Chemical Reaction Engineering II
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Lecture - 19
Fluidized bed reactor design 2

Friends, it is a good time to summaries what you have learnt the last lecture. We initiated discussion on the fluidized bed reactor and the objective is to design fluids fluidized bed reactor. What is a fluidized bed reactor? Fluidized bed reactor is essentially a tube which is which has a certain catalyst particles and then the gas is flown through this tube. And as the velocity of the a gas stream will increases, then the drag force that this fluid stream exits on the gas particle on the a solid catalyst particle that is equal to the weight that is actually gravitational force excited by this particles because of its natural weight.

So, when that equals then the catalyst particle starts raising and that is called the fluidization phenomena. Now, once a fluidization occurs then these gas bubbles are formed. And when these gas bubbles are formed there is transport between the transport of the reactance from the gas bubble to the catalyst particle, where the reaction occur in the catalytic sides of the catalyst particle which is already fluidized. And then the product which is formed in the sides is actually transported back into the bubbles, which is the gas stream and then the bubbles carry these products and leave the reactor. So, this is the process that occurs in a fluidized bed reactor and then we looked a different regimes different fluidization regimes in the a fluidized bed reactor.

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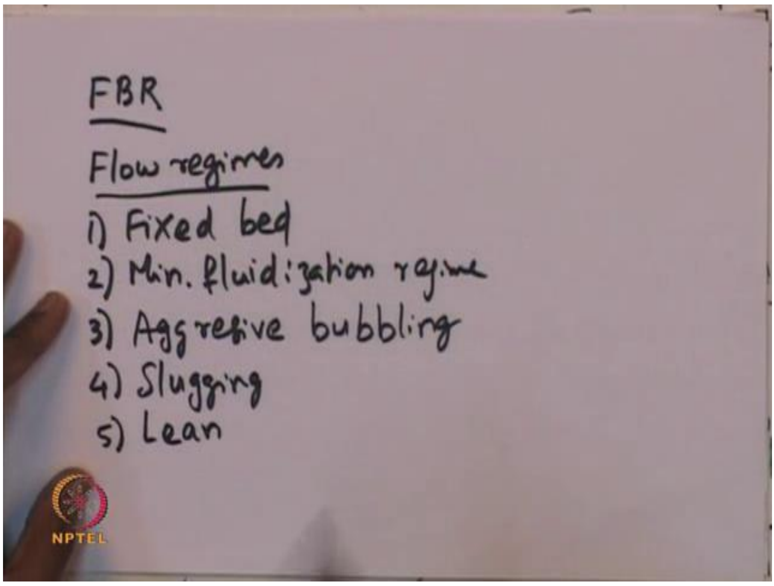

FBR

Flow regimes

1) Fixed bed
2) Min. fluidization regime
3) Aggresive bubbling
4) Slugging
5) Lean

So, if FBR stands for the fluidized bed reactor we looked at different flow regimes 1 is the fixed bed regime in a fixed bed regime the fluid velocity is not significant enough to of set the gravitational force which is exerted by the catalyst particle. And as a result the particle they remain pact at the bottom of the reactor were there sitting on a perforated order a pores plate. Then the second regime is called the minimum fluidization regime minimum fluidization regime.

Now, in this regime the velocity of the fluid is just sufficient to offset the gravitational force. That is the a drag force that is that the a particles experience because of the flow of this gas which is flowing at a certain superficial which is being flown into the bed at a certain superficial velocity you not. There the drag force offsets the or it is just equal to the gravitational force exerted by the catalyst particles then the particle starts raising or they get fluidize. And that velocity minimum velocity is called the fluidization velocity and that regime is called the minimum fluidization regime.

A typically the bubbles which are present in the min near the minimum fluidization regime they are a bubbles or form near the perforated plate. And then the bubbles starts travelling through this bed which is being fluidize. And the third regime is called the aggressive bubbling regime. So, when the when the velocity with which the gas stream is being flown inside the bubbling significant increases and there is aggressive bubbling lots of bubbles are formed which causes tremendous mort of recirculation of the fluid and also the catalyst particles. And so that regime is called the aggressive bubbling regime. And then the fourth 1 is call the a slugging regime, where these velocity is significantly higher that there are channels of these a channels are actually created. And through these streams the gas stream simply escapes the bed and that are what is called the slugging ray a slugging regime.

The last 1 is the lean phase were the all the particles are suspended and the density of the precocity is a significantly higher and there all suspended all through the reactor. So, that is what is call the a lean phase regime.

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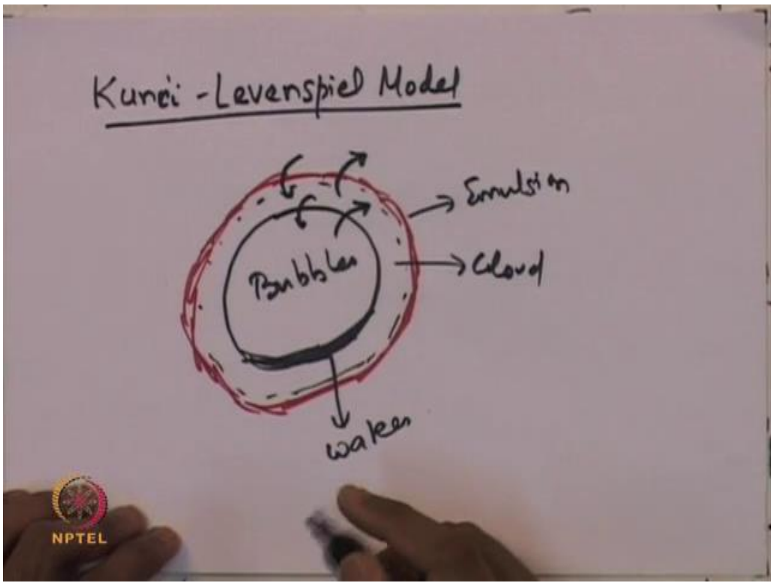

So, these are the 5 different regimes at we described in the last lecture and we initiated the a discussion on Kunii Levenspiel model. So, the Kunii Levenspiel model assumes that all particles are of same size and it also assumes that the solid flown the at the solid flow emulsion phase as though like it is a pluck flow. And then the emulsion phase exist at a minimum emulsion phase always exist at the minimum fluidization velocity.

Then it also assumes at the gas wide fraction is equal to the wide fraction as that of at the minimum fluidization velocity. And then it assumes that the solid which is a flowing downs downwards is actually the concentration of the solid in the emulsion phase is equal to the concentration of the solid which is present in the wakes which are actually form just below the bubble.

Just to recap the bubbles are formed as soon as the fluid actually is going through the bed the bubbles are formed. And then the bubbles carry a certain amount of particles and then there is a wake which is formed below the bubble, where lot of particles of high concentration is actually carried along with the bubble. Around this around the bubbles there is a phase call the cloud phase there is a phase call the cloud phase and in this cloud a there is some particles are present in this cloud.

Then around the cloud is the phase called the emulsion phase which also contains lots of particles. And the emulsion phase is essentially has the same porosity as that of the nearly the porosity of the resting bed. And therefore, the transport which occurs the mas transport process which occurs which are transported from the bubble to the cloud phase or this is the cloud phase and this is the emulsion phase and this is the wakes.

So, the mass transport occurs from the bubble phase into the cloud phase and the reactants are transported from the cloud phase into the emulsion phase. Where, the particles are present in the reaction occurs in the particles, and then the product is actually transported back into the cloud phase and back into the bubble phase. So, once this happens the bubbles carry the product and then the product leaves the fix fluidized bed reactor. So, this is the process that occurs in a fluidized bed reactor. So, now we looked at some of the expressions for the there are several parameters that 1 makes to actually find out before we can the fluidized bed reactor.

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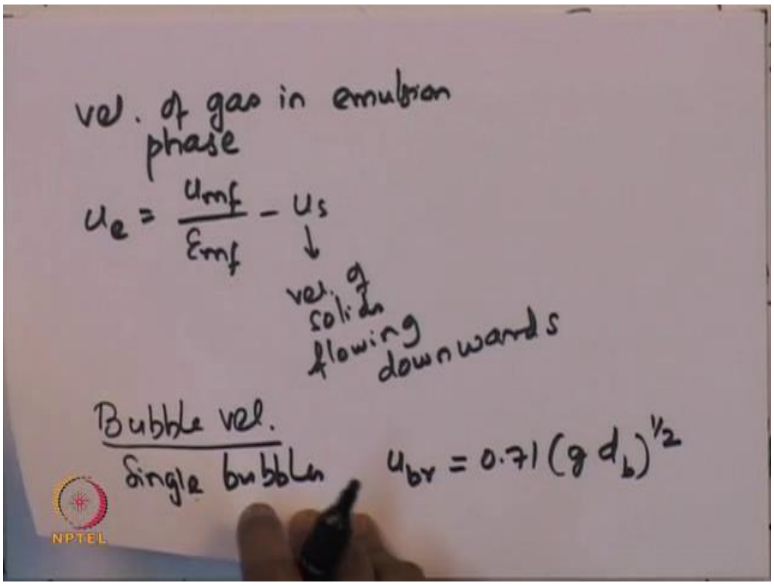

vel. of gas in emulsion phase

$$u_e = \frac{u_{mf}}{\varepsilon_{mf}} - u_s$$

u_s ↓ vel. of solids flowing downwards

Bubble vel.

Single bubble $u_{br} = 0.71 (g\, d_b)^{1/2}$

So, the velocity with the velocity of gas in emulsion phase is given by ue equal to umf which is the velocity of the minimum fluidization divided by the velocity at minimum fluidization minus us were us is the velocity of solids flowing down wards. Now, the bubble velocity is one of the important aspects, that control the conversion or the performance of the fluidized bed reactor is the time that will spends by the bubble in the fluidized bed reactor, because the reactants are carried inside the bubble. And the reactance have to get in contact with the solids in order for the catalytic reaction to occur. So, therefore, the amount of time that is spends by the bubble inside the reactor a significantly contribute to the performance of the fluidized bed reactor. So, the time that is spend by the bubble inside the reactors controlled by the velocity with which the bubble is actually raising inside the fluidized bed reactor.

