Chemical Reaction Engineering 2 (Heterogeneous Reactors)
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Module 01
Lecture 32
Packed bed Design Continued

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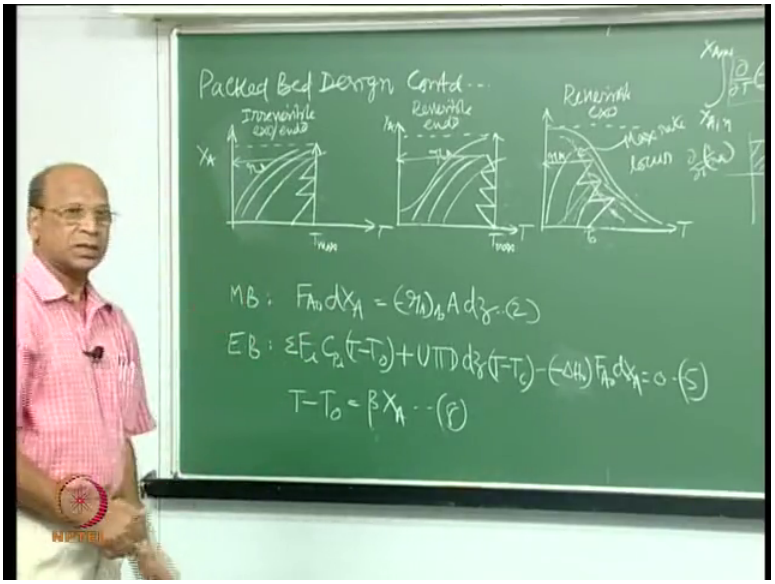

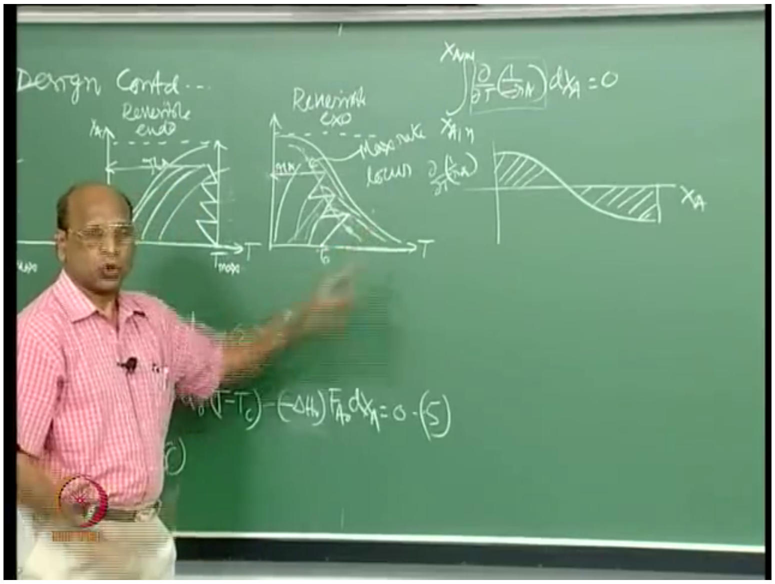

These are the figures which we have discussed yesterday and this is the equation, okay. So if you have ideal packed bed rector meaning it is a following plug flow then these are the two equations material and energy balances what we have to use to design the reactor. So what I have told yesterday was that if it is an adiabatic system then you draw the straight lines using this equation 8 and then we know how to get the number of stages if it is required otherwise a single stage simply drawing the line like this if it is exothermic or like this if it is endothermic and take corresponding Xa and these are the rate curves, okay this is the rate curves.

So the intersection between X and then rate curve you will take and X versus 1 by minus ra take area under the curve and you will get the weight of the catalyst or volume of the reactor, okay this procedure is very very simple straight forward one. So still if you have adiabatic system and then theoretically real optimization if you want to do that means you would like to get the minimum reactor volume or minimum weight of the catalyst for a given conversion so you have to be there theoretically on this line, that means it is isothermal condition which will give you the maximum rate and you will have the minimum reactor volume.

So how do you operate that if you want to be on in un-isothermal condition, so because most of the time we have been telling that you know isothermal isothermal conditions but any reaction will be either exothermic a little bit exothermic or endothermic unless otherwise you dilute the reactant to such a level where delta Hr is almost 0 then you will have isothermal that no one does, why? Because you have so much waste inert material where the reaction is not allowed the inert material is not allowing the reaction then you have to separate all these inert material from the products, so then it is again very very costly for us so that is why no one will do.

The other possibility also is for packed bed rectors take inert catalyst and mix with active catalyst and then again conduct the reaction there again you are deliberating limiting the rate of reaction so rate of reaction limiting means delta Hr you know the amount heat released will be very very minimal again you will have isothermal condition but you can imagine that if you have 1 gram of catalyst so probably you have to use 100 grams of inert material. So that means almost 100 times the volume will be larger when compared to the only active material, correct no? So these are the other methods but if it is absolutely necessary people will go for that otherwise no.

So that is how you make system isothermal, otherwise you have to go for multistage theoretically speaking we have to be here that mean it is an exothermic let us say it is an exothermic reaction easy to understand and when I have exothermic reaction adiabatic case no heat removal there so adiabatic case and we start somewhere here and it is adiabatic reactor exothermic so you will move that means I just drawing this length, okay you will move in this direction because this adiabatic line as the conversion as the temperature increases conversion increases. So then you cannot cross beyond this, why? It may be dangerous for the reaction for the reactor and also for the catalyst all this.

