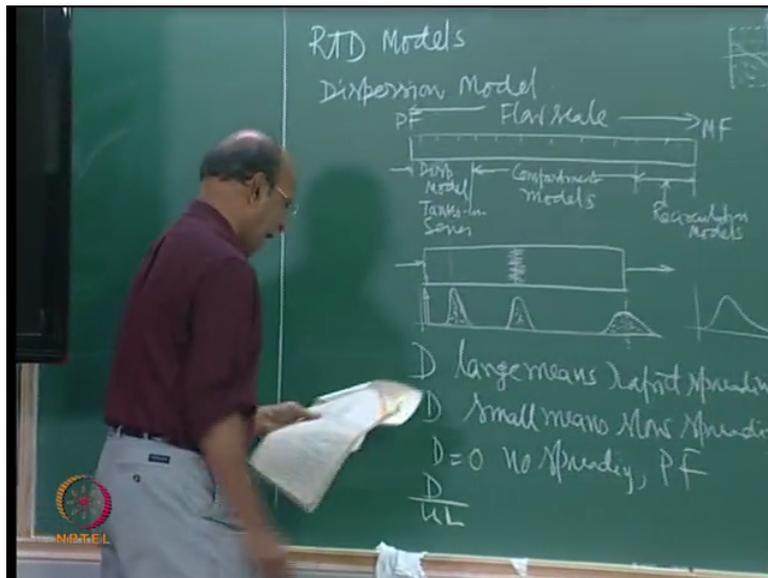


**Chemical Reaction Engineering 1 (Homogeneous Reactors)**  
**Professor K. Krishnaiah**  
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**Lecture 55**  
**Dispersion Model**

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Okay, it has got also other names know yesterday we thought ya yesterday we also told that dispersion model, it is also called axial dispersion model, okay it is also called plug flow with dispersion there are so many things axial mixing all these names are given for dispersion model. So in general when you have this RTD Models you can have a small scale just to have an idea what kind of models we are going to use this is just an analytical scale where we have this end PF, this end you have MF, okay so the dispersion model and tank in series model normally it is not exact but you know somehow approximate distance you can see so this is the distance between which you use dispersion model, okay dispersion model or tanks in series model, okay. So this end normally we call them as recirculation models, okay right okay.

So in between we have what are called compartment models, okay so compartment models meaning is that we have plug flow and parallel to that you can put a mixed flow and you can put two parallel plug flows when do you use that two parallel plug flows? When you have channelling, okay channelling, see one channel is plug flow, another channel also is plug flow so two plug flows in parallel if you put, okay you are talking about reactors what I am talking

is that once you have the tracer data so depending on the type of response you get you know the type of curve you get yesterday only we saw that right various types.

So depending on the types you have to choose what are the models, right and you know very well that when you are near plug flow you will get that axial dispersion beautifully like this so that means here either you can use a dispersion model or tanks in series model, okay or otherwise in between we do not know I think like dead space is there, then you add CSTR or mixed flow sorry both are same plug flow with dead space, right or plug flow and then parallelly to that dead space all kinds of models one has to prime, right and you will try the correct model if you have good physical sense, what is really happening in reactor it is only one reactor only thing is you are imagining like you know we have the stomach and our digestive system someone was asking know so our digestive system can be modelled with mixed flow and also followed by plug flow so all that I mean we have only one digestive system.

So similarly reactor is only one but looking at the response curves then you will think that okay this may be a combination of two CSTR since it is depending on the type. So that means you have to now take two CSTR's in series write the equation tracer equation how much concentration is entering the procedure is universal approach is same, right so write the concentration versus time you know that model like how much is entering tracer, how much is leaving so you will get a differential equation and you have to solve that that will become concentration as a function of time concentration as a function because it is unsteady state tracer is always unsteady state you are just giving a pulse input and then with respect to time slowly it may increase or decrease or continuously decrease depending on mixed flow for example, right and you have to write the corresponding equations what is entering, what is leaving.

And once you have concentration versus time some equation because you are having a differential equation, you are solving it after solving that you are now having C versus T information as a equation, how do you find out ET, ET definition wise  $C$  by  $y_a$  0 to infinity  $ct$   $dt$ , right. So you have an equation for C you have an equation for C, right so that C equation you substitute there the simplest equation what you can see if if you are trying for mixed flow pulse input pulse input so procedure is same again you are writing what is entering, what is leaving but only thing is input is 0 after sometime because you know pulse input only at time  $t$  equal to 0 you add and then start analysing at the outlet.

So input is 0, output is  $V$  into  $C$  and accumulation is because it is unsteady state there is no reaction plus  $VDC$  by  $DT$  so  $0$  equal to  $VC$  plus  $VDC$  by  $DT$  that is the equation you have to solve and corresponding boundary condition you have to take. So equation what you get for that equation is  $C$  equal to  $C$  not into  $t$  bar that is the equation now you have to substitute  $ET$  equal to that  $C$ ,  $C$  equal to  $C$  not by  $e$  power minus  $t$  by  $t$  bar divided by integral  $0$  to infinity  $CDT$  that  $C$  is again  $C$  not  $e$  power minus  $t$  by  $t$  bar  $dt$  that is all.

