Chemical Reaction Engineering 2 (Heterogeneous Reactors)
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Lecture 43
Slurry Reactor Design

So let us start this slurry reactor, okay. And this is the last part. You know we have done fluidized bed, packed bed and now this is slurry reactor, three phase reactor, right? So the objective in the beginning of course even though first day I did not mention. Generally I was telling that you know we should understand for heterogeneous systems how do we develop that rate equation, right? And we have taken some examples including slurry reactor at that time, okay, catalytic reactions, non catalytic reactions.

But mainly the course has been divided into three parts, okay. The first one is of course introduction and all that. Then we have non catalytic part which we have done and we used the same funda what we have discussed in the first part, okay. That means identifying the number of steps and writing for each step the equations, eliminating the intermediate steps. In all these things that is the common thing. When I was given that award they asked me to speak. I told the same thing. I have a beautiful quotation by some J P (())(01:11).

I think he told that you know I am not telling great teachers. I am not referring to me. So the quotation is that great teachers just not only teach the subject matter but they teach an attitude towards the subject, okay, an approach to the subject. Without knowing myself that is what I have been doing, okay. So now you have an approach to the subject. I do not know whether you understood or not but you know you have an approach to the subject. What is the approach?

All heterogeneous systems there is only one approach, identify the system first either three phase, two phase, catalytic, non catalytic. Then you can imagine the entire system in terms of steps. What is step 1, what is step 2, what is step 3? So once you have this idea in your mind try to put on the paper how to draw the profiles. Even yesterday also we have done that. So the moment you have drawn that profile then mathematics are very simple because in the first profile what is the equation, second profile what is the equation, third profile what is the equation?

Then what do you get? An average global rate. Once you have the global rate you already learnt contacting. Fortunately we have only two contacting continuous one batch, right? So with this information of global rate you have to just go to the correct contacting pattern, substitute and then integrate. Even yesterday we have integrated and we have taken the contacting pattern for gases, plug flow and other steps. And you got indirectly what is called an effective rate or global rate, observed rate.

That is what we have given yesterday for fluidized beds. So fluidized beds very thoroughly used. I think you know I mean most of the time used in the industry that we have done thoroughly. Packed beds we have done thoroughly but before doing packed beds we spend some time on understanding the catalyst, okay. So that means you know how do you design the size of the catalyst for example without having diffusional limitations and what is effectiveness factor, what could be the temperature profiles, concentration profiles, all that.

That may be required for actually understanding the packed bed catalytic reactors. Not only packed bed, even slurry reactor, even fluidized bed reactors because individual particles are there in all this. So you should know when the individual particles whether they are really concentration gradients or temperature gradients. Our preference is you should not have temperature gradients or also you should not have any concentration gradients. Then you will get the maximum conversion or rate for the particles.

The moment you have maximum rate you will have the minimum reactor volume. That is what is the objective. So that is all. That is an approach. That is really an approach, okay. So that is what we are trying to do and the last part is slurry reactors where we have now here three phases, okay. So please take this one. A slurry reactor with three phases, in the bracket gas, liquid, solid, you do not have any other, may assume various forms like stirred tank, bubble columns, tray staged reactor.

But whatever the geometry the reaction phases are gas, in the bracket reactant, liquid in the bracket reactant slash inert. It can also be inert liquid. Bracket closed there, that is liquid and solid in the bracket catalyst. Yes, the solid catalyst is suspended in the liquid in the presence of dispersible gas good, okay. Next para you can write, examples are 1 hydrogenation of vegetable oils, okay.

So here what is gas? What is liquid? What is solid? So this is unsaturated oil , okay. This is hydrogen. This is oil unsaturated. This one is nickel catalyst N i, okay. So another one is polymerization of ethylene or propylene. Here we have again gas, liquid, solid. Yes gas is of course ethylene or propylene correspondingly. Then we have solid catalyst. Catalyst is solid Ziegler Meta, right? Yes, right. Yes and liquid is cyclohexane.

How do you know? You worked in polymer industry or what? This is cyclohexane, okay. So that is another example. And here the presence of cyclohexane is not to participate in the reaction. It is only to absorb heat. It is a very good heat absorbent because lot of liquid will be there so that can take a lot of heat.

So the third one is have you heard of this Fischer Tropsch synthesis, where you have here gas, liquid, again solid. Yes gas is hydrogen or C O. Hydrogen and C O, okay. That is the one. Then we have solid iron catalyst and liquid is hydrocarbon oil, okay.

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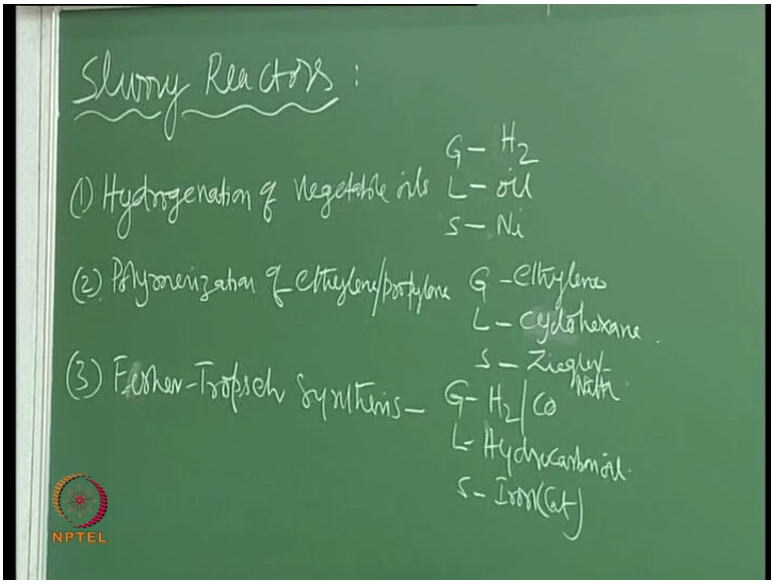

Slurry Reactors:

(1) Hydrogenation of Vegetable oils G – H_2
L – oil
S – Ni

(2) Polymerization of ethylene/propylene G – ethylene
L – cyclohexane
S – Ziegler-Natta

(3) Fischer-Tropsch Synthesis – G – H_2/CO
L – Hydrocarbon oil
S – Iron (Cat)

So I mean just to want to justify that you know we are not discussing something totally academic, okay. So slurry reactors are very widely used in industry for many purposes. That is what is the beauty in chemical engineering I have told you. So how many chemicals you can list? You can list thousands of chemicals, right? So each chemical has a beautiful history, beautiful process, beautiful family of reactions all that. So that is why really we are very lucky because you can never get satisfied with all this.

And each chemical may have ten different processes, it is not one. May be directly, maybe after two steps, maybe after ten steps all that we have to decide which is academic, that is all. That is why it is totally open field. I think you know this kind of opportunities in no other engineering you have because they do not have chemical simply, right? And chemistry I said that is why where chemistry stops chemical engineering starts, okay. This I have been telling. When I told last time also in chemistry department they were very happy.

So who are the starting points for you? But I think you know they were the starting points for us. That is true. They are making so many chemicals and they stop only with 1 gram, 2 grams, 1 microgram or maybe 10 grams maximum. Very big scale 10 grams. But for us 10 grams I think is not even a scale, okay. So that is the problem. So it can go to tonnes you know. Ammonia if you take ten thousand tonnes per day you can just imagine in one plant.

So I think you know all engineering problems come the moment you go for larger and larger productions. Heat transfer is a problem, fluid flow is a problem, okay. Like everything, filtration is a problem, crystallization is a problem on large scale and heat maintenance is a problem on large scale again because I told you I think chemistry will take most of the time the reactor is test tube. So he will go to the (())(09:55) and burner, put there like this, reaction complete.

So then he goes to gas what is that chromatograph or some HPLC and then tries to find out what is the conversion. But can you take our ammonia reactor which is I think you know 2 metres diameter and height maybe some 15 metres, 40-45 feet, then take it and then shake, impossible. So then that is the reason why you should now have what kind of heat transfer you should have. What is the mode of heat transfer? How do you remove the heat or how do you add heat? So that is why I said that statement is very good.

Where chemistry stops chemical engineering starts, okay. But it is not their business to go beyond that, okay. Even though sometimes we go to their business to find out whether this reaction can I also try? That is why we have lab scale, we have wind scale, we have pilot plant scale, then we have industrial scale. Why so many scales by the way? Not cost. Particularly fluidized bed is a deadly example for this kind of scale because on a small scale fluidized bed when I construct in the lab, the type of bubbles I get, okay.

And the contact between solid I get. The moment I go for large scale totally it may be different. So that is why in between I would like to see how this you know phenomena is changing when you go to very small, slightly bigger, slightly bigger, industrial scale. You would have seen in books also. Scale-up in chemical engineering there are books. Scale-up rules are there, okay. That is the problem because particularly when you have two or three phases then all these problems will come.

Particle when you have bubbles and drops and particles, this scalar problem is automatic. And in which process you do not have bubbles, drops and particles? In every process we have. So that is why you cannot escape. That is why Kavya, beautiful subject is chemical engineering. No, you do not agree. Still you are sleeping. No, okay. Good. So that is why I thought you know I will just give you some ideas for this, okay. Good. So advantages you can just write.

Advantages one, the high heat capacity of the slurry is conducive to isothermality. And number two is heat exchange and therefore heat recovery is very good. See sometimes you can put even tubes inside the slurry reactor if it is very highly exothermic reaction, okay. The liquid is not entirely taken up this heat because the temperature of that may be increasing beyond certain values. So then you can also put inside tubes and all that because it is liquid. So easily heat transfer will be more. So that is what is the meaning.

Number three is very small particles can be accommodated without intraparticle diffusion, correct. Smaller the particle, diffusion length will reduce so without intraparticle diffusion. Number 4 is the reactor can be simple stirred tank or autoclave. Stirred tanks we are famous no, so easy for design. So that is the simplicity you know.

The reactor can be simple for example stirred tank or stirred autoclave if you are using pressure. What could be the disadvantage because for everything there will be something bad. Relative velocity between the particle and then liquid is one thing, relative velocity because you know mass transfer may not be high. The other one is product separation particularly. How do you separate the particles from the product? You have the catalyst particle so that is why sometimes when you use Dalda be careful in the hostel.

Sometimes you will get nickel particles. That is products separation you know. Tiny nickel particles sometimes you make get, right? So that is why you have to be careful particularly in the product separation right because those are solids, gas anyway will go no problem and liquid and solids you have to separate them. So that it is one of the problems there, okay. Good. So now what is our approach? Our approach is to have the reactor first. So the reactor maybe yes like this is the simple vessel. Then we introduce gas. This is simple pipe.

Of course you may have (())(14:43) and all that. This is gas. Yes, so here we have the liquid and you have the bubbles in fact so many bubbles. Yes, so in between you also have solid particles. Yes so we have this is liquid, okay. So here I have liquid. Gas may be coming out here. So then this is bubble. That is gas phase. Then we have here one particle which is slightly bigger. This is catalyst, solid.

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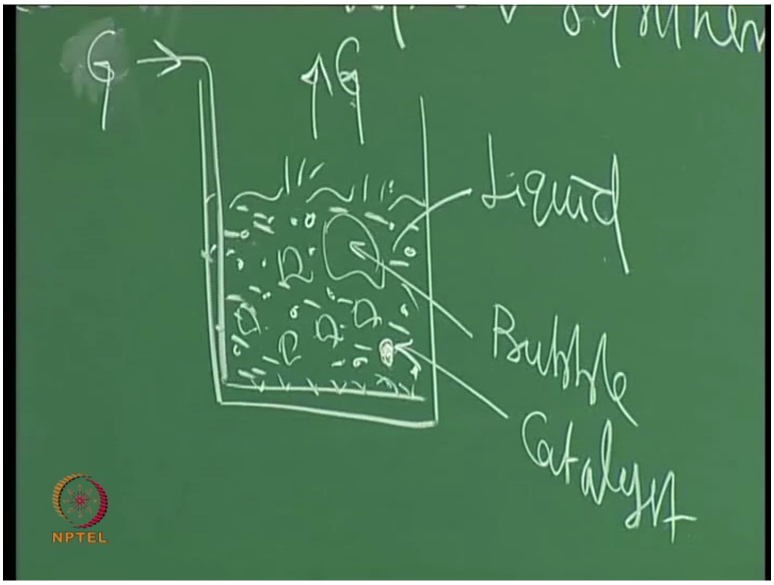

So this is the picture. So then if I also take one bubble for our imagination, okay right? And also you have inside gas film if I have different gases. This is gas film, this is liquid film because all surrounding I have liquid, right?