So then you have to cool again, again heat again cool again heat, so like that you have to be almost be actually here you know this border you should not cross but always you are on this line but this imagine this is only three stages if I want to be completely on this line, how many stages are required? Infinite. So that means I will start here go like this, go like this, again go like that you know we theoretically you will be on this line which is not possible that means so many heat exchangers so many sections you have to make, right?

So that is why multistage always will be limited to a certain number maybe 5, 6 depending on everything but not infinity, infinity is the correct one, right? So infinite means I will get the minimum reactor volume or minimum reactor I mean minimum catalyst weight. So similarly if I want to do the same thing it is optimal for endothermic reaction it is optimal that means you know the lowest amount of catalyst we should get but it is an endothermic reaction in this case reversible, how do we do it? We start from this and we know that definitely we are going to have you know it is adiabatic system, so that means when you are conducting endothermic reaction adiabatic system temperature falls as conversion increases so you move in this direction, okay.

So of course this length will be depending on your slope so you may go something like this again heat now not cooling in this system because if you go further you are going to get less and less conversion. So that is why you again heat it, come here again go heat so like this you can continue till the desired conversion if this is the desired conversion, similarly here also if this is the desired conversion till then you have to do that, right?

So this is how we use multistage adiabatic reactors if you want more conversion and if you are very near to optimum, right? So these are the things what we have to do here and here what we do yesterday I have already explained this theoretically speaking we should have we should be on this line like this, this is the optimum line that means the maximum rate line where if I am there on this line because it is a packed bed rector everyplace you will have a rate of reaction. So you have between this and this you have infinite rates between this and this you have infinite rates between any two rates also you have infinite number of rates so some of those rates will be in your rector existing, okay all that.

So that the reason why theoretically speaking you should be on this line but it is not possible that is why again you go here, start and come here go here and if it is three reactors what you are using if this is the desired conversion you have three stages but you see we are almost on the line there, right? This is the optimum line you are somewhere on the average you are only staying on that particular line but if you want to I mean really minimize that means optimize you will get the minimum reactor volume possible then you have to be only go like that, right? So that leads infinite number of stages infinite number of stages is nice word infinity mathematical word but I think no one has ever seen infinity, right? So if they have seen they would have never come back to tell us I have seen infinity, okay so both are possible.

So that is the reason why we never go to infinity and then we will choose some finite number of stages and finite number of stages depend on of course the outlet conversion and in fact there is a trial and error procedure you know graphical procedure gives you lot of information as I told you yesterday here this is anyway this is fine these two but here we start at this point let us say I have T0 that is what your starting point, okay this is what is starting point but how do you know that this starting point is right, we do not know so that is why again here we will have trial and error, okay no kinetics cannot tell you what is the starting you know temperature the reactor inlet temperature, reactor temperature? It is exothermic adiabatic system if you already know that the dangerous temperature is around let us say 500 degree centigrade if you started 500 it is exothermic system definitely you will have higher temperature then you will have catalyst spoilt already, okay.

So that is why it must be something less how much less, okay so that we do not know that is why again we should have a trial and error business here I will just guess, okay let me start at this point T not, okay so maybe 350 I am starting, so then I draw the line because this information I know beta 1 by beta values are nothing but you have F total F and Fa not, delta Hr and one more thing Cp, okay all these things I know that means I know the slope so I will draw with that slope, right?

So I will move on this line till a point where my criteria the other criteria yesterday what we had written Xa in Xa out equal to dou by dou Tr 1 by minus ra dxa equal to 0, right? What I do is every time I draw this line take all the rates I can draw any number of rates here so then take all the rates take the slope of that if I plot with temperature because I know also know the temperatures that is the beauty with this you will know the temperature you will know the conversion you will know the rate, right?

So all this I can have there that information and I extend this line till this integral becomes, right? And from the dynamic programming it automatically falls that this same rate if it is stopping somewhere here let us say on this rate so I should have my cooling system till this temperature where because I have to be on the same rate, logical one because this is a heat exchanger there is no catalyst there is no rate going on, okay.

So that is why I will be on this rate only and through dynamic programming it can be proved ra out equal to ra in after I mean, okay ra in for heat exchanger is also equal to ra out for heat exchanger that means heat exchanger does not have any is not a reactor it is only just removing the heat. So that is why you will be there on the same line you cannot draw beyond this and then have because there is another line which is going like this you cannot go there this is automatic.

So that is why you stop here from again you draw the line and of course again on this line this criteria must be tested that is only the optimum and like that you also go to the third one cooling third one like that again this criteria is tested finally when it is 0 then you will have some conversion here now you have check whether this conversion is the conversion which you wanted or not because it is a for a given conversion only you are trying to minimize the catalyst. So that is the reason why you go back again if it is not tallying you go back again you move either this side or this side depending on you will get some idea whether it should be you will be having you know a temperature this side or this side higher or lower. So like that with few trial and errors you can easily locate that temperature which will end up with the exact conversion what you wanted that is how it is done for exothermic reversible reactions, okay which condition? You know this condition tells you that always you are on this, okay theoretically you should be on this line, okay.