So the approach is same the procedure is universal, so only thing is if it is not ideal CSTR, ideal mixed flow, if it is dispersed plug flow you will get more complicated differential equation which will give you more complicated  $C$  versus time equation the simplest one is  $C$  equal to  $C$  not into  $e$  power minus  $t$  by  $t$  bar is the one for mixed flow reactor. So any complicated I mean what you do know for ya this compartment models is that you assume many things like you know you have one CSTR and also parallel to that plug flow, plug flow will come as a direct delta function ideal so CSTR will have that.

So now write the material balance for both I mean you should know what is the flow speed how much is going through plug flow, how much is going through CSTR that is also a parameter you start with  $V_1$  and  $V_2$  volumetric flow rate 1 and volumetric flow rate 2 that is also a parameter for modelling the reactors that is one parameter, right so because you do not know this is only black bugs you know that you are sending 100 litres per minute out of 100 minutes per minute how much is going through this plug flow section where there is a pipe which is simply coming out, okay in a tank for example we do not know I mean just imagination, right the other one is may be perfectly mixing that is parallel you take PFR ideal PFR as parallel and to that CSTR.

So now you write in this both what is entering and at the end what is coming again you know both have to be combined and write the material balance we get  $C$  versus  $T$  data equation and that equation convert to  $ET$ , okay and you know how to convert  $ET$  into  $E$  theta if you want to convert as you know dimensionless dimensionless, right. So that is the overall approach that is why I think I am taking more time only because of those reasons you know that approach approach is more important that doing individual problems, once you understand this approach because this is universal.

Like I told you reactor design what is the information needed, only kinetics and contacting that is all and you know how to choose contacting and you know how to find out kinetics that is all even next semester also the chemical and catalytic heterogeneous systems also the

approach is same but there the methods are different because you have number of phases you may have two phases, three phases, right.

So that is why approach is universal for us either in this one or in any subject you know that is why in any subject first of all approach should be mentioned and atleast you remember the approach you do not have to remember the individual details of equations how to derive and all that if you do not want, right but approach you should not forget anytime and approach is the one which is asked in interviews, okay that is the approach which you ask always in approach, okay I have to design a batch reactor what is the procedure (9:30) what is the approach, okay.

I have a system coal combustion how do I find out kinetics, I do not ask what is the temperature what is the exact activation energy or what is the order of reaction those things we do not ask what we ask is okay I have a coal combustion you know I have find out kinetics so then tell me what is the approach, how do I proceed if you are able to tell that I think you will definitely get the jobs so even here it is same thing.

So we have the this is the flow scale we say entire thing our flow scale is not like our laminar or turbulent but this flow scale is from PF to MF mixed flow to plug flow, right. So in between you have very near to plug flow you use this model, very close to mixed flow and here also this recirculation is a general model I mean general name but at this point when I have a single tank I may have to use for example dead space and depending on the type of response I get so normal approach is first conduct RTD experiment, right because otherwise how do you imagine you do not know there are so many possibilities and by looking at that okay dead space will be something like this or bypass will be something like that that means I am talking about this area mixed flow yesterday we have seen some curves.

So when I have that kind of bypass suddenly a sudden peak will go and then afterwards it is slowly coming out or otherwise your I know long tail in fact mixed flow also will have a very long tail. So what is the time required for the tracer to come out theoretically speaking, infinity because  $ET = e^{-t/\bar{t}}$  so that has to become 0 or  $FT = 1 - e^{-t/\bar{t}}$  so that has to become 1 then only all tracer should have come out so that  $e^{-t/\bar{t}}$  must be infinity, right but infinite time we cannot wait.

So it has got long but the way the tail moves in the ideal CSTR is totally different then when compared to if you have dead space and then slowly tail moving that you should be able to

identify, it is exactly like doctors a very good doctor by looking at your face itself will tell that you are sick, okay and by touching he will tell that where you are sick which part of the body is sick, correct know.

So like that is you a very good chemical engineer just by looking at the the graph itself you know that RTD response curve itself you can find out okay this fellow has this disease, right and then you can estimate the ya the idea of this RTD models is to estimate those non idealities like axial mixing how much is that it only tell you that you know there is a axial mixing but how much dead space for example in mixed flow, right if there is a dead space I would like to find out how much of is actually dead space, is it 10 percent of the volume or 20 percent of the volume if the volume is let us say 50 litres may be 10 litres may be dead space that means the mixing is not proper there, right.

So and also bypass bypass you are sending 100 litres per minute so out of that how many litres is actually bypassing bypassing means almost that fraction of material is not spending any time inside the reactor you will find out that that means that portion is totally removed from your calculations because that fellow is unnecessarily just bypassing and then mixing in the already converted products, the other portion goes to mixed flow, right you know when you have bypass bypass comes without spending any time almost without spending any time in the reactor the other portion is getting mixed and getting reacted.

