Fluidization Engineering
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Lecture – 28
Mass transfer in fluidized Bed-Gas-solid system

So, welcome to massive open online course on Fluidization Engineering. Today's lecture is on Mass transfer in fluidized Bed that is in Gas solid system.

So, we have already discussed several hydrodynamic characteristics in 2 and 3 phase fluidized bed like a flow pattern, like particle characteristics, particle interaction, bubble, size distribution in bubbling fluidized bed and what is that particle bubble interaction even coalescence of the bubbles and bubble break up characteristics, even attrition of the particles and the classification and the segregation phenomena of the particles in the fluidized bed. And also what would be the entrainment characteristics inside the bed that has already been discussed.

So, those hydro dynamic characteristics of course, will be relating to that mass transfer characteristics even other heat transfer characteristics. So, totally you can say that the transport processes; the main important factor based on that hydrodynamic characteristics in the fluidized bed.

And whenever you are going to apply this fluidized bed for that particular industrial applications, for a specific chemical or biochemical processes there; we will see that of course, that mass transfer and heat transfer characteristics are the main important component; they are upon that reaction for their processing. And this the mass and heat transfer characteristic that depends on several hydrodynamic characteristics; that is why we have finished those parts those are very important in the fluidized bed for several hydrodynamic phenomena there.

So, in this case we will discuss something about that what is the mass transfer phenomena in fluidized bed, basically in this lecture that the gas and solid fluidized bed what should be the mass transfer characteristics there.

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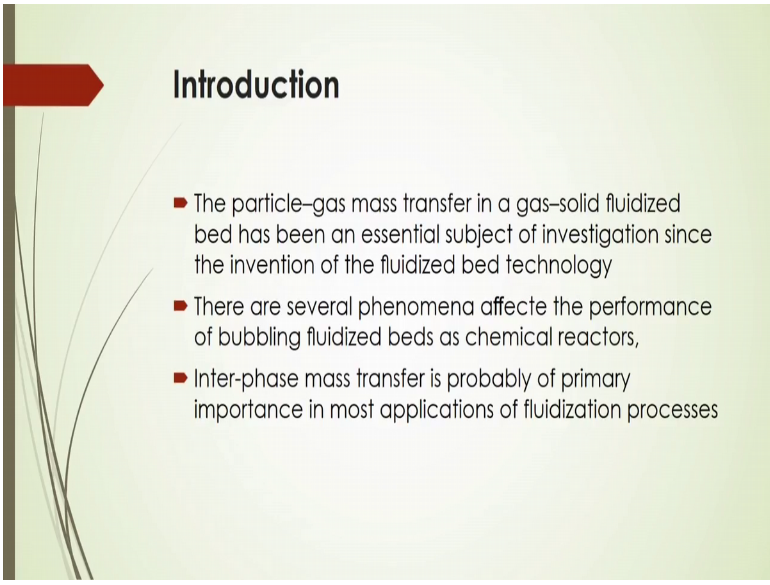

Now, you will see that in fluidized bed of course, that there will be a particle and there will be a gas. So, there may be or you can say of course, there will be a transfer of component of any phases between that particle and gaseous. So, there will be particle gas mass transfer in a gas solid fluidized bed.

There are several phenomena effects that performance of this bubbling fluidized bed as a chemical reactors. And because of which you will know what would be the phenomena of mass transfer and the bubbling fluidized bed. You will see that that in bubbling fluidized bed there are several phenomena bubble maybe a pressure drop, maybe mixing characteristics, maybe a entrainment characteristic the solids by in the bubbling fluidized bed by rising bubble and fluidized bed.

So, of course, those phenomena will affect the performance of the bubbling fluidized bed and of course, because of which consequently that chemical reactions inside the bed, in the bubbling fluidized bed will be enhanced or you can say there will be a some extent of beneficiation of the reactions or selectivity or processing will be there in the bubbling fluidized bed.

And there will be a you will see that interface mass transfer is there in the bubbling fluidized bed. And that interface mass transfer is probably of the primary importance in most applications of the fluidization process.