So on this line means this is the maximum rate line maximum rate locus I have not written earlier maximum rate locus, right? Okay Kaviya I know I have to be on this line but it is not possible for me exactly to be on that line so that is why I have to be around that line giving me this you know the average rate supposed to be the maximum and that rate you will be maximum average rate that is important average rate you will get average 1 by minus ra is the one which you get for a plug flow reactor or packed bed, right?

So to get that I have you know this condition will tell me that I am now when I am moving in this direction if I am able to follow it here yesterday I have also drawn that graph you know you remember, you have this kind of thing, okay. So if I plot this is the one which I have to plot here dou by dou T pf 1 by minus ra, and this side I have Xa so this condition will automatically tell me that I am on the optimal path, okay.

So but mathematical we can prove that this is you know it is simple optimization where your first derivative equal to 0, okay that is the one only but the same derivatives are used but the objective function and all that will be a slightly different function if you go to actual dynamic programming if I am not able to cover that but if someone is interested a little bit of that in a most understandable way given in Froment and Bischoff yesterday I have written that book name chemical reactor analysis and design.

It is in the packed bed rector there is a chapter on packed bed rectors highly complicated you know really taken very very complicated level but I think I cannot cover all that but only give you the information if someone is interested you can see there and as far as dynamic programming there is concerned the mathematics are not that difficult you get this condition very easily it is not at all complicated and you also get the first condition as r1 equal to r2 that means this condition you should be on the same rate Levenspiel also mentioned without mathematics the same conditions, okay I think in third chapter in third edition it must be twenty-first chapter or twenty-second chapter packed beds, okay catalytic packed bed reactor design is given but I think analytically only he just explain, okay.

So that is why to satisfy this then only I have combination of increasing rates combination of decreasing rates which will give me the maximum points, that means around this I will be there that point is achieved if I go beyond this, okay if I do not go beyond that let us say I have drawn till there let us say, that means I am not crossing this, so when I am not crossing that so all these rates that means I have to move necessarily this way when I am going this way the all these rates are lower rates because this is ra equal to 0.1, ra equal to 1, ra equal to 10 like that.

So that is why when I am doing that definitely I am not doing the correct job because I am now only taking only the lower rates you can also say that I know I can go this way, right? When I am going in this way then I am going to again lower final conversions equilibrium conversion itself is you know this if I draw a line here it is so small like conversion for me. So that is why that combination will give me this kind of equation where I am on optimal path, so that is the reason why we have to satisfy that condition and then by trial and error also you can fix this T not otherwise which T not is the better T not we do not know, this is the reason why you know flow is automatically developed if I am using this kind of reactor and my T not says that, okay your feed stock that is coming from some other place maybe 100 degree centigrade but T not will be let us say 250 degree centigrade, okay you have to pre-heat.

So that means you have to add another extra heat exchanger so that is an addition equipment in the plant that is how the flow chart is automatically developed. So at the end of the reactor if you want to separate the gases then you have to use some other technique probably you have to cool it and then it becomes liquid and then use distillation to separate them, so now you see there is a condenser for the gases for condensing the gases to in the liquid form and then afterwards you again distill to separate the products and reactants you have another equipment.

So that is how automatically the equipment in the flow chart increases and between anyway when you are pumping from one place to the other place you need the pumps so that is why in every plant you have the pumps, heat exchangers and you know condensers, distillation columns or absorption columns reactor, reactor is only one that is why I said if I have my dream reactor we do not need all that everything is happening at room temperature, 100 percent conversion, 100 percent pure you know the other day last Monday I was there in (())(17:50) when I told that people are also really happy when I said that, okay because sir I think is very good I also told that then you do not have to read chemical technology because there is no flow charts it is only reactor you learn other than that we do not need anything, okay otherwise you have that kind of reactor you have to necessarily have all these possibilities that is why really thrilling things are there in the reactor design, okay.

So that is as far as graphical procedure is concerned, now using this, okay if you hate graphs because some people may not like art I like I think you now drawing graphs for me on the board is excellent, right? So but some people you know always like writing equations, so for them we can use these two equations to design in fact what you are doing is we are only trying these two by solving here so this line is energy line, okay so adiabatic you know that is energy balance and these things are (())(18:51) balance line so the solution between every when it is crossing then that intersection is a solution, okay so that is what what we are indirectly doing but now let us see those people who hate this and can use this equations but you can see that here I have three unknowns like dz I do not know length of the reactor, right? And also I do not know corresponding dxa in that dz and I also do not know what is delta T the increase in temperature, so temperature I do not know conversion I do not know corresponding length I do not know, how many equations I have? I have only two equations if three there is no problem because there are only two equations now I have to go and guess what is happening.

So what we do normally here is to solve equation 2 and 5 and please remember I have changed this a little bit I do not know whether you observed this or not yesterday I have written da dashed that da dashed is nothing but you know that is the pi pi d into that length and this length because I am taking about you know these are called the finite difference methods so I take a finite difference that means finite difference in conversion you can also take finite difference in temperature finite difference method, okay.

So I will take for example delta x, okay let me write this is pi D dz if I take the entire reactor then of course I have pi D here that is no problem, okay.