So now these two will again come and together and you will get less conversion that is the problem but you should definitely identify how much is the bypass and if you really identify that okay 50 percent is bypass then you have to now take the necessary steps to correct like medicine giving correct know after identifying the disease you have to also give the medicine, right.

So if there is a dead space what do you do? 10 litres dead space is there in a mixed flow reactor what do you do ya either (13:59) or stirring, okay (14:04) may not improve that much because of the (14:05) in fact if you put more (14:06) you will have more dead space, right so (14:10) will not solve the problem everything (14:14) only will eliminate you know that vertex mixing ya breaking of vertex.

So like that again otherwise you will give the wrong medicine, correct know this is wrong medicine of a dead space (14:25) is not the solution, okay ya sorry ya you know see you have already designed the reactor, okay so then only you took the RTD test whether your

assumption of perfect mixing is right or wrong and that says some dead space. So again you cannot design another reactor fabricate and then throw this out so best thing is changing the stirrer which is easy, okay so that is how what you do.

Like for example when you have a this channelling in packed beds plug flow what do you do? You will try to find out which corner that channelling is happening, right and then you open that reactor and if it is a packed bed and then see that whether that packing is proper or not, if the packing is not proper wherever there is less packing more amount of gas will go or more amount of liquid will come that is channelling that is why what you do is you open, see that and again put all the particles uniformly and then put one distributor plate on the top, another distributor plate on the bottom and uniformly uniform packing and then start again doing it in fact there are cases where in industry they found it packed bed has been designed for 80 percent of conversion of so I think Fogler book has given that example, okay that reference also.

So then it was given around 60, 65 percent conversion, right then they found that there must be something wrong they conducted RTD test RTD graph also is given it gave 2 peaks, okay. So then definitely they know that it is channelling when they open and saw same mistake they have done what they have done was that they have not filled up okay this is the packed bed there is another distributor plate on the top they have not filled up you know it was not completely filled from this point to this point, it was only till when they opened they found that kind of packed bed that is packed bed.

So happily this fellow was going like this short know least resistance that we know as students very happy if there is a class without reading without doing anything if you are able to get yes Swami that is the short circuiting you are okay that is channelling because do have to work it is normal stream so go there sit and get yes without doing anything same thing here fluid also because all of us behave on this planet exactly same Monkeys also behave like us and Elephants also behave like us many things will behave exactly even trees behave like us but only thing is we do not know we are not able to find, right good okay.

So that is how afterwards they put out you know I think may be like this they have brought it down and then arranged because during start up what happened was they put initially something like this, okay but the mistake is that they have to completely fill up, only half of that they filled up, right. So during start up what happened was sudden pressure drop and all

that it pushed the pack into one side then the other side became short circuit, okay channelling so that is what happened.

So like that I think even in industry also one can find out like Doctors very happily just go and conduct some test or otherwise you ask your other mechanics to do the test and they bring the curve to you and then looking at the curve you should be able to tell this is the disease and this is also the medicine medicine also we should give, right. So that is the overall picture for RTD models in all these models any model procedure is same, what is that conducting an experiment and then getting an idea like that okay long tail or dead space how it behaves or two parallel paths, what kind of curve you get.

So now when I have two parallel paths then I should imagine that okay two PFR's okay or may be two CSTR's also in series how the response curve comes I will give you some hand out later for various models. So looking at them we will give an idea so what is really happening so then you have to go to mathematics you write the model equations for that, normally model equation is only for concentration not normally always so then that concentration has to be converted to ET, right and then now when you are writing the model itself then you will have some parameters like dead space should be there, channelling will be there as a parameter and now you test this experimental data with the model and estimate now what is the amount of channelling, what is the amount of dead space, what is the amount of you know that what else ya recirculations all that, right so that is the overall picture.

So models will give me the quantification of non-idealities, so what we take now is the simplest models, right one parameter model is the simplest model and those things we try to understand and for multi parameter model one or two or only one we will do just I will tell you the procedure but that is extendable to any kind of multi parameter models, okay good. Please this this okay dispersion model I mean we know that in dispersion model diffusion is main important criteria, right that too in the axial direction.

So when I have a plug flow reactor something like this and what I expect is a flat velocity profile but over which we have this kind of disturbance, okay this is called axial mixing that is why I told you if I imagine that we have this disc coming in and then disk going out, right if it is ideal plug flow that disc will not be disturbed at all in a value but if it is not ideal then here at the entry you will have, okay at the entry you will have almost that direct delta function that disc as it is and here you may have ya like this it will be normally Gaussian, okay and at this point you may have peak will not be that much ya you see now this is peak

top and then it is slightly spread, this is slightly spread if I go further this may still further spread so like that you will have the tracer coming out. So this is at the outlet so that is the kind of spread, correct no.