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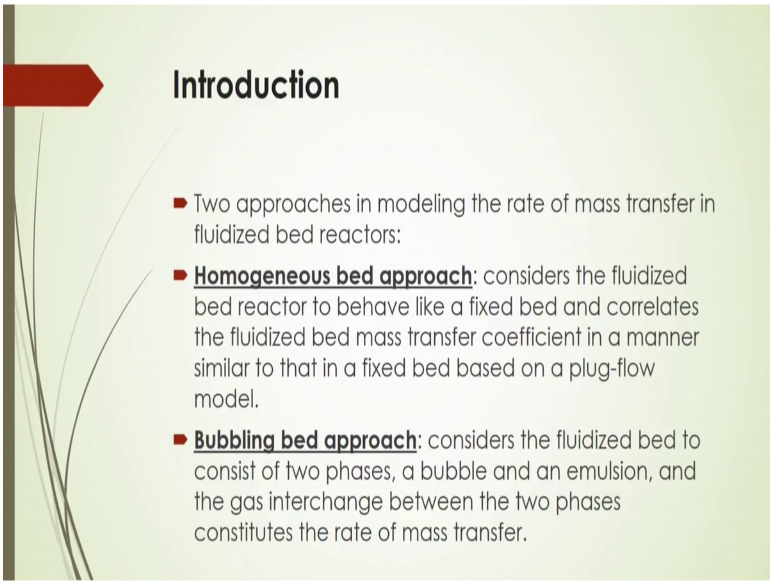

Generally, two approaches in modeling the rate of mass transfer in fluidized bed reactors there. Of course, that you will see whenever mass transfer happens that is from particle to gas or gas to particle; there will be a change of that what is that component either phases because of transfer of component from one phase to another phase. And those things can be actually analyzed basically in the two way or approaches and like it is called homogeneous bed approach and then bubbling bed approach.

Now, homogeneous bed approach generally it happens when the fluidized bed reactor behave like a fixed bed and you can say that correlates the fluidized bed mass transfer coefficient in a manner similar to that in a fixed bed based on the plug flow model.

Whereas, in the bubbling bed approach that considers the fluidized bed to consist of two phases that is one is bubble phase another is emulsion phase. Emulsion phase means they are particle and the gas mixture they are outside to the bubble and that is why bubbling bed approach actually in this case the total phases are divided into two parts; one is called bubble another is called emulsion.

So, basically those things are called as two phases phenomena will be considered in this case. So, two phases like a bubble and an emulsion phase and also you will see there will be a exchange of gas between these two phases that also are constitutes the rate of mass transfer inside the bed.

So, in bubbling fluidized bed whenever we are going to discuss about the mass transfer phenomena; of course, you have to consider that there will be a two phases one is bubble phase and another is emulsion phase.

And that mass transfer will be occurring not only that that transferring of one component to another component by diffusion, there may be a exchange of mass or component of gas from this bubble phase to the emulsion phase or you can say reversed emulsion phase to the bubble phase. So, this is the mass transfer phenomena; so, there will be interchange of gas between the phases there.

Now, what should be then the mechanism of mass transfer?

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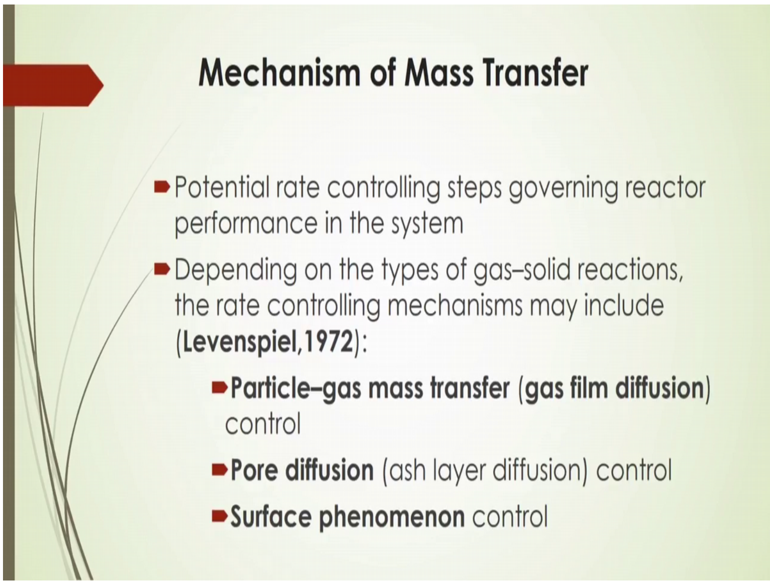

Inside the bed generally you will see that there will be a some rate controlling steps that governs the reactor performance in the system. So, there should be some potential rate that will control the steps are that governs the reactor performance. And that depends on generally types of gas solid reactions and the rate controlling mechanism may include generally particle gas mass transfer that is called gas film diffusion.