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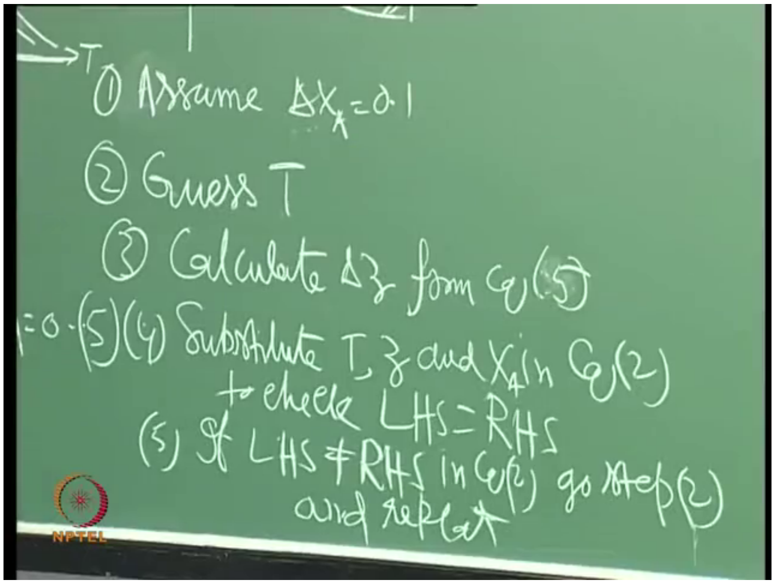

① Assume $\Delta X_A = 0.1$

② Guess T

③ Calculate Δz from Eq(5)

(4) Substitute T, z and X_A in Eq(2) to check LHS = RHS

(5) If LHS ≠ RHS in Eq(2) go step (2) and repeat

So that is why I have substituted here then I have here this is delta T T minus T T not I know, okay T not I know and then dz T I do not know length z I do not know starting with z equal to 0 and dz I do not know dxa also I do not know, that is why what we do is to solve equation 5 and 2 first guess not guess assume step 1, assume delta X for example 0.1, okay if you use point not only you will get more accurate, good.

So then for this delta X assumption that means you are now telling that let me assume that I have 10 percent conversion, now guess what do you guess what is the temperature in that 10 percent conversion, you know initial conversion initial temperature is maybe 250 centigrade. So for 10 percent conversion probably you may aspect 270, 270 degrees, so T not I know so definitely delta T I can now calculate, okay so that much increase is there in the temperature. So then using this temperature and using delta X equal to 0.1 I know now this I know also, okay the temperature because I am now guessing the temperature and now you can calculate what is dz, okay.

So number 3 is calculate delta z because finite difference method I have written so that is why I am writing deltas calculate dz from equation 5 I gave yesterday’s number so that is why in between you have that, okay so then what you do because I have to check weather my guess is right or wrong, so then what I have to go? I have to go to equation 2 equation 2 has dz and also dx and also I have temperature because in this minus ra I have k into you know Ca for if it is first order reaction simple otherwise there will be k so that k value has temperature.

Now I know the temperature I guessed I know X I assumed and now I calculated delta z all these three values substitute in equation in equation 2, okay so 4 is substitute T, z and Xa in equation 2 that means of course equation 2 has left hand side right hand side if this equal to this by substituting all that temperature is this side and also length is this side conversion is this side so if LHS equal to RHS or otherwise the difference between those two is 0 then you will have correct that means you guessed the correct temperature, if you have not guessed correct temperature again you have go to step 2, okay substitute, okay substitute equation 10 to check LHS equal to RHS, okay in equation 2.

If number 5 if LHS is not equal to RHS in equation 2 then what you do? Again guess, so go to step 2 and then repeat, okay go to step 2 and step 2 and repeat so that is how what we do of course I do not know whether your memory is still working or not you have done the same thing in the last semester, okay you have solved also I think one problem or not solved exam I given I do not know whether given in the exam or not, okay.

So this is the one but now the same procedure is also extendable generally trial and error I have not given there in the examination but this time I can give because this is high level course no, so that is LKG this is now Phd so that is why I can give that one now and the same procedure used by Smith chemical engineering kinetics in thirteenth chapter he has solved a problem, okay I think this is some styrene production or so styrene production wonderful problem do not neglect that try to understand but notation will be different and equations maybe different in the sense rate will be expressed per volume of the catalyst or weight of the catalyst or surface area of the catalyst but you should not get confused because we know that in heterogeneous system we have to be very careful with the units, okay and another thing Cp sometime Cp can be expressed in terms of mass or moles lot of difference between those two, okay.

So that is the reason why you have to be careful and then please see that one I think example 10.3 or so if I am right or 10.2 or 10.3 styrene production real industrial type problem so how to calculate conversion and then corresponding weight of the catalyst both are I think he has solved that problem and even though it is solved example but understand the solved example first then I am going to give the assignment tomorrow I will give the assignment, okay.

So this is the one and these are all simple because still we are in the dream word in the sense that assuming that only we have plug flow, right? And the dream world is most of the time true in chemical industry because we do not want to complicate things. So when I calculate with this procedure the catalyst let us say 2 tons I will happily take 2.2 tons, okay so then all radial non-uniformities or actual non-uniformities all that will be taken care of, okay so that is why we do not solve those equations but as academicians we have to know how to solve those equations.

So that is why now we will develop equations for the you know general equations for design of packed bed reactor, okay.