So that is why you know intelligent people in this RTD studies what they do is there is no ideal direct delta function anywhere because how can you inject a tracer with 0 time because as per the definition of direct delta function what is the thickness of the pulse zero, right you can never inject definitely in zero time you cannot there will be definitely some finite time it may be 0.00001 second but still that is a time, right.

So that is why what they do is somewhere here they take, somewhere here they take I mean at the outlet ofcourse they can take that means it is spread already a little bit here, okay. So they used what is called deconvolution I do not know whether you heard of this name deconvolution right the deconvolution tells me that that means I am subtracting this distribution from this distribution, right.

So that will tell me exactly what is the kind of mixing that is there inside the reactor that is why test section alone in fact we have also done (( ))(22:42) has done for his P Hd work with me this kind of work so we also do I mean no one knows how to exactly put the pulse so we allowed some distance and measured there and at the outlet measured and deconvoluted you will get beautiful curves again if it is a small axial mixing very very Gaussian curves you get, if it is not ideal mixing then if there is some kind of more axial mixing is supposed to be very very small if you have a large axial mixing you will have a problem again the curve will get screwed that means you will get like this you know this is cute that means more this side ya spread, okay so that is the kind of curves what you will get, good.

So and this spread this spread is characterized by what is called dispersion number or diffusivity, okay good please take this. Okay the assumption underlying the dispersion model is that of a diffusion like process. Here fluid elements move at different speeds for a short while, then redistribute themselves, take on a different speed and so on many many times the key the key is the random rearrangement of particles and a continual forgetting of the past, okay that is a nice sentence you know forgetting of the past, okay.

If you do not know that you are there on that point, right so again you may end up there that is why the drunkard path I think people try to model the walking of a drunken drunker (( ))() model finally they found that wherever he goes he will come back to the same spot where he

started where he started because no remembering of the past so that is why he does not know where he started and where he is ending so he goes like this, like this, like this and comes back and stays in the original place that also without knowing that also he does not know that that is the original place, okay.

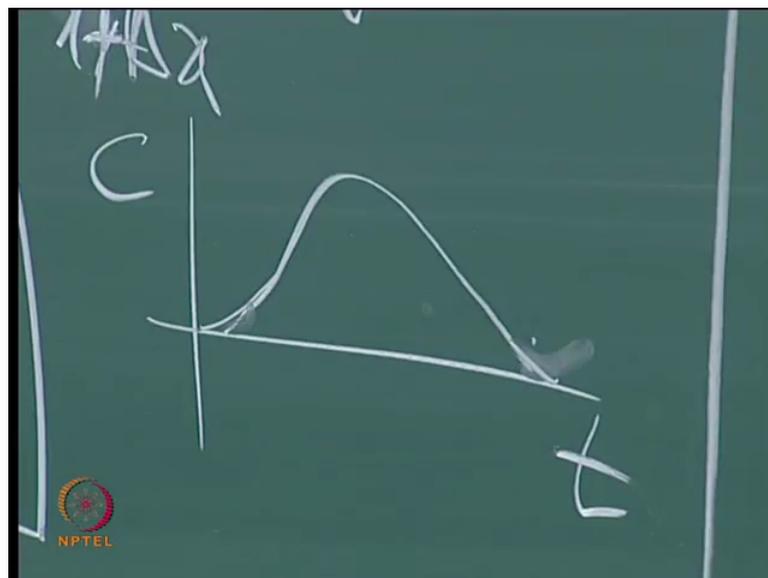
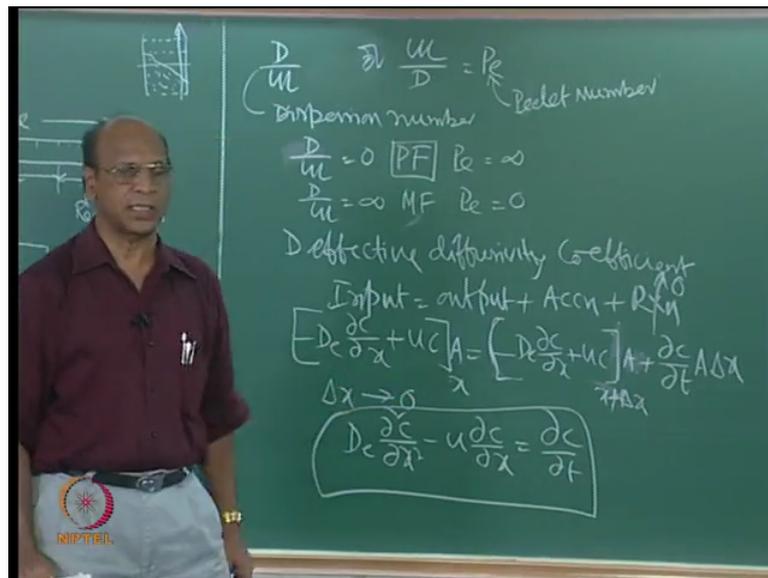
So I think there are many many things I think there are wonderful things like this there was also a question when it is raining if you run you will get more wet or if you walk you will get more wet do not answer go and see the websites no really very good you know these are (( )) (25:19) basic fundamental questions what every day we see, okay if I remember correctly I think if you walk you will get no if you run you will get more wet ya so that is why better walk, okay Abdul no running do not increase the speed of your Motor Bike, okay anyway.