And you can say that pore diffusion is also one important mechanism that that case it is sometimes called as ash layer diffusion control mechanism. And another and important phenomena of for the mass transfer mechanism is called that surface phenomenon control there. So, surface phenomenon control and the pore diffusion control particle gas mass transfer that is called gas film diffusion control are the three mechanism generally that governs the mass transfer inside the fluidized bed.

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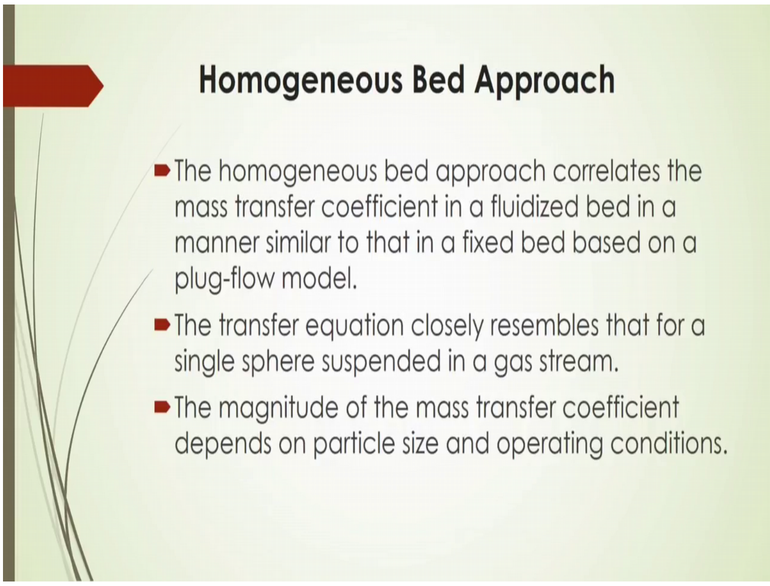

Let us start with one by one there are we have told that generally two approaches, two analyze the mass transfer in the bubble in the fluidized bed. And homogenous bed approach generally correlates to the mass transfer coefficient in a fluidized bed; in a manner that will be exactly similar or in a fixed bed based on the plug flow model. And in this case the mass transfer equation that will be inject the almost you can say that similar to that for a single sphere suspended in a gas system. And the magnitude of the mass transfer coefficient that depends on particle size and the operating conditions.

So, what is that mass transfer coefficients actually; you know that mass transfer is happened because of the concentration gradient. And what would be that proportionality constant of the mass flux or you can say more flux that that is called the mass transfer coefficient. And these mass transfer coefficients it is not that inherent property, but depends on the difference say or several operating conditions also.

There are you know that n number of different operating conditions will be there; maybe in fluidized bed you will see that you can say if there is a geometrical variables like reactor size diameter and cross sectional area, length of the column and these things that is called geometric variables. And the operating variables or we can say dynamic variables dynamic variables such gas velocity of fluid velocity or gas solid fluidized bed and the gas liquid solid state that will be is equal to a gas velocity and liquid velocity. And also the physical properties of the system is very important which governs this mass transfer coefficient there, these three variables which are very important to actually change the mass transfer coefficient inside the bed. Because of which you will see different mass transfer inside the bed as per the different operating conditions.

Now, if we consider that mass transfer between single sphere and the surrounding gas inside the fluidized bed; if you are consider only one particle inside the fluidized bed then what should be the mass transfer between single particle and the surrounding gas?