So, let us look at how to estimate this velocity of the bubble which is raising inside the fluidized bed reactor. So, the bubble velocity is calculated for a single bubble; there are correlations that exist for a single bubble, which is given ubr and that is equal to 0.71 into gravity into diameter of the bubble to the power of half. So, 1 needs to know what is the diameter of the bubble in order to estimate what is the single bubble velocity.

So, now, if many bubbles are present which is typically the case in a in a fluidized bed reactor. Then the velocity with which a single bubble is going to raise a together with many bubbles is going to be very different, because of the presence of other bubbles.

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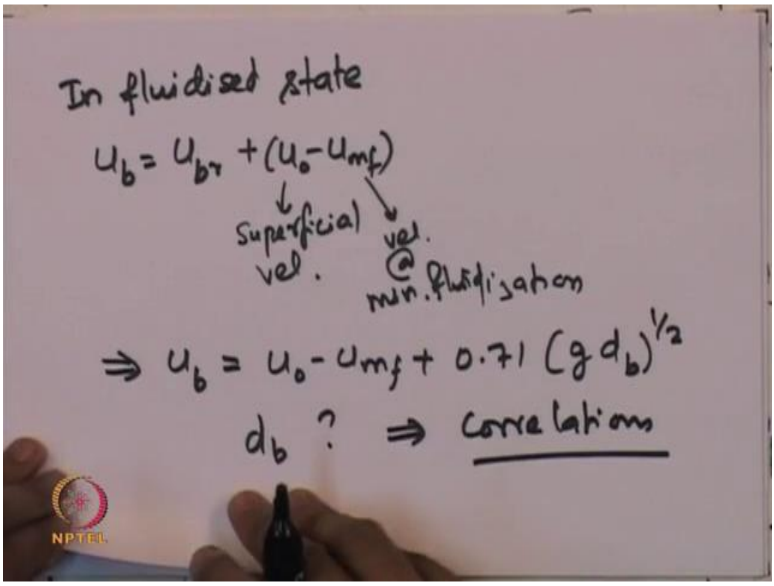

In fluidised state

$u_b = u_{br} + (u_0 - u_{mf})$

superficial vel.

vel. @ min. fluidisation

$\Rightarrow u_b = u_0 - u_{mf} + 0.71\,(g\,d_b)^{1/2}$

d_b ? $\Rightarrow$ <u>correlations</u>

.

So, therefore, in a fluidize state in fluidize state the bubble velocity is given by the bubble ... There has to be some correction that is associated with the bubble velocity is there were to be just a single bubble. So, therefore, the correction is basically given by u not minus umf. That is the correction to the single bubble a velocity and that tells us what is the velocity of the bubble in the fluidize state. Where, u not is the superficial velocity with which be gas stream is being flown into the fluidized bed reactor and umf is the corresponding velocity of at minimum fluidization point.

So, therefore, plucking in the correlation for the for the velocity of the single bubble if we can which find that the velocity of the bubble in a fluidized bed reactor a fluidize state is given by u not minus u m f plus 0.71 into gravity into diameter of the bubble to the power of half. So, now we need to find out what is the diameter of the bubble what in terms of the other properties of the. So, there are correlations which are actually available. So, needs to correlations in order to estimate the diameter of the bubble. So, let us look at what these correlations are.

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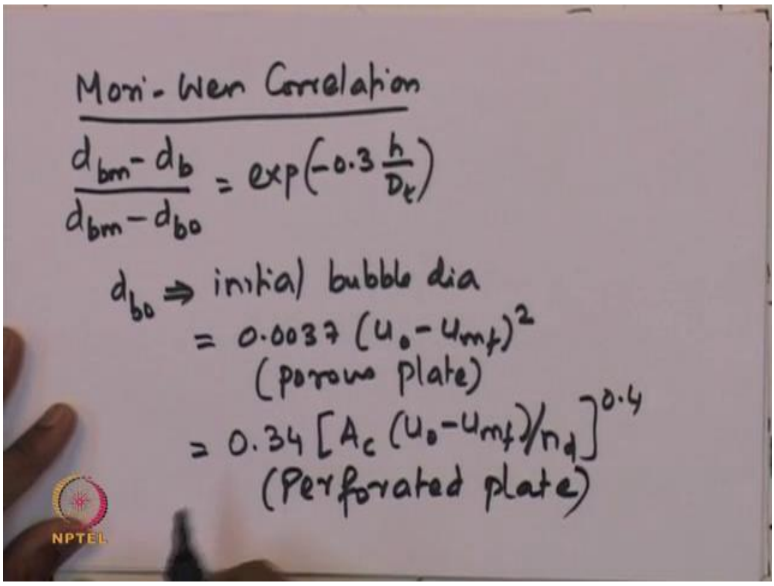

Mori-Wen Correlation

$$\frac{d_{bm}-d_b}{d_{bm}-d_{bo}} = \exp\left(-0.3\frac{h}{D_t}\right)$$

$d_{bo} \Rightarrow$ initial bubble dia

$= 0.0037 (u_0 - u_{mf})^2$

(porous plate)

$= 0.34 [A_c (u_0 - u_{mf})/n_d]^{0.4}$

(Perforated plate)

.

So, the 1st correlations that we going to look at there is quality Mori Wen correlation this is the Mori Wen correlation they correlation is as it goes like this. So, d bm which is the maximum possible bubble diameter minus the diameter of a particular bubble divided by the maximum possible diameter minus the diameter of the bubble, when the bubble is just for of that the initial bubble diameter. And that should be equal to exponential of minus point 3 into x by dt. Where H is the height at which the particular bubble is being observed and d t is the bed diameter of the bed.

So, now d bo which is the initial bubble diameter initial bubble dia that is given by 0.0037 into u not minus umf the whole square. If it is a perforated plate if it is a porous plate then the correlation that gives an estimate of what is the initial bubble diameter is given by 0.0037 superficial velocity minus the corresponding fluidization velocity and square of that difference.

That is equal to 0.347 multiplied by the area of cross section into u not which is a superficial velocity minus the minimum fluidization velocity umf divided by the number of perforations which is actually present in perforated plate to the power of 0.4. So, this is the correlation for estimating the initial bubble diameter. If the plate which actually holds these particles are actually a it is a perforated plate it is a perforated plate; then this is a correlation that actually gives an estimate of what is the initial bubble diameter.

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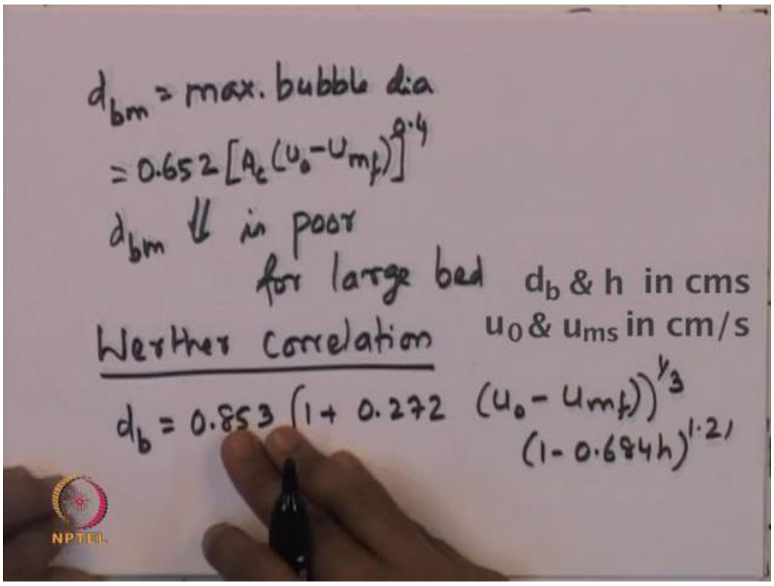

d_{bm} = max. bubble dia

$= 0.652\left[A_t(u_0 - u_{mf})\right]^{0.4}$

d_{bm} ⇓ in poor

for large bed

d_b & h in cms

u_0 & u_{ms} in cm/s

Werther correlation

$$d_b = 0.853\left(1 + 0.272\,(u_0 - u_{mf})\right)^{1/3}(1 - 0.684h)^{1.21}$$

So; next we need to know, what is the maximum possible bubble diameter? So, the maximum bubble diameter is given by d bm is the maximum bubble diameter maximum bubble dia. And that is given by the correlation 0.652 into the area of the cross section of the bed into u not umf, u not is the superficial velocity with which the gas stream is let inside the fluidized bed reactor. And umf is the a minimum fluidization velocity a whole to the power of 0.4. So, that provides an estimate of what is the maximum possible bubble diameter.

It is known that the predictions are poor if the bed is very large. So, the d bm prediction by using this correlation is poor for large beds for a large fluidized bed reactor. The correlation does not work very well the experimental observations suggest that this correlation does not give a good estimate if the bed is very large.

The other correlation which is also available it seems to work over a wide range of a fluidized bed reactor is call the Werther correlation. The Werther correlation is that the diameter of the bubble is given by 0.853 into 1 plus 0.272 into u not minus umf whole to the power of 1 by 3 into 1 minus 0.684 into H which is the height of the bed and that particular instance into the power of 1.21 per. So, this correlation is known to give a better prediction of the diameter of the a bubble and the fluidic conditions. So, the next estimate that we need to make is the velocity of the solid when it is flowing in the emulsion phase.