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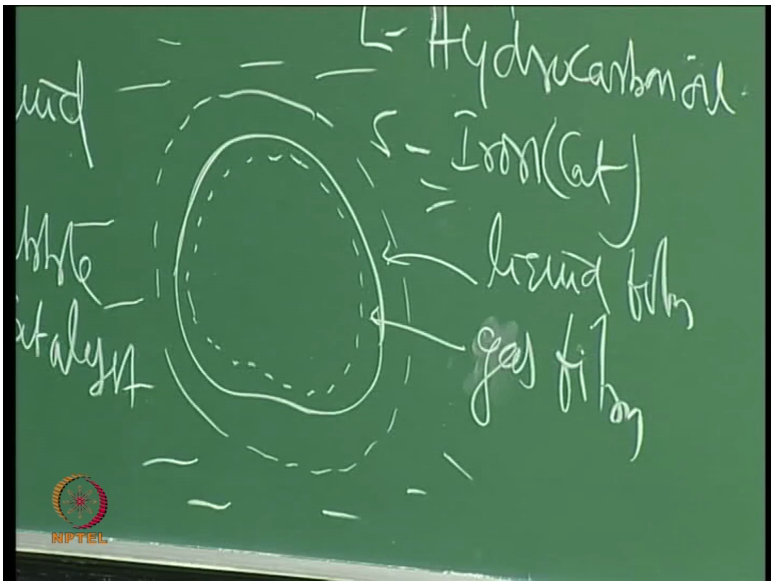

So then somewhere here I have catalyst particle, right? So then again this has a liquid film, right? This is also in the liquid. So now we know the steps. The reactant gas in the bubble should first come through the gas film and this is the gas liquid interface and this is liquid solid interface, okay. You have two interfaces.

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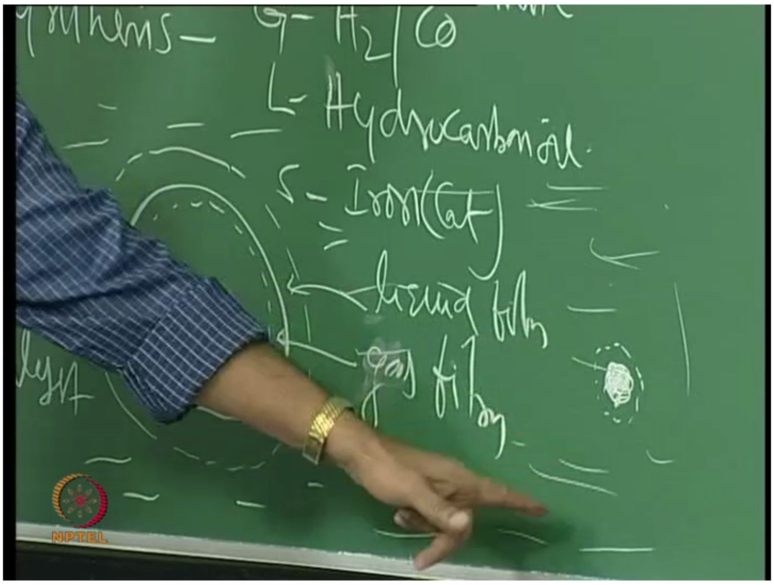

So the first step is the gas should come through the gas film, the reactant gas. Then it has to cross this interface and then go to the liquid film, right? Then it has to cross the liquid film. Then it will dissolve in the bulk liquid. So after dissolving in the bulk liquid then it can go to the liquid film again which is surrounding the solid particles, catalyst particle. And then it has to touch the surface. If the particle is not porous then reaction occurs only on the surface.

Or if it is porous then the reactant has to defuse inside but now it is in the form of not gas but liquid, correct. The gas has to dissolve in the liquid. That liquid dissolved reactant will go to the internal pores and then it will get reactant. And we are experts now how to take care of even if I have this porous particle then if I know the effectiveness (fact) factor of the particle then I will know the rate of reaction in the particle, okay.

But that reaction definitely depends on what is the concentration here, what is the concentration here, what is the concentration here, what is the concentration here, what is the concentration there? Good.

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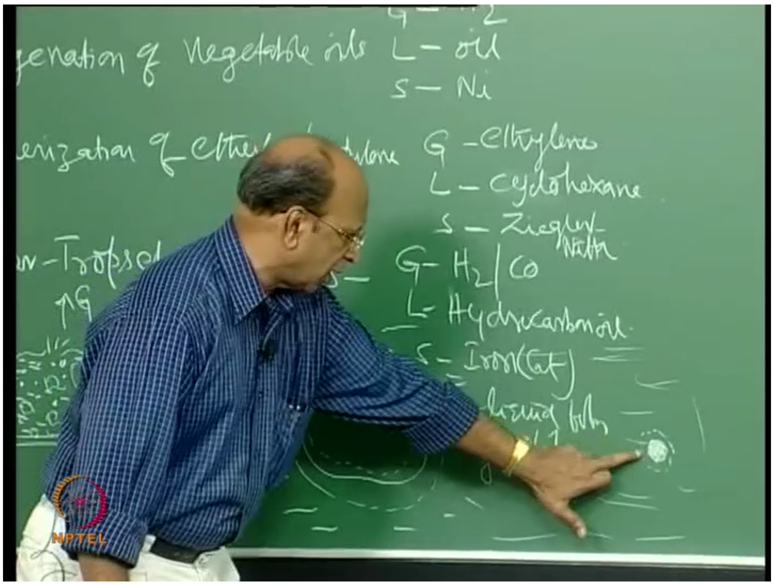

So now this phenomenon we have to now just show in the form of profiles, okay. So that profiles let me draw. We have , okay, let me write concentration profiles. So we have this is the gas film and I have here liquid film. This is gas film, liquid film. What is this one? This is in fact G L interface, that line, okay. So here I have bulk gas C g . I am not using any A there. That means I have here the bubble, right? Bulk gas and anyway afterwards we will draw the other one also.

Then we have here the bulk liquid and , okay, I will also draw highly exaggerated but still, okay. This is the solid so this is again liquid film, good. That is the liquid film. Then this is bulk liquid.

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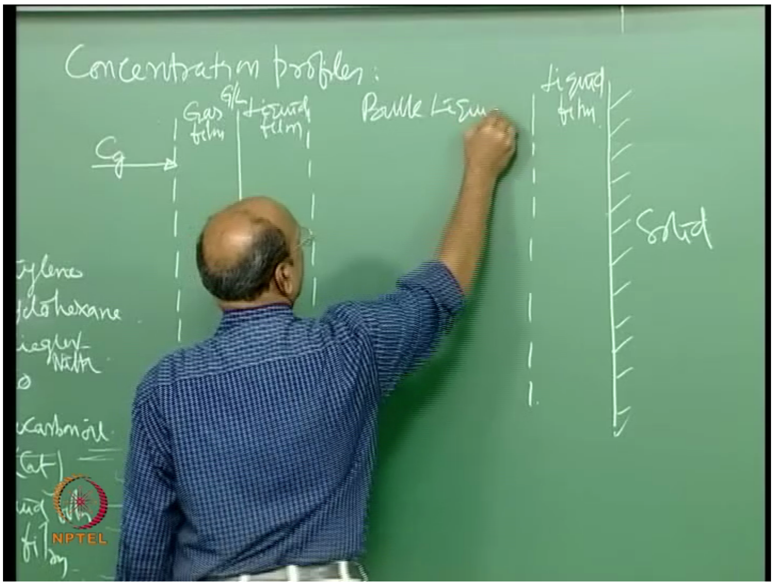

If I remember correctly I have given this one as a surprise test. I think most of you also written this, okay. So then we have here a concentration drop. This is C g i, right? And depending on your Henrys law constant this can be C L of i and C g i, C L i are related with Henrys law constant, okay. Then from here again it goes to bulk and this is C L. C L is interface and from here what we normally assume is that we have constant C L, okay. That means because of vigorous mixing.

This mixing can be here because of large agitation created by the bubbles or it can also be if it is not sufficient because particularly when you have heavy catalyst, high dense catalyst so they will try to settle because the buoyancy created by gas bubbles may not be sufficient. So that is why you also put sometimes external stirrer yes impellers, okay. That impeller will also serve as the gas distributor as well as mixer. Yes it can also create very fine bubbles of gas, okay, that also possible. So then from here it goes to C s, okay, C L to C s. Good.

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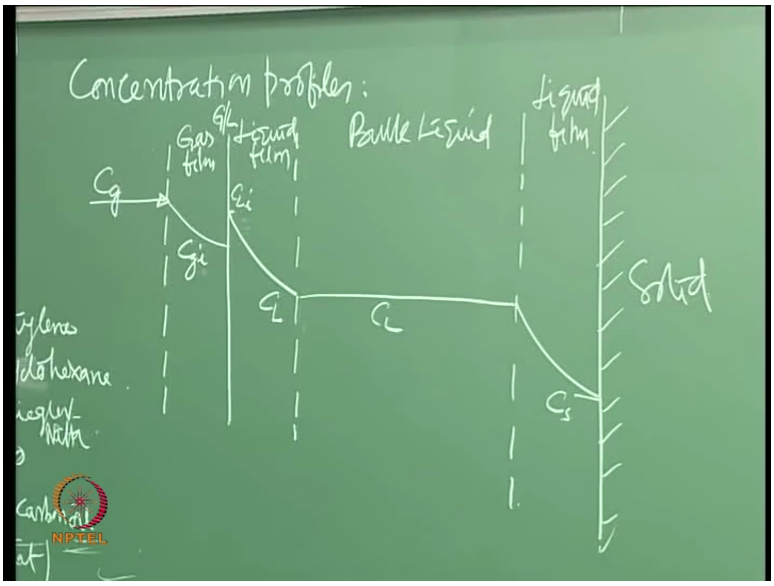

So now what are the steps here? Of course steps I will write. Step 1, M T of gas, mass transfer of gas through gas film. Step 2, then we have M T of gas through liquid film of course surrounding the bubble. So step 3, yes that is bulk dissolving in bulk gas. Step 4 is that dissolved gas has to go to mass transfer of dissolved gas through liquid film. And step 5, reaction on the surface, okay.

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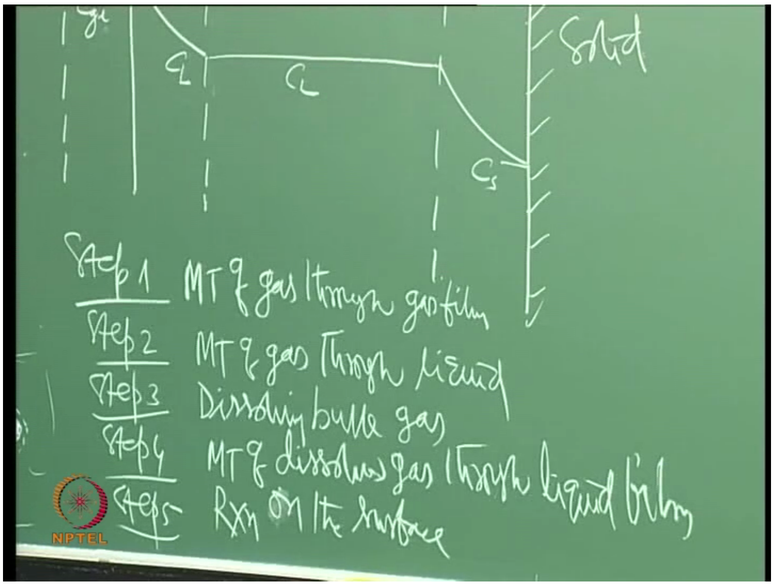

Step 1 MT of gas through gas film
Step 2 MT of gas through liquid
Step 3 Dissolving bubble gas
Step 4 MT of dissolved gas through liquid film
Step 5 Rxn on the surface

So we can also say if I have a porous particle then it is now diffusion through the particle, right? Next step will be diffusion through the particle then reaction. But anyway that step can be combined as a step with factor, okay. Good. So now when I write the equations for this which you already know, the overall observed rate must be equal to k g mass transfer coefficient through this. We introduced here as a g. C g minus C g i where a g I will tell you. A g is you have surface area.

