Chemical Reaction Engineering - II
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Lecture - 41
Fluidized Bed Reactor Design III

Friends it is a good time to summarize what you have learned in the last lecture. We initiated discussion on the fluidized bed reactor and the objective is to design a fluidized bed reactor. What is a fluidized bed reactor? Fluidized bed reactor is essentially a tube which has a certain catalyst particles and then the gases flown through this tube.

And as the velocity of the gas stream increases then the drag force that this fluid stream exerts on the gas particle on the solid catalyst particle that is equal to the weight that is actually gravitational force exerted by these 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 the fluidization occurs then these gas bubbles are formed and when these gas bubbles are formed there is transport of the reactants from the gas bubble to the catalyst particle where the reaction occurs in the catalytic sites of the catalyst particle which is already fluidized and then the product which is formed in the sites is actually transported back into the bubbles which is the gas stream.

And then the bubbles carry this product and leave the reactor. So this is the process that occurs in a fluidized bed reactor and then we looked at different regimes, different fluidization regimes in the fluidized bed reactor.

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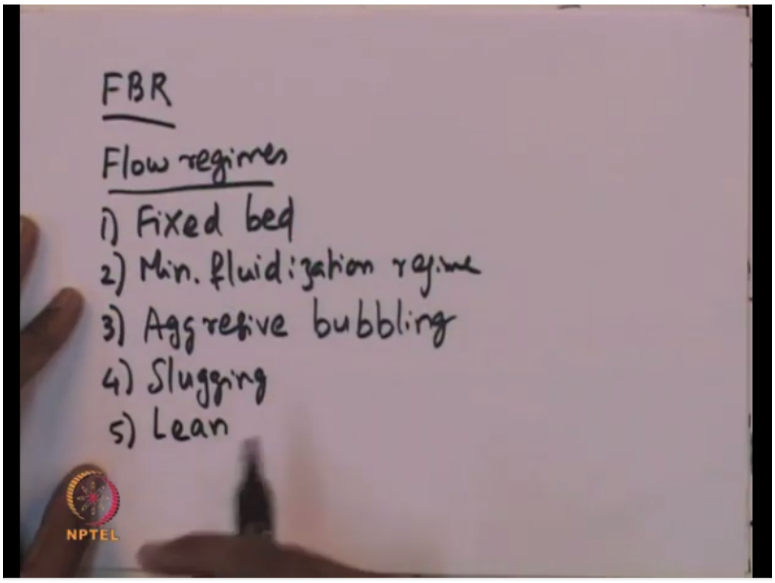

FBR

Flow regimes

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

So if FPR stands for the fluidized bed reactor, we looked at different flow regimes. One is the fixed bed regime. In a fixed bed regime, the fluid velocity is not significantly enough to offset the gravitational force which is exerted by the catalyst particle and as a result the particles they remain packed at the bottom of the reactor where they are sitting on a perforated or a porous plate.

Then, the second regime is called the minimum fluidization regime. Now in this regime, the velocity of the fluid is just sufficient to offset the gravitational force that is the drag force that the 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 U0. Then, the drag force offsets or it is just equal to the gravitational force exerted by the catalyst particles.

Then the particle starts raising or they get fluidized and that velocity minimum velocity is called the fluidization velocity and the regime is called the minimum fluidization regime. Typically, the bubbles which are present near the minimum fluidization regime, they are bubbles are formed near the perforated plate. And then the bubble starts traveling through this bed which is being fluidized and the third and regime is called the aggressive bubbling regime.

So when the velocity with which the gas stream is being flown inside, the bubbling significantly increases and so there is aggressive bubbling, lots of bubbles are formed which causes tremendous amount of recirculation of the fluid and also the catalyst particles. And so that regime is called the aggressive bubbling regime and then the fourth one is called the slugging regime where the velocity is significantly higher that there are channels of these.

Channels are actually created and through these streams the gas stream simply escapes the bed and that is what is called the slugging regime and the last one is the lean phase where all the particles are suspended and the density of the porosity is significantly higher. And they are all suspended all through the reactor. So that is what is called the lean phase regime. So these are the 5 different regimes that we described in the last lecture.