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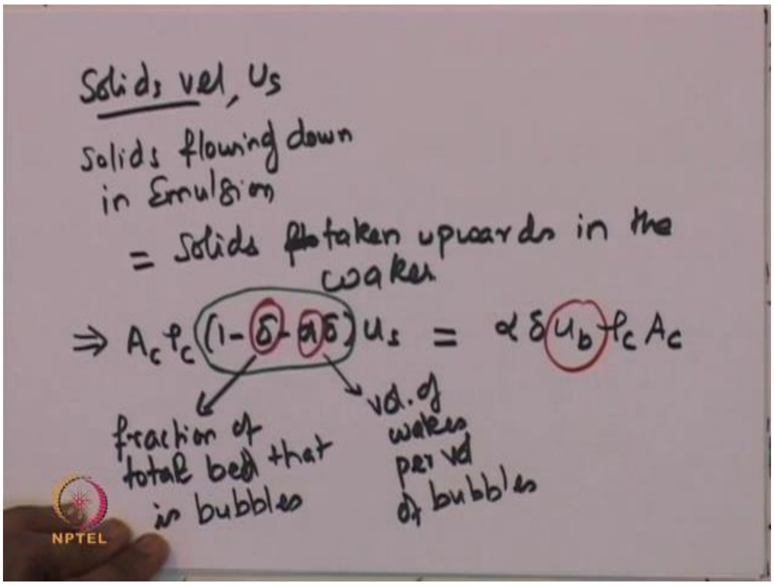

Solids vel, u_s

Solids flowing down in Emulsion

= Solids taken upwards in the wakes

$$\Rightarrow A_c \rho_c (1-\delta-\alpha\delta) u_s = \alpha \delta u_b \rho_c A_c$$

So, we need to find out what is the solids velocity u s that is what that is the next parameter that needs to be estimated. So, suppose way in order to estimate the solids velocity we can perform a very simple material balance. This is because of the fact that whatever solid particles which are actually flowing down in the emulsion phase, should be equal to what are the solids which are actually being taken up in the wakes which is actually following the bubbles.

So, wakes actually have the maximum concentration of the solid particles that are being lifted because of fluidization. So, therefore, the amount of solid particles which are actually a flowing upwards in the wake, should be equal to the amount of solid particle which are actually transported in the emulsion phase. So, therefore, why if we make a material balance across the solids flowing in these 2 phases and we should be able to estimate. What should be the relationship for finding the solids velocity?

So, let us look at this material balance. So, these solids flowing in emulsion face that should be equal to flowing down in emulsion phase should be equal to solids flowing solids actually taken upwards in the in the wakes. So, now putting the corresponding expressions a solid flowing down in the emulsion is given by area of cross section Ac multiplied by the density of the catalyst row c into 1 minus delta minus alpha into delta into us. Where, delta is basically the fraction of the total bed that is actually bubbles.

So, delta is the fraction of total bed that is bubbles. Now, this excludes the - this is a clue excludes the wakes that are actually formed this is just the bubbles. This is the fraction of the total bed which is basically the bubble; so that is delta. And then alpha is essentially alpha is the fraction of or the volume of the wake per volume of the bubbles which are actually formed because of fluidization. This is the volume of wakes per volume of the bubbles which are actually formed by fluidization.

So, therefore, this quantity 1 minus delta into alpha delta it actually estimates as to how much what fraction of cross sectional area is actually filled with solids is given by 1 minus delta minus alpha into delta. So, therefore, using there this relationship for the solids flowing in emulsion that can be equated to the fraction that contains fraction of volume in a given cross section that is actually filled by wakes is alpha into delta. Because, alpha is the volume of wakes per volume of the bubbles and delta is the fraction of the bed that is actually bubbles multiplied by ub, which is the velocity with which the bubble is raising up upwards into multiplied by row c into Ac.

So, this material balance of a the solid which is going down emulsion and the solids which are actually taken upwards in the wakes can be used to estimate in us. And note that the ub is the bubble raising velocity which can be obtained using the correlation that is Mori Wen or the Werther correlation. And alpha and delta are in a suppose it be a known property for a for a particular fluidized bed reactor.

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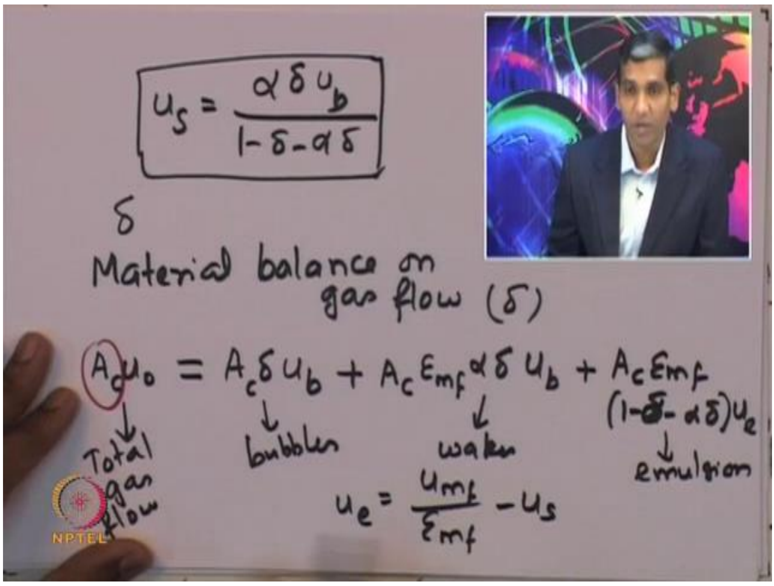

$$\boxed{u_s = \frac{\alpha\delta u_b}{1-\delta-\alpha\delta}}$$

δ

Material balance on gas flow (δ)

$$\underbrace{A_c u_0}_{\text{Total gas flow}} = \underbrace{A_c \delta u_b}_{\text{bubbles}} + \underbrace{A_c \varepsilon_{mf} \alpha \delta u_b}_{\text{wake}} + \underbrace{A_c \varepsilon_{mf} (1-\delta-\alpha\delta) u_e}_{\text{emulsion}}$$

$$u_e = \frac{u_{mf}}{\varepsilon_{mf}} - u_s$$

.

We are going to see how to estimate that. So, based on this correlation we can find out that the velocity of the solids us is actually given by alpha into delta into ub divided by 1 minus delta minus alpha into delta. So, that is the expression for the that is the expression for the velocity with which the solid flowing. So, the next step is to find out to what is this value of delta which is basically the fraction of the bed which is actually filled with the bubbles.

So, now, let us write a simple material balance on the gas flow to find out what is this value of delta which is the fraction of bubbles fraction of the bed which is actually bubbles. So, this we can write material balance on gas flow to estimate the value of delta. So, that is what we going to do next.

So, material balance on gas flow basically is just to account for what is the how the gas is being split into a different sections and what is the total material balance for the gas flow. And that is given by Ac into u not were u not is the superficial velocity. So, that is the superficial velocity with which the fluid is actually being pumped into the fluidized bed reactor. So, the total gas that enter the reactor should be equal to the cross section area of the if fluidized bed reactor multiplied by the corresponding superficial velocity.

So, that should be equal to the gas that is actually carried by the bubbles. So, that will be the cross sectional area into delta which tells you what is the area a fractional area that contains that is actually occupied by the bubbles. Multiplied by the velocity ub tells us what is the flow rate mass flow rate of the a of the gas that is actually carried by the bubbles plus some of this now going to go in the wakes. So, that can be estimated as Ac which is the cross sectional area multiplied by the porosity at the minimum fluidization velocity here pestilent mf into alpha into delta into ub. So, alpha is basically the volume of wakes per volume of the bubbles.

Then there is another component which is basically the gas that may be present in the emulsion phase. So, that is actually Ac into pestilent mf into 1 minus alpha minus alpha 1 minus delta into alpha into delta into the velocity with which the emulsion. So, this basically tells us what is the material balance for the gas flow now we know that this is the this is the total gas flow; this is the gas flow in the bubbles; and this is gas flow in wakes and this is in the emulsion phase, that is in the emulsion phase. So, that tells us what is the total amount of material balance on gas flow and we know that the velocity of the emulsion phase is given by umf divided by epsilon mf minus the velocity of the solids.

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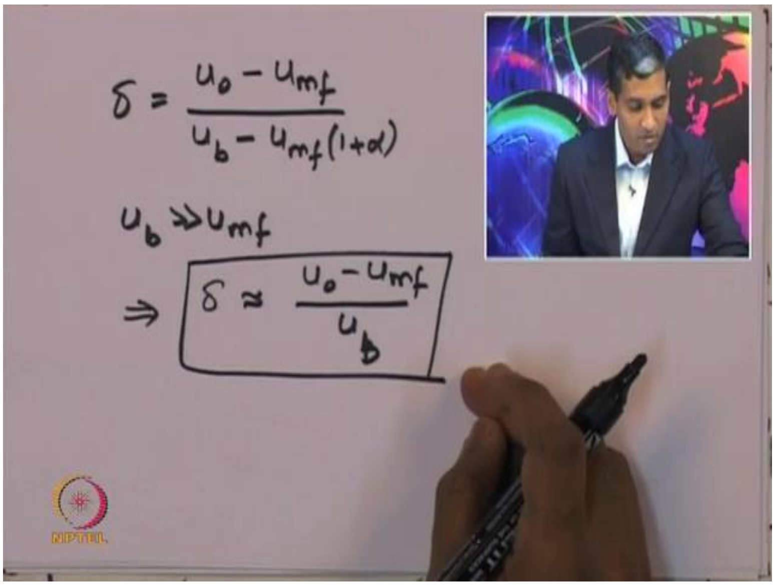

$$\delta = \frac{u_0 - u_{mf}}{u_b - u_{mf}(1+\alpha)}$$

$$u_b \gg u_{mf}$$

$$\Rightarrow \boxed{\delta \approx \frac{u_0 - u_{mf}}{u_b}}$$

So, now I plugging in these expressions we will be able to find out what is delta. So, delta is now given by u not which is the superficial velocity minus umf which is the minimum fluidization velocity divided by ub minus umf into 1 plus alpha. Now, if ub is significantly larger than umf; that is if the velocity with which the bubbles are actually raising is higher than the minimum fluidization velocity. Then we can further simplify the expression for the delta which is the fraction of the bed that is actually occupied by the bubbles; that given by u not minus umf divided by ub. So, now we have estimated what is delta.