Yes, bubble liquid interfacial area, a g please write. Or no I think we can write that later after writing all. So under steady state conditions that is also equal to k L a g C g i minus C L, correct, okay, which of course you can write through the other equation. Then I also have k c a c C L minus C s. Yes, you can later. Later you can substitute. I will give you another equation, okay.

Yes, so you know with Henrys law you can substitute that one as C L i. Okay, I think correct. What she said is correct because you are talking about this point to this profile, not this continuous profile, right. You are right, okay.

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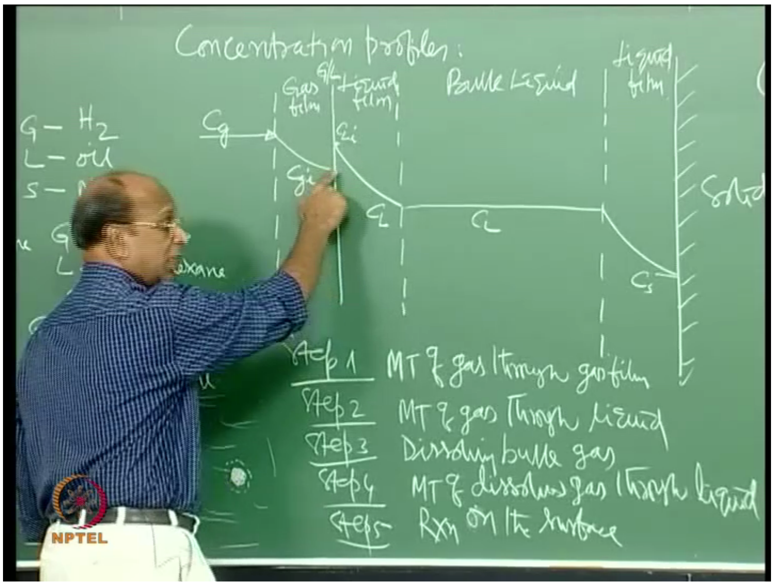

Step 1 MT of gas through gas film
Step 2 MT of gas through liquid
Step 3 Dissolving bulk gas
Step 4 MT of dissolved gas through liquid
Step 5 Rxn on the surface

So now of course you can add this one here C g i in terms of H. Then you can cancel out all that. So that is correct Kavya, thank you. So then we have the next step is all these three steps mass transfer steps. Then we have rate of reaction step where we have eat k a c C s. So if I take this one as 1, 2, 3, 4, right? Then you have the 5th equation that is C g i equal to H C L i. That is the equation. Good, very good.

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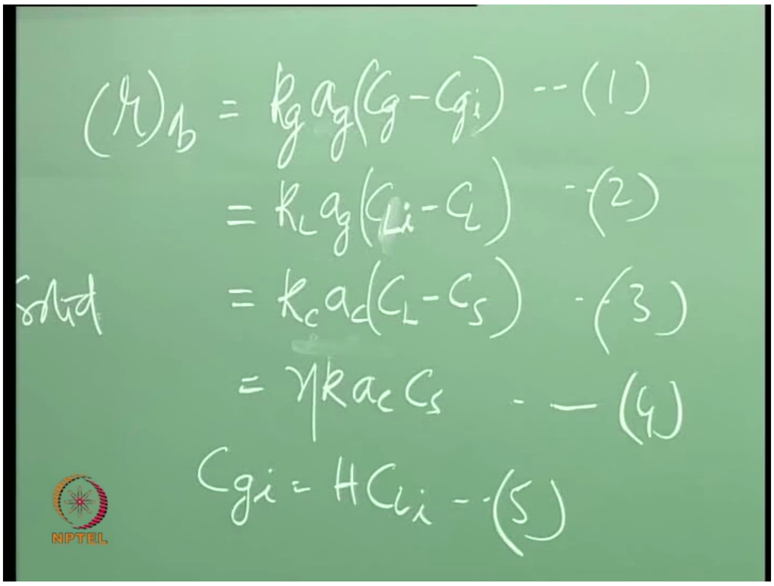

$$(r)_b = k_g a_g (C_g - C_{gi}) \quad --(1)$$
$$= k_L a_g (C_{Li} - C_L) \quad -(2)$$
$$= k_c a_c (C_L - C_s) \quad -(3)$$
$$= \eta k a_c C_s \quad --(4)$$
$$C_{gi} = H C_{Li} \quad --(5)$$

So this you have already done. That means using this eliminating all the intermediate concentrations like C s C L, C L you know. In terms of C g you can write this equation, right? So when you do that what you get is, I am skipping because you already done this. So r o b equal to a c C g whole thing divided by I have a c by a g into 1 by k g. That is the first resistance. A c by a g, H by k L plus H by k c a c plus again H by eta k a c. So this is the rate equation, okay. So this is equation number 6.

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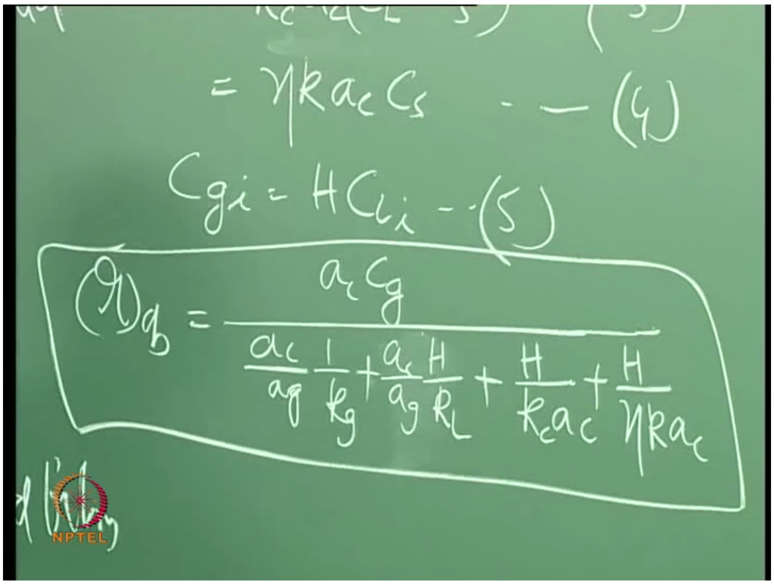

$$= \eta k a_c C_s \quad \text{---} \, (4)$$

$$C_{gi} = H C_{Li} \quad \text{--} \, (5)$$

$$\boxed{(r)_b = \frac{a_c C_g}{\frac{a_c}{a_g}\frac{1}{k_g} + \frac{a_c}{a_g}\frac{H}{k_L} + \frac{H}{k_c a_c} + \frac{H}{\eta k a_c}}}$$

Now I have to tell you what is a c? You can please take that. I think all other things we know, all mass transfer coefficients. H is Henrys law constant. A g equal to bubble dash liquid interfacial area per unit volume of bubble free liquid, okay. Or in the bracket slurry, bubble free liquid. Yes that is bubble liquid interfacial area per unit volume of bubble free liquid or bubble free slurry.

A c is external surface area of catalyst particles per unit volume of bubble free slurry, okay. And r o b, this also please write, r o b is expressed in moles per metre cubed bubble free slurry per second. Minus r a is expressed as moles because I know that I have to clearly define you know every time when you talk about heterogeneous systems, okay. We have to define otherwise you will have problem. So r a is expressed in moles per metre cubed bubble slurry, okay, bubble free slurry per second.

That is the rate of reaction. Good. So now as usual like in the yesterday's thing also this is the overall rate. Now I have to find out corresponding contacting pattern. For example if I want to use that equation for bubbles here, gas phase, right? So gas phase will be moving in the form of simplest assumption is moving in the plug flow. So now I have to use V by F a not equal to integral 0 to x a, d x a by minus r o b where this is the minus r o b, okay.

So now when I want to integrate for example it is a first order reaction, this C g will be written in terms of conversion. If it is no volume change, C g equal to or any time C g equal to C g not into 1 minus x a or x, okay. That you have to substitute and then integrate, you will get first order very simple on 1 minus x but all this. So when I want to use this the next step is to find out. How do you find out a c, a g, k g, k L, k c, k? K is the intrinsic rate constant. So this is an approach I have been telling you.

Now you take any system. I do not have to do now gas liquid because gas liquid is already part of it. If I am stopping only here then that will be equal to gas liquid bubble columns, right? So then liquid-liquid but only thing is replacing this gas with liquid. You know extraction, okay. Extraction with chemical reaction, so then I have two different liquids then I have one liquid film, another liquid film then the procedure is same, approach is same.

So that is why entire heterogeneous engineering even though we have not done the details, details are how to find out for example mass transfer coefficients? The beauty in heterogeneous system is there will be six or seven mass transfer steps and only one will be reaction step, okay. So all the time our duty is to find out mass transfer coefficients and if there is a problem with heat transfer also, heat transfer coefficients.

Here we do not have to worry about heat transfer because isothermality is maintained throughout the inside the particle, okay, because small particles and also inside the liquid because I have large amount of liquid where all the heat is absorbed. And liquid is moving very vigorously so uniformly the heat is distributed. In the liquids you will get isothermal temperature, okay. Good. So now quickly there is another thing here.

Even though there are some correlations for k g, okay, most of the time it is not at all rate controlling step. That will be the much faster because gas-gas diffusion is the easiest one. In the bubble I have here let us say two gases, hydrogen plus some other gas.

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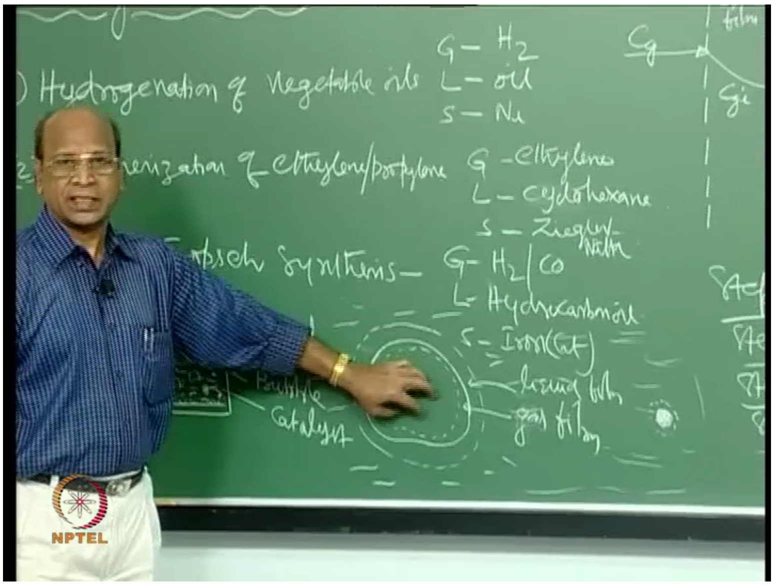

Hydrogen can happily go without any problem whatever gas you put because that is the latest, okay. Diffusion is very easy for that. That is why you know very fat people cannot move faster and very thin person can go like this, like this, like this, like our autos on the road, okay. Or motorbikes on the road, like this he will go, right? That is diffusion through the packed bed. Particularly if you go around 9 o'clock to Mount Road then it is a packed bed.

And you can see the hydrogen molecules moving through autos slightly bigger molecule and two wheelers hydrogen, less than two wheelers what equipment you have?

Student: Cycle.

Professor: Cycles, but cycles, police will not allow. Otherwise cycle will also go through. So that is what is the diffusion there. That is all. So that is why that is easy. So most of the time this gas-gas diffusion is easiest so k g will be usually very large so this will not be present in most of the slurry reactor design expressions, okay. K g can be safely ignored in the sense that it is not ignored. K g is so large so 1 by k g that term will be zero so you can remove that. Then you will have only the remaining three terms, okay, k L.

Particularly two terms because this is the intrinsic rate constant and it depends on your ingenuity how to find out this k without any interface and intraface transport processes like we have discussed. That is one of the very difficult problems but we have not done that. And you know so that is why most of the time we will try to express this in terms eta of square. It is observable. Here also you can do that, right? So that was the reason why eta of square observable we have. Observable equal to r o b L square divided by d e c b yes, okay, bulk.

