Chemical Reaction Engineering - II
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Lecture - 40
Fluidized Bed Reactor Design II

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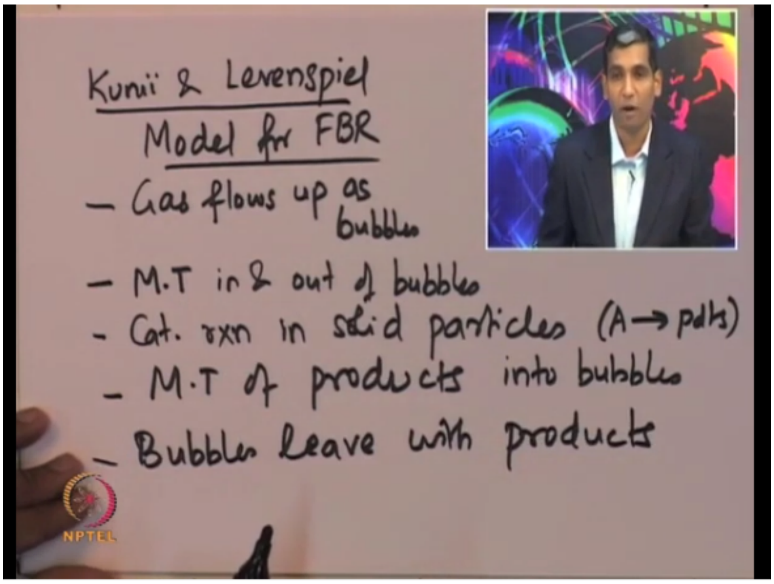

Kunii & Levenspiel
Model for FBR

- Gas flows up as bubbles
- M.T in & out of bubbles
- Cat. rxn in solid particles ($A \rightarrow$ pdts)
- M.T of products into bubbles
- Bubbles leave with products

So Kunii and Levenspiel came up with a model. Kunii and Levenspiel they came up with a model for the fluidized bed reactor. So the model that we will describe here is basically that of Kunii and Levenspiel and there are certain assumptions important assumptions that were made while formulating the model. The assumptions are that the gas flows up as bubbles. So as long as the velocity with which the gas is flowing is above the minimal fluidization velocity.

That is the velocity at which the drag force exerted by the solid by the gas on the solid particles is equal to the gravitational force that is actually exerted because of the weight of the catalyst. So if that equals then the fluidization is going to occur, so as long as the velocity of the fluid is slightly higher than the fluidization velocity then we will see that these gases will start bubbling at the plate which is present at the bottom of the reactor.

So the model assumes that the gas flow actually it flows up as bubbles. In fact, the velocity at which the bubbling will start and the velocity at which just the fluidization will start will be very insignificantly different. They are expected to be very close to each other. In fact, it has been observed that these two velocities are where these two superficial velocities are very close to each other.

Therefore, the assumption that the gas flows up as the bubbles is not a very poor assumption and then the other process is that there will be mass transport in and out of bubbles. So remember that the reaction is occurring at the surface of these catalyst particles. The reaction is occurring in the active sites of these catalyst particles. So therefore the reactant stream which is actually being carried in the gas phase has to get transported from the bubble.

So the reactant is now present in the bubbles and this species has to be transported from the bubble into the catalyst. So therefore there has to be mass transport in and out of the bubbles and after the reaction is completed, the product which is formed in the catalyst is now going to get transported to the gas stream and the gas stream takes the product out of the fluidized bed reactor.

So therefore the next step will be there is a catalytic reaction in the solid particles and then there will be mass transport of products, the reaction could be some species A giving some corresponding products and so mass transport of the products into bubbles and the bubbles leave the reactor. So bubbles essentially leave the reactor with products. So it carries the products and it leaves the reactor.

So now let us look at what are the factors that actually affect the performance of a fluidized bed reactor.