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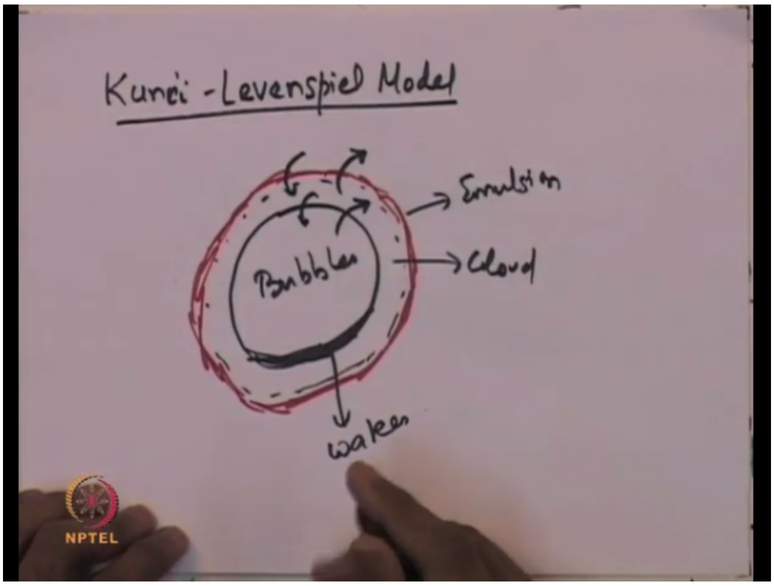

And we initiated the discussion on Kunii-Levenspiel model. So the Kunii-Levenspiel model assumes that all particles are of same size and it also assumes that the solid flow in the emulsion phase as though like it is a plug flow and then the emulsion phase exists at a minimum emulsion phase always exist at the minimum fluidization velocity.

And then it also assumes that the gas void fraction is equal to the void fraction as that of at the minimum fluidization velocity and then it assumes that the solid which is flowing downwards is actually the concentration of the solids which is present in the emulsion phase is equal to the concentration of the solids which is present in the wakes which are actually formed just below the bubble.

Just to recap the bubbles are formed as soon as this 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 bubbles where a lot of particles of high concentration is actually carried along with the bubble. Around the bubbles, there is a phase called the cloud phase and in this cloud there are some particles are present in this cloud.

And 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 mass transport process which occurs is the reactant species are transported from the bubble to the cloud phase, so 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 and 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 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 one needs to actually find out before we can model the fluidized bed reactor.

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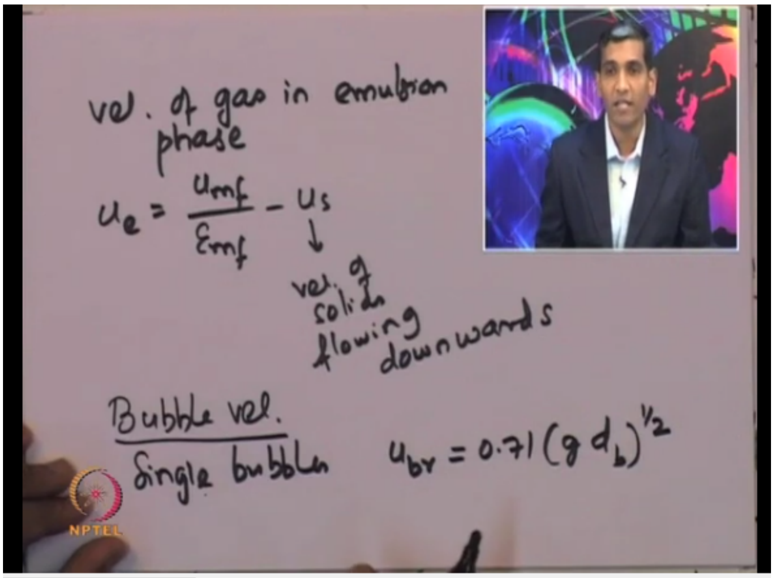

vel. of gas in emulsion phase

$$u_e = \frac{u_{mf}}{\varepsilon_{mf}} - \underset{\substack{\downarrow \\ \text{vel. of solids flowing downwards}}}{u_s}$$

Bubble vel.

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

So the velocity of gas in emulsion phase is given by Ue=Umf which is the velocity of the minimum fluidization/the porosity at minimum fluidization-Us where Us is the velocity of solids flowing downwards. Now in the bubble velocity, so remember that the one of the important aspects that controls the conversion or the performance of the fluidized bed reactor is the time that is spent by the bubble in the fluid as bed reactor.