So that is what is observable because c b you know, d e you know. You are supposed to know d e, okay, through correlations and all that. So then the shape of the particle we know L square and also rate you are measuring, okay. Using that k also can be calculated. In fact k can be estimated using this technique. That is pure intrinsic constant where you measure all this then you can separate before converting that into eta of square what you have done? You have actually eliminated k from that.

If you remember the original derivation so you can go back finally there and then substitute and get pure k. That can be done. So now the rest is k L and k c and k L mass transfer coefficient. You see now automatically actually these last few classes are very important classes. Till now what you have learnt is only the background, okay. But unfortunately climax comes only for some time, okay. Climax cannot be 40 classes, okay. Climax will be last 3-4 classes where all the knowledge will automatically come here, okay.

Correct no (())(35:37). Yes good. So she is a teacher so that is why I asked her, okay. So that is why for any system this is the now procedure. What is that? Write the equation, find what are the things not known and I can tell you people have spent their life only to find out k L. That is all, entire life. There are so many correlations. If you go find out in slurry literature what are the correlations for k L, there will be at least 50-60. That means 50-60 people minimum should have worked because each one will have his own correlation.

Not one, normally professor and his student, okay. And if you go to some other department each paper even though it is PhD work, five student’s names are there. This has become a fashion now in some science departments, okay. Then I do not allow that. I mean I am asking as a dean that in synopsis meeting you cannot have in PhD five names. Naturally examiner will have a doubt there who has worked out of five? Correct. Five names means you are all equally supposed to contribute that paper that is why five names are there.

So that is why I request the HOD and also the individual faculty members please do not put this kind of practice. At least there must be one or two papers for that particular student on his or her name alone because that she can proudly say that this is my work. Otherwise she is one fifth of that crowd, okay. Beyond three we call crowd. So that is why I think five six are common so that is why I told you that is why at least minimum if it is single other papers 50 people would have worked there.

And 50 people would have worked lifelong. That also on that. So like that same thing with k c and effectiveness factor here, okay. So that is why what we are telling here is some of the correlation they are not the only correlations that are available in the world, okay. But some correlations which have come to the textbook means it is accepted by many other people. So this information I am taking from Smith, chemical engineering kinetics, okay, this information, okay. So now mass transfer coefficient M T C k L, this is bubble to liquid, okay. Bubble to liquid.

Yes even in fact this equation also will change the moment I see that you know here so this is now horizontal almost. There is no concentration gradient there. So we will have there, C g i and C L i related directly, okay. So now I can express this equation in terms of C L i. That is another very simple thing because the reason there is it is very good for me to estimate concentration of gas dissolved in the liquid is much easier than estimating the gas concentration because gas means again H P C L something like that you know or gas chromo GC and all that one has to use, okay.

So that is the reason that is also another simple thing there that will come, okay. Good. Of course H C L, H also will come. So, simply this will become H C L equilibrium because Henrys law is equilibrium law yes. Good. So this is k L is bubble to liquid.

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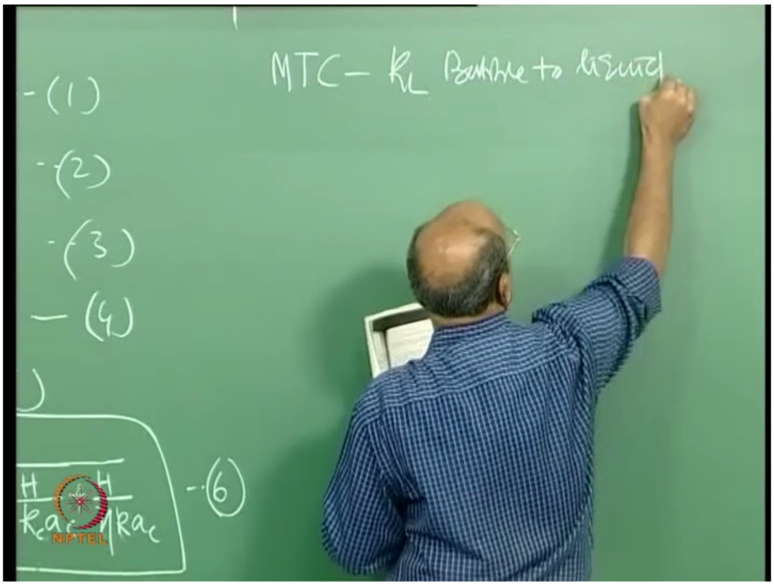

That is the mass transfer because always when you say mass transfer coefficient your question should be immediately from where to where, okay, otherwise you do not know where to where. Good. So you have k L equation given as point 592. This is gas diffusivity to the power of half by nu to the power of 4. If I go to 6 this is 7, okay. So now where sigma is N P rho L N cubed D I to the power of 5 by W into phi. So this is equation 8. I think here we have to write where you know, okay.

Again where D, okay I think all we have to write, okay. First let me write D I is impeller diameter. Now you can see. That means they have used an external impeller in the reactor, okay. Impeller diameter, this is in centimetres and D, this is molecular diffusivity of reactant in liquid. So this is centimetre square per second. That is diffusivity. Then I have nu kinematics viscosity. Then I have k L. K L is of course this is M T C liquid side, units simply centimetre per second.

Then we have N small N r p s, okay, revolutions per second. Then W, mass of liquid slurry. Slurry means liquid only. Yes, this is grams. Anything else is missing. Rho L is of course is centimetre square per second.

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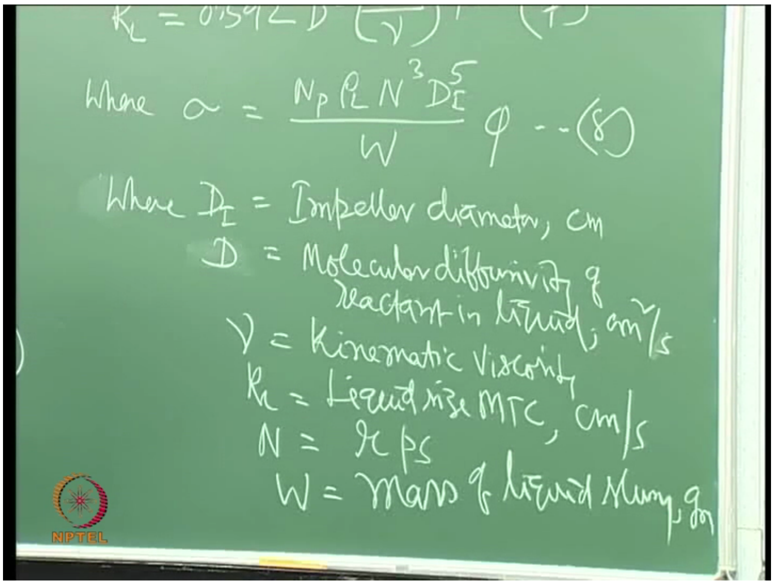

$k_L = 0.592\, D \left(\frac{\ }{\nu}\right) \quad (7)$

Where $\alpha = \frac{N_p \rho_L N^3 D_I^5}{W} \varphi$ --(8)

Where D_I = Impeller diameter, cm

D = Molecular diffusivity of reactant in liquid, cm²/s

ν = Kinematic Viscosity

k_L = Liquid side MTC, cm/s

N = rps

W = Mass of liquid slurry, gm

What did I write? Okay, units I have not written. Write it centimetres square per second, okay. Good. Yes, so then the next rho L is the density and now N P has another equation. I think I have to remove this. See everything that has a beginning has an end. So even it is so beautiful I have written it has to go sometime. Correct. Only god does not have starting point, does not have end point that is all, okay. Good. So N P, see the problem. That is why I said you know lifelong these people would have worked only on this.

Now N P has another equation. Power number where this is equal to capital P rho L liquid density, N cubed. So this is equation number 9, where phi is a correction factor given by phi equal to 1 minus 12 point 6 cube by N D I cubed. This is equation 10 where, yes Q this side phi this side, Q equal to gas flow in centimetre cube per second, okay.

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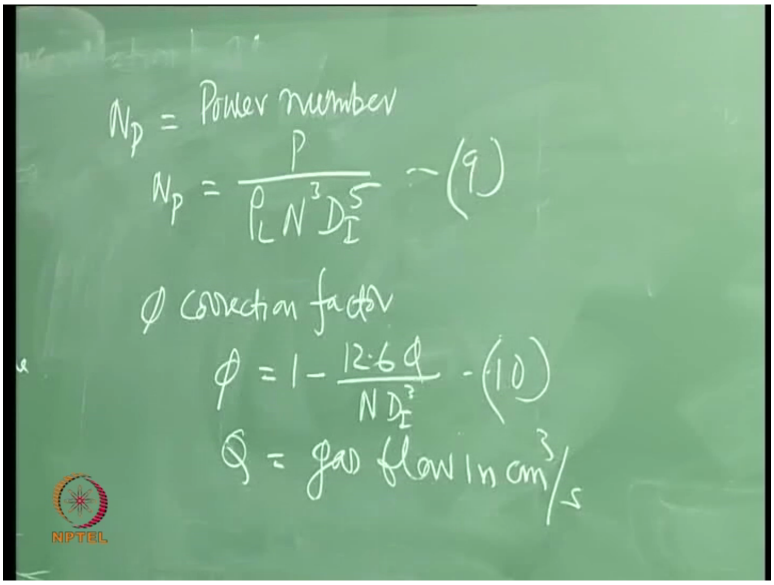

N_p = Power number

$$N_p = \frac{P}{\rho_L N^3 D_I^5} \quad -(9)$$

ϕ correction factor

$$\phi = 1 - \frac{12.6Q}{N D_I^3} \quad -(10)$$

Q = gas flow in cm^3/s

You see now just to calculate k L alone how much work would have gone particularly when you are using impellers, okay. So k L equation is that .That is related to sigma. Sigma is there in that equation 7. Now to calculate sigma you also need phi. So phi and N P yes. So N P has another equation, phi has another equation so that is why you will really scold me if I give this in the examination, okay. Correct. Yes, why? Because you do not want to learn.

You really appreciate me if I give this in the examination because wonderful problem because it is the real problem, okay. Good. So this is one correlation. There is another very simple correlation where you like it. Yes?

Student: P is power.

Professor: P is power yes. (())(45:47) No that has not come. So P equal to power ergs per second. Anything else missing? Yes, so that is why we have another equation for examinations, okay. So another equation for examination is that do not use agitator, then you do not have to worry about power number, rpm, rps and all that. So without agitation that is mechanical agitation, okay, so without or in the absence of mechanical agitation you have k L equal to mu L liquid all, rho L and of course D diffusivity.

So this whole to the power of 2 by 3 equal to point 31 delta rho. That means rho L minus rho g, into mu L g by rho L square. So this is the equation 11, okay. This k L can be used to find out the mass transfer if you do not have mechanical agitation if the simply bubbles are going with buoyancy, right? Good. Where all the things we know, rho L we know, mu L we know, mu L is the viscosity of the liquid, delta rho is the density difference, g we know, D is the diffusivity all that fine excellent. Good.

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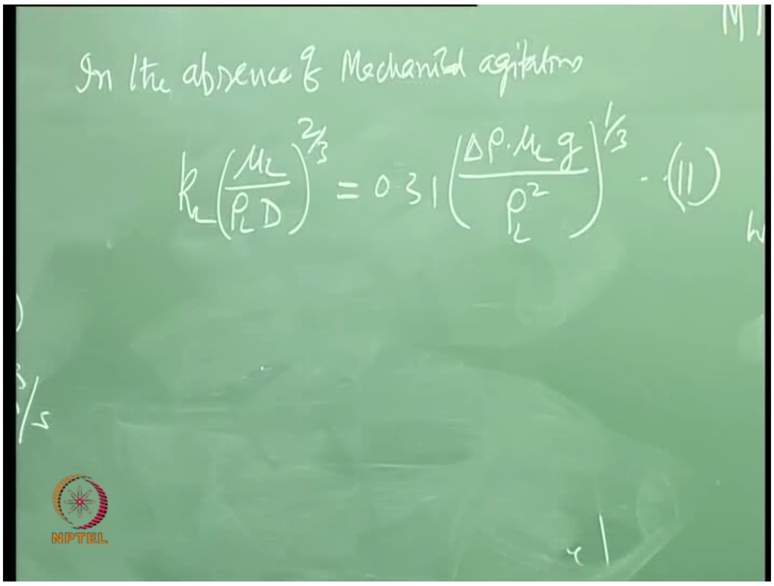

In the absence of Mechanical agitation

$$k_L\left(\frac{\mu_L}{\rho_L D}\right)^{2/3} = 0.31\left(\frac{\Delta\rho\cdot\mu_L g}{\rho_L^2}\right)^{1/3} \cdot (11)$$

So that is the one for k L. So now you have k c. K c we have saved because we do not have that we can fit in the form of equation but we have a graph. Sherwood number versus what should be the other number for k c? So this is in fact 1 and number 2 is M T C k c liquid to particle solid, okay. Actually this is the real life, right? Actually real life you know given example in all romance will be only for one year, before marriage and after marriage, okay, afterwards reality. This is reality. And you know what has romance?