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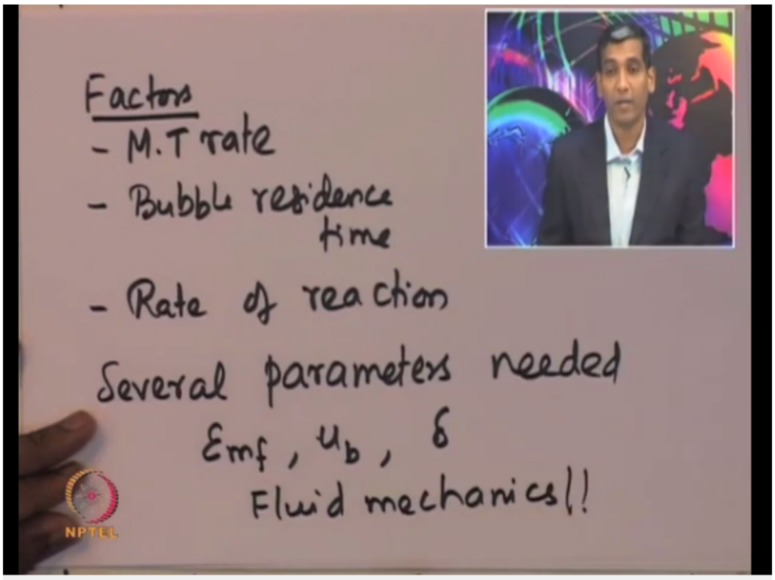

Factors
- M.T rate
- Bubble residence time
- Rate of reaction

Several parameters needed

ε_{mf}, u_b, δ

Fluid mechanics!!

So the key factors which affect are the mass transport rate because there is transport of species from the gas phase into the solids and also transport of the products which is formed because of the catalytic reaction in the solid phase that is transported back into the bubbles into the gas phase. So the mass transport rate is actually a key factor in determining the performance of the fluidized bed reactor.

And then another key factor which dictates the performance of the reactor is the bubble residence time. So this characterizes the time for which the bubble actually stays inside the fluidized bed reactor. In fact, it is related to the superficial velocity and the velocity with which the bubble raised. Superficial velocity is the velocity with which the gas is actually fed into the reactor and then the bubble is now going to raise with a different velocity.

And so the residence time is now going to be a function of the superficial velocity and also the velocity with which the bubble is actually raising inside the fluidized bed reactor and the third factor which is obvious is the rate of reaction. So these 3 factors are very important. In fact, there are several fluidized bed reactor properties need to be known in order to get these 3 important in order to estimate these 3 factors.

And also account them in the mole balance which would be writing in a short line. So several parameter needs to be defined. Several parameters are needed in order to perform a design of such a fluidized bed reactor. For example, what is the porosity of the bed under the minimum fluidization conditions, what is the velocity with which the bubbles are actually raising inside the fluidized bed reactor.

And then what is the fraction of the reactor which is actually consisting of bubbles which is characterized by this value delta and so there are all kinds of parameters which are required to be estimated. So if we do not estimate this, we do not know what these parameters are then design of a fluidized bed reactor cannot be conducted and these parameters as can be discerned, they depend upon the fluid mechanics of this particular problem.

They strongly depend upon the fluid mechanics. So let us look at some of these fluid mechanics aspects and then try to estimate some of these parameters which is going to help in the design of the fluidized bed reactor. So now the first step is we have to look at what is the mass of the solid which is present inside the bed.

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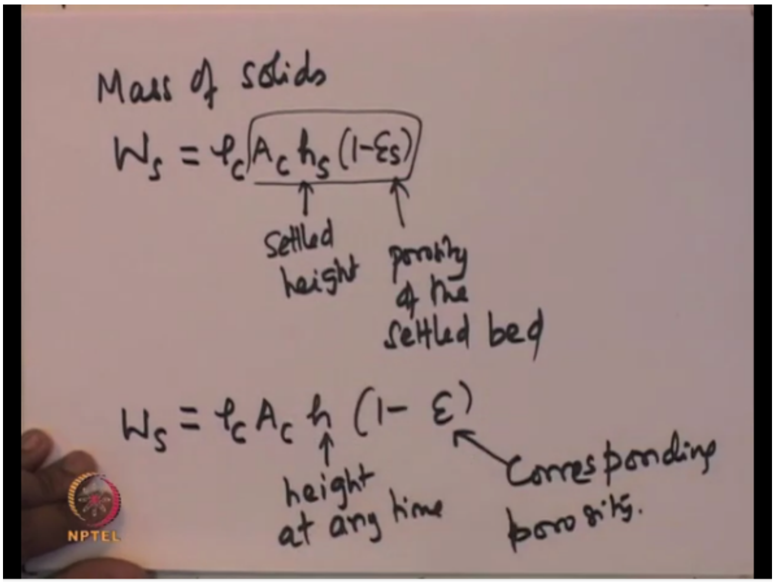