Because the reactants are carried inside the bubble and the reactants have to get in contact with the solids in order for the catalytic reaction to occur. So therefore the amount of time that is spent by the bubble inside the reactor significantly contributes to the performance of the fluidized bed reactor. So the time that is spent by the bubble inside the reactor is 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 single bubbles which is given by Ubr and that is equal to 0.71*gravity*diameter of the bubble to the power of 1/2. So one need 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 fluidized bed reactor. Then, the velocity with which a single bubble is going to raise together with many bubbles is going to be very different because of the presence of other bubbles.

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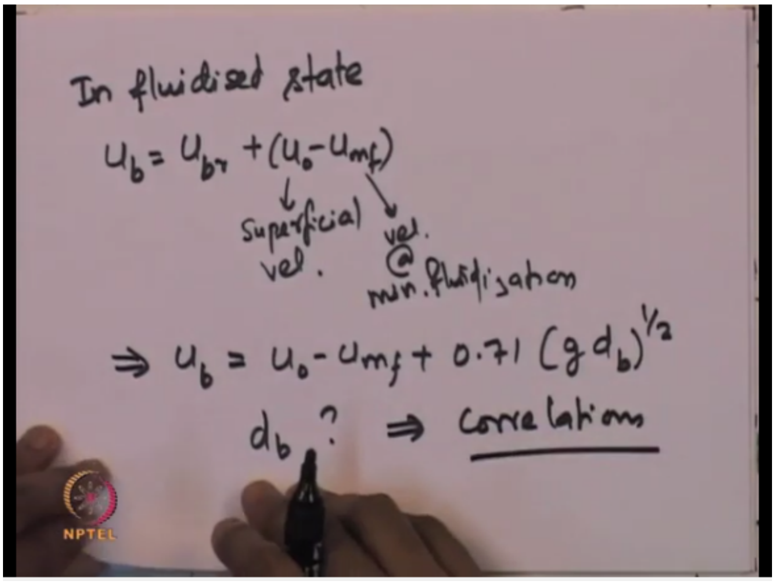

In fluidised state

$$u_b = u_{br} + (\underset{\text{superficial vel.}}{u_0} - \underset{\text{vel. @ min. fluidisation}}{u_{mf}})$$

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

d_b ? $\Rightarrow$ Correlations

So therefore in a fluidized state, the bubble velocity is given by the bubble velocity or there has to be some correction that is associated with the bubble velocity if there were to be just a single bubble. So therefore the correction is basically given by U0-Umf that is the correction to the single bubble velocity and that tells us what is the velocity of the bubble in the fluidized state where U0 is the superficial velocity.

Superficial velocity with which the gas stream is being flown into the fluidized bed reactor and Umf is the corresponding velocity at minimum fluidization point, at the minimum fluidization and so therefore plugging in the correlation for the velocity of a single bubble if we can find that the velocity of the bubble in a fluidized bed reactor in the fluid state is given by U0-Umf+0.71*gravity*diameter of the bubble to the power of 1/2.

So now we need to find out what is the diameter of the bubble in terms of the other properties of the reactor. So there are correlations which are actually available. So one needs to use correlations in order to estimate the diameter of the bubble, so let us look at what these correlations are.

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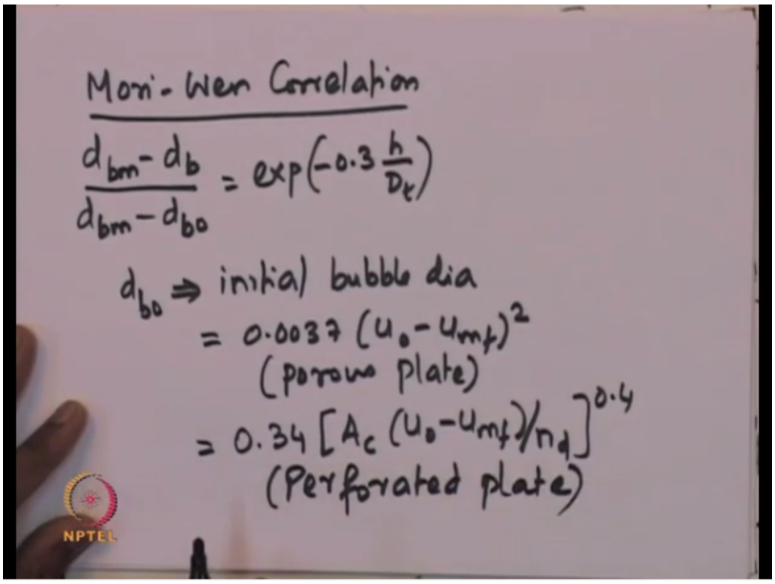