Beautifully writing this step equal to this step, this step equal to this step, this step equal to this step, okay, and finally you have that equation. That is the reality. So now that equation contains unfortunately this k L, k c, k eta and all that so you have to go for only correlations where there is no romance in correlations, correct. Where is the romance in correlations? Because I think you know someone has to really work very hard and after working maybe 5 years 6 years for PhD so finally you will give one equation, okay.

So that is why all chemical engineering design people will not like because there is no romance simply, absence of romance. Whereas I think the other steps are for example drawing this.

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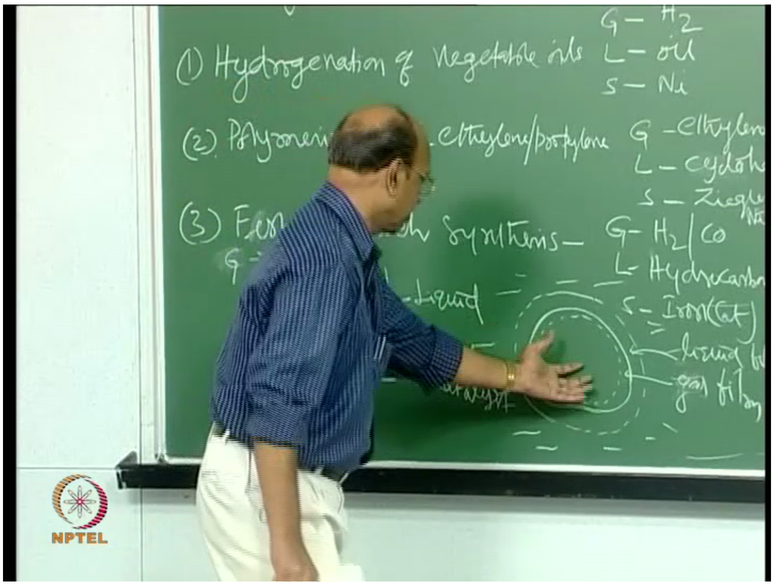

And then writing these steps eliminating intermediate concentrations, okay. So then even if you do not like and then if you hate that one as romance, you are not good for anything. So that is why you have to either like this or like that or like both, okay. So you do not have a choice now. So for k c we should have another correlation so that correlation this is again agitation, speed and all that. Please take this. This interaction I think you will have, okay.

The relative velocity between particle and liquid determines the extent to which convection increases the Sherwood number above that for stagnate conditions, that is above, you tell me the value, above dash. I know you did not understand what I said there. You have simply written there without understanding. The relative velocity between the particles and the liquid determines the extent to which the convection increases the Sherwood number above that for stagnate conditions.

That means for stagnate conditions what is Sherwood number? Excellent, above 2. The 2 is the minimum basic, right? So I told you example, come with beautiful scent and then sit here. Now this is still. There is no movement of any gas. So the smell comes by diffusion, okay. So then if someone put the fan behind then that comes convection. So now the total mass transfer is that fan speed convection plus diffusion, okay. The diffusion is 2. Sherwood number equal to 2. That is a beautiful derivation.

I do not know whether any one of you have done it in mass transfer and also heat transfer also that comes. That comes so beautifully, okay. So that is the one. And the basis for correlating k c as a function of agitation speed and particle size is based on, you heard of this fellow's name, Kolmogoroff? Transport phenomena or Fluid Mechanics people would have told turbulence. Kolmogoroff's theory of isotropic turbulence. It would have come in other subjects also. Kolmogoroff's theory of isotropic turbulence.

That is the basis. According to this theory the Reynolds number is defined as R e equal to d P to the power of 4 by nu cubed whole to the power of half for xi greater than d P, okay. Sigma you know, sigma is again same thing what we have used there, okay.

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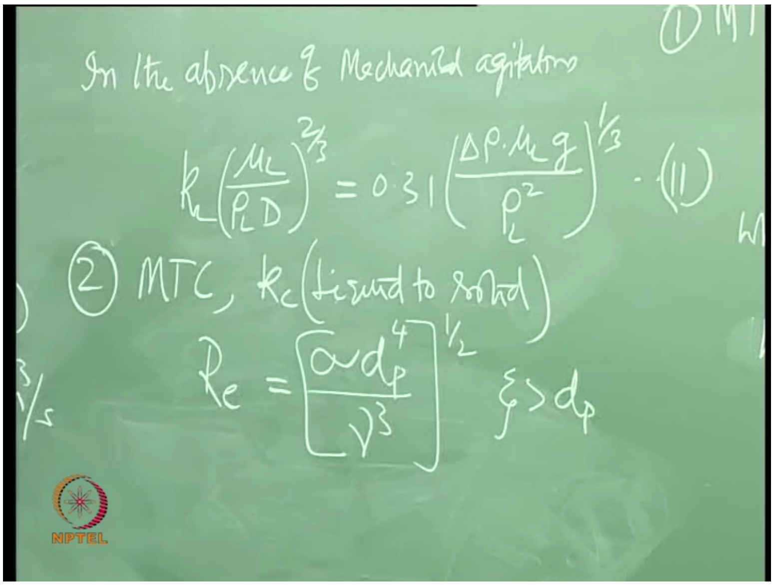

① MT

In the absence of Mechanical agitators

$$k_L\left(\frac{\mu_L}{\rho_L D}\right)^{2/3} = 0.31\left(\frac{\Delta\rho \cdot \mu_L g}{\rho_L^2}\right)^{1/3} \cdot (11)$$

② MTC, k_c (liquid to solid)

$$R_e = \left[\frac{\sigma d_p^4}{\nu^3}\right]^{1/2} \quad \xi > d_p$$

Sigma is in ergs per second per gram. That is same as in equation 8. And xi is size of the a d. And this is valid of course xi greater than d P, okay. So yes otherwise that means if you have xi less than d P, Reynolds number equal to sigma d P to the power of 4, this is 1 by 3 instead of 1 by 2 where a d size also one can find out that is xi equal to nu cubed by sigma whole to the power of 1 by 4. So if I write equation this will be 12, 13, 14, okay. Good.

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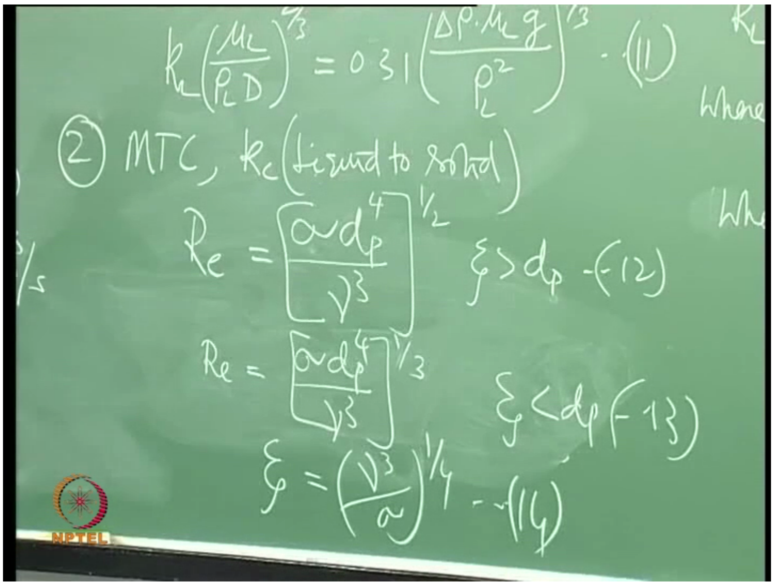

$$k_L\left(\frac{\mu_L}{\rho_L D}\right)^{2/3} = 0.31\left(\frac{\Delta\rho \cdot \mu_L g}{\rho_L^2}\right)^{1/3} \quad \text{-- (11)}$$

② MTC, k_c (liquid to solid)

$$Re = \left[\frac{\alpha d_p^4}{\nu^3}\right]^{1/2} \quad \xi > d_p \quad \text{-- (12)}$$

$$Re = \left[\frac{\alpha d_p^4}{\nu^3}\right]^{1/3} \quad \xi < d_p \quad \text{-- (13)}$$

$$\xi = \left(\frac{\nu^3}{\alpha}\right)^{1/4} \quad \text{-- (14)}$$

So I think this I have to remove now. Yes, so here you have a graph relating this Sherwood number and Reynolds number. Reynolds number defined in that fashion. This is Reynolds number that is equation 12 and 13 depending on xi values, okay. So then here I have Sherwood number. Okay, actually this is Sherwood number by, what is this number, mu L by rho L D? Smith number.

So this is to the power 1 by 3. Sherwood number by that is slotted. So here this is a log-log scale. I have here point 1 starting somewhere here and 10. This side we have again point 1, 10, 100. See this is another way of defining Reynolds number.

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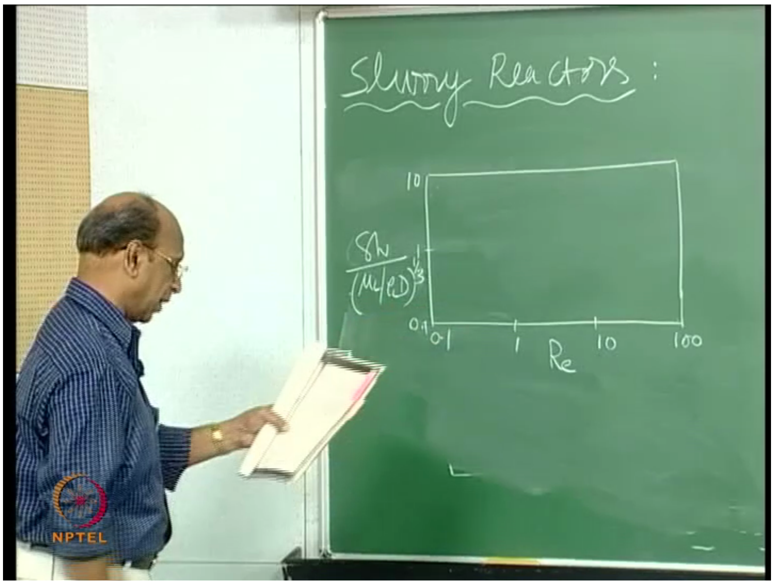

So you have approximately this is point 2, point 4, point 6, point 8. Of course log scale only. Yes then again here I have 2, 4, 6 and 10. Yes, you will have a line somewhere near 4 it starts, like this it goes. That is not exactly straight line but slightly. This way that way it goes there. Yes, so this is the correlation.

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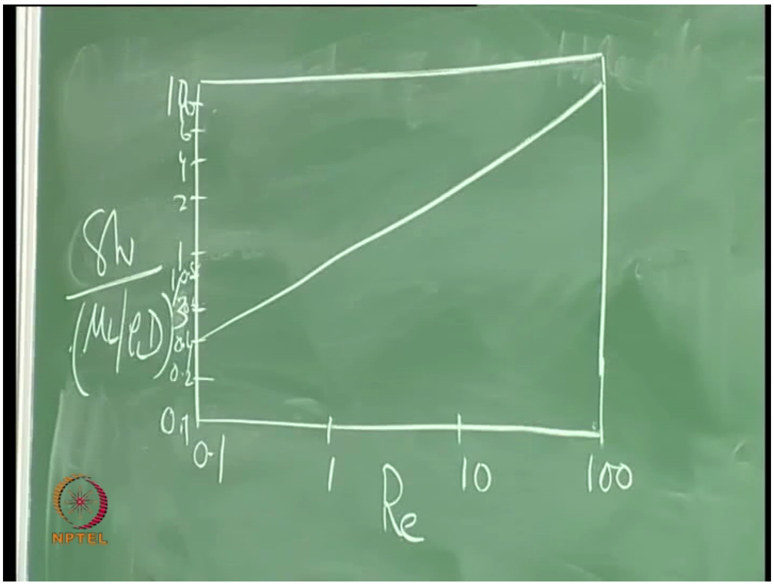

That means if you want to design then I have to give you this. Even if you want to calculate if I give the problem I have to supply this information and then first calculate Reynolds number. If it is 10, go there, read and this coordinate you know so that is Sherwood number is again defined as k c here, okay. Yes, so that value you have to substitute k c d P by D diffusivity again, okay. So using that you can calculate what is k c from this. Good. Yes, so that is the correlation and good. What else is now? Everything we know.