Mass of solids

$$W_s = \rho_c \boxed{A_c h_s (1-\varepsilon_s)}$$

settled height

porosity of the settled bed

$$W_s = \rho_c A_c h (1-\varepsilon)$$

height at any time

Corresponding porosity.

So the mass of the solid which is present so if Ws is the total mass of the solid catalyst particles which is present inside. So that is given by the density of the catalyst rho c*the cross sectional area Ac*the height of the catalyst. Suppose if the catalyst particles are completely settled, then hs refers to the settled height, the height inside the bed up to which the catalyst particles are settled*1-epsilon s.

Epsilon s is the porosity. It is the porosity of the settled bed. What is the porosity? And so density of the catalyst*the area Ac hs which is the settled height*1-epsilon. So this gives the volume and multiplied by the corresponding density will tell you what is the weight of the catalyst. Similarly, the same expression Ws, suppose if the bed is fluidized then what is the weight of the catalyst?

The weight remains the same because we are not adding new catalyst particles but the height of the bed is now changed because some of the particles are now fluidized and they have started raising. So therefore the weight of the catalyst bed at any time during the fluidization process is given by rho c which is the density of the catalyst*Ac which is cross section of the fluidized bed*height which is the h which is the height at any time*1-epsilon.

This is the corresponding porosity. That is the corresponding porosity, so that provides an estimate of what is the mass of the solid. So if we know the height at any time, then we should be able to estimate the value of porosity by simply equating these two expressions here because this is the settled height and this is the porosity of the settled bed, so we should be able to estimate what is the porosity of the bed at any time simply by using this expression.

And that is also because the height of the bed at any time is something that can be measured, it is a measurable quantity. So now the next process, next parameter that we need to estimate is what is the minimum fluidization velocity.

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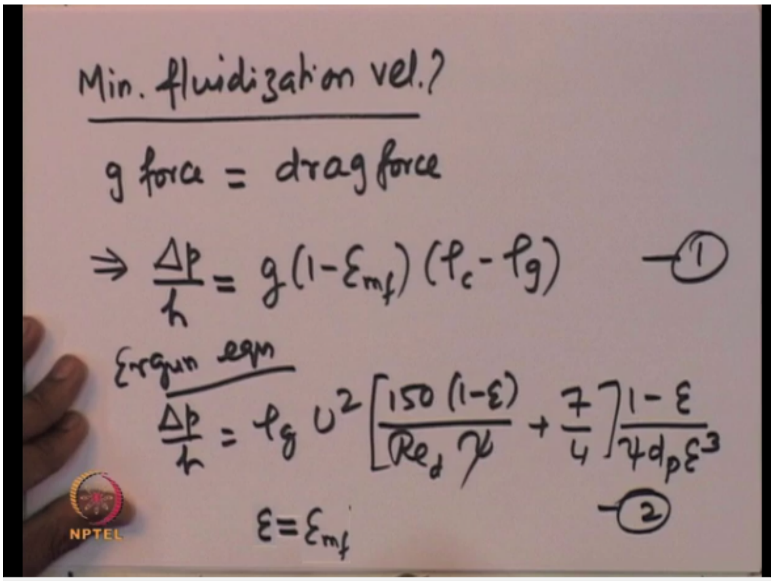

Min. fluidization vel.?

g force = drag force

$$\Rightarrow \frac{\Delta p}{h} = g(1-\varepsilon_{mf})(\rho_c - \rho_g) \quad -①$$

Ergun eqn

$$\frac{\Delta p}{h} = \rho_g U^2 \left[\frac{150(1-\varepsilon)}{Re_d \psi} + \frac{7}{4}\right] \frac{1-\varepsilon}{\psi d_p \varepsilon^3} \quad -②$$

$$\varepsilon = \varepsilon_{mf}$$

What is the minimum fluidization velocity? So the fluidization occurs when the drag force that is exerted by the gas stream which is moving which is raising up if that balances the gravitational force that is exerted by the catalyst particle because of its natural weight. So clearly you can estimate the minimum fluidization velocity by simply balancing the drag force that is exerted by the gas phase.