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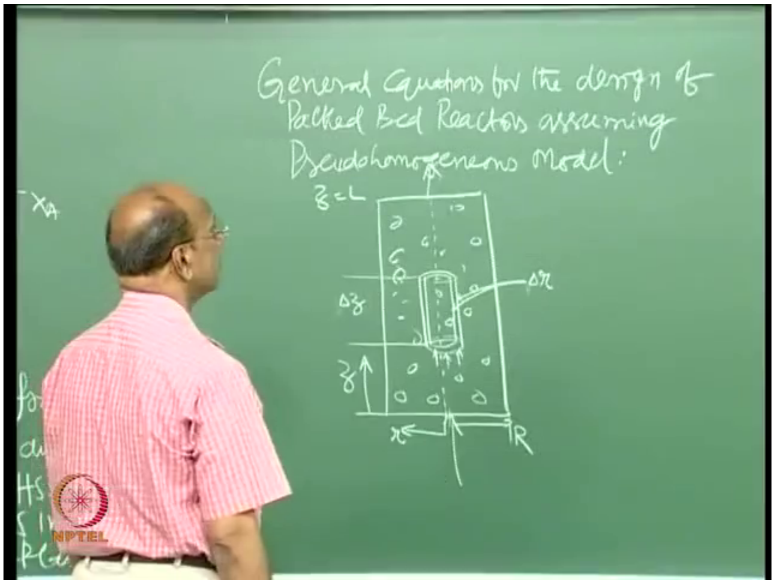

So general equations for the design of packed bed reactors assuming again pseudo homogeneous model assuming pseudo homogeneous model. So here we say that we have a packed bed is normally very fat packed bed so l by d should be a little bit better so this is we have the catalyst particles throughout touching one another they are not hanging, okay so you may have input this is the output and I may take, this is the center of the bed so I will take a small volume here, good.

So this is the volume element and through which I have material entering that means you the reactant or reaction mixture at this point entering let me say that this is delta z this thickness, okay this is also show that this is z direction and this is r direction from the center, okay radius. So now this will be delta r, so here z equal to l so now we have to this is r and then this may be total length is capital R, good. So now we have to write our universal expression that is input equal to output all that stuff, so right you are right maybe I think I will use this and then remove that later, okay.

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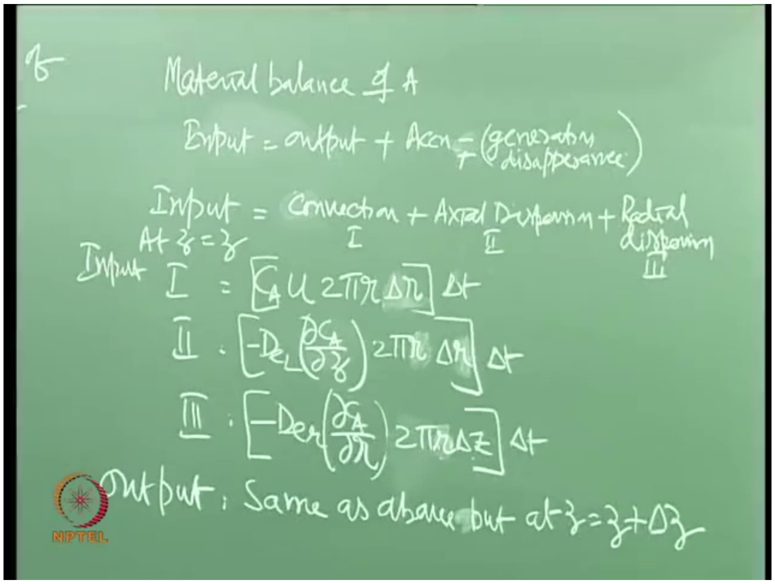

Material balance of A

Input = output + Accn $\mp$ (generation / disappearance)

Input = Convection + Axial Dispersion + Radial dispersion
I II III

At $z = z$

Input $I = \left[C_A u \, 2\pi r \Delta r\right] \Delta t$

$II : \left[-D_{eL}\left(\frac{\partial C_A}{\partial z}\right) 2\pi r \Delta r\right] \Delta t$

$III : \left[-D_{er}\left(\frac{\partial C_A}{\partial r}\right) 2\pi r \Delta z\right] \Delta t$

Output : Same as above but at $z = z + \Delta z$

So here material balance or energy balance also same thing we have material balance over this there we have output material balance is always for a component so material balance of A if I take A as the reactant, okay so output not why I written output, input equal to output plus accumulation plus r minus generation or disappearance if it is generation it will come this side, okay maybe I think I will better put minus plus, okay generation is equivalent input no so it is happening there so this is the equation.

So now for mass we have to over this element and we never said that it is plug flow, right? But how the material is moving? Material is moving it is entering and we never say it is ideal plug flow that means there may be axial dispersion, okay and also there may be radial non-uniformity in the sense that if you have concentration gradients in the radial direction also have transport, right?

So that is why you have at this point just entering same thing also here at this point also I have material entering by in this direction axial direction entering by plug flow, plug flow means convection I do not say plug flow by convection and also by axial diffusion both are in the axial direction because convection is in this direction because flow is in that direction manly flow is in the axial direction so you have the convective term and also axial dispersion as I told you axial dispersion can be easily imagined when you are walking on a conveyor belt, conveyor belt speed alone is the convection, okay and there are all molecules standing there and some molecules cannot move and some molecules will move because of the concentration gradient, okay.