Mori-Wen Correlation

$$\frac{d_{bm}-d_b}{d_{bm}-d_{b0}} = \exp\left(-0.3\frac{h}{D_t}\right)$$

d_{b0} ⇒ initial bubble dia

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

(porous plate)

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

(Perforated plate)

So the first correlation that we are going to look at is called the Mori-Wen correlation. It is the Mori-Wen correlation. The correlation is as it goes like this. So dbm which is the maximum possible bubble diameter-the diameter of a particular bubble/the maximum possible diameter-the diameter of the bubble when the bubble is just formed, that is the initial bubble diameter and that should be equal to exponential of -0.3*h/Dt where h is the height at which the particular bubble is being observed and Dt is the bed diameter, diameter of the bed.

And so now db0 which is the initial bubble diameter, initial bubble dia that is given by 0.0037*U0-Umf the whole square if it is a perforated plate, if it is a porous plate sorry. 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-the corresponding fluidization velocity and square of that difference.

And that is equal to 0.347*the area of cross section into U0 which is the superficial velocity-the minimum fluidization velocity Umf/the number of perforations which is actually present in the 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 it is a perforated plate. If it is a perforated plate, then this is the correlation that actually gives an estimate of what is the initial bubble diameter.

So next we need to know what is the maximum possible bubble diameter.

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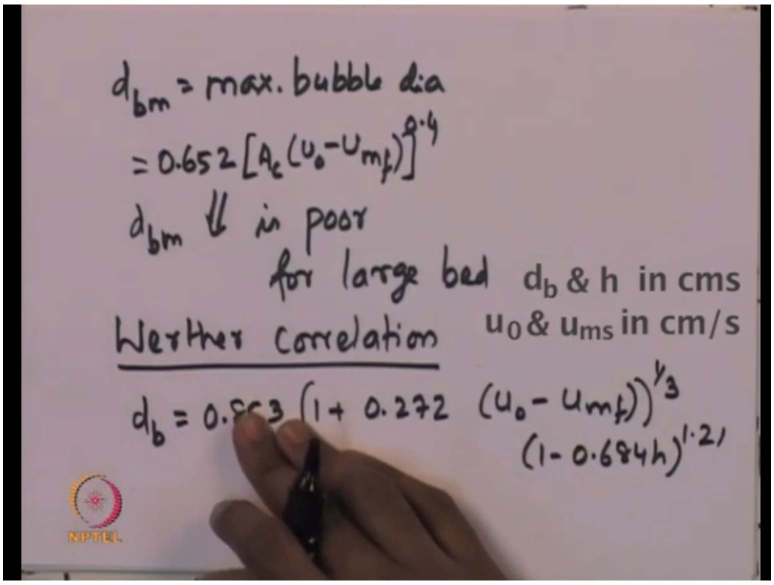

d_{bm} = max. bubble dia

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

d_{bm} ⇓ in poor

for large bed

d_b & h in cms

u_0 & u_{ms} in cm/s

Werther correlation

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

So the maximum bubble diameter is given by dbm is the maximum bubble diameter. Maximum bubble dia and that is given by the correlation 0.652*the area of cross section of the bed*U0-Umf, U0 is the superficial velocity with which the gas stream is let inside the fluidized bed reactor and Umf is the minimum fluidization velocity whole to the power of 0.4. So that provides an estimate of what is the maximum possible bubble diameter.

And it is known that the predictions are poor if the bed is very large. So the dbm 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 which seems to work over a wide range of fluidized bed reactor is called the Werther correlation.

