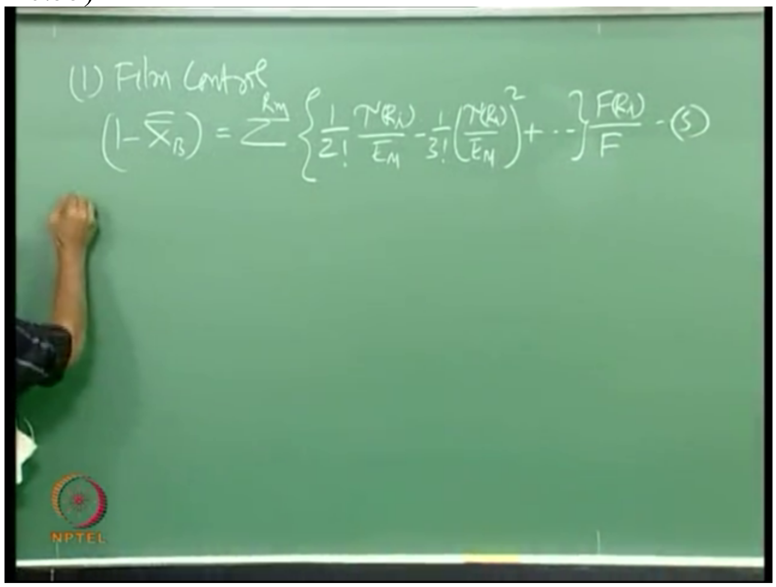

So, if I write again for practice, you have to anyway note down these for film control. We have an equation, this is maximum RM 2 factorial Tau of Ri t bar M minus 3 factorial Tau of Ri by t bar M whole square plus, etc. Sorry, given only two terms. Please check, if I am writing something wrong, you have to tell me. Yeah, so this is equation 5. You have to remember all this.

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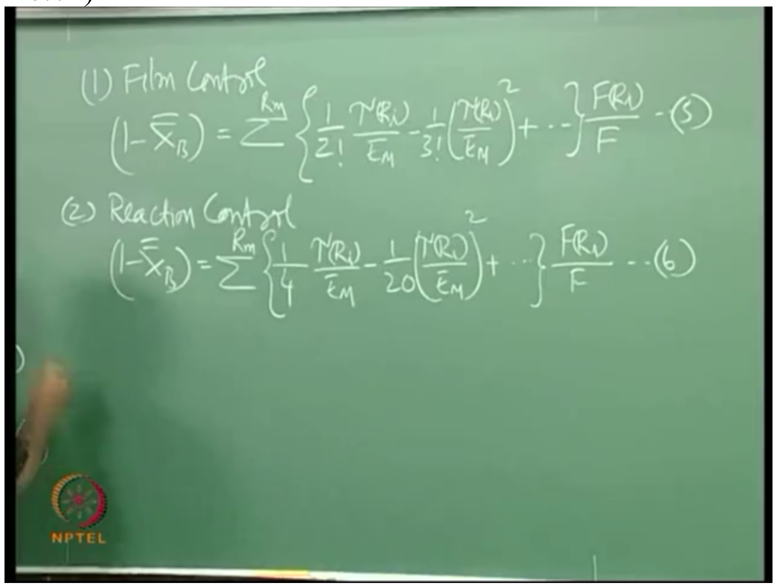

So, then 1 minus X bar double B, sorry, for reaction control, number 2, I have to write reaction control. For reaction control, we have 1 by 4 Tau of Ri by t bar M minus 1 by 20, F of Ri by F, this is equation 6.

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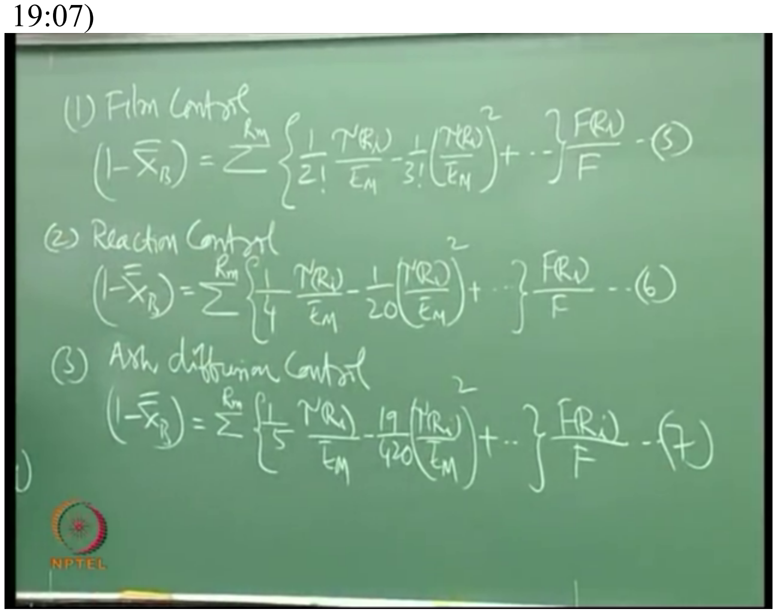

And for diffusion control, ash diffusion control, we have again X bar B t bar M minus 19 by 420 whole square F of Ri by F, this is equation 7. And, definitely, you will have much more difficulty, if you have 2 control or 3 control from this equation, okay.