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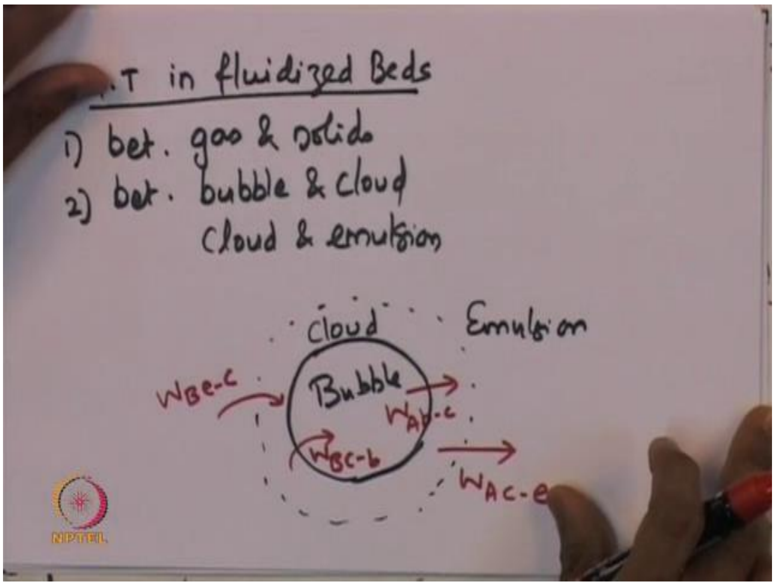

.T in fluidized Beds

1) bet. gas & solids

2) bet. bubble & cloud

cloud & emulsion

So, the next exercise is to characterize the mass transport in a fluidized bed reactor. Characterize the mass transport in fluidized bed. Now, there are 2 forms of mass transport which actually occurs in the fluidized bed reactor: one is there is mass transport between the gas and solids. So, that is very much like the gas solid transport and gas solid reactions. So, gas solid catalytic systems.

Then the second type of transport is basically between the bubble and the cloud phase, and also between the cloud and the emulsion. So, remember that when for the reaction catalytic reaction to occur the reactance which is actually ca present in the gas stream is carried by the bubbles. And this mass transport of the reactance from the bubble phase into the cloud phase and cloud phase into the emulsion phase which actually contains the particles, where the reaction occurs. And then the products are now transported back. So, therefore, the mass transport process in fluidized bed reactor is slightly different from the slightly in addition to the g a classical a mass transport in the gas or it catalytic systems.

So, let us look at what happens here. So, suppose if this is the bubble, suppose the bubble is here and then if the cloud is present around here. Now, in a represent W if A is the specie if WA B to C is essentially the transport from to the cloud region and this is the emulsion region. Then W W A C to e is basically the flux of transport or rate of transport from the cloud to the emulsion phase. And similarly, after the product is formed the WB if B is the product at this form that is the transport from the emulsion to the a cloud phase. Then WA WB C to B is a transport of the product from the cloud to the bubble phase. So this is the, an addition to the classical gas solid transport in the catalytic reactors this is an extra transport mechanism which is been observed in which is observed in the a fluidized bed reactor.

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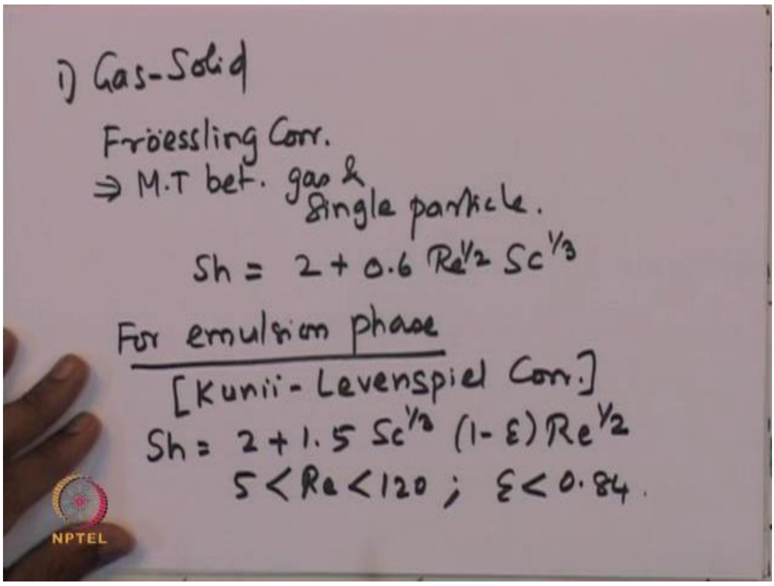

i) Gas-Solid

Froessling Corr.

⇒ M.T bet. gas & single particle.

$$Sh = 2 + 0.6\, Re^{1/2}\, Sc^{1/3}$$

For emulsion phase

[Kunii - Levenspiel Corr.]

$$Sh = 2 + 1.5\, Sc^{1/2}\, (1-\varepsilon)\, Re^{1/2}$$

$$5 < Re < 120\,;\quad \varepsilon < 0.84.$$

So, let us look at how to characterize the gas solid mass ... How to find the gas solid mass transport coefficient first and then we look at the other mode of transport. So, now, between gas and a single particle there are correlation which is called the Froessling correlation. And that is basically characterizes the mass transport between gas and single particle. And that is given by Sherwood number that is equal to 2 plus 0.6 into Reynolds number to the power of half into Schmidt number to the power of 1 by 3.

For emulsion phase for emulsion phase the Kunii and Levenspiel have developed a correlation to estimate the mass transport coefficient in the emulsion phase and that is given by Sherwood number equal to 2 plus 1.5 into Schmidt number to the power of 1 by 3 into 1 minus epsilent into Reynolds number to the power of half. And the validity of this correlation is basically between the Reynolds number of 5 and 120. And epsilon should be less than 0.8 0.84. So, is the porosity is less than 0.84. Then this correlation works in the emulsion phase.

So, there are different mass transport coefficients and 1 need to actually combine all of this mass transport coefficient in order to estimate what is the overall mass transport coefficient. Because, mass transport occurs through both these cases both these mechanisms.

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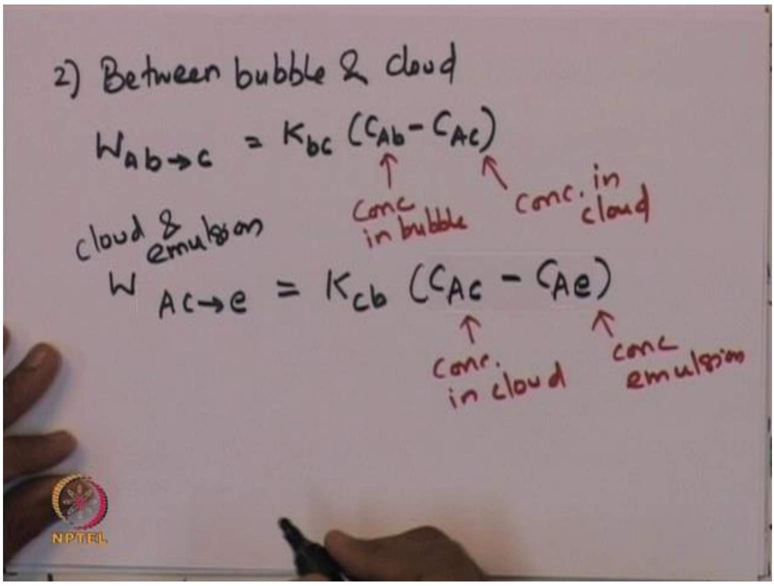
2) Between bubble & cloud

$$W_{Ab\to c} = K_{bc}(\underset{\substack{\uparrow\\ \text{Conc in bubble}}}{C_{Ab}} - \underset{\substack{\uparrow\\ \text{conc. in cloud}}}{C_{Ac}})$$

cloud & emulsion

$$W_{Ac\to e} = K_{cb}(\underset{\substack{\uparrow\\ \text{conc. in cloud}}}{C_{Ac}} - \underset{\substack{\uparrow\\ \text{conc emulsion}}}{C_{Ae}})$$

Then let us look at the mass transport between bubble and cloud. So, suppose if the; so say let us first look at the transport of the reacted from the bubble to the cloud. So, the suppose if a is the reactant. So, the flux at which the sepsis a is being transported from the bubble to the cloud they a flux at which the transported is actually given by the mass transport coefficient Kbc multiplied by CAb minus CAc. Where CAb is basically, the concentration, so that is the concentration of the species on the bubble phase. And this is the concentration in the cloud phase. So, this expression provides the flux at which this species is being transported from the bubble phase to the cloud phase.

Similarly, the transport from the cloud phase to the emulsion phase the expression can be written as Kcb. Where Kcb is the corresponding mass transport coefficient and the previous there Kcb is the corresponding mas transport coefficient multiplied by CAc minus CAb were Cac is the concentration of species A. So, CAc in the in the cloud phase and this is the concentration of the species in the emulsion phase. So, this is for this is for the mass transport between the cloud phase and the emulsion phase.

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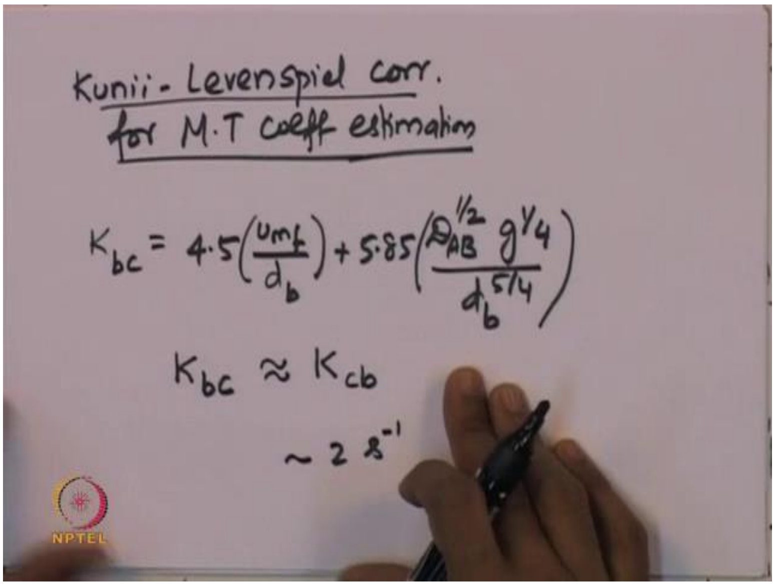

Kunii-Levenspiel corr.
for M.T coeff estimation

$$K_{bc} = 4.5\left(\frac{u_{mf}}{d_b}\right) + 5.85\left(\frac{D_{AB}^{1/2}\, g^{1/4}}{d_b^{5/4}}\right)$$

$$K_{bc} \approx K_{cb}$$

$$\sim 2\ s^{-1}$$

So, similarly 1 can actually write a similar transport for the a product species which is being transported back from the emulsion phase back into the cloud phase and back into the bubble phase. So, Kunii Leven Speal once again they have developed by correlation in order to find out what these mass transport coefficients are. So, they have developed a correlation for estimating these mass transport coefficients.