Of course intrinsic rate equation only other one left but I think that you have to use some other technique to find out. That we do not have. Then you know some kind of simplifications, right? That equation where you have three resistances. Sir, whether you have to go for tiffin or what? Okay. So some simplifications for that equation where you have r o b equal to, okay, tell me that equation. I have a c H C L equilibrium I substituted there, okay, already. That is correct no.

Anything else missing there? Yes, so this whole thing divided by, 1 by k g I am dropping out so then we will have a c by a g, H by k L plus H by a c k c plus we have H by again a c will come. Yes, a c eta k, so that is the equation. And most of the time this equation if I say 15, I have not written this equation earlier, okay. Yes, so this equation most of the time this term also is neglected. Do you know why?

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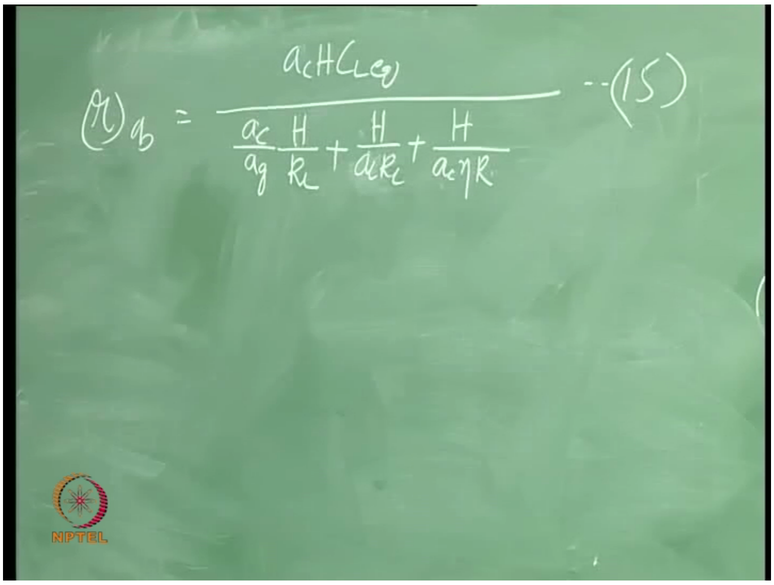

$$(r)_{ab} = \frac{a_c H C_{L(eq)}}{\frac{a_c}{a_g}\frac{H}{k_L} + \frac{H}{a_c k_L} + \frac{H}{a_c \eta k}} \quad --(15)$$

The last one, neglected in the sense the k must be large value. Why?

Student: (())(58:16)

Professor: Yes, most of the time this (())(58:19) and nickel all that and that very find powder what we use so very active catalyst only are used for slurry reactor most of the time. So that is the reason why 1 by k value or k value will be very large so this term also will disappear. So finally what you have all the time in the design will be H also will get cancelled, a c C L equilibrium divided by a c by a g, 1 by k L plus H will go, a c k L. That is the equation. This is the most practical equation, most of the time people can use that, okay.

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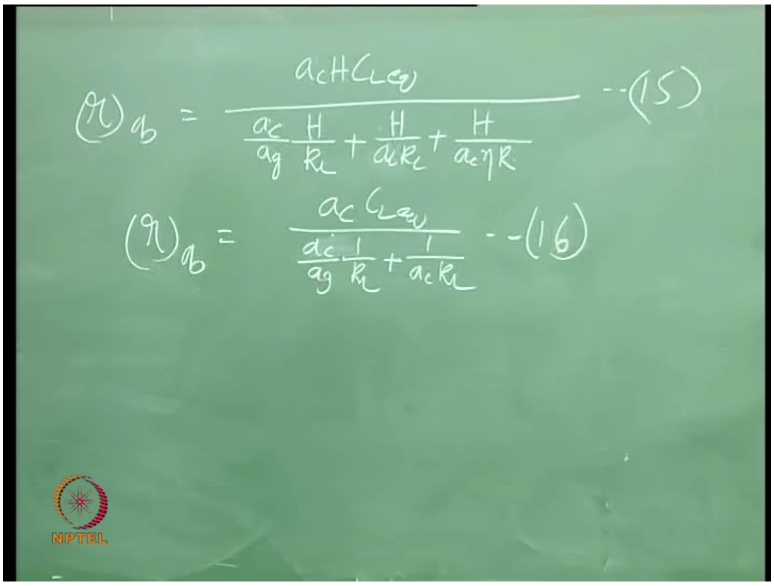

$$(r)_{ab} = \frac{a_c H C_{Leq}}{\frac{a_c}{a_g}\frac{H}{k_L} + \frac{H}{a_c k_L} + \frac{H}{a_c \eta k}} \quad \text{--(15)}$$

$$(r)_{ab} = \frac{a_c C_{Leq}}{\frac{a_c}{a_g}\frac{1}{k_L} + \frac{1}{a_c k_L}} \quad \text{--(16)}$$

So now again further simplifications because as an engineer you should be able to simplify things as easy as possible so that you know your design will be the simplest, right? So you also have something in your mind. Something, that means if I am taking large number of very fine particles then the ratio a c by a g will be very large, a c by a g, okay. So then can I neglect this also? A c is what by the way? External surface area of catalyst per unit volume of bubble free slurry, okay. Do you know how do you find that?

Student: (())(59:55)

Professor: If I want you to develop an equation for that a c. Surface area of external surface area per unit volume of the particle multiplied by volume of the particle and divided by volume of the slurry, okay. Anyway I think you would have not got that but I will tell you because that is also how you find out. A c, then we can discuss that. A c is surface area per unit volume of bubble free slurry, okay. So surface area per unit volume of slurry liquid, okay, liquid I am writing, okay. Good.

So now this can be also written surface area per volume of particles, total surface area per total volume of particles into volume of particle divided by same thing, volume of liquid. What is this surface area per unit volume of particle? I can multiply by n and multiply by n there, number of particles total volume at surface area. What do you get there? 6 by 6 by d p. Good. So this is 6 by d p and this one, for volume of particles. Mass divided by density, m s by rho s.

So this is what is this, you know, surface area per unit volume of the particles. So the corresponding equation is 6 m s divided by rho s d p where m s is normally taken as directly if you want to use that equation, m s is weight per unit volume of the bubble free slurry. Very simple no, to get that.

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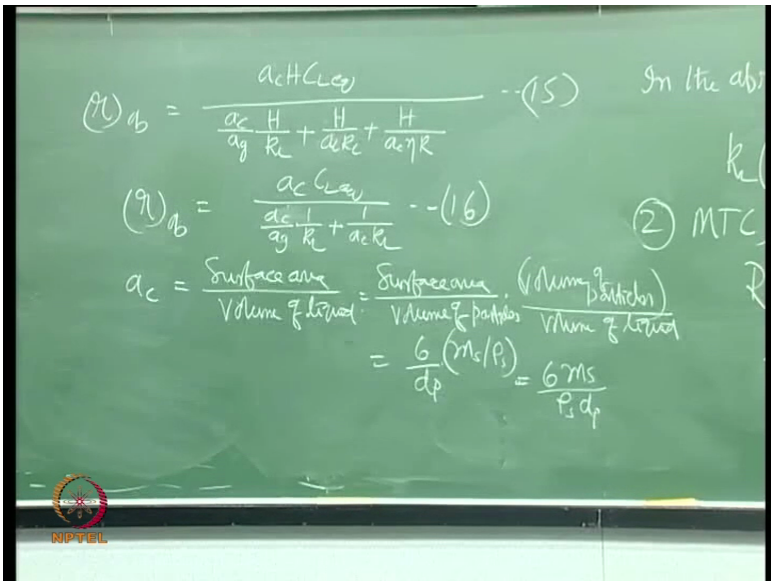

$$(r)_{ab} = \frac{a_c H C_{Leq}}{\frac{a_c}{a_g}\frac{H}{k_L} + \frac{H}{a_c k_L} + \frac{H}{a_c \eta k}} \quad \text{--}(15)$$

$$(r)_{ab} = \frac{a_c C_{Leq}}{\frac{a_c}{a_g}\frac{1}{k_L} + \frac{1}{a_c k_L}} \quad \text{--}(16)$$

$$a_c = \frac{\text{Surface area}}{\text{Volume of liquid}} = \frac{\text{Surface area}}{\text{Volume of particles}} \cdot \frac{(\text{Volume of particles})}{\text{Volume of liquid}}$$

$$= \frac{6}{d_p}(m_s/\rho_s) = \frac{6 m_s}{\rho_s d_p}$$

Volume of liquid. This one is volume of liquid, right? We are not substituting. That comes by definition so in between only we substitute volume of particles and volume of particles. This can get cancelled, okay. Yes, so that means if I know what is the total amount of solids I am taking, total mass, if I know the density, if I know diameter of the particle I can calculate a c. Yes, Kavya has doubt.

Student: It is not dimensionally matched.

Professor: Tell me which one is different there. This is you know m s is the weight of the single particle, rho s is the density of single particle. So that will be the volume of particle, right? Volume of liquid by definition I am keeping as it is.

Student: Per unit volume.

Professor: Where is per unit volume? Yes, a c definition itself per unit volume. I mean that is what in the beginning itself we have written only per unit volume of liquid, right? Yes, this is simply volume of particles and this is also volume but I know surface area per unit volume of particle. Is there any problem? Not able to get that?

Student: Why do not you try volume of liquid?

Professor: Where is volume of liquid because I introduced here volume of particles, right? Per unit volume because the definition here is surface area per unit volume of liquid. See normally what we have to do is that you know volume of the surface area per unit volume of particle we use. You know normally surface area per unit volume of the particle only we are talking but definition given here is surface area per unit volume of liquid.

But this I can also write surface area per unit volume of particle multiplied by volume of particle divided by same volume, volume of the liquid. So that way I can use this equation to calculate a c. Similarly can you also find out interfacial area of the bubble per unit volume of bubble free slurry? Same thing, same technique but there you cannot use density. So a g is surface area per, same thing again, volume of liquid which can be written as surface area. What is m b? That we do not know. Here you get another beautiful term.

See this is surface area of bubble divided by volume of bubble, okay. If I am inserting in between, right? So surface area, n number of bubbles divided by n number of bubbles also that will be simply 6 by d b. Then this side I have to write n into volume of bubble. Kavya, this side I have to write n into volume of bubble, okay, bubbles.

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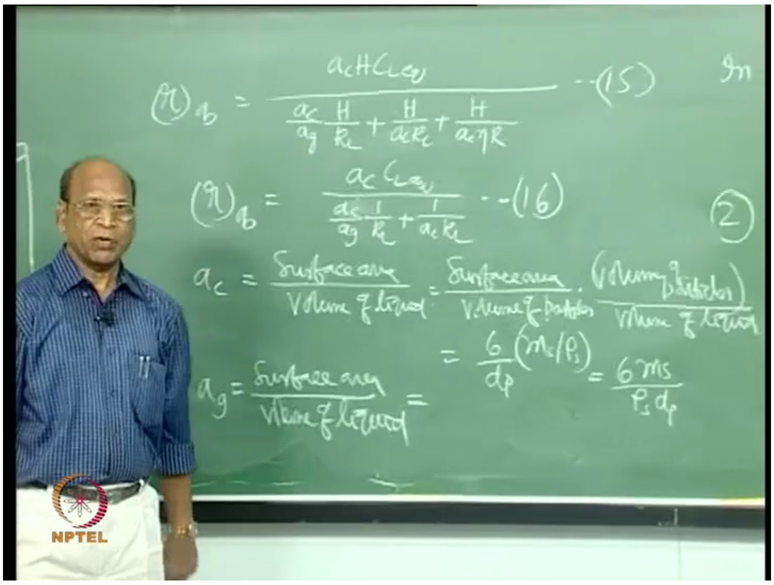

And what is that? I think volume of bubbles I will simply put as v b. Yes, is what? Hold up. So that is why finding out gas hold up is also very important in slurry reactors, okay. That v b is the hold up where we have now here 6 by d b into v b, volume of bubbles. And volume of bubbles by this will be hold up, okay. So this is that means if you know the volume this volume of bubble by volume of the liquid will be hold up. Please write that volume of bubble by volume of liquid will be the hold up. This is another equation.