But, one has to do. It is only a mathematical technique. That is all. Conceptually, you do not have to understand anything more, but only mathematics will be messy. So, that is why, there is nothing new to learn conceptually. So, that is fine, good. So, this is the one and as usual I can tell you that, if I know, the reactor volume or holdup and then flow rate, flow rate, we should know, anyway, right. So, then you will know t bar M and then is easy to calculate X bar. For a new reactor, X bar will be given, normally, okay, maybe 90 percent. That is what the problem was also checked and given that is, for plug flow, right. So, then X bar B, you will know, then you have to solve this equation to get t bar M, yeah. Once, you know, t bar M, this is the equation we have to use to calculate W, right.

So, F is known to you and W. W, let us say, you got two terms of solid. So, how do you put them as a fluidized bed? General, thumb rule is fluidized bed, packed bed before packing. You know, fluidized bed when fluidization starts before that all the particles will be in packed condition. When the drag force of this gas which you are sending from the bottom of the distributor, bottom of the bed when it is equal to weight of the particles, total weight of the bed then starts moving, okay.

So, that means, you are floating, you are making these particles float in fluid stream. And at that point of time, if you look at this mixture, now, the solids as well as gas. All the liquid properties you will or fluid properties you will see for this mixture. Mixture is, now, gas and solids or liquid or liquid and solids. That is why, the name fluidization is given. That means imparting fluid properties for, yeah, normally, immobilized solids. Otherwise, solids cannot move, right. So, by putting this fluid then you can transform this solids into a fluid like state. That is why fluidization, okay, good.

So, for that of course, the even, now, if you go to research papers in chemical engineering and see every journal will have at least minimum 2-3 papers in fluidization. So, that means, we have not yet understood thoroughly, because, we have put so many assumptions it is very easy for us to understand the problems. But, in reality I have shown you here this bubbles. Those bubbles are the biggest headaches in any fluidized bed but these bubbles are also good for mixing, unless, there are bubbles, there is no good mixing.

So, that is why, where do you cut. I mean how many bubbles you need and how many bubbles you do not need. That is very important thing in fluidization, okay. Because, if you have very-very large bubbles and all that. You know, there will be chaotic conditions, you do not know, what is happening in the bed. And, that is why, actually, these models will not be exactly suitable for calculating there is what is called bubbling bed models and also two phase models.

So, these are the models which we will also discuss when you come to fluidized bed reactors, okay. But, right now, it is simple decomposition, I told you know, I think, I promised you any reactor you bring on this planet to me then we can definitely imagine that either that want to be in mixed flow reactor, mixed flow conditions or plug flow conditions. That is why, this fluidized bed, also, has been imagined as a fluidized, yeah, as a mixture flow reactor. Because, the conditions look like mixed flow.

But, the actual phenomena, if you go and see inside the bed, it is slightly different than complete mixing, okay. Solids are complete mixing, but, how gas is transported to the solids and all that will be slightly different. That we will read, when you come to fluidized bed, okay. So, many times, I am repeating about the design objective always, you know, whether X is given, calculate the volume or W, here hold up or when hold up is given that means, already, available reactor with you. Then calculate conversion. So, these are the things, okay.

So, now, let us take with elutriation. That is slightly more realistic when the bubbles are just going from the through the particles and when the bubbles break here. Some of the solids also will just jump-up, okay, into the space. So, at that time, if there is slight change in the particle size due to attrition and all that. Those particles will be carried away. And it is inevitable in any fluidized bed, okay. So, that is why, that is more realistic condition with elutriation and let us take, now, design of fluidized bed with elutriation. Same conditions but with elutriation, good. Yeah, again size is not changing the way of what we are imagining. I told you that in reality we have size change, because of the collisions attrition and all that.

But, in our problem here when you are talking about elutriation. The particles are not changing size, only thing is, I have some small particles and large particles. Some of the small particles may get elutriated, right. So, that means, those particles are not going to spend more time in the bed. So, under those conditions how do we now design the reactor? That is what, what we do. I think I have to remove all this. If I use this diagram, I think you would also draw the same diagram, I think there, so, that is why, you have to try a new diagram. So, I will just, I use this diagram, but, please draw this diagram again for you in your notes, okay.

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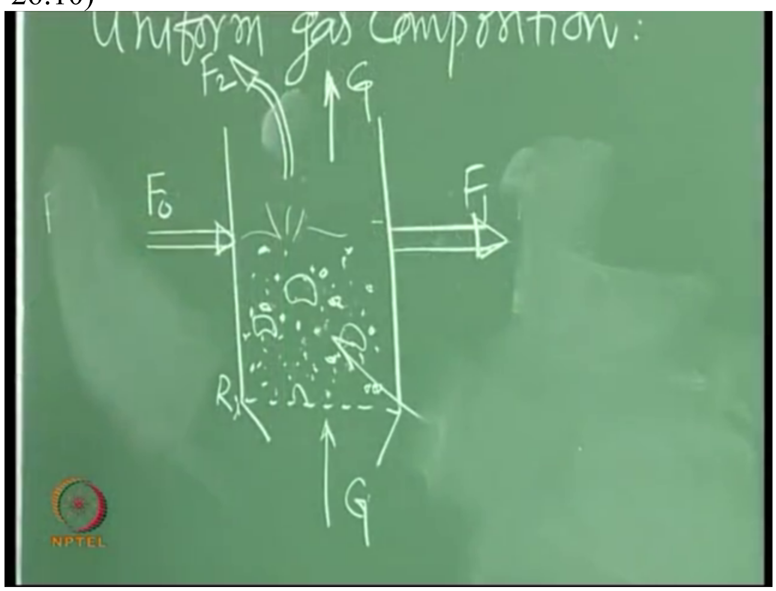

Yeah, but, the only thing here is that you have that also have to show gas is going up anyway. But, there are some solids also. This is F0, F1, F2. Solids are just going up.