And the gravitational force that is exerted by the solids because of its weight, so therefore the gravitational force that should be equal to the drag force that is which is exerted by the gas stream on the fluid on the catalyst particles. So that balance will give us a pressure relationships, so that will be delta p/h that should be equal to gravity g*1-epsilon mf which is the porosity at the minimum fluidization velocity*difference in the densities.

So rho c and rho gas are the densities of the catalyst particle and density of the gas stream. So if I call this equation 1 and we also know that there is we also know from the fluid mechanics that the Ergun equation provides a relationship between the pressure drop and other parameters of the system that is superficial velocity etc. So therefore delta p/h is equal to rho g*U square.

So that this is the pressure relationship because of the gravity force and then we can find out what is the drag force because of the gas stream. So that is given by the Ergun equation*150* 1-epsilon/Reynolds number*size the sphericity of the particle+7/4*1-epsilon/psi*diameter of the particle*epsilon cube. So that is the drag force. Now by equating these two expressions 1 and 2, we can find out what is the minimum fluidization velocity.

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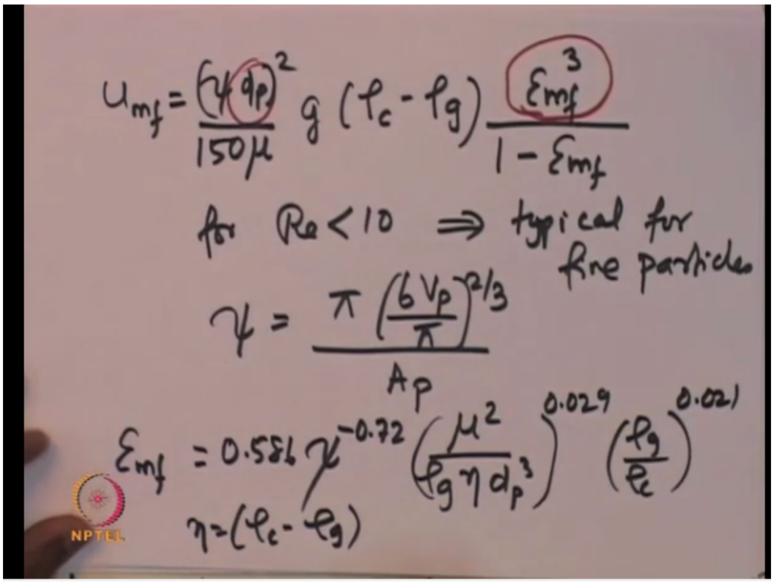

$$U_{mf} = \frac{(\psi d_p)^2}{150\mu} g(\rho_c - \rho_g)\frac{\varepsilon_{mf}^3}{1-\varepsilon_{mf}}$$

for $Re < 10$ ⇒ typical for fine particles

$$\psi = \frac{\pi\left(\frac{6V_p}{\pi}\right)^{2/3}}{A_p}$$

$$\varepsilon_{mf} = 0.586\,\psi^{-0.72}\left(\frac{\mu^2}{\rho_g \eta d_p^3}\right)^{0.029}\left(\frac{\rho_g}{\rho_c}\right)^{0.021}$$

$\eta = (\rho_c - \rho_g)$

So the minimum fluidization velocity is given by psi dp square/150 mu*gravity*the difference in the density of the catalyst and the density of the gas stream*the porosity at the minimum fluidization velocity/1-epsilon mf okay. Now this is valid only for Reynolds number which is <10 and this is typically the case for fine particles. It is a typical Reynolds number for fine particles.