The Werther correlation is that the diameter of the bubble is given by 0.853*1+0.272*U0-Umf whole to the power of 1/3*1- 0.684*h which is the height of the bed at that particular instance to the power of 1.21. So this correlation is known to give a better prediction of the diameter of the bubble in the fluidized 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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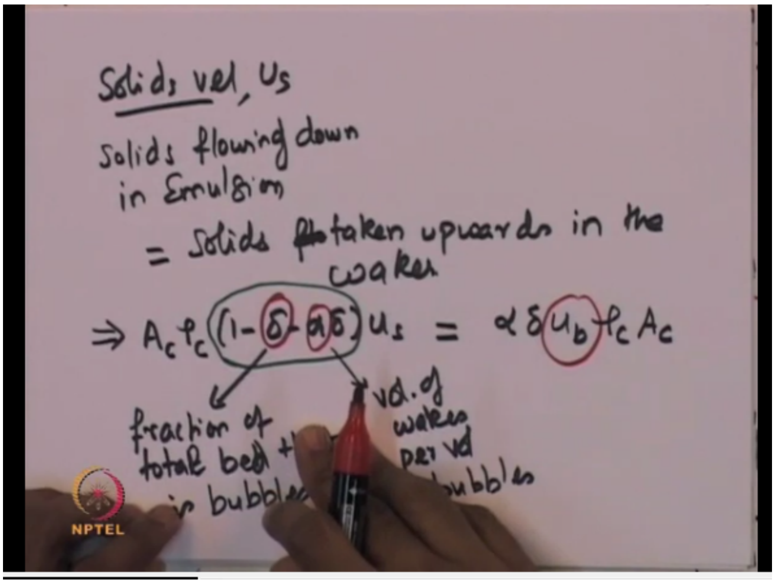

Solids vel, U_s

Solids flowing down in Emulsion

= Solids ~~fl~~ taken upwards in the wakes

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

fraction of total bed in bubbles

vol. of wakes per vol ubbles

So we need to find out what is the solids velocity Us that is the next parameter that needs to be estimated. So suppose so 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 flowing upwards in the wake should be equal to the amount of solid particles which are actually transported in the emulsion phase. So therefore if we make a material balance across the solids flowing in these two phases then 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 the solids flowing in emulsion phase that should be equal to flowing down in emulsion phase should be equal to solids actually taken upwards in the wakes. So now putting the corresponding expression solids flowing down in the emulsion is given by area of cross-section Ac*the density of the catalyst rho c*1-delta-alpha*delta*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 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-delta*alpha delta, it actually estimates as to how much what fraction of the cross-sectional area is actually filled with solids is given by 1-delta-alpha*delta.

So therefore using 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*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*Ub which is the velocity with which the bubble is raising up upwards*rho c*Ac.

So this material balance of the solids which is flowing down an emulsion and the solids which are actually taken upwards in the wakes can be used to estimate Us and note that the Ub is the bubble raising velocity which can be obtained using the correlations that is Mori-Wen or the Werther correlation and alpha and delta are supposedly a known property for a particular fluidized bed reactor and we are going to see how to estimate them.

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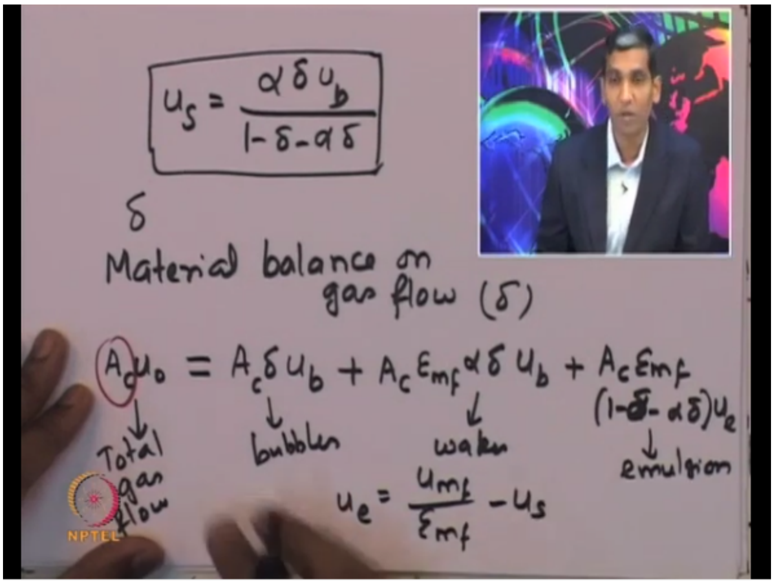

$$\boxed{u_s = \frac{\alpha\delta u_b}{1-\delta-\alpha\delta}}$$

δ

Material balance on gas flow (δ)

$$A_c u_0 = A_c\delta u_b + A_c\varepsilon_{mf}\alpha\delta u_b + A_c\varepsilon_{mf}(1-\delta-\alpha\delta)u_e$$