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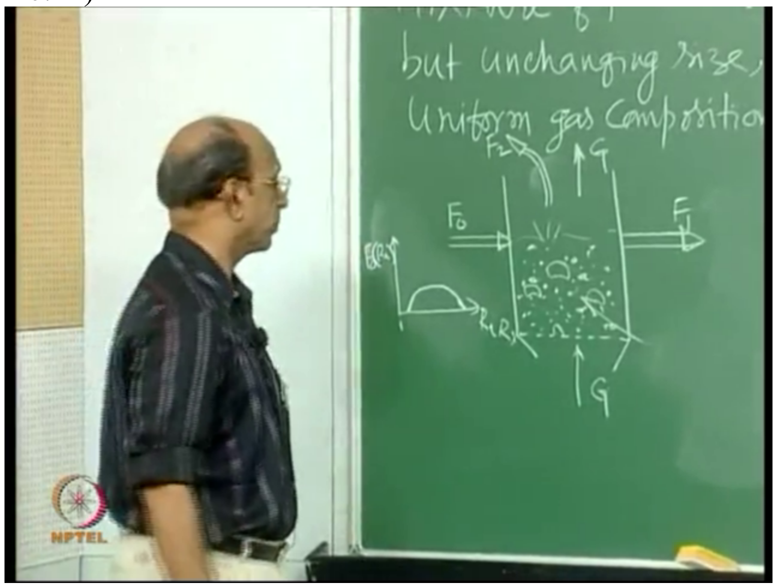

The distribution, because, now, we have a little bit more number of different sizes. So, I may have a distribution something like this. This is F of Ri versus Ri, 0 Ri, F0 Ri. So then in the bed as well as outlet I have the same composition, because again even here we have perfect mixing, right.

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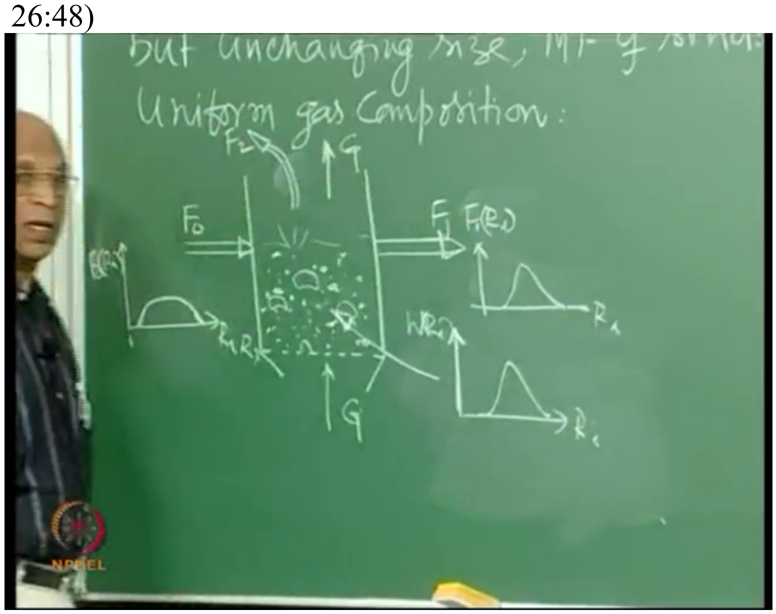

So, in the bed, I may have something like this. That is in the outlet and in the bed we have again, yeah, so this is W of Ri versus Ri. This is F1 Ri, Ri.

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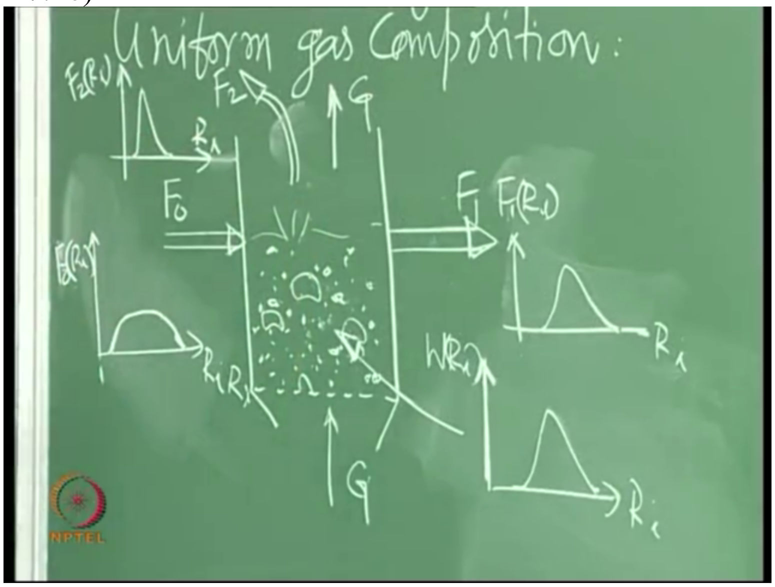

But, now, here, also, you will have the distribution in the outlet here also. So that, will be if I plot here, this is F2 of Ri will be narrow size like this. This is Ri. Because, only fine particles are going, no? Small diameters, so, that is why, this moves this side, this moves slightly the other side. The distributions qualitative distributions.