So, that is given by Kbc which is the mass transport coefficient for reactance species go from or species the go from the bubble phase into the cloud phase. And that is given by 4.5 multiplied by the minimum fluidization velocity umf divided by the diameter of the bubble plus 5.85 into the diffusivity DAB to the power of 1 by 2 into gravity to the power of i by 4 divided by the diameter of the bubble to the power of 5 by 4. So, that is the correlation which provides an estimate of what is the mass transport coefficient between the bubble phase and the cloud phase.

Now, because the mass transport actually occurs by the exchange of volume between the cloud phase and the bubble phase, 1 could assume that the a mass transport between the mass transport coefficient for transport from the bubble to the cloud phase should be approximately equal to the mass transport coefficient from the cloud phase back into the bubble phase. And will typically the order of magnitude of this mass transport coefficient is of order of 2, second minus 1 that Kcb is a mass transport coefficient.

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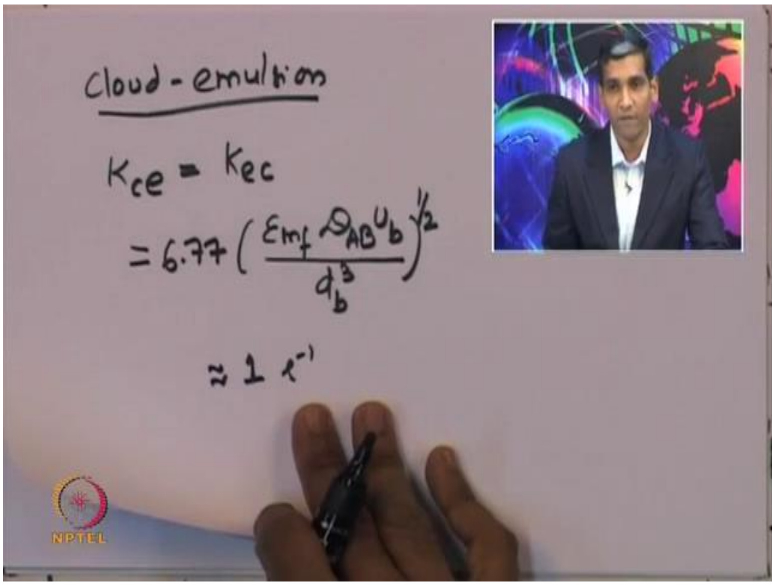

Cloud - emulsion

$$K_{ce} = K_{ec}$$

$$= 6.77\left(\frac{\varepsilon_{mf}\,\mathcal{D}_{AB}\,u_b}{d_b^3}\right)^{1/2}$$

$$\approx 1\ s^{-1}$$

So, now let us look at the a correlations for cloud to emulation, mass transport from cloud to emulation. And that is typically given by Kce equal to Kec: address the Kce is the mass transport coefficient for transport from the cloud phase to the emulsion phase and Kec is the transport of products, let say from the emulsion phase back to the cloud phase. So, that is given by the correlation 6.77 into epsilon mf which is the porosity at the minimum fluidization velocity multiplied diffusivity DAB into the velocity of the raising bubble divided by the diameter of the bubble to the power of 3 cube of that to the power of 1 by 2 square root of the whole expression. And this is typically of the order of 1 second minus 1.

So, that is the order of magnitude of the mass transport coefficient. So, let us next look at the reaction in the fix fluidized bed reactor. Remember there are 3 factors which are controlling. 1 is the mass transport of the a reactance species from the bubble phase into the cloud and into the emulsion in order for it to get in contact with the catalytic particles. And then the next chapter the reaction which is actually accruing inside the catalytic sides to form the product catalytic reaction a which is happening inside the catalytic side to form the products. And once the products are form they are transported back into the bubble phase.

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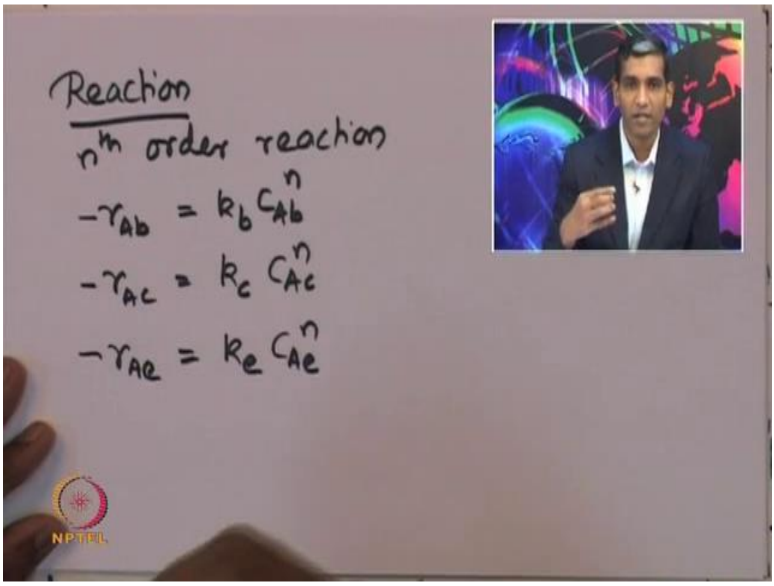

Reaction

n^{th} order reaction

$$-r_{Ab} = k_b C_{Ab}^n$$

$$-r_{Ac} = k_c C_{Ac}^n$$

$$-r_{Ae} = k_e C_{Ae}^n$$

.

So, let us look at the reaction in the fluidized bed reactor; let us look at the reaction. So, suppose if it is an n-th order reaction, then the reaction rate in the bubble phase can actually be given is kb into CAb to the power of n. So, that is the bubble phase and similarly for the cloud phase it can be given as kc into CAc to the power of n or kb and kc are the corresponding rate constants. And then for the emulsion phase is can be written as ke into CAe to the power of n. Where, the CAb is the concentration of the species in the bubble phase and CAc is the concentration of species in the cloud space and CAe is the concentration of species phase.

Now, it is important to write these rate rate expressions in all 3 phases although the emulsion phase actually contains the maximum number of particles. The bubble phase and the cloud phase also will have some particles, and therefore important to write these expressions, because the reaction can in principle occur in the catalyst particles in the each of these phases. So, now next we can write a mole balance we know the reaction rate we can now write a mole balance in the fluidized bed reactor in order to capture, the behavior of the a concentration of the a reactance species should the reaction.

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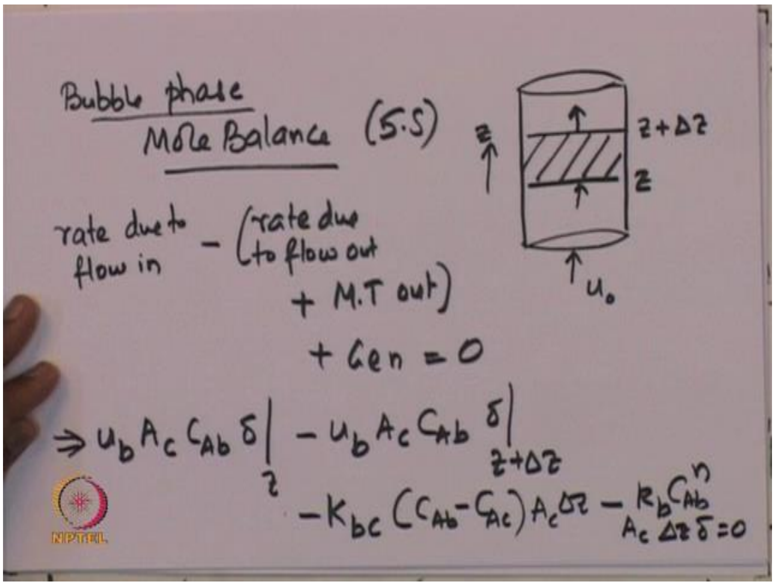

Bubble phase

Mole Balance (S.S)

rate due to flow in − (rate due to flow out + M.T out) + Gen = 0

$$\Rightarrow u_b A_c C_{Ab} \delta \Big|_{z} - u_b A_c C_{Ab} \delta \Big|_{z+\Delta z} - K_{bc}(C_{Ab} - C_{Ac}) A_c \Delta z - k_b C_{Ab}^{n} A_c \Delta z \delta = 0$$

So, now let us consider a small element let us consider a fluidized bed reactor. And if let say that the fluid is entering at a superficial velocity of u not and then there is a small element between z and z plus delta z. And if you assume that the upward motion of the direction of the fluid flow is the positive direction. Then we can now write a mole balance for the bubble phase which is basically rate due to flow into the bubble phase minus the rate minus with which the fluid stream these because of flow plus the rate at which the fluid species is actually leave in the bubble phase because of mass transport plus whatever is being generated. That should equal to 0 and are a steady state condition.

So, if you assume in a steady state condition and this is the mole balance. So, now when we plug in all the corresponding expressions rate due to flow that is into the bubble phase is given by the velocity of the bubble ub multiplied by the corresponding cross section Ac into concentration of species in the bubble phase multiplied by delta.

So, delta is basically the fraction of the bed that is actually a in the bubble phase and that at that particular location z, that is the rate at which the a species is entering the small element in the bubble phase. And then the rate at which the species is leaving in the bubble phase at z plus delta z is given by ub Ac CAb into delta z plus delta z. And mass transport is given by minus Kbc into Cab that is the concentration of the species in the bubble phase minus the concentration of species in the cloud phase multiplied by cross section area into delta z.