It is a typical Reynolds number for fine particles and the sphericity is given by pi*6 times volume of the particles/pi to the power of 2/3 whole divided by area of the particle. So now if we know what is the porosity at the minimum fluidization velocity and the diameter of the particles, then we should be able to estimate the minimum fluidization velocity. So we need to know what is the porosity at the minimum fluidization velocity.

And there are correlations which are available to relate the porosity at minimum fluidization velocity with the other system parameters. So epsilon mf which is the minimum fluidization velocity is given by 0.586*the sphericity to the power of -0.72*mu square/rho g*eta. Eta is essentially the difference in the density. So eta is essentially the difference in the density of the catalyst particle and the gas mu square/rho g*eta*dp cube to the power of 0.029*rho g/rho c to the power of 0.021 okay.

So this is basically the relationship which gives what is the porosity at the minimum fluidization velocity and plugging in this value here one can find out what is the minimum fluidization velocity. So remember that this is a correlation and it has been obtained it has been found to be correct for different systems and particularly if we assume that the catalyst particles are approximately all of them are of same size then this gives a very good estimate.

Now if there is a distribution of the catalyst particles then one needs to use a certain weighted average in order to find out what is this diameter of this particle. So the diameter of the particle if all the particles are of same size then we have to use a constant value for the diameter, if there is a distribution then we need to use some weighted average diameter which is a representative diameter for the whole distribution.

So next let us look at what is the maximum fluidization velocity. So the maximum fluidization velocity occurs when the drag force is significantly higher than the gravity force.

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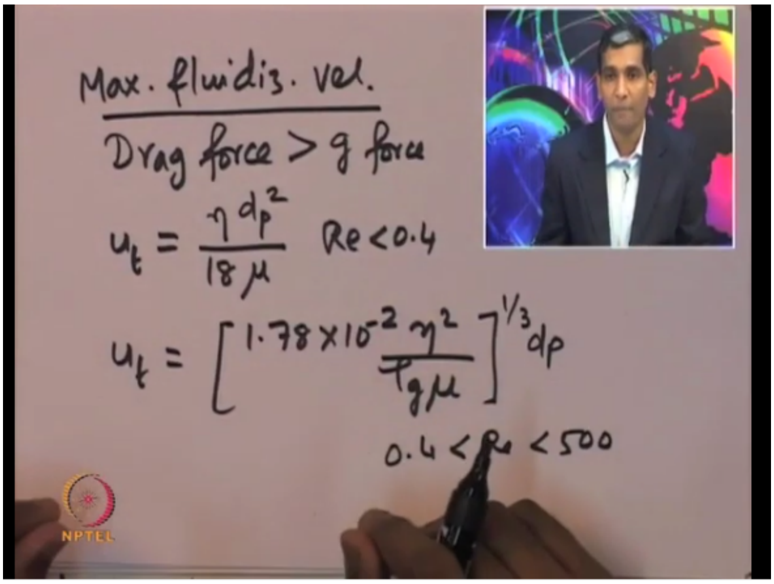

Max. fluidiz. vel.

Drag force > g force

$$u_t = \frac{\eta d_p^2}{18 \mu} \quad Re < 0.4$$

$$u_t = \left[1.78 \times 10^{-2} \frac{\eta^2}{\rho_g \mu} \right]^{1/3} d_p$$

$$0.4 < Re < 500$$

So the maximum fluidization velocity, this is when the drag force is>the gravity force and remember that this velocity should not be greater than a certain value such that the particles would actually leave the reactor. So the maximum fluoridation velocity will be<the velocity at which the particles would leave. So which is typically given by certain correlations which is ut it is called the eta*dp square/18*mu for Reynolds number of<0.4, eta once again is the difference between the density of the catalyst and the density of the gas stream.

And for other ranges of Reynolds number, the correlation is 1.78*10 power -2*eta square/the density of the gas stream*the corresponding mu to the power of 1/3*dp. This is for Reynolds number of between 0.4 and 500. So this range of Reynolds number pretty much covers most of the fluidization operations that has been observed so far, that has been used so far in real systems.