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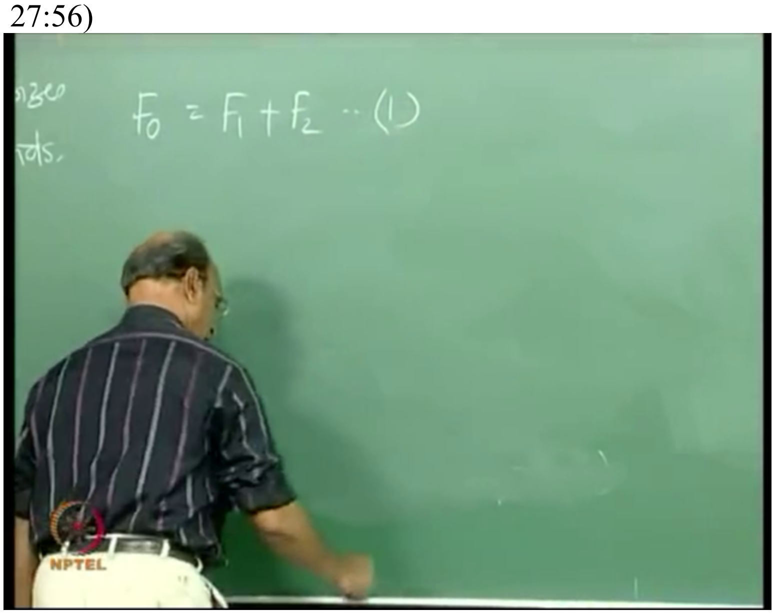

Yeah, so, now, we will write the material balance for the solids. The material balance for the entire streams F0 equal to F1 plus F2, this is equation 1. That we know very easily.

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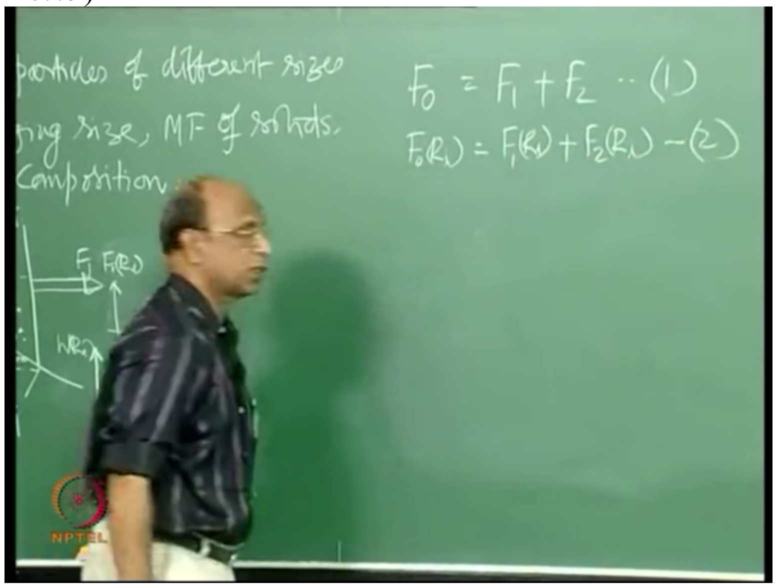

Then we also have the size distribution mass conservation that is F of 0 of Ri equal to F1 of Ri plus F2 of Ri. So, this is equation 2. That means 1 mm particles, if they are there in the inlet how many coming, outlet, here, this stream and this stream together that balance, okay, good. Yeah, please again take this. Since, the mixed flow of solids is assumed, the composition of the under stream.

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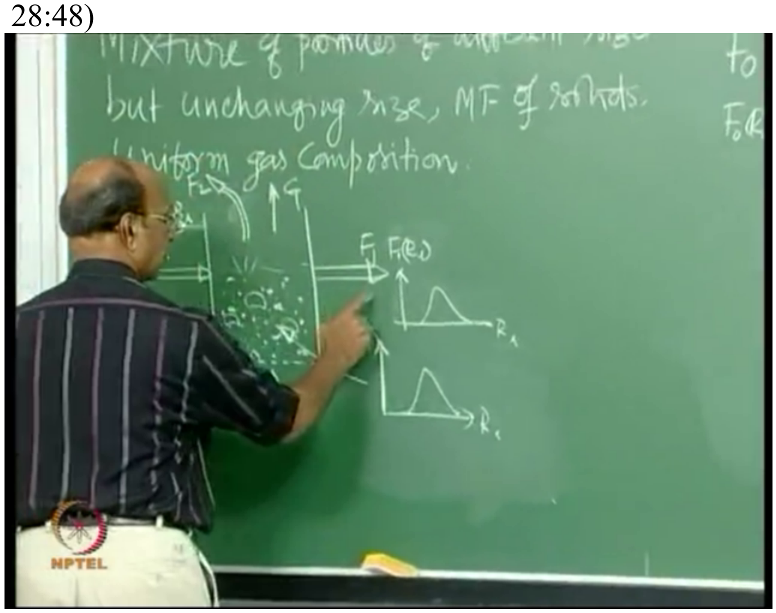

This is called under stream F1.

You know, you can write there. Since, the mixed flow of solids is assumed, the composition of the under stream F1 still represents the composition within the bed.