So, that is the rate at which the species is actually leaving the bubble phase and going into the cloud phase minus the corresponding reaction rate. So, that is k kb if that kb is the reaction rate constant into CAb to the power of n. So, that is the CAb is the concentration of species in the bubble phase multiplied by the cross section into delta z into delta. So, that should be equal to 0. So, that is the mole balance for the species in the bubble phase.

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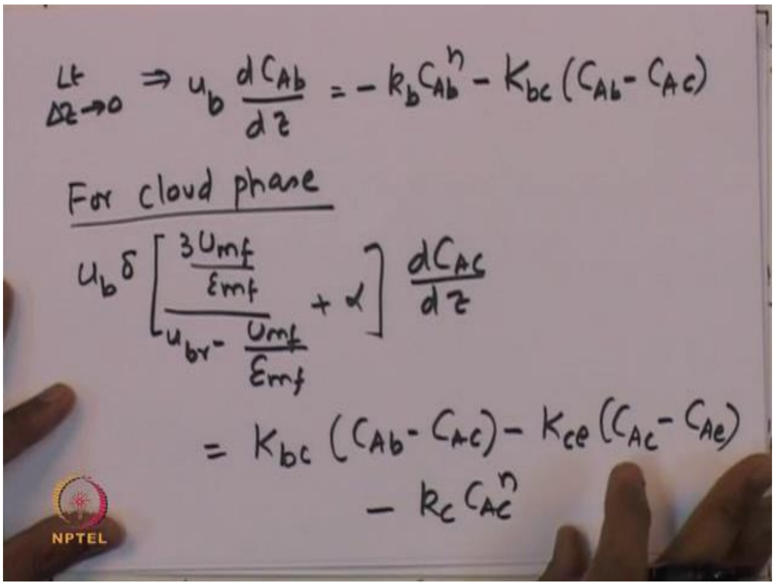

$$\underset{\Delta z \to 0}{Lt} \Rightarrow u_b \frac{dC_{Ab}}{dz} = -k_b C_{Ab}^n - K_{bc}(C_{Ab} - C_{Ac})$$

For cloud phase

$$u_b \delta \left[\frac{\frac{3U_{mf}}{\varepsilon_{mf}}}{u_{br} - \frac{U_{mf}}{\varepsilon_{mf}}} + \alpha \right] \frac{dC_{Ac}}{dz} = K_{bc}(C_{Ab} - C_{Ac}) - K_{ce}(C_{Ac} - C_{Ae}) - k_c C_{Ac}^n$$

So, now we can rewrite this mole balance as by taking a limit that by taking limit that delta z goes to 0. We can rewrite this model as ub which is the velocity with which the bubble is raising inside the a fluidized bed reactor into d CAB by d z that should be equal to minus kb CAb to the power of n minus kbc which is the mass transport coefficient between the bubble and the cloud phase multiplied by CAb minus CAc. So, that is the model the mole balance of the bubble phase.

So, similarly for the cloud phase the mole balance is given by ub into delta into 3 times umf; a very similar balance can be written and taking the limits of delta z going to 0. 1 would get that the expression for a mole balance for the concentration of the species in the cloud phase is basically given by this expression here into d CAc by dz. That should be equal to the mass transport coefficient of the species from the bubble to the cloud phase.

That is basically added into the cloud phase multiplied by CAb minus CAc minus kce, that is the mass transport coefficient for transport of the species from the cloud phase into the emulsion phase. That is given by CA c minus CAe minus kc which is the rate at which is the rate constant for the reaction if the catalytic reaction is happening in the catalyst particles which may be present in the cloud phase. So, that is the a mole balance for the cloud phase.

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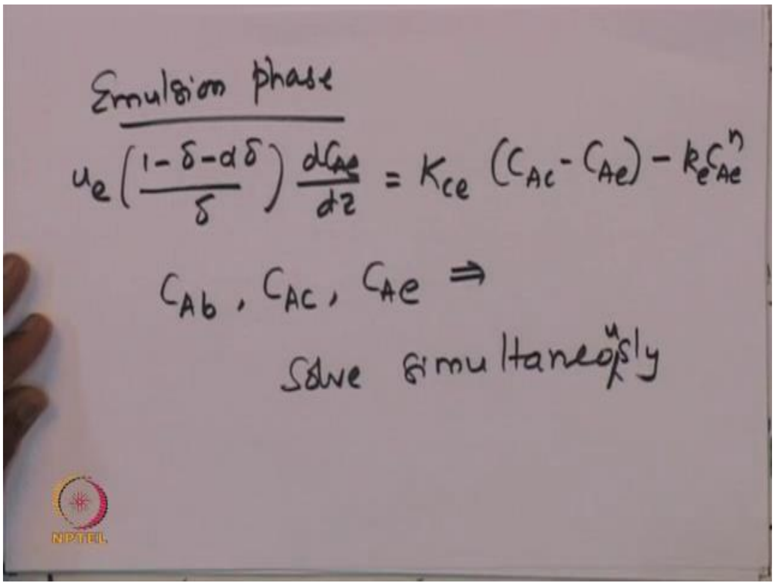

Emulsion phase

$$u_e\left(\frac{1-\delta-\alpha\delta}{\delta}\right)\frac{dC_{Ae}}{dz} = K_{ce}\left(C_{Ac}-C_{Ae}\right) - k_e C_{Ae}^{n}$$

C_{Ab}, C_{Ac}, C_{Ae} ⇒

Solve simultaneously

.

Then the mole balance for the emulsion phase is given by for the emulsion phase, that is that is given by ue which is the velocity with which the emulsion phase is into 1 minus delta minus alpha into delta divided by delta in d CAe by dz. That should be equal to the mass transport coefficient between the cloud and the emulsion phase into CAc minus CAe minus the rate at which the species is actually being consumed, because of the reaction that may be happen in the emulsion phase.

So, if we need to find out what is the concentration of the species in the bubble phase, in the cloud phase and the emulsion phase then these 3 equations have to be solved simultaneously. So, these things have to be solved simultaneously. So, once we solve them simultaneously then we can find out the expression for a Cab, CAc and Cae. What is its relationship how the profile changes with respect to the position inside the fluidized bed reactor? As this is a non linier equation it cannot be solved analytically and 1 has to resort to numerical techniques to solve these set of equations.

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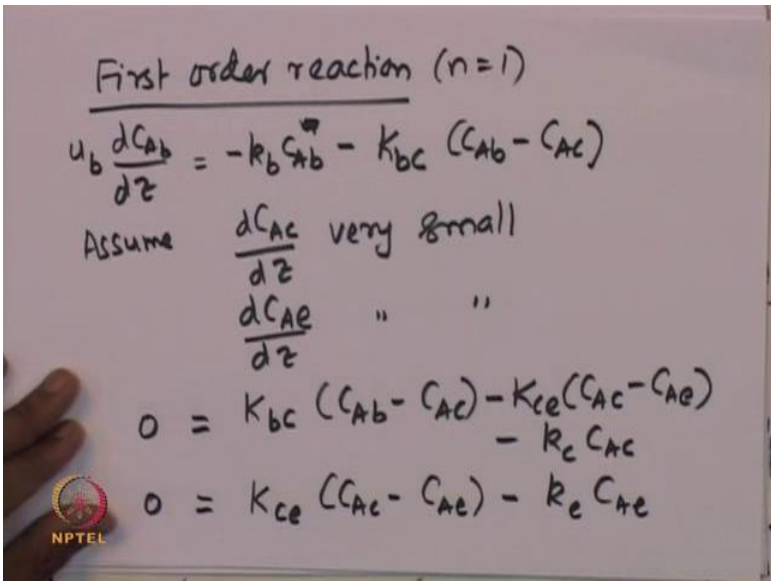

First order reaction (n=1)

$$u_b \frac{dC_{Ab}}{dz} = -k_b C_{Ab} - K_{bc}(C_{Ab} - C_{Ac})$$

Assume $\frac{dC_{Ac}}{dz}$ very small

$\frac{dC_{Ae}}{dz}$ " "

$$0 = K_{bc}(C_{Ab} - C_{Ac}) - K_{ce}(C_{Ac} - C_{Ae}) - k_c C_{Ac}$$

$$0 = K_{ce}(C_{Ac} - C_{Ae}) - k_e C_{Ae}$$

However, if we make an assumption that the reaction is a first order reaction. Suppose, if we assume that it is a first order reaction; suppose if the reaction which is happening is a first order reaction. Then we can actually write the expression as ub into d CAb by dz that is equal to minus kb into CAb to the power n minus the mass transport coefficient Kbc into n equal to 1, CAb minus Cac. And the other ec suppose if we assume that that d CAc by dz which is the rate of change of the concentration with respect to position the cloud phase is this is very small.

Similarly, if you assume that d CAe by dz is also very small. Then we can write the model equations or the these 2 concentrations as they basically become like this, were the master 0 equal to the mass transport coefficient Kbc multiplied by CAb minus CAc minus Kce into CAc minus CAe minus kc into Cac. And similarly, for the emulsion phase the mole balance will become Kce into CAc minus Cae, so minus ke into CAe. So, that is the mole balance for the for the emulsion phase.