So like that there are so many wonderful things which are just around Gopi, right but we do not really you know care to notice that there are so many wonderful things, okay good. Please take the next one.

The dispersion coefficient or diffusion coefficient or axial diffusion coefficient these are the names you know or axial diffusion coefficient  $D$  capital  $D$  represents the spreading process capital  $D$ , okay  $D$  large means rapid spreading, of course  $D$  small means slow spreading,  $D = 0$  means no spreading plug flow very good no spreading, PF right. So the parameter of course which  $D$  is one of the parameters but the characteristic dimensionless number what we use here is the dispersion number  $D$  by  $UL$   $D$  by  $UL$ , where  $D$  is the diffusivity,  $U$  is the velocity and  $L$  is the length of what? Length of the reactor if it is intuitive, okay.

So if it is a packed bed then we will also we can also define  $D$  by  $UDP$  into  $DP$  by  $L$  that is also  $D$  by  $U$  but there are two geometric parameter is one, okay and you have actual  $D$  by you know that mixing group, good so this is the one.

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And  $D$  by  $UL$  0 means okay this is also  $D$  by  $UL$  or you also have another group  $UL$  by  $D$  just reverse of the you know what is this called Peclet number already I think I told sometime, okay right this is  $D$  by  $UL$  is dispersion number dispersion number and this is called Peclet number Peclet number, okay good okay. So  $U D$  by  $UL$  equal to 0 I should not write that now, now I will write  $D$  by  $UL$  equal to 0 also equal to okay this is PF correspondingly Peclet number equal to infinity for PF, for MF  $D$  by  $UL$  equal to infinity and Peclet number equal to 0, okay so these are the extremes what we have, good.

So what we do is that in this one I think now let us write the material balance quickly and here I will take a small element tracer entering, tracer leaving, tracer reacting there is no tracer reaction and only tracer accumulated. So when we write that I am not explaining

quickly I think we will do that just one thing I want to tell you here is this  $D$  is not alone molecular diffusion it is not molecular diffusion then what else ya because of convection also there will be disturbance, there will be mixing all that put together it is called dispersion number that is not equivalent to your simple molecular dispersion  $D$  where you have some equations to calculate  $D$ .

But here depending on the flow structure you have to always find out from the experiment, out of that out of that  $D$  some may be molecular diffusion and some may be convective diffusion that is why sometimes it is also called effective diffusivity coefficient  $D$  is called effective diffusivity coefficient effective diffusivity coefficient. So there are so many things I say that is why in fact this effective diffusivity again will be a different effective diffusivity when compared to diffusion through catalytic particle this is inside the reactor when the flow is there molecules will be moving faster by nature because by dispersion by molecular diffusion.

But again this kind of mixing some molecules will be thrown forward, backward and all that, right because of the flow so both together we are calling it as effective diffusivity. Now if I take a single catalyst particle there are lot of pores, right I mean the porosity is there for the particle.

Now the gas molecules or liquid molecules have to diffuse through the pores through the pores inside the pores also I will have some due to convection, some due to what is called Knudsen diffusion heard of it and some diffusion called configurational diffusion heard of it ya Knudsen diffusion definition is that the mean free path of the molecule should be comparable with the pore diameter that is Knudsen diffusion and convective diffusion is (the molecule size) the pore size will be 100, 200, 500 times compared to molecule diffusion that means very free movement that is convection and Knudsen diffusion means the molecules will collide with the walls because it is almost the free the mean free path is almost same as diameter of the pore so that is why it collides number of times.

Configurational diffusion is one molecule goes and sits in the pore and another molecule will go and push it that moves, another molecule will come and push it that means if you look in the pores when you have this configurational diffusion you can see the one molecule behind, the other, one molecule behind the other that fraction may be very very less all that three together is also called effective diffusivity for catalytic particles, this is for the reactor, that is for the particle alone and like that I have thousands of particles in my reactor.

So the diffusivity inside the particle and this is the diffusivity in the reactor, even if I have packed bed there are two diffusivities now what are these two? One is between the packings where the fluid is moving between the packings you have the porosity there the liquid enters or gas enters may be turns a little bit because of the stirring you are not putting a stirring but because of some kind of circulations within that thing then move, then go, again may come back all kinds of things will happen but that is outside the particle but within the (( ))(33:32) lost totally or (( ))(33:35) no I think it is very clear only know.