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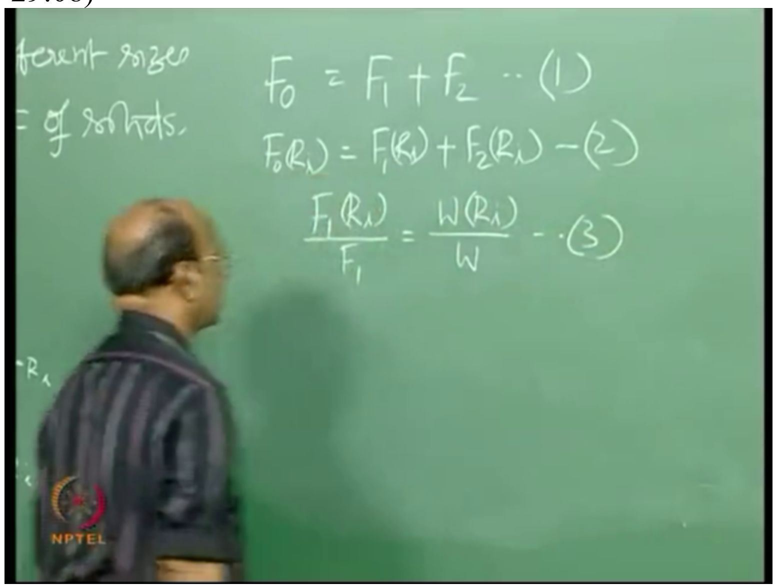

So that, we have F1 of Ri by F1 equal to W of Ri by W, this is equation 3. Yeah, please take this. Again next line, the mean residence time of material of different size may not be the same. In fact, small particles will be blown out or elutriated out of the bed and these particles spend less time in the bed than large particles, okay.

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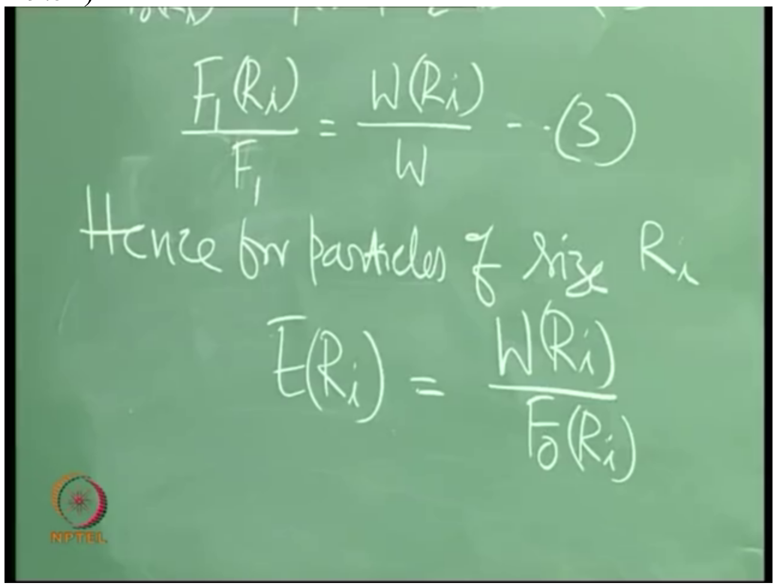

Hence, for particles of size Ri t bar of Ri equal to W of Ri divided by F0 of Ri, correct, no? W is in the bed and F0 in the inlet, okay.

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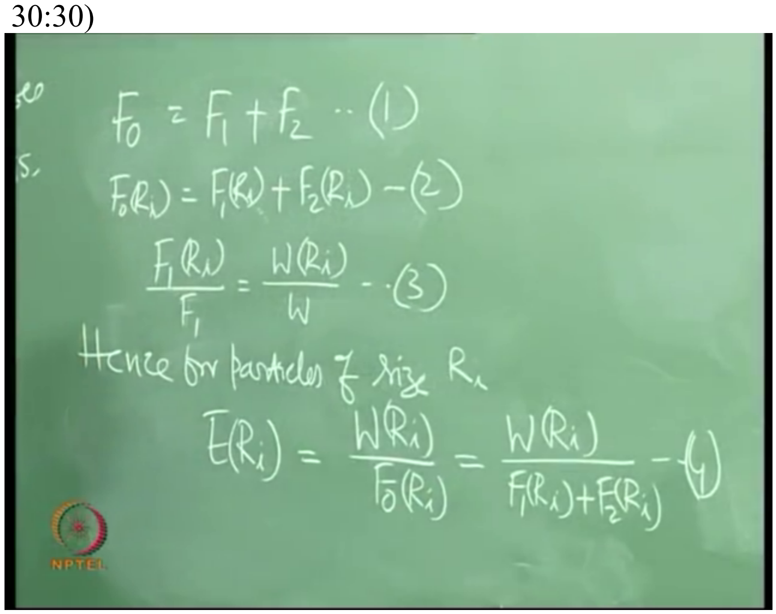

So, this is, yeah, which can also be written, we have F0 of Ri, this equation 2, okay. Which also can be written, this as W of Ri, yeah, F1 of Ri plus F2 of Ri. This is simple substitution only, okay. So, F0 is simply written like this.

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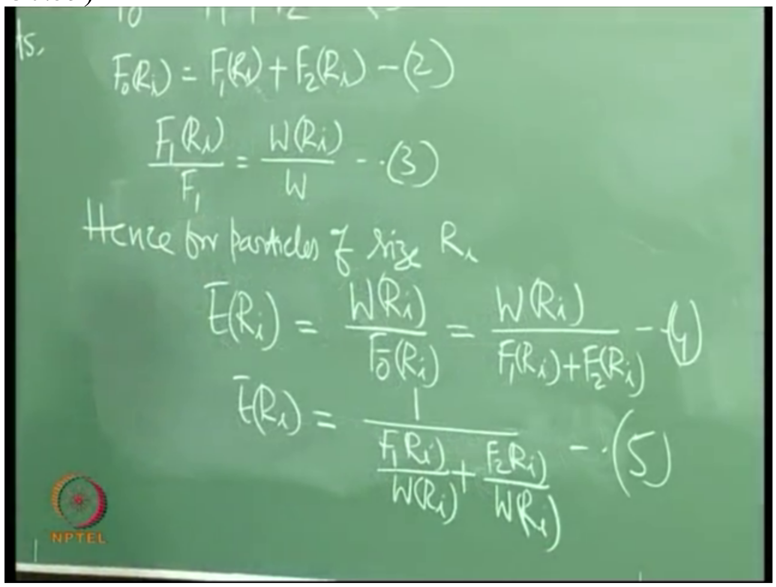

So, this also can be written, of course, just by adjustment of the terms. You will have here this is 1 by F1 of Ri by W of Ri plus F2 Ri W of Ri, okay. Yeah, this is equation 5.