Then we have to substitute now what is the hold up of the liquid. Good, okay. Good. So now we assume that we know this a c and a g because once I give you what is the hold up this also can be written in terms of 6 d p into epsilon b in the normal term. Epsilon is the voidage, okay. So that is nothing but hold up of the liquid, okay. So now this may be equation 17, this is equation 18.

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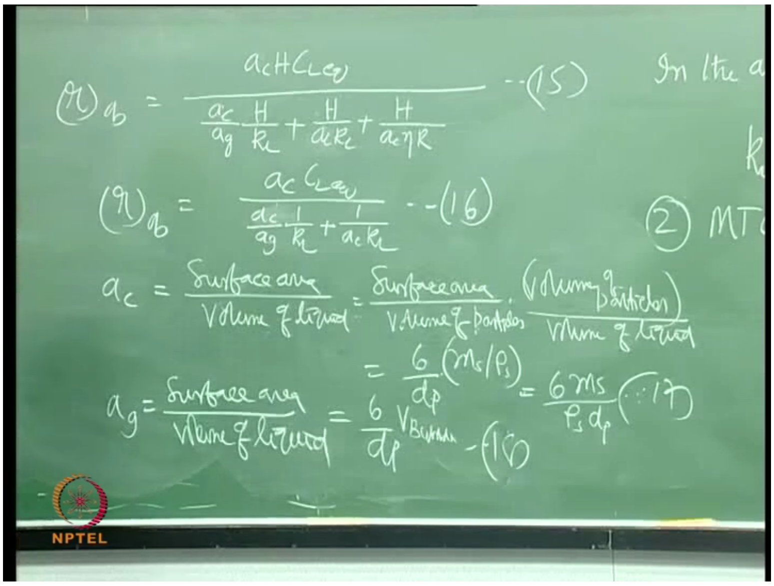

$$(r)_{ob} = \frac{a_c H C_{Leq}}{\frac{a_c}{a_g}\frac{H}{k_L} + \frac{H}{a_c k_L} + \frac{H}{a_c \eta k}} \quad \text{--(15)}$$

$$(r)_{ob} = \frac{a_c C_{Leq}}{\frac{a_c}{a_g}\frac{1}{k_L} + \frac{1}{a_c k_L}} \quad \text{--(16)}$$

$$a_c = \frac{\text{Surface area}}{\text{Volume of liquid}} = \frac{\text{Surface area}}{\text{Volume of particles}} \cdot \frac{(\text{Volume of particles})}{\text{Volume of liquid}} = \frac{6}{d_p}(m_s/\rho_s) = \frac{6 m_s}{\rho_s d_p} \quad (\cdots 17)$$

$$a_g = \frac{\text{Surface area}}{\text{Volume of liquid}} = \frac{6}{d_p} V_{\text{Bubble}} \quad \text{-(18)}$$

In the a

k

② MT

So now again you know another simplification. If I am finding out that I have large number of small catalyst particles so that means I can neglect now this term because a c is very large. So 1 by a c because large number of very fine particles so that means this surface area is very large. I cannot neglect this but I can only neglect this right, okay. Good.

So if I do that what is the rate expression I get? Go to r o b. If a c is very large naturally a c by a g also will be large. So in this equation we can neglect only this then what is r o b?

Student: K L into a g into C L.

Professor: K L into, excellent, K L into a g into C L. That is what. So now what I am trying to say is a g contains what? Now everything has focus now on a g. But if I want to calculate a g what I should know? This is not d p this is d b. Hold up and diameter of the bubble. So I am just trying to pose the problem to you, okay. So now hold up that is the reason why most of the time in heterogeneous systems we are worried about hold up. I have been telling this long time. In hydrodynamic studies we always try to find out what is the hold up, correct no.

Many times I have told that. So these are the problems now. You are now really facing that, right? So when I want to use this equation, a c is there but all my focus is only a g but a g now depends on d b and how accurately I measure d b is important thing for me.

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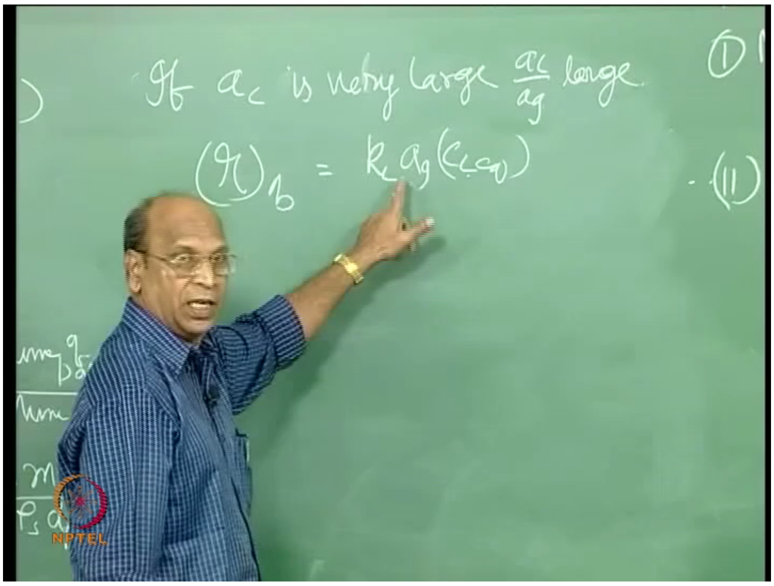

How do you measure bubbles in slurry? If I ask you in aquarium you have you know fishes moving but gas bubbles also are moving. If I ask you to find out what is the diameter of that how do you find out?

Student: Bubbles free we subtract that with the volume.

Professor: Yes, that is the most you know engineering way of doing things but what is assumption? All the bubbles are same, okay. Bubble size, but clearly you know that the bubbles are not same. That is what you know someone told centipede has hundred legs but anyone counted weather centipede has hundred legs? Okay. Similarly here you know why I am telling is we believe many things.

So one of the simplest way of finding out bubble size is that you measure the volume without introducing the gas of the liquid, then introduce the gas because gas has volume so volume will increase. So subtract that increased volume minus this liquid volume then assume that you have uniform bubbles. Then how do you calculate bubble size now? Spherical bubbles. How many number?

Whatever number you have, whatever number you can get some other value. See all that increased volume I will say that I have thousand bubbles and then each bubble has 1 millimetre.

Student: (())(01:12:20)

Professor: What is the use of that?

Student: Sir, we have only one bubble.

Professor: I do not have one bubble. I have thousands of bubbles inside. Taylor bubble experiment is to find out the characteristics of the bubble, okay. But here in the presence of so many large bubbles how do I find out the size? So normally what we do is that is why we do most of the experiments in you know transparent columns or glass columns. We will now approximately find out maybe you know by looking, carefully observing, okay this maybe 5 mm, okay. All may not be 5 mm.

You see how many approximations are involved. Particularly Abhinav was asking yesterday some question because engineering is approximation. Like that in bubbling bed model also there are many approximations, okay. But now no I am a scientific engineer not engineering scientist, okay. Now I want to find out exactly the bubble size. That is where is the challenge for you now. First of all you have to find out how many bubbles are there and you find out how many bubbles are with 1 mm, 2 mm, 5 mm, 10 mm.

So that means you are talking about bubble size distribution. Challenging task for chemical engineers. Even now we do not have good method. Even now we do not have good method. It is approximate. That is why there are many challenging problems I say and people live with bubbles, drops and even how do you find drop size in liquid-liquid extraction? Thousands of people are working on liquid-liquid extraction in industry. They are producing wonderful products after extraction but still we do not know how do you measure drop size.

Same thing here, bubble size. Only we are sure about particle size. That is all. I think you know because particles are not changing in time, okay, size wise unless you have tremendous iteration and all that. So particles are the things only we can characterize. And there are many theories. I do not know you are not in DD no? None of you are in DD, all of you in B Tech, okay. So they have a course called multiphase system, okay. I think M Tech you also have that course. Entire multiphase system is only to talk about bubbles, drops, particles.

That is what is entire multiphase, okay. So every time what you say? All this, finding out hold ups because each system will have a different hold up, right? Bubble liquid you know gas liquid columns different and gas liquid solid different, fluidized bed different, packed bed different. So like that you can list out you know rotary kills different.

What is the hold up you use in rotary kill? Because luckily they are solids. They are not changing. So that is why you said that it must be less than 10 percent, okay. So why cannot you use 90 percent? Kavya, why cannot you use 90 percent?

Student: Contacting (())(01:15:32).

Professor: How?

Student: Mixing will not happen.

Professor: Yes, mixing will not happen and you know there will be contacting but I think the way you expect particles will be lifted to the top and then fall, again lifted to the top again fall. So that kind of beautiful motion is not there. So that is why 10 percent or less than 10 percent is fantastic. Same thing even with you know centrifuging if you go to that level of rpm. Rpm also only 3, 4. If you go to 100 where centrifuging happening then what happens, all the particle stick to the walls as if it is part of the wall. So where is the contact?

All the gas will go in the central annular region and very small contact will be there but whereas when you have this normal method what you operate with low rpm and low hold up goes falls, goes falls. There is no more residence time for the exposure and good exposure, okay. So all chemical engineering equipment is really a trick to design. Even though there is no romance after derivations, okay. Because correlations may be boring but still that is what is life.

After you marry I think you remember my words, it is routine. It is routine, everyday get up, take breakfast, go to work, afterwards come and if you are in very good mood fight with the wife, if you are not in good mood go to the room and then sleep. So all this kind of that is the routine till we die. Same thing are also correlations, even though we develop theory every paper has a new theory.

But how much of that is used in chemical engineering equipment design is very small. That is why you have to appreciate chemical engineering. Whereas every theory developed by computer science engineers, electronic engineers is thrilling. Immediately it is applied to the field. But Mechanical Engineering, Chemical Engineering is not that easy. Mechanical Engineering is particularly it is not that exciting because they do not have chemicals. They do not have so much equipment.

They have only one equipment called IC engine, okay. Only outside shape will change, okay. Bonnet may change or you know that front design may change, tyres may change or top they may put that ladder or may not put ladder. That is all what they can do. Engine is always engine. I think 1800s they invented, it is the same thing. Not much improvement. Only thing now we are trying to do is that put better petrol or put some oil, put some alcohol and then try to find out how the car goes? Okay.

So that is how other than that now even Aeronautical engineers their entire life is only one engine, correct, jet. That is all. They may be trying on that variation but for us even one process there are thousands of variations. Just one process, packed bed alone how many ways you can design. Fluidized bed how many ways you can design, okay. So you can try to put you know somewhere input, somewhere inlet, somewhere outlet, multi inlet, multi outlet, all the things you can try just to get good efficiency, okay.

So that is why this is the equation and now this a g to find out we need correlation. That one correlation I will give you for d b, there are many. D b correlation, so now I just want to trying to tell you connections you know one after the other. So d b now because this a g depends on d b, right? So now we should have a d b correlation.

So 1 point 35 u by g delta by delta u square rho L divided by sigma L to the power of half into rho L delta g, no sigma L , rho L whole to the power of 1 by 3 where simplest of thing of course is d b bubble diameter centimetres, okay. And we have u gas velocity. This is again you know particularly this is only for porous plate. Please remember porous plate is different than perforation plate.