So next what happens when the bubble raises, so what is it is actually happening inside the reactor. So suppose if we look into the details of what happens inside the fluidized bed reactor. So when the gas stream flows into the reactor through the perforated or the porous rate, then the bubbles are initiated, the bubbles are generated at the plate and while the bubbles move, they also carry these particles along with them. How do they do that?

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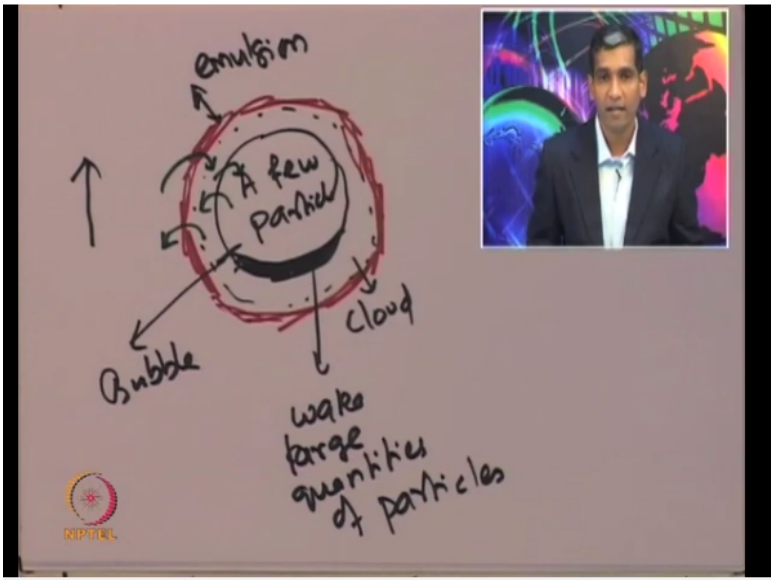

So suppose if you have a bubble which is typically not very spherical. Then, these bubbles will carry a few particles. So this is the bubble, now when the bubble raises they carry a few particle along with it and more importantly there is a region which is just below the bubble when it is raising suppose if I assume that the bubble is raising in the direction pointed by the arrow then this region called wake which actually contains large quantity of.

So this wake essentially which is the trailing part of the bubble, it carries large quantities of particles and then there is a small cloud region. So this is called the cloud region where the density of the particle is not significantly higher and then there is this emulsion region which is basically the, this emulsion region around the clouds so this is called the emulsion region.

And in fact this emulsion region actually has the particles which is as dense, densely packed as the resting particles. So this is basically the emulsion region. So now the transport of the species occurs from the bubble, so the transport of the species occurs from the bubble to the cloud phase and from the cloud phase to the emulsion phase. Remember that the catalyst particles are predominantly present in the emulsion phase.

So therefore the reaction is actually occurring in the emulsion phase. So the reactant species, they have to get transported from the bubble into the cloud and from the cloud into the emulsion phase and the product has to be transported back into the cloud into the bubble phase. So that is basically how the transport occurs in the bubble and which actually facilitates the catalytic reaction.

And that dictates so this process actually dictates the performance of the fluidized bed reactor. So let us look at a little bit more detail of the model of the Kunii and Levenspiel model.

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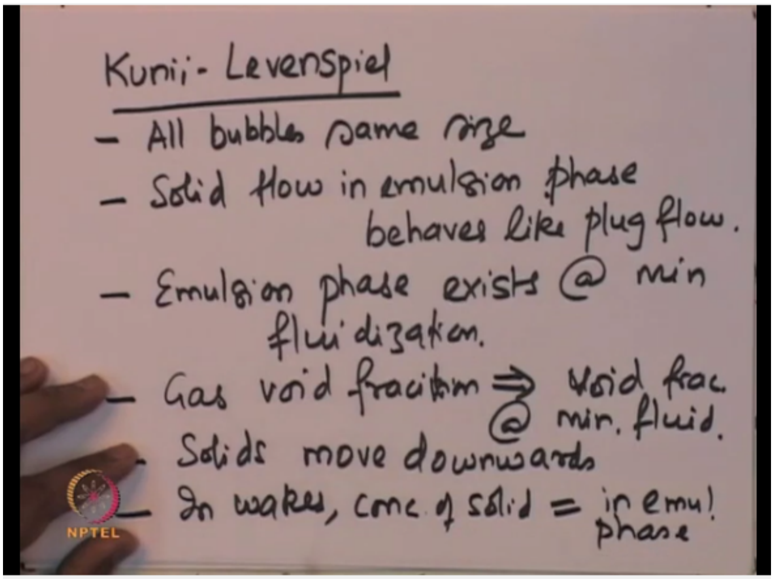