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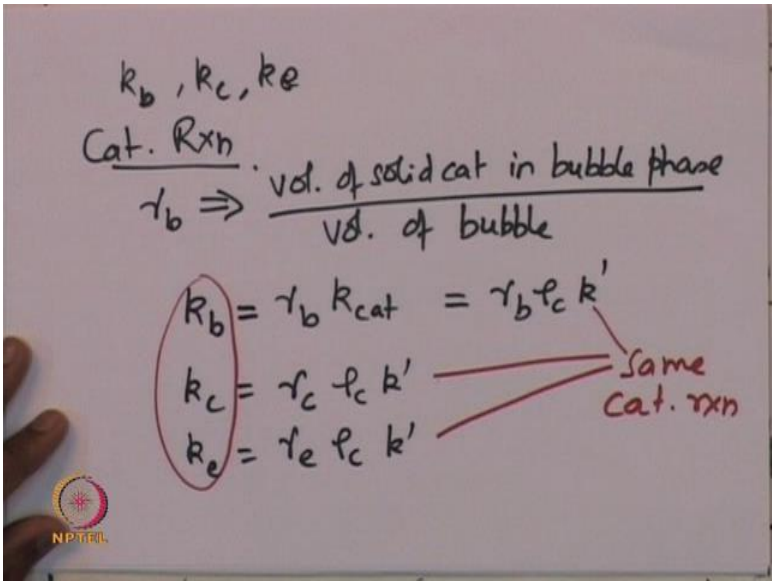

k_b, k_c, k_e

Cat. Rxn

$$\gamma_b \Rightarrow \frac{\text{vol. of solid cat in bubble phase}}{\text{vol. of bubble}}$$

$$k_b = \gamma_b k_{cat} = \gamma_b \rho_c k'$$

$$k_c = \gamma_c \rho_c k'$$

$$k_e = \gamma_e \rho_c k'$$

same Cat. rxn

Now, because it is a catalytic reaction, so we kb which is the corresponding rate constant suppose kb, kc and ke is are the corresponding a rate constance; for the reaction which is actually occurring in the a bubble phase, cloud phase and the emulsion phase respect of the and emulsion phase respect of the. So, now, suppose if it is a catalytic reaction and if gamma b is basically the ratio of volume of solid catalyst, in the bubble phase divided by the volume of the bubble.

So, this provides an estimate of what fraction of the bubble volume is actually contained by the solid particles which are actually carried by the bubble phase. So, if we know this expression then we can actually rewrite the rate constant in terms of the intrinsic rates. So, that will be equal to kb is given by gamma b which is the fraction of the volume with inside the bubble which is basic which is occupied by the solid particles carried by the bubble into the corresponding a reaction rate which is accruing in the catalyst surface of the particles.

So, now that can actually be rewritten as gamma b into row c into k prime, that k prime is the grand mole that is the reactor per unit weight of the catalyst per unit time and row c is the corresponding density of the catalyst. So, similarly we can actually write we can write k c is basically equal to gamma c which is the volume of solid catalyst which is in fraction of volume of the cloud phase which is occupied by the solid catalyst that multiplied by row c into k prime. So, the and similarly k e equal to gamma e into row c into k prime.

So, notice that the k prime is basically same because it is the same catalytic reaction which is happening in the solid particles which are present in these 3 phases. The overall reaction rate is different in these 3 phases because the amount of catalyst particles which is present in each of the phases are different and therefore, that is actually accounted for in the overall reaction rate constant.

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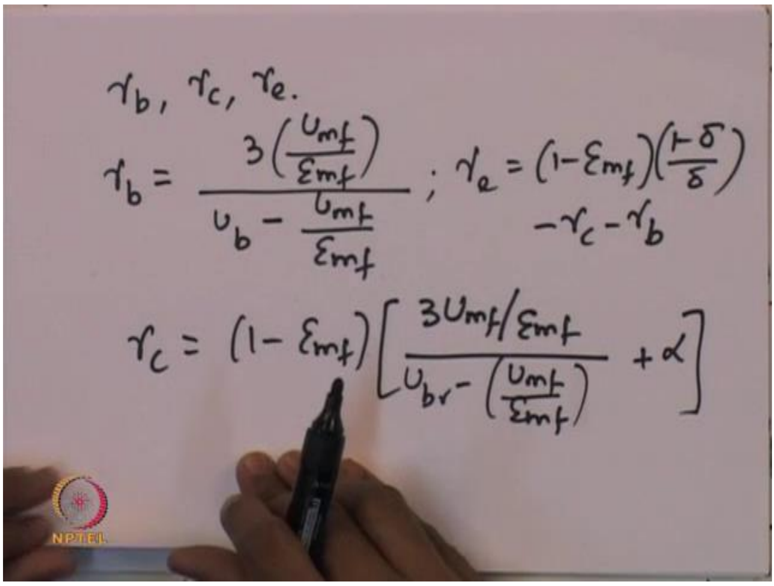

$\gamma_b, \gamma_c, \gamma_e.$

$$\gamma_b = \frac{3\left(\frac{U_{mf}}{\varepsilon_{mf}}\right)}{U_b - \frac{U_{mf}}{\varepsilon_{mf}}} \; ; \; \gamma_e = (1-\varepsilon_{mf})\left(\frac{1-\delta}{\delta}\right) - \gamma_c - \gamma_b$$

$$\gamma_c = (1-\varepsilon_{mf})\left[\frac{3U_{mf}/\varepsilon_{mf}}{U_{br} - \left(\frac{U_{mf}}{\varepsilon_{mf}}\right)} + \alpha\right]$$

So, now we need to estimate what is this a a gamma b gamma C. And gamma e are. So, if we know that estimate then the mo mole balance can actually be solved. So, we need to find out what is gamma b gamma C. And gamma e. So, once we know this we can actually a solve the model equation and. So, gamma b is essentially given by 3 into umf by epsilent mf divided by ub minus umf by epsilon mf. And similarly, gamma e is given by 1 minus epsilent mf into 1 minus delta by delta minus gamma c minus gamma b.

So, that is gamma e is the fractional volume in the emulsion phase which is occupied by the solid catalyst. And gamma b is the corresponding fractional volume in the bubble phase and gamma c is the fractional volume in the cloud phase occupied by the solid particles which is be 1 minus epsilon mf into mf by epsilon mf divided by ubr minus umf by epsilon mf plus alpha.

So, these things can be estimated simply by estimating in terms of the properties such as the porosity and the minimum fluidization velocity extra. What is the volume of the bubble and what is the fraction of the bubble which contains the solid particles; what is that volume. So, once we estimate these volume and take the ratio we can find out these expressions for the volume fractions in the in the each of these respective a phases that is contained by the solid particles.

So, now, if we know all these expressions then we can now solve for the solve the model equations in order to find out the design parameters of the fluidized bed reactor. So, the complete mole balance for the first order reaction is basically the set of mole balance equations are. Suppose, if we assume that the time is equal to z by ub. So, remember that the time that it spend by the a bubble inside the bed is actually an important parameter, that controls the performance of the fluidized bed reactor.

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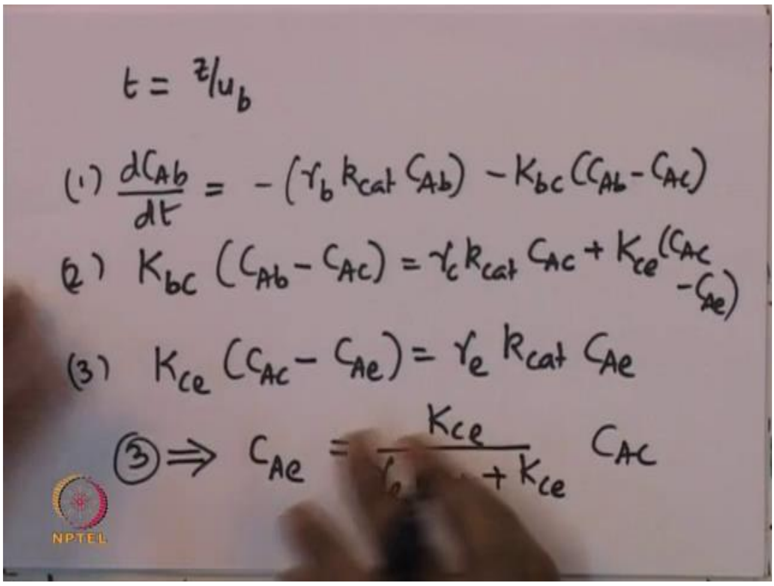

$t = z/u_b$

(1) $\frac{dC_{Ab}}{dt} = -(\gamma_b k_{cat} C_{Ab}) - K_{bc}(C_{Ab} - C_{Ac})$

(2) $K_{bc}(C_{Ab} - C_{Ac}) = \gamma_c k_{cat} C_{Ac} + K_{ce}(C_{Ac} - C_{Ae})$

(3) $K_{ce}(C_{Ac} - C_{Ae}) = \gamma_e k_{cat} C_{Ae}$

③ $\Rightarrow C_{Ae} = \frac{K_{ce}}{\gamma_e \text{[illegible]} + K_{ce}} C_{Ac}$

.

So, t here refers to the time that is actually spend by the bubble inside the fluidize bed reactor till this position z. So,ub were ub is basically the velocity with which the bubbles are actually the raising inside the fluidized bed reactor. So, the mole balance will be dCAb by dt, that is equal to minus gamma b into the rate const into the a specific rate constant for the catalytic reaction multiplied by CAb minus Kbc into CAb minus CAc.

The second equation is Kbc which is the mass transport coefficient between the bubble and the cloud phase that multiplied by CAb minus Cac. That should be equal to gamma c into rerate constant for the catalytic reaction into CAc plus the mass transport coefficient Kce into CAc minus Cae. And then the third equation would be kce into CAc minus CAe that should be equal to gamma e into the rate constant for the catalytic reaction into CAe. So, now if I look at the third equation from third equation I can actually rearrange the third equation and find an expression for Cae. And that CAe is equal to Kce divided by gamma e into k catalyst which is the reaction rate constant for the catalytic reaction plus Kce into Cac.

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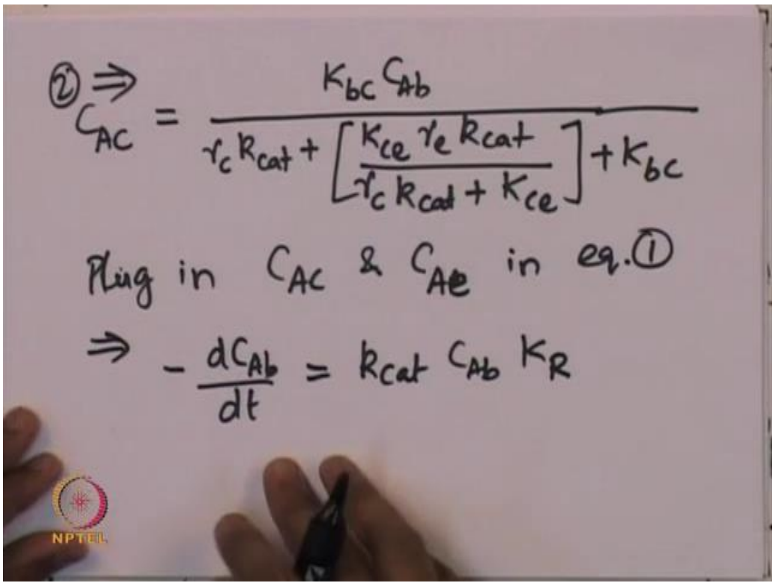

② ⇒ $$C_{AC} = \frac{K_{bc} C_{Ab}}{\gamma_c k_{cat} + \left[\frac{K_{ce} \gamma_e k_{cat}}{\gamma_c k_{cat} + K_{ce}}\right] + K_{bc}}$$

Plug in C_{AC} & C_{Ae} in eq. ①

$$\Rightarrow -\frac{dC_{Ab}}{dt} = k_{cat} C_{Ab} K_R$$

.