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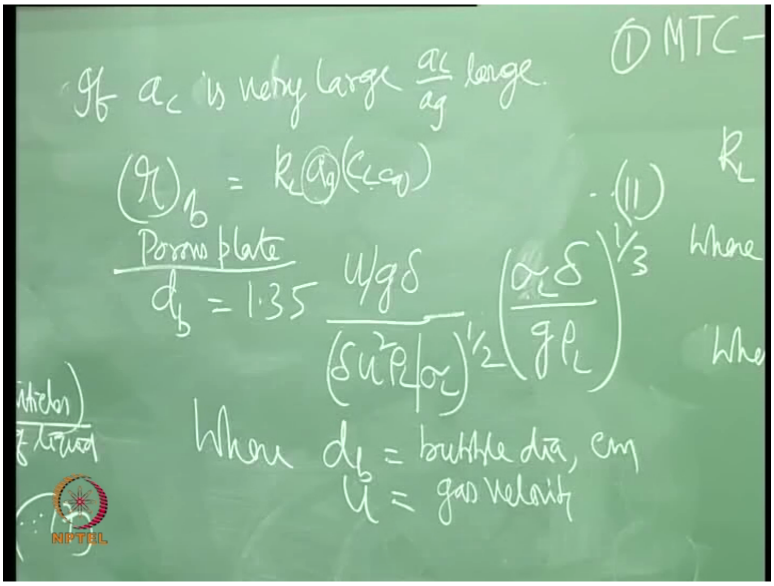

If a_c is very large $\frac{a_c}{a_g}$ large.

① MTC –

$(r)_b = k_L a_g (C_L - C_0)$ .... (11)

Porous plate

$d_b = 1.35 \frac{u/g\delta}{(\delta u^2 \rho_L/\sigma_L)^{1/2}} \left(\frac{\sigma_L \delta}{g \rho_L}\right)^{1/3}$

Where d_b = bubble dia, cm

u = gas velocity

So if you have perforated plate you will have different correlation, okay. So u g is gas velocity through porous plate centimetres per second. Then we have delta, pore diameter of porous plate. Then sigma L here is used as surface tension that is ergs per centimetre surface tension. So that is the one, per centimetre. And then you have rho L of course density of liquid grams per centimetre cube. Anything else? All those things are covered.

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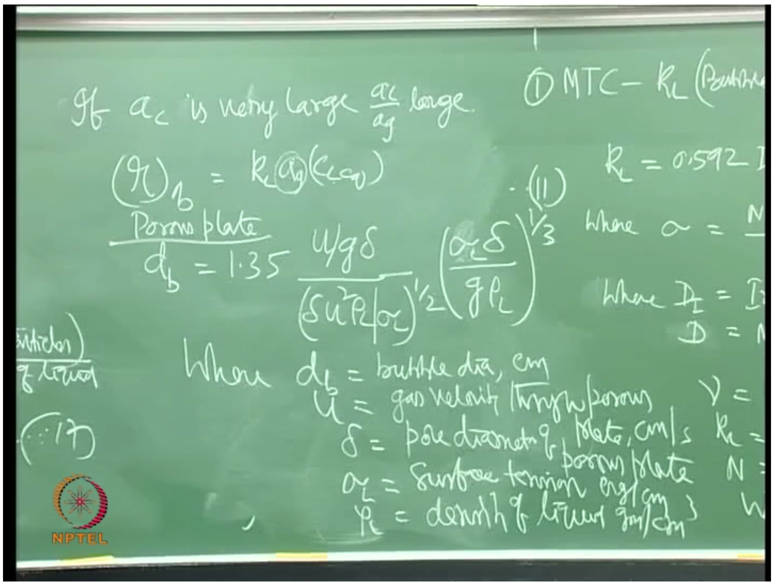

If a_c is very large $\frac{a_c}{a_g}$ large.

① MTC – k_L (Bubble

$(r)_b = k_L a_g (C_L - C_0)$ .... (11)

$k_L = 0.592$

Porous plate

$d_b = 1.35 \frac{u/g\delta}{(\delta u^2 \rho_L/\sigma_L)^{1/2}} \left(\frac{\sigma_L \delta}{g \rho_L}\right)^{1/3}$

Where α =

Where D_L =

D =

Where d_b = bubble dia, cm

u = gas velocity through porous

δ = pore diameter of porous plate, cm/s

σ_L = surface tension erg/cm

ρ_L = density of liquid gm/cm³

Dynes per second, not centimetre. No, second or centimetre? Centimetre only, length, dyne , okay. So like that you know it goes on and on. Good okay. Fine, so I think the next part is (()) (01:22:22) sorry, I think it may take some more time. But you do not fall now because no breakfast, okay. So now we have sufficient information now for the rate expression. You know how to derive the general rate expression and how to get the constants that are involved k L, k c, k g and all that.

So then you also know how to find out that a g, ac. All that information you have now. Now it is application to slurry reactor. So application to slurry reactor this is very simple. It is not that difficult. Good. So we will have the slurry reactor design, okay. I will write here design. We have the slurry reactor, okay. I think maybe let me close this and then put. So you have bubbles, we have particles and we have liquid, right? So one thing is that you can also take based on liquid phase because we want to design now, right?

So your interesting phase maybe liquid. If it is liquid that is equivalent to batch liquid and you have the rate expression. What is the equation? T by C a not equal to, it is liquid, integral 0 to x a d x a by minus r a. This minus r a is that. If it is plug flow for gas so solids is in batch. But solid is a catalyst so we are not going to try anything on that. So when it is gas, gas one assumption is that it is moving in the form of plug flow. So then we will take a small because again that approach only I am trying to tell you. This is delta z, this is z plus d z, this is z that is delta z, okay.

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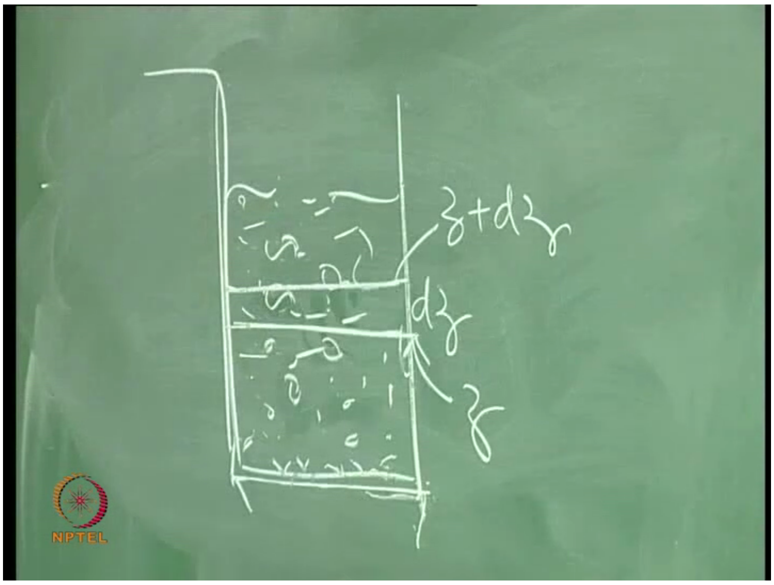

So in a simple manner if I have cross sectional area a when you have or otherwise if I write in our normal plug flow fashion ideal plug flow F A plus d F A , okay. Now I have to write the material balance. Moles entering will be F A, right? Moles entering will be F A because you know that is why I am not writing that. That is input equal to output is F A plus d F A. Please remember this is moles per second all the time. So the moles per second yesterday also we did the same moles per second.

Plus it is a continuous reactor where there is no accumulation for the gas. Gas is moving continuously. So, then that accumulation equal to 0 plus reaction. What is reaction? Minus, okay, r o b, okay, I have not written same thing into d v. This is d v which can be A c into d z. So now tell me what is the equation you get here? Time to stop. F A, F A will get cancelled. So minus F A equal to, yes can you tell me the integral expression. You can leave it as length you do not have to write. In terms of v also we can leave it as it is.

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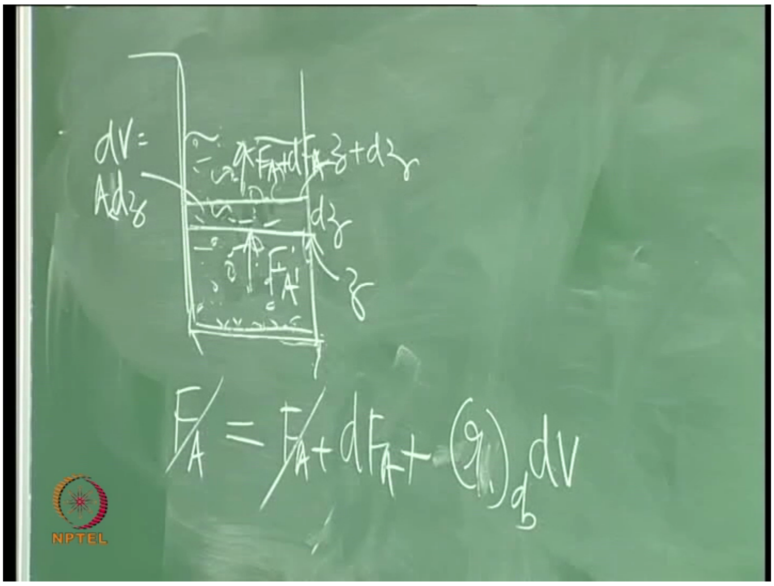

V by, this will give me v by integral. Integral expression I am asking. D x A by, that is the one. So now this volume is not simple volume in metre cube but that is volume of bubble free liquid. Why? Because here what we have used is volume of bubble free liquid. This balance what you are writing this must be only bubble free liquid. That is only thing you have to take care of in heterogeneous systems. What is that corresponding one what you are writing, okay.

So because our r o b is defined as the volume moles converted per unit volume of bubble free slurry per time, right? So when I am multiplying to get moles per, okay, if I write moles per time I have to multiply only by that corresponding v. That is the only thing which you have to be careful when you are writing the material balance for heterogeneous systems. So this is again nothing but your ideal plug flow equation. That is what I have been telling, okay. Minus r o b, good.

Now if it is first order like this system what we have so the C L, okay, correspondingly can be converted into 1 minus x A, okay, C A not into 1 minus x A. Then that you substitute and then we can integrate. That is all. You know that is why I told you in fact contacting is much easier to remember, right? Whereas it is heterogeneous reaction rates which will give you hell. Already this is one hell, okay. Yesterday another hell because fluidized bed and sometime before packed bed another small hell because in packed bed things are not moving except gas, okay.

So that is why and we have not done again you know moving bed. Moving bed again will be another hell, okay. But what you have to remember is the mass transfer coefficients and heat transfer coefficients will be changing the moment how the phases are moving change. The moment of phases will determine mass transfer coefficients and heat transfer coefficients. That is the reason why for each and every equipment you have different mass transfer coefficients, different heat transfer coefficients.

Whereas reaction rate is same for any system, reaction rate. That will not change, okay. So that is the reason why heterogeneous systems are very beautifully I mean exciting things and to close we started with this. I told you everything that starts with a beginning will also end. So now we will end here with the same diagram. So this is reactor, input, output, kinetics, contacting.

So here I have batch, continuous, then we have P F, M F. Here we have physical, chemical. So performance equation is output, okay. Remember is a function of kinetics, contacting.

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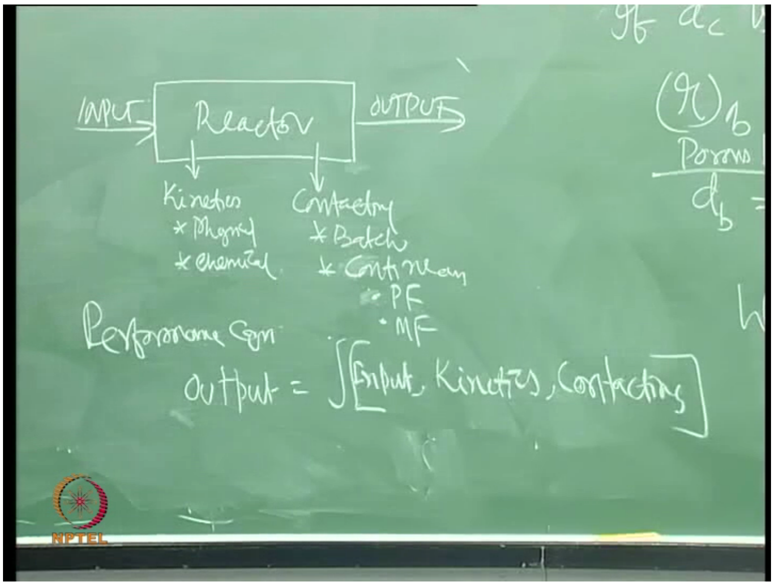

Yes, so that is the one. And now of course here what you are trying to say is that we are only talking about all the time ideal contacting. So the moment you have non-ideal contacting this equation will change again. So that will be more and more complications only. Other than that there is nothing, okay.