Then there is another diffusion and that liquid or gas which has entered into this (( ))(33:45) between the particles that has to diffuse through the pores. Now that pore diffusion and also you know in pore diffusion we have again convective, Knudsen, Configurational all that also will have another diffusivity coefficient it is very complicated if you go deeper and deeper, okay but it is not so complicated if you want to use your brain and then try to understand because all these things is difficult what I told you know, I have a packed bed and packed bed naturally will have some (( ))(34:18) between the particles.

So what we are describing here is that flow, not inside the particles but when you go to inside the particle and look what is happening to the molecules few molecules will diffuse and when they are diffusing they will come through convective diffusion because large pores and diameter of the molecule is small very happily can walk, right because on the road if no one is there the way you want you can happily go that is convection, right if you go to Rangnathan street now there is one street (( ))(34:50) you have to go and see, particularly during Diwali time it is worse than packed bed because I think you know packed bed atleast you move and all that oh every Sunday need not be Diwali time, okay.

So it is like a packed bed only there the moment is very very there you hit more number of people than you are freely moving Knudsen diffusion, okay you go and hit him and he will throw you and you will go and hit him so like that you know ya sometimes you may feel happy in hitting others, okay particularly boys hitting girls, girls hitting boys these are all natural you know we cannot avoid them, okay otherwise you know the species will not produce know so all these things are there in life all these things are there in life you know, okay.

So that is why that is Knudsen diffusion but sometimes even in that road there are some people who can walk only behind him another person, behind him another person if you look carefully husband, wife, daughter, son all those people will be Configurational diffusion

because one behind the other very carefully they will push and then moving but the overall diffusion when you see in the pipe you know pipe means that road that is what is effective because people are finally going know from this end to that end but different people are taking different routes, some people hitting, some people trying to walk freely, some people again you know going behind this same thing is happening even in the catalytic particle, okay so that is what good.

So that is why this effective diffusivity is a peculiar word in chemical engineering can be used for different things, okay good. So when I write now balance here for this diagram input equal to output plus accumulation plus reaction this fellow is 0 and I am writing here at least once let me write, okay see I have automatically written  $D_e$  that is effective diffusivity effective diffusivity this is  $\frac{dC}{dx}$  if I take this is the  $x$  direction plus  $u_c$  at  $x$  that is this is  $x$  and this is  $x + \Delta x$ , okay I will explain this one later and same terms  $\frac{dC}{dx}$  plus  $u_c$  oh  $(\Delta x)$  okay brackets square bracket on I am putting this is  $x + \Delta x$  and accumulation inside that volume will be  $\frac{dC}{dt} A \Delta x$  where  $A$  is cross sectional area oh sorry where  $A$  is cross sectional area  $A$ , okay good let me now explain okay.

So, Swami why there are two terms here? Excellent this is convective, this is diffusion, okay so the same thing that means here because of axial mixing, right so I have two terms here that is convective diffusion and axial diffusion and if I have ideal plug flow this fellow will be 0 because  $D$  is 0 because no dispersion  $D$  equal to that is what no  $D$  equal to 0 and no spreading PF, right.

So this term will be is not there so then also we can write the balance and then try to find out for ideal plug flow, right. So when I take this one as  $\Delta x$  tending to 0 and all that, right and also I have written  $\frac{dC}{dx}$  because it is a function of concentration variation is a function of two variables ya distance and time that is why that  $\frac{dC}{dx}$  has come there, right otherwise sometimes without knowing we write sometimes  $\frac{dC}{dx}$ , sometimes  $\frac{dC}{dt}$ , okay and you do not see even though there is  $u_c$ , okay all these things will be there okay.

So now this is going to  $D_e \frac{d^2 C}{dx^2} - u \frac{dC}{dx} = \frac{dC}{dt}$  so this is the this is very very famous equation because this fellow comes in many many many places in chemical engineering, okay it is simple second order see for most of the time for modelling so Ramkrishna it is very good in chemical engineering, generally in all engineering problems you will not go beyond second order differential equation except civil engineers where they go Arya for bending movement you are a true civil engineer know not

environmental background and all that, okay civil engineering converted to environment engineering or atleast trying to do now environment engineering.