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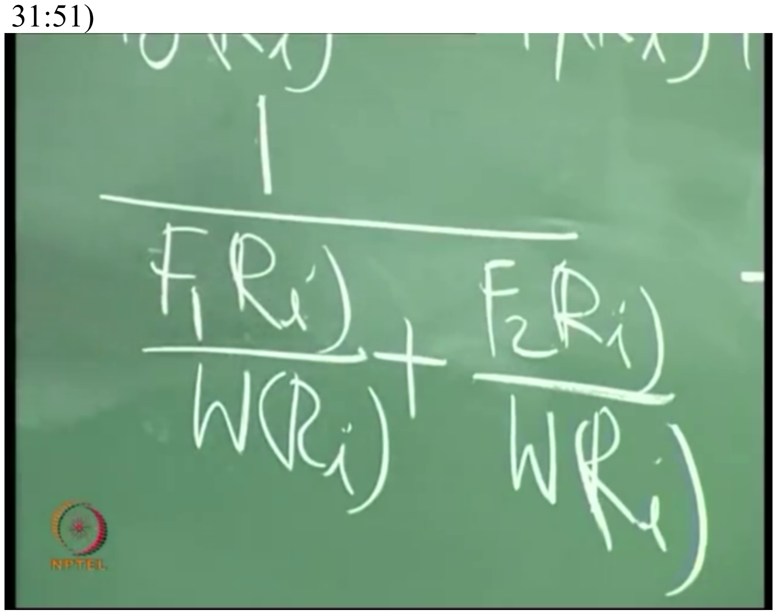

But, do you have anything here connected in terms of easily measurable quantities? This is individual solids Ri 1 mm, 2 mm, 3 mm like that. F1 of Ri F1 of 1 mm particles divided by holdup of 1 mm particles, okay. And, again, you can write somewhere, substituting equation 3 in 5, okay.

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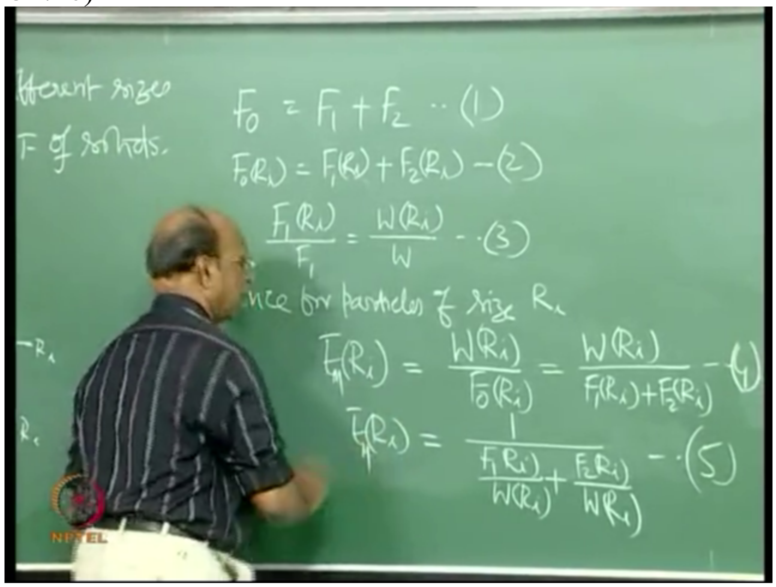

Somewhere, it is a, okay, I have to write here M to be specific. I have been maintaining that.

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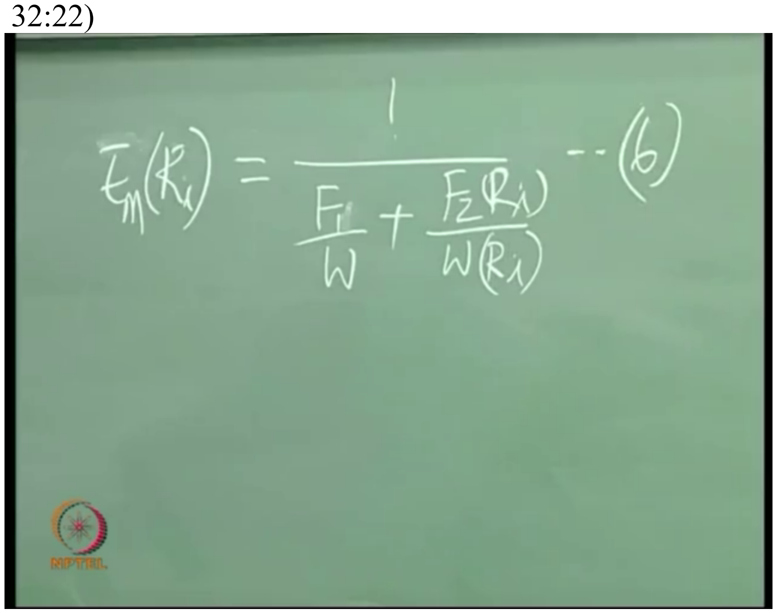

So, let me write that. So, t bar, this is not over t bar that is equal to 1 by W by F1 plus F2 of Ri by W of Ri (())(32:47) F1 better, F1 by W, good. So this is one equation what we have.