So that is why the base molecules which are not moving they are moving only with the speed of conveyor belt is the conviction and over that when you are walking then that is the diffusion, in plug flow what we normally do is we neglect that diffusion that means almost there is no axial dispersion, okay or even if it is there it is negligible when compared to total conviction, so that is the reason why we neglect that, okay. So those two terms will be there in the axial direction and mass transfer also in the radial direction that is trumping to radially entering here and leaving here because we are writing middle balance over this, okay.

So that means if I turn like this assuming that I have the thickness we are now writing what is entering there and how it is moving and in this thickness what is coming out, right? So temperature also same thing and concentration also same thing material balance also same thing but now we are first writing the material balance that means in the input itself I have three terms in the input itself that means what are the three terms convection itself, diffusion and radial diffusion, okay so all three will be there so that is why we will write here please take that, okay let me write here afterwards I will tell you input equal to bulk flow or convection so let convection or bulk flow convection plus I have axial dispersion plus we have radial dispersion, okay in this element that means here this is the one which I have taken from here inside, right? Here when I say axially what is entering by convection it is something entering in that element and also by diffusion something is entering and in the radial direction because at the concentration gradient something is coming out, okay good.

So that is the one and if I write the equations let us say this term as 1, 2, third term if I write I think this three terms separately then you will understand. So the first term is it is C concentration Cu is the conviction term Cu, what are the units of Cu? C into moles per, it is flux Cu is flux moles per meta square second or moles per centimeter square second, okay it is a flux, right? So that is why it is a flux multiplied by I have to write the cross sectional area that is why asked that, okay cross sectional area so when I write that cross sectional area what is cross sectional area I am talking where it is entering, it is entering this annular space that is what my control volume so like this you know this is the thickness where it is entering, so what is that area? 2 pi r into dr, okay so that is all there so you will have here 2 pi r, okay delta r, okay.

And of course I can also write if I want what are the units of now this? Moles per second, so I want to write only mole balance I can also put there into delta T time units, so that means moles entering not rate moles entering, moles leaving, moles reacting, moles accumulating because unsteady state equation I want to write that is why delta T also I am taking so that delta T tending to T0 delta r tending to 0, delta z tending to 0 will give me a differential equation, okay taking all these things into account.

So number 2 that second term will be this is axial dispersion who will write now this one as Del axial direction D is affective diffusivity l is in the axial direction so Del this is now dou Ca by dou z because its time is varying r direction it is varying so that is why this dou and this multiplied by 2 pi r delta z of course this is minus this entire thing multiplied by delta T, okay that is axial direction, good so this is the one and third term will be the radial dispersion that is the one so that term will be minus Der, okay affective diffusivity in the radial direction into this is dou Ca by dou r into delta z, no 2 pi r delta z where you are telling, this one right, correct thank you (())(39:52), small r thank you.

So this again multiplied by delta T, okay similarly all this is at r equal to at z equal to z at this point this is z this is z plus delta z. So all those three terms again will be there for at, okay now let me say that this is at z equal to z in this figure all this three terms as output will be there at z equal to z plus delta z so I am not going to write that same terms so finally I will give the equation.

So but what are the other terms we have accumulation term and generation term, right? So accumulation term will be, okay output I think shall I write here, okay this is input I have here output same as above but at z equal to z plus delta z that is the output exactly same thing and time Shekhar you do not have class no have you class, no no class today? Today is what? Tuesday it is only Thursday and Friday.

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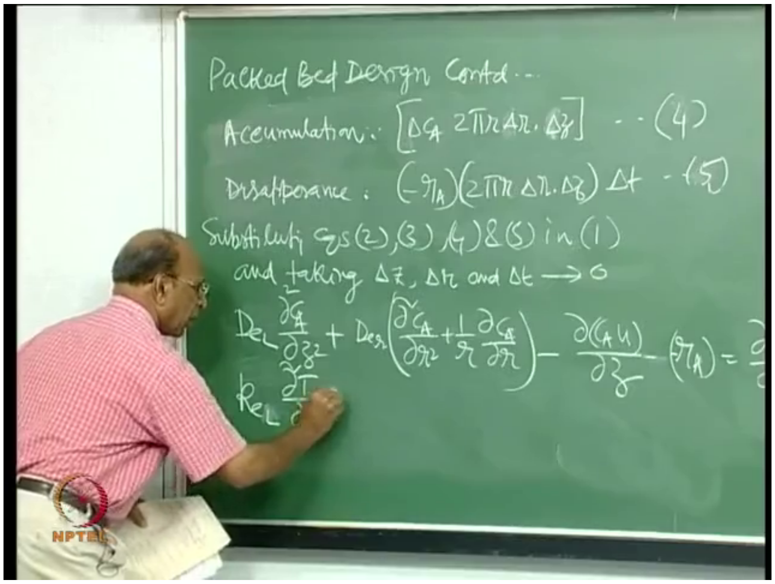


Packed Bed Design Contd..