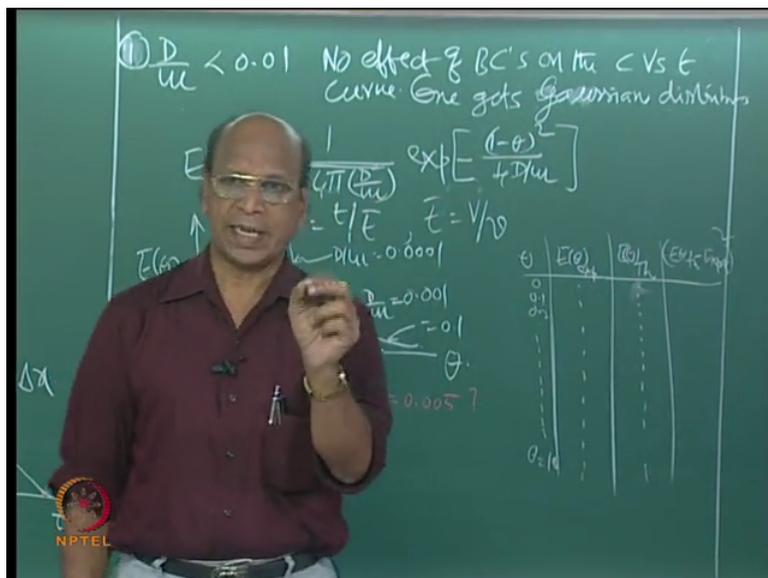
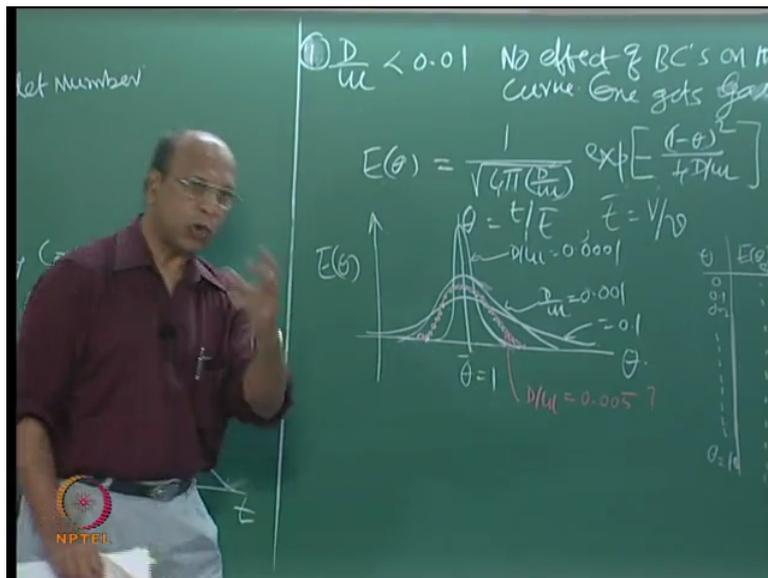
So bending movement and all that they go to even differential equation  $D$  to the power of 4 or something, correct know for bending movement when you solve the problems, okay there is a reason beautiful reason I have forgotten that physics because why you have to go to bending movement and all that you know 4th order differential equation, otherwise in main engineering problems you will go only maximum go to second order differential equation main you take in mechanical or you take in aeronautical and all that, only civil engineers have that greatness there, okay good.

So this is the equation now so this equation we need two boundary conditions because second order differential equation and on this equation alone I can tell you there would have been atleast 500 papers I am not joking 500 papers not on this means the use of this it can be used in rotary kilns, it can be used in moving beds, it can be used in you know ya I mean this fast fluidized beds any any many many places or flow through channels, right.

So so many places that can be used and the boundary conditions are also one of the very important discussion point, right. So I will come back to when you are talk about reaction but here I think Levenspiel Levenspiel is a real expert for RTD, okay where I think from the beginning he liked that and then only his book gives very good information on RTD but even then that will be some kind of slight confusion will be there because RTD is not that easy to grasp easily so you have to also carefully observe that, good.

So this equation is simplifies in the sense that if this  $De$  is very very large, okay to start with let us say  $De$  is very very small whatever boundary condition you use you will get only one type of response that means when I saw response means concentration versus time data.

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And that number also he put that if  $D$  by  $UL$  equal to less than  $0.01$  if  $D$  by  $UL$  is less than  $0.01$  so this is ofcourse  $(\theta)$ (42:38) I think I will write. So in this case what you get here the response is what we want to get here is what Swami this is always  $C$  versus  $t$ , right. So you will get a beautiful Gaussian curve not Gaussian the way ya slightly better. So that kind of Gaussian you know what is Gaussian curve know beautifully spread, symmetry is maintained, okay exactly if you can cut in and there you will have the mean also exactly at the centre at the peak all those properties are there for Gaussian curve.

So that kind of curves you get if  $D$  by  $UL$  is less than  $0.01$  so that means boundary conditions will not be really effective there, okay but the moment you go for more and more dispersion that means  $D$  by  $UL$  is greater than this  $0.01$  then it will try to  $(\theta)$ (43:39) that means this  $(\theta)$

(43:41) will come on the right hand side so it goes like this and then it goes like this, right. So that is why beautifully changed that you know I mean depending on the boundary conditions, okay the first one is if  $D$  by  $UL$  equal to no effect of BC's boundary conditions on the  $C$  versus  $t$  curve  $t$  curve. One gets Gaussian Gaussian Gaussian distribution Gaussian distribution is also called normal distribution, okay Gaussian distribution or normal distribution, okay so this is the kind of thing.

And for this there is an expression available for  $E$  theta, right how do you get in all that you do not have to worry. So our idea is to find out concentration versus time diagram or time equation after solving this converting that into  $ET$  of  $E$  theta, right. So it is already given in the literature  $E$  theta for this case as  $E$  theta equal to  $1 - \frac{1}{4 \pi D \text{ by } UL \text{ square root}}$  is here exponential minus 1 minus theta square  $4D$  by  $UL$ .