So, that means, if I am able to find out F1 and W and F2 and W Ri F2 of Ri. Then I have time known for each size, residence time. So, once, I know this, now, I will go to my 1 minus X bar B equations and then try to find out, okay, for 1 mm, what is the conversion? 2 mm, what is the conversion? 3 mm, what is the conversion? That is all, okay, good. But, the problem is, do I know F1? Do I know, F2? W is easy, okay. W Ri, at least, they are not that difficult, okay. So, that is why, we have to try to find out those things.

But, before that, what we do is, we will now assume that we know this t bar of RM t bar M Ri and then write the design expression. Then question, how do I use that design expression? Right. Question is do I know t bar M of Ri for a particular size? If I do not know, what else I can do with this equation to find out t bar M of Ri, okay.

So, that is why, design expressions first, let us write, again design expressions are not new - same thing, if it is film control, reaction control, ash diffusion control those are the same equations, same summation. Because, you have three different sizes, okay. That will not change. So, that is why, the 1 minus, okay.

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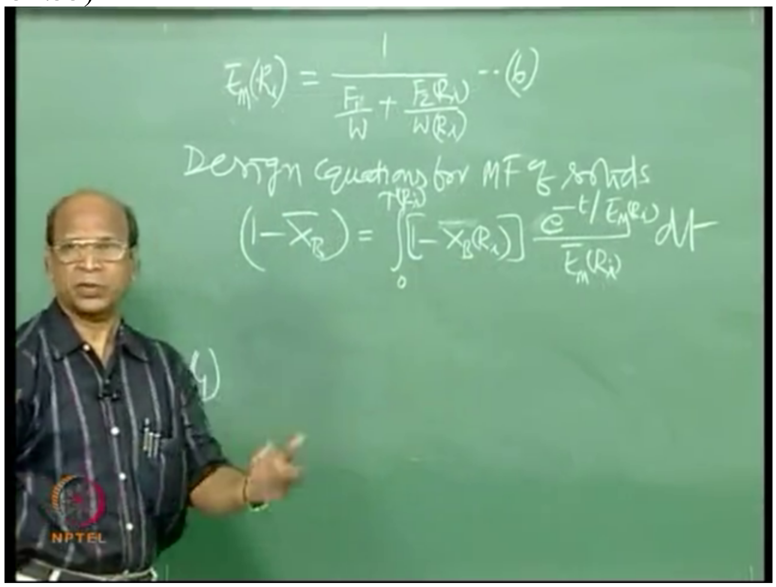

Let us call design equation, design equations for MF of solids is one minus, okay, I think, let me also write once more X bar B equal to, again, 0 to Tau of Ri, here, now, you see Tau of Ri. Then 1 minus X bar B of, not X bar. So, this equations again, t by t bar M. Now, please remember this, this will be Ri divided by, yeah, Ri dt, okay. So, if I know t bar M of Ri for each particle, right. So, now, this equation everything, I know. 1 minus XB will give me the kinetics. So, that means, whether ash diffusion control or reaction control or whatever control we take.

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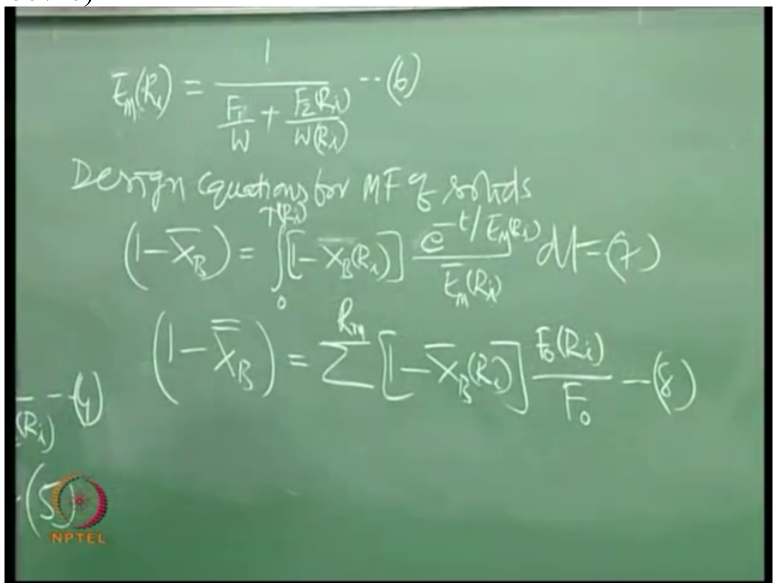

And, from this, we know the extension for multi-particles that means summation of that equation in terms of in all the particles, okay, sigma of all. So, that is equal to sigma of 1 minus X bar B of Ri into F naught Ri by F naught. So, somewhere, I have to this is equation 7, this is equation 8, right.