So, further rearrangement of the expressions can actually be performed in order to estimate, what is the concentration of these species in the cloud and that is from second equation we can find out. So, substituting the expression for the a concentration of the species in the emulsion phase into the expression for the concentration mole bal into the mole balance expression for the concentration of the species in a cloud phase. We can find out the expression for the concentration of the species in the cloud phase. And that is given by Kbc into CAb divided by gamma c into k catalyst plus Kce into gamma e k catalyst divided by gamma c into k catalyst plus Kce plus Kbc. So, that is the corresponding mass transport coefficient.

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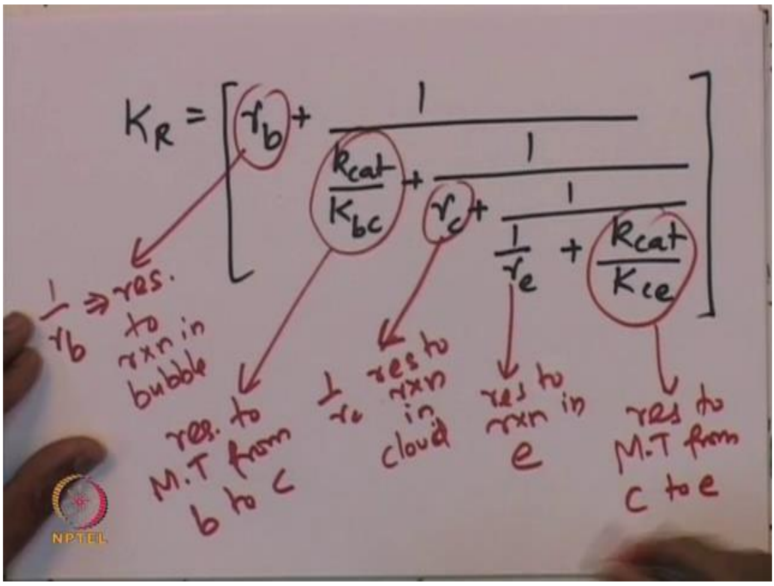

.

Now, plugging in all these expressions into the into equation 1. So, plug in expression for Cac and CAe in equation 1 will get. So, what we can find is that minus d CAb by dt that equal to k cat into CAb into some overall constant KR. And this KR is essentially given by the overall constant KR is given by gamma b plus 1 divided by k catalyst by Kbc plus 1 divided by gamma c plus 1 divided by 1 by gamma e plus k catalyst divided by Kce.

So, that is the expression for the overall reaction rate and if I look at this expression gamma b gamma b is basically captures the 1 by gamma b is the resistance for resistance to reaction in the bubble. And k cat by Kbc is the resistance to mass transport from bubble to cloud and gamma c is resistance to 1 by gamma c is resistance to reaction in the cloud phase. And this is the resistance to reaction in the emulsion phase and this is the resistance to mass transport from the cloud to the emulsion phase. So, this over all constant essentially captures the resistance is that is the all the resistance is that are actually present in this system.

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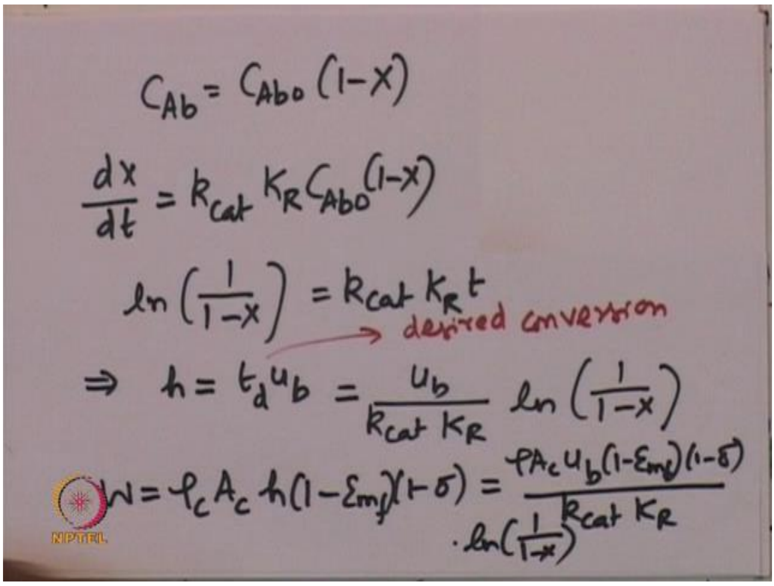.

$$C_{Ab} = C_{Ab0}(1-x)$$

$$\frac{dx}{dt} = k_{cat} K_R C_{Ab0}(1-x)$$

$$\ln\left(\frac{1}{1-x}\right) = k_{cat} K_R t$$

desired conversion

$$\Rightarrow h = t_d u_b = \frac{u_b}{k_{cat} K_R} \ln\left(\frac{1}{1-x}\right)$$

$$W = \rho_c A_c h(1-\varepsilon_{mf})(1-\delta) = \frac{\rho A_c u_b(1-\varepsilon_{mf})(1-\delta)}{k_{cat} K_R} \cdot \ln\left(\frac{1}{1-x}\right)$$

So, now, using the appropriate a stoichimetry we can say that CAb is equal to CAb 0 into 1 minus x. Where CAb 0 is the concentration of the species are the of the fluidized bed reactor. So, we can now rewrite the mole balance as dx by dt k cat KR that the overall rate constant which captures all the resistance is which are involved into 1 minus x.

So, now we can solve this equation and you can find that lon of 1 by 1 minus x that is equal to k cat into KR into t. So, this provides a relationship between the conversion as a function of the time that is actually spend by the raising bubble inside the fluidized bed reactors. So, from this we can find out what is the over height that is required.

So, that is equal to t into ub, that is the height that is required for suppose if a specific conversion is said what should be the conversion; supposing, if for a desired conversion if t td is the time that is required from this expression for the desire conversion. So, this corresponds to the desired conversion if this corresponds to the time for the desired conversion. Then the height of the bed can actually be estimated by using this expression td into ub and that is equal to ub divided by k cat into KR into l o n of 1 by 1 minus x.

Then from here we can find out what is the weight of the catalyst that given by row c Ac into a h into 1 minus epsilon mf into 1 minus delta. So, that is given by row ac ub into 1 minus epsilon mf into 1 minus delta divided by k cat into KR into l o n of 1 by 1 minus x. So, that is the expression for the weight of the catalyst.

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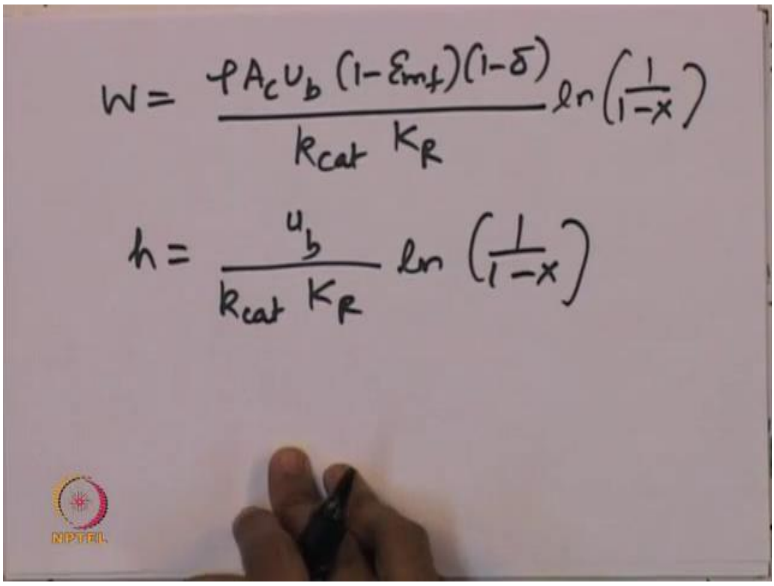

$$W = \frac{\rho A_c u_b (1-\varepsilon_{mf})(1-\delta)}{k_{cat} K_R} \ln\left(\frac{1}{1-x}\right)$$

$$h = \frac{u_b}{k_{cat} K_R} \ln\left(\frac{1}{1-x}\right)$$

So, let us quickly just rewrite the weight t expression for the weight of the catalyst. So, that is given by row Ac ub into 1 epsilon mf into 1 minus delta divided by k cat into KR which is captures the which is basically the reflects the overall resistance into lon of 1 by 1 minus x. And the height which is required for the bed which is in important design parameter is basically u b divided k cat into k r into lon of 1 by 1 minus x.

So, let us summaries what we have learnt in this lecture. So, a what we have seen is we have actually designed a fluidized bed reactor we started by looking at various parameters estimating the various parameters which is required to find to design a fluidized bed reactor. For example, what is the a how to estimate the velocity of the raising bubble how to estimate what is the fraction of the bed that is actually occupied by the bubbles etcetera.

Then we found out what is the, a rate law that that corresponds to the catalytic reaction that is happening in the particles which may be present in the bubble or cloud or the emulsion phase in any of these 3 phases. And then we looked at the a mole balance for the species in each of these phases with which incorporated the transport or species the bubble phase to the cloud phase and cloud phase to the emulsion. And using this mole balance, we actually assume that it is a first order reaction and found out what are the important design parameters, which as the height of the fluidize bed and weight of the catalyst which is required for a given to be achieve use in a fluidized bed reactor.

Thank you.