So ofcourse you can also convert where theta equal to usual definition  $t$  by  $t$  bar where  $t$  bar equal to volume by volumetric flow rate or length by velocity because this model we are using mainly we cannot use axial dispersion model when you are very close to mixed flow because that dispersion is too much you never get this kind of nice Gaussian curve, okay that also you have to remember. So what else is there theta,  $t$  bar and ofcourse other things we know good.

So that means when I plot this this equation what is the parameter here theta I have to plot  $E$  theta this side, what is left there only  $D$  by  $UL$ , so when  $D$  by  $UL$  equal to very very small let us say for example four zeros one 0.0001 you may get ya this may be  $D$  by  $UL$  equal to 0.0001 and you may also get this may be  $D$  by  $UL$  equal to 0.001 I am just giving you know it is rough, right or I may get this kind of curve or may be on this scale  $D$  by  $UL$  equal to 0.1 check your plotting even though I think you know 0.01 is the limit just to show you that you know how it can spread, right.

And here all these peaks will be same, what is this one mean, what is mean here?  $\Theta$  bar in  $\theta$  bar what is the value? 1, that mean  $t$  bar by  $\tau$  equal to 1, okay so then how do I use this information, how I use this information is after conducting the experiment I will put on this curve my experimental data I have all this I have plotted because I can put any number you know I can also go to in between 0.00005 okay 0.0005 and also here may be 0.0002 like that they can generate any number of graphs here particularly with the available computers and all that.

So then I will also put my experimental points so if experimental points are going like this really beautiful curve really wonderful curve. So if then I join this ya so definitely this will tally with one of the D by UL so may be here this D by UL may be this is 0.01, this is 0.1, so this may be I am just giving 0.005 I mean just to give you some value that is all so like that otherwise you can use many other techniques, okay what is the other techniques?

I will give this equation into MATLAB, I will give for D by UL some guess value, right and then ask MATLAB to match these two experimental value as well as the theoretical value, what it does is what MATLAB does is so we give the data as theta versus E theta experimental, okay and also E theta E theta theoretical, right. So here E theta you have to give 0, 0.1, 0.2, etc may be theta equal to till 10 that means 10 times mean residence time if you have data till 10.

So now what it does? First it goes to theoretical value because theoretical equation is there, right so then it will calculate E theta value for the given D by UL, right I think those who are learning MATLAB or you know this kind of matching the data should know this but to calculate you know this E theta we need definitely what is D by UL that is why you give initial guess, right.

So let us say it is you have given some initial guess as 0.01 then this is fixed then only theta it will vary and then calculate E theta. So then it will ya calculate all those E theta values 1, okay okay like this it will calculate all the values you already listed out all the experimental values. So now it will program will take the difference between E theoretical minus E experimental I mean that you can define ya I think all that criteria you can give square and then you know it must be 0 and also what is the limit, okay theoretically 0 but no computer can handle 0's that is where we score your point when compared to correct know it does not know how to handle infinity, it does not know how to handle 0's immediately it comes what is that value ya something like that it will come immediately it throws up, right.

So I mean atleast we are happy that we have slight intelligence than computer at that point, good okay so like that and then you give the total value that the average of all these must be 0.000000 are 10 to the power of minus 5, or 10 to the power of minus 6 the difference then it brings ya okay so I think I have not told the other one. So now this D by UL for 0.01 it will calculate and then checks then it does not know whether that is correct or not then you have to give all this anyway that will be in the program then it will take 0.01 I have given as a guess value so you have to give what is the step change in D by UL that means instead of

0.01 it will take 0.015 positive and similarly one negative value that means 0.01 means 0.95 no 0.095 no 0.0095 ya so third decimal 0.5 difference, right third decimal 0.5 difference.

Then it will see that which direction it is moving that means whether it is positive that means the difference between these two whether it is narrowing down when you reduce the value or when it is narrowing down when you are increasing the value it sees the difference between those two then if it finds that by increasing the difference is small then it moves in that direction. So then it tries I told you 0.015 and it may take again 0.015 ya 0.15 ya may be 0.02 later so like that 0.25, 0.3 like that it goes.

And finally when you specified the difference between these two and average overall average because you have to give that then when it is almost the value which you have specified then it will say this is the correct D by UL value but for that you should have a feel if you want to have a feel this is the best one, atleast few runs you have to do the experiment and then anyway you are doing the experiment and you have to plot this and plot your experimental data with this theory and then choose the closest one that you give as the initial guess then the optimization search is very very fast all of you have to do that in your MS, or P Hd, or M Tech if you are doing a project matching experimental data and theoretical model, if you do not have your own experimental data someone else experimental data atleast you have to match, if you do not have your own model so then your experimental data should be matched with some others theoretical model.