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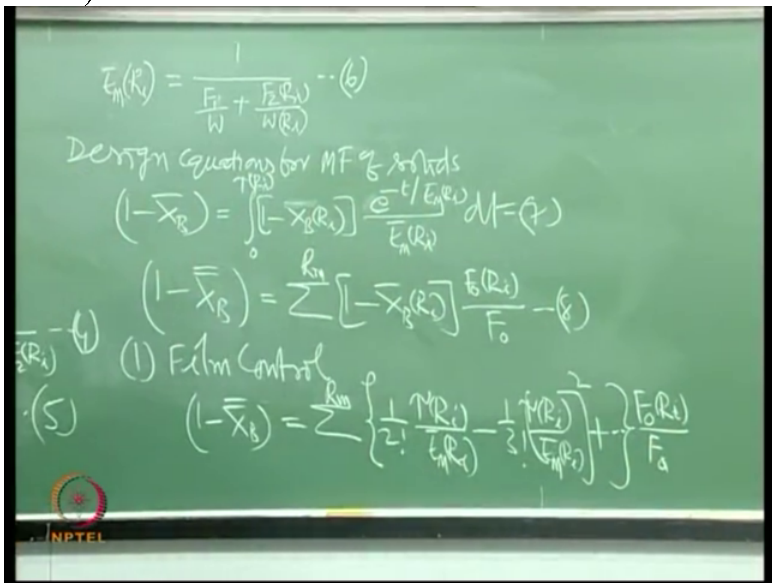

I think we will write once more the equations that is for ash diffusion control, sorry, first film control, number of times you will write, you know, you will remember. So, let me write that, so, 1 minus for film control, yeah, can someone tell me? You know, 1 by 2 factorial Tau of Ri by t M of Ri minus 1 by 3 factorial Tau of Ri by t bar M of Ri whole square, right. Yeah, so, other terms will come into F naught of Ri by F naught, okay, good.

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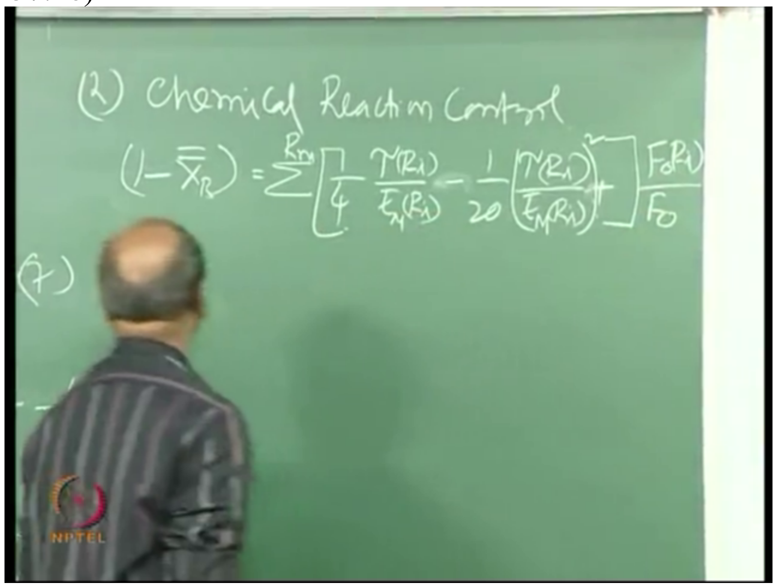

So, I think the other one or other two also let us write. So that, I think at least you remember once more reaction control, number two chemical reaction control when you have. Then we have 1 minus X double bar B equal to sigma of all particles. So, 1 by 4 Tau of Ri by t bar M of Ri minus 1 by 20 Tau of Ri by t bar M of Ri plus we have other terms, okay. This is whole square, right. So, you also tired? So this is f naught of Ri divided by F naught.

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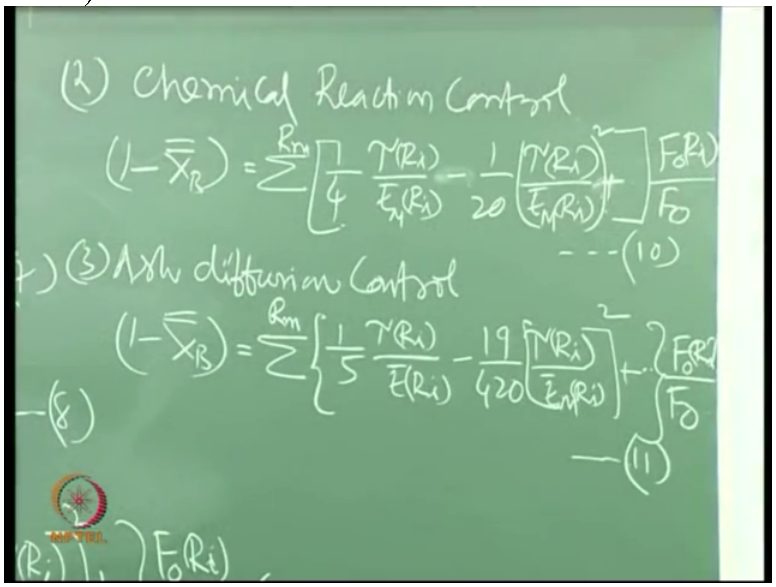

So, the other one is diffusion control, ash diffusion control. So, here, we have 1 minus sigma of all Rm. So then we have 1 by 5 Tau of Ri t bar minus 19 by 420 whole square, here, we will put plus F naught of Ri by F naught. So, if I put number this is 9, this is 10, this is 11, okay.

Yeah, so, now, of course, in the next class we will try to find out that t bar of Ri for these different sizes, how do I know? Definitely, I do not know. Because, I do not know what is F2, okay. And also W Ri and W, of course, as a total holdup I may know and F1 as they underflow I may know. But, we have to use this equation and then try to find out this t bar and that is what we do in the next class, okay, good. No question, Sir? Yeah, as usual no questions, okay. Thank you.