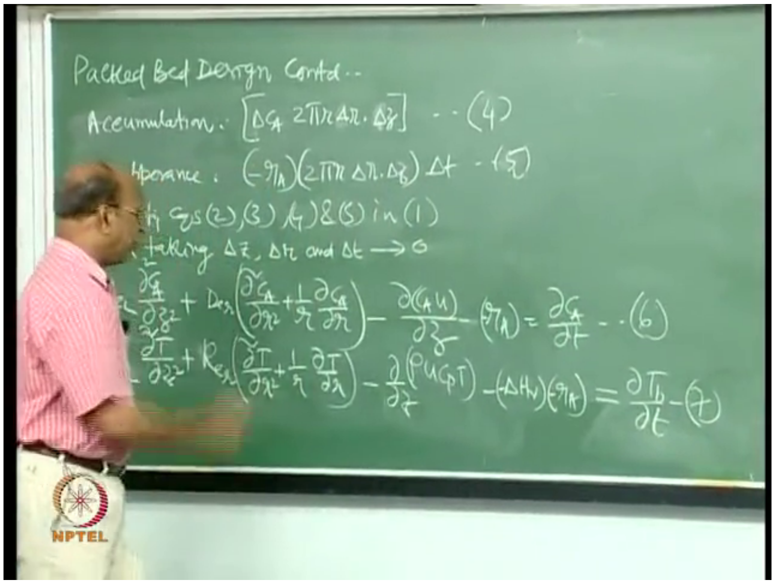
Accumulation: $[\Delta C_A \, 2\pi r \Delta r . \Delta z]$ .. (4)

Disappearance: $(-r_A)(2\pi r \, \Delta r . \Delta z)\, \Delta t$ - (5)

Substituting Eqs (2), (3) (4) & (5) in (1)
and taking Δz, Δr and $\Delta t \rightarrow 0$

$$D_{eL}\frac{\partial^2 C_A}{\partial z^2} + D_{er}\left(\frac{\partial^2 C_A}{\partial r^2} + \frac{1}{r}\frac{\partial C_A}{\partial r}\right) - \frac{\partial (C_A u)}{\partial z} - (r_A) =$$

$$k_{eL}\frac{\partial^2 T}{\partial}$$



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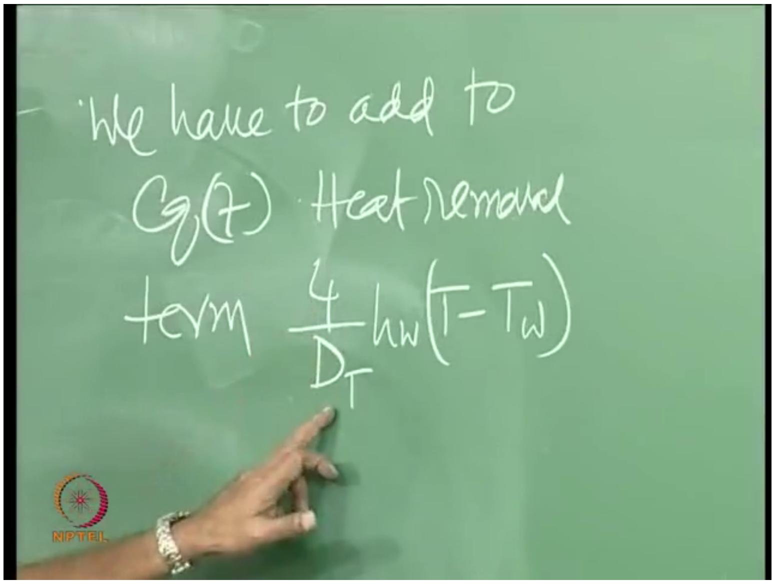
$$\frac{\partial^2 C_A}{\partial z^2} + D_{er}\left(\frac{\partial^2 C_A}{\partial r^2} + \frac{1}{r}\frac{\partial C_A}{\partial r}\right) - \frac{\partial (C_A u)}{\partial z} - (r_A) = \frac{\partial C_A}{\partial t} \quad .. (6)$$

$$\frac{\partial^2 T}{\partial z^2} + k_{er}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) - \frac{\partial}{\partial z}(\rho u C_p T) - (\Delta H_r)(-r_A) = \frac{\partial T_b}{\partial t} \quad - (7)$$



We have to add to

Eq(7) Heat removal

term $\frac{4}{D_T} h_w (T - T_w)$

So now I have to write the accumulation term, accumulation term will be what I have minus ra minus raob in fact, okay minus ra I will just write accumulation it is not generation through accumulation. Accumulation term will be the volume and you know delta Ca, okay so I have delta Ca 2 pi r dr into dz, okay or otherwise I think I should not write dr's I think there delta r's I have to write here this is delta I make mistakes because time whether I can complete this I do not want to write whole thing again next class so that is why.

So this is the term accumulation and now we have the generation or disappearance because we are writing, we are writing for A no, A is disappearance disappearance term will be minus ra into the volume 2 pi r delta r and delta z, that means this minus ra is based on what? Volume and you have to be really careful with this because it is heterogeneous system. So if I based on let us say on weight of the catalyst then I have to multiply by bulk density because entire volume we are taking no not individual particle density so all that I think I have to tell you that, okay.

So now substituting no accumulation delta T will not come you check the units, see every time we are talking about moles no by the by, what are the units of this? Moles only and here also, moles, right? So here also simply moles concentration versus volume, Kaviya? Dou C by dou T if I am not taking time here if I remove time here, time here, time here then that will be automatically accumulation, okay if I remove time here, time here, time here, time there, okay then I have to write dou Ca by dou T because now I am balancing moles per time that is the reason.