Kunii - Levenspiel

- All bubbles same size
- Solid flow in emulsion phase behaves like plug flow.
- Emulsion phase exists @ min fluidization.
- Gas void fraction ⇒ void frac. @ min. fluid.
- Solids move downwards
- In wakes, conc of solid = in emul phase

So the Kunii and Levenspiel model, it makes certain important assumptions and one important assumption besides all those that we have that has been elucidated so far will be that all bubbles are of same size. Now bubbles that is generated inside the fluidized bed reactor are definitely not of same size; however, because the distribution of the size is not going to is not expected to be significantly larger.

So it is reasonable to assume to start with that all bubbles are of same size. Then, the next important assumption is that these solids which solid flow in emulsion phase behaves like a plug flow. If we look at the different phases that we just elucidated, we will find that the these particles which are actually carried by the bubble phase, these particles which are carried in the bubble phase and the wake phase, they actually move into the emulsion phase and they start moving downwards because of its natural weight.

And therefore the movement of these particles in the emulsion phase, the velocity with which it moves strongly depends upon the velocity of the bubbles which carries these particles and so it is assumed here that the solid flow in the emulsion phase actually behaves like a plug flow where it moves like a plug stream and then it also assumes that the emulsion phase exists at minimum fluidization conditions.

So remember that minimum fluidization is essentially a situation where the drag force that is actually experienced by the solid particles because of the flow of the gas stream is actually balanced exactly with the balances the gravitational force exerted by the catalyst particles because of its natural weight. So as we observed before the bubbling process, the superficial velocity with which the bubbling process is going to occur is very close to that of the superficial velocity which is required for minimum fluidization.

So therefore it is virtually not possible to distinguish in practice whether the emulsion phase whether the bubbling phase is actually present during the minimum fluidization stage or not so therefore it is safe to assume that the bubbling phase exists at the minimum fluidization and therefore the emulsion phase also coexists along with it and then the next important assumption is that the gas void fraction.

The gas void fraction that actually is experienced in the emulsion phase that is considered to be approximately equal to the void fraction at the minimum fluidization conditions. Then, it is also assumed that the solids which actually move out of the bubble phase into the emulsion phase they actually move downwards.

Solids move downwards because of the gravity and then it is assumed that in the wakes which are present in wakes which are present note that the wakes are essentially these particles which are actually carried along with the bubbles and it is now present at the receiving end of the bubble. So in wakes the concentration of solid is assumed to be equal to that of the concentration in the emulsion phase.

So with these assumptions let us look at how to estimate different parameters and different quantities and also find how to design this fluidized bed reactor.

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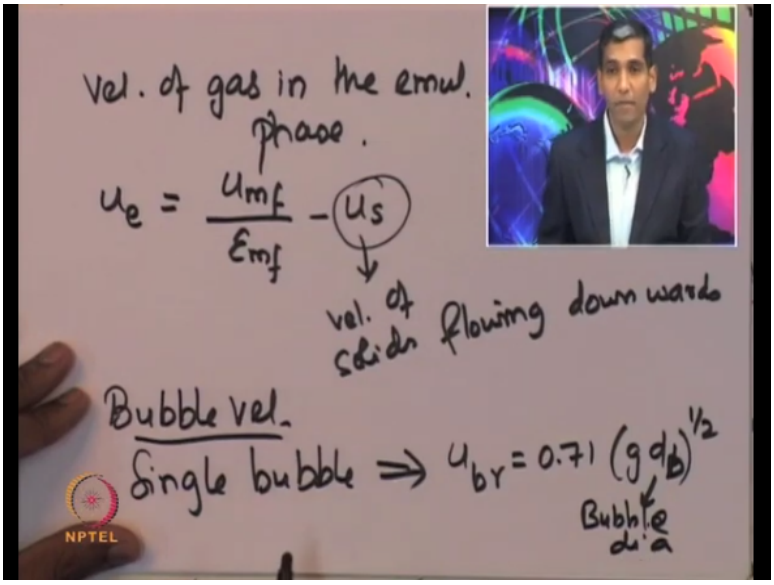