Total gas flow

bubbles

wakes

emulsion

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

So based on this correlation we can find out that the velocity of the solids Us is actually given by alpha*delta*Ub/1-delta-alpha*delta. So that is the expression for the velocity with which the solid is flowing. So the next step is to find out 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 a material balance on gas flow to estimate the value of delta. So that is what we are going to do next okay. So the material balance on gas flow basically is just to account for how the gas is being split into different sections and what is the total material balance for the gas flow.

And that is given by Ac*U0 where U0 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 enters the reactor should be equal to the cross section area of the fluidized bed reactor*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*delta which tells you what is the fractional area that contains that is actually occupied by the bubbles*the velocity Ub tells us what is the flow rate mass flow rate of the gas that is actually carried by the bubbles+some of this gas is now going to go in the wakes.

So that can be estimated as Ac which is the cross sectional area multiplied by the porosity which at the minimum fluidization velocity epsilon mf*alpha*delta*Ub. So alpha is basically the volume of wakes per volume of the bubbles and then there is another component which is basically the gas that may be present in the emulsion phase. So that is actually Ac*epsilon mf*1-delta*alpha*delta*the velocity with which the emulsion is moving okay.

So this basically tells us what is the material balance for the gas flow. Now we know that 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 okay, 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/epsilon mf-the velocity of the solids. So now plugging in these expressions, we will be able to find out what is delta.

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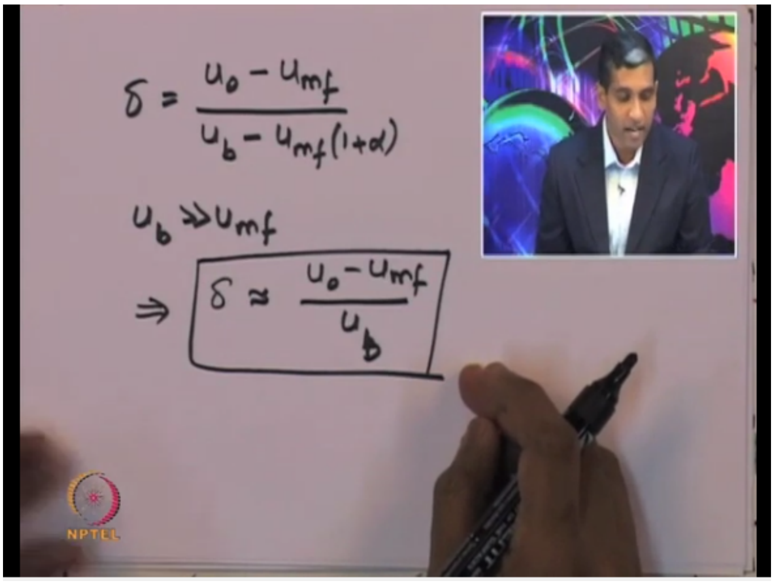

$$\delta = \frac{u_0 - u_{mf}}{u_b - u_{mf}(1+\alpha)}$$

$$u_b \gg u_{mf}$$

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

So delta is now given by U0 which is the superficial velocity-Umf which is the minimum fluidization velocity/Ub-Umf*1+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 is given by U0-Umf/Ub. So now we have estimated what is delta. So the next exercise is to characterize the mass transport in fluidized bed reactor.