So now if you if I am substituting let us say this equation 1, okay and all this is 2, 3, 4 substituting equation 2, 3, 4, okay I think here also there is an imaginary equation this is 3 outlet so this is 4 this is 5, right? 3 the same equation but only at z equal to z plus delta z, so if I substitute 2, 3, 4, 5 in 1 and then take substituting equations 2, 3, 4 and 5 in 1 and taking delta z delta r and delta T tending to 0 all three because normally many people will not do this balance for every term.

So that is why I thought at least one time I will do it so that you will know how to write this balance but only thing is you have to substitute them patently and then write the entire equation and you yourself see in terms of only finite differences like delta T, delta z, delta r and then take the limits on your own because for every class yesterday there was some people from Milano, polytechnico Milano Polytechnico Di Milano or something from Italy they told that the courses will have credits of, how many they said I think 20 to 30 credits one course, I said what is this I think here we have 1 hour equal to 1 credit.

So if I have 3 classes in a week then we call 3 credit courses, but how can you call 30 credits? It seems they are going to calculate that credit for the students work, for every hour the student is supposed to work it seems 6 hours or so depending on the subject, okay so all that also counted as hours if you are working let us say 6 hours in particular course in room plus 1 hour here, right? Then sometimes you know parallel you have the liberties, right? Library also you work some hours for that also you have I think there they said library they are working before us so if they work 4 hours 4 credits.

So 4 plus 7 plus 1, how many? 12 that is 12 credit course so like that why I am telling is then I told that you we do not know whether our students working or not so that is why we never (()) (47:47) that is why we never take how many hours they are working, we take that how many hours we are working, good, okay. So substituting all this and then taking what you get for material balance is, I think I have here this equation which you would have seen many times this is Del dou square Ca dou square Ca by dou z square plus Dr dou square Ca by dou r square plus 1 by r dou Ca by dou r minus dou of Cau by dou z minus ra minus of minus ra minus ra is an indication minus means you are writing for do not take literally that is negative term, okay the value what you substitute is only positive Kca only not minus Kca , right? So this is equal to dou Ca by dou T so this is equation number 6. Similarly you write the heat balance equations that means now you have to write only in terms of calories alone, okay calories alone so that means you can write row Cp, u, all the terms I am not writing there so what you get exactly same thing that is what you know transport phenomenon approach so I do not have to tell the other thing you will get exactly similar equation for heat balance now this is kel thermal conductivity effective thermal conductivity in axial direction that multiplied by dou square T by dou z square plus ker radial direction effective thermal conductivity dou square T by dou r square 1 by r dou T by dou r we have minus dou by dou z of equivalent row u Cp T, right? Exactly equivalent to your this u this entire thing, okay.

So then you have minus delta Hr minus delta Hr minus of minus delta Hr and minus ra, so there is another term here which I have not shown at the if you really take at this outlet that comes as a boundary condition if I expand this entire thing here then you will get a term for heat removal from the walls heat removal from the walls (())(50:57), okay heat removal from the walls, okay anyway.

So this is equal to, correct no this is equal to dou Tb by dou t so this is equation 7 and for equation 7 you have to add I think last one we have to add two equation 7 the heat removal term 4 Dt diameter of the tube hw T minus Tw, okay otherwise that also will be 4 pi not 4 pi I mean 2 pi dz 2 pi dz, okay 2 pi d dz you know I do not whether you have really those people we have observed this sometimes we used 4 by Dt and sometimes we use pi d pi into d into dz you know what is the reason, cross section but I think that also you know heat is removed only through the this outer walls this way, okay.

No please remember this once we use directly the actual area that is removed that is pi d into dz other times what you do is surface area per unit volume of that element surface area that means pi d by your pi d dz divided by you have unit volume of that element what is the unit volume of that element, pi d square by not pi d square pi by 4 d square into dz that is why you get here 4 by dt many people would have not noticed it there even in heat transfer even in what is our transport phenomenon in real heat transfer you would have got that, see there are two ways but you are talking about same thing but how are you writing the balance that is what only most important there this is based on per unit volume of the element where you are writing the balance otherwise you simply take like the other one what you have done was simply taking the area, okay.

So these two methods I think please make a notes somewhere otherwise I am sure that you are going to forget but in the books some books use this equation some books use pi d into dz so then you should not get confused he told wrong one, it is not wrong it is only based on on what basis you are writing the heat transfer, okay good. So that is why anyway add this one later to this term and this is purely now adiabatic system, okay adiabatic system anyway here I do not have to add anything because material is not coming out of the system and I can tell you variation of this is your membrane reactors you know membrane reactors where thorough the walls also you have some amount coming out there you have to add similar term in this these two are the basic equations in almost all chemical engineering, okay.

So if there is no reaction these terms will not be there all other terms will be there to be solved, so this is what the general model unsteady state with all diseases like radial non-uniformity, okay and axial non-uniformity all kinds of things, now we have to see that you have to make it more and more healthy that means best healthy person is only plug flow so remove this term, remove this term, remove this term only these two terms very happy, okay I think I will stop here next class we will discuss a little bit about this.