Vel. of gas in the emul. phase.

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

Bubble vel.

Single bubble $\Rightarrow u_{br} = 0.71\,(g \underset{\text{Bubble dia}}{\underset{\uparrow}{d_b}})^{1/2}$

So the first step is to estimate the velocity of gas in the emulsion phase. If Ue is the velocity of the gas in the emulsion phase and that is typically given by the minimum fluidization velocity Umf/the porosity of the bed under minimum fluidization conditions-Us. What is Us? Us is the velocity of solids flowing downwards, velocity of the solid which is actually flowing downwards in the emulsion phase.

It is flowing downwards in the emulsion phase. So therefore in order to estimate this one we can write a certain material balance in order to find out the velocity of the solids with which it is velocity of the solids which is literally flowing downwards. So in the next lecture we will actually write material balance in order to estimate the velocity of the solids and the next step is to estimate what is the bubble velocity.

Suppose if it is a single bubble, then there is a correlation which actually relates the diameter of the particle to the velocity of the single bubble and so that is given by Ubr which is equal to 0.71*gravity*diameter of the particle to the power of 1/2 and this is the diameter of the bubble. This is the bubble diameter, so now there is in the fluidized state when many bubbles are present together then the velocity of the bubble is expected to get affected because of the interaction between different bubbles.

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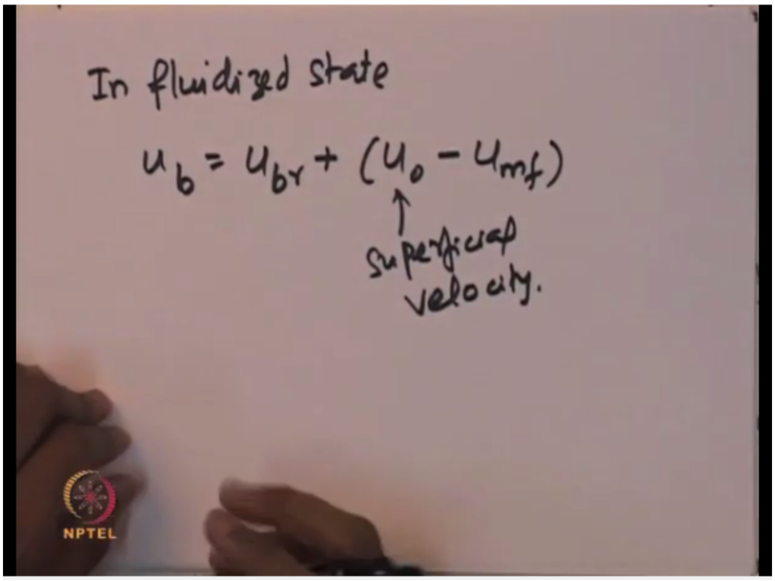

In fluidized state

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

$\uparrow$ superficial velocity.

So in fluidized state, the bubble velocity is expected to be Ub which is equal to Ubr+U0-Umf where U0 is the superficial velocity. So once we know these parameters and there are several other parameters that need to be estimated, particularly we need to know what is the diameter of the bubble and there are different correlations which are available which is what we will see in the next lecture.

So what we have seen in today's lecture is essentially an example problem for how to use the packed bed reactor to find out what is the length of the reactor and also we initiated discussion on the fluidized bed reactor and looked at what are the different flow regimes which actually exists in the fluidized bed reactor and what are the different parameters and properties that need to be estimated in order to design the reactor. Thank you.