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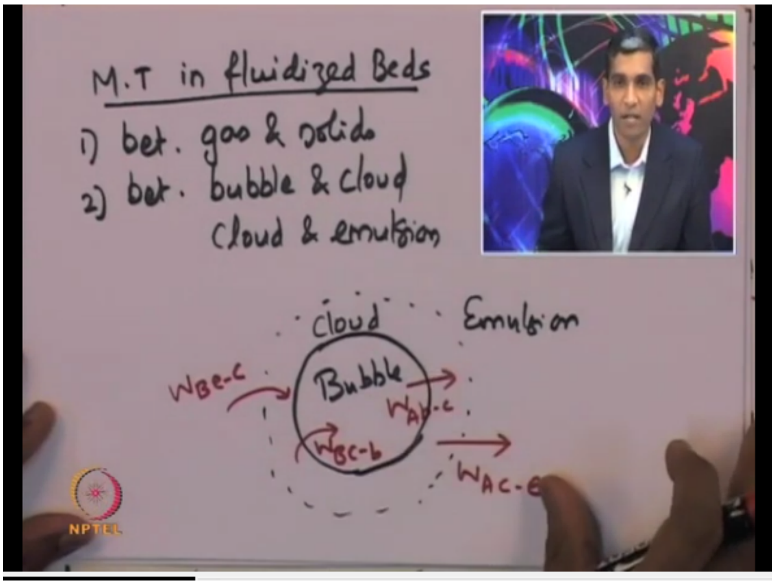

M.T in fluidized Beds

1) bet. gas & solids
2) bet. bubble & cloud
   cloud & emulsion

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 and 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 reactants which is actually present in the gas stream is carried by the bubbles and there is mass transport of the reactants 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 classical mass transport in the gas solid 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. So now we may represent W if A is the species WAb to c is essentially the transport from bubble to the cloud region and this is the emulsion region.

And then where WAc 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 that is formed that is the transport from the emulsion to the cloud phase and then WBc to b is the transport of the product from the cloud to the bubble phase.

So this is the in addition to the classical gas solid transport in the catalytic reactors this is an extra transport mechanism which is observed in the fluidized bed reactor. So let us look at how to find the gas solid mass transport coefficient first and then we will look at the other mode of transport.

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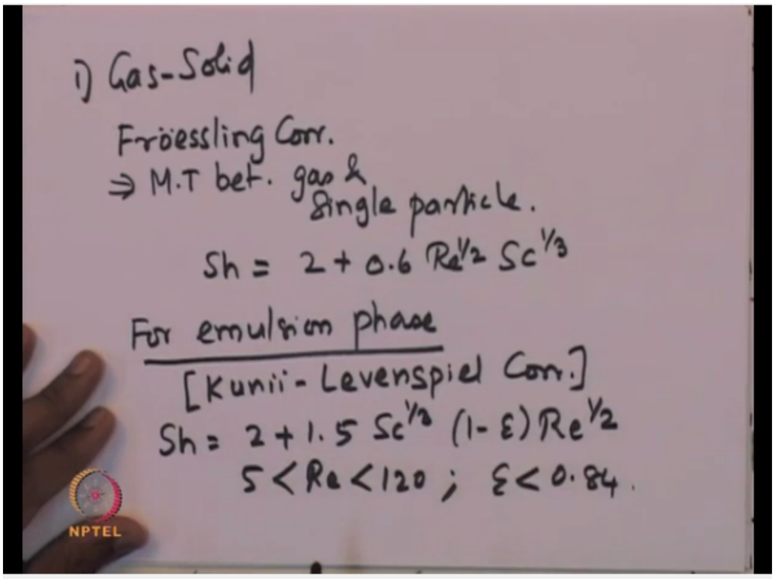

i) Gas-Solid

Froessling Corr.

⇒ M.T bet. gas & single particle.

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

For emulsion phase

[Kunii-Levenspiel Corr.]

$$Sh = 2 + 1.5\, Sc^{1/3}\,(1-\varepsilon)\, Re^{1/2}$$

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

So now between gas and single particles, there are correlations which is called the Frossling 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+0.6*Reynolds number to the power of 1/2*Schmidt number to the power of 1/3 and for emulsion phase the Kunii and Levenspiel have developed a correlation.

Kunii and Levenspiel have developed a correlation to estimate the mass transport coefficient in the emulsion phase and that is given by Sherwood number=2+1.5*Schmidt number to the power of 1/3*1-epsilon*Reynolds number to the power of 1/2 and the validity of this correlation is basically between the Reynolds number of 5 and 120 and epsilon should be<0.84.

So if the porosity is<0.84, then this correlation works in the emulsion phase. So there are different mass transport coefficients and one need to actually combine all of these mass transport coefficients in order to estimate what is the overall mass transport coefficient because mass transport occurs through both these cases both these mechanisms.