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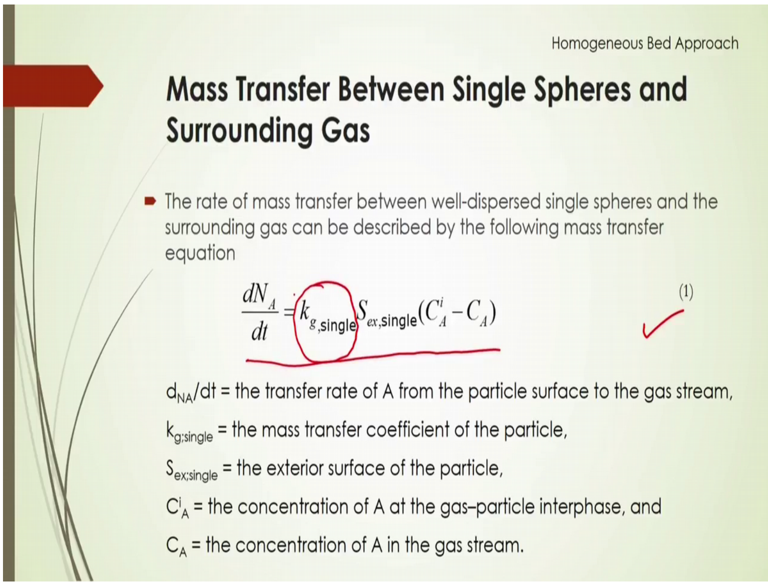

Now, the rate of mass transfer between this well dispersed single spheres and the surrounding gas can be described by this equation 1 here shown in slides there here it is seen that this d N A by d t that will be is equal to k g to single into S e X single into C A dashed C A i minus C A here.

Now, d N A by d t that would be is equal to transfer rate of A from particle surface to the gas stream and k g here single it is called that mass transfer coefficient of the particle. And S e X particle is representing the exterior surface of the particle whereas, this C A i the concentration of a at the gas particle interface and C A representing the concentration of a in the gas stream there.

So, by this equation 1 you can represent what should be the mass transfer rate which is occurred from the single particle to the gaseous stream.

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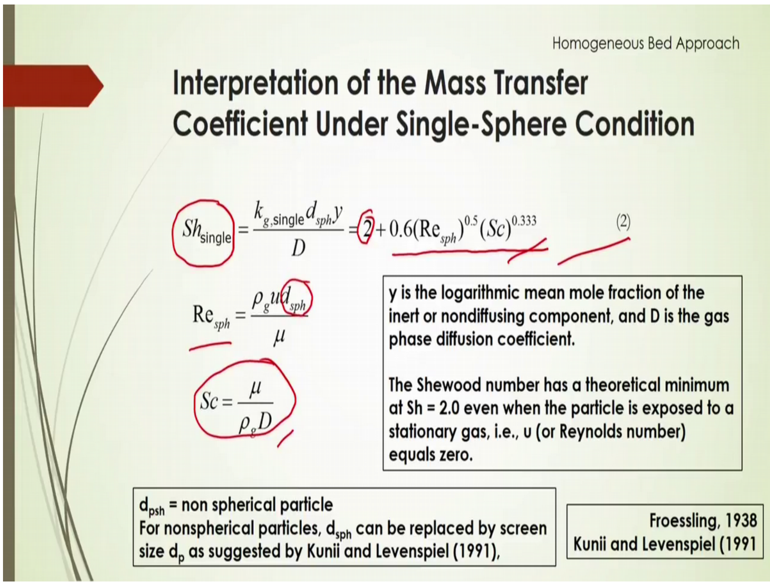

And what should be that mass transfer coefficient that we have got here in this equation that k g single here. This k g single will be representing that can be actually represented by the correlations given by different investigators here very important correlations that is given by that is Froessling in 1938 and the Kunii and Levenspiel 1991.

They have given these correlations, they have suggested this correlations based on their experimental data by obtaining that mass transfer phenomena from their experiment. And this can be represented by this Sherwood number of single here which is defined as k g single and to d sph into y by D that is equal to 2 plus 0.6 into Re sph into the power 0.5 into smith number to the power 0.333.

Here Reynolds number of that spherical particle ah; that means, sphere Re sph that will be defined as that is rho g u d sph by mu and smith number is defined as this mu by rho g into D. Here this capital D is called diffusivity of the gas and y is one important parameter here which will represent the logarithmic mean mole fraction of the inert or non diffusing component and these gas phase diffusion coefficient.

The Sherwood number has a theoretical minimum value in this case you will see if suppose gas flow is 0 gas flow is 0; then in this case you will see Reynolds number will be equals to 0. So, this part will be is equal to 0; so, minimum value for this Sherwood number will be is equal to 2. So, the Sherwood number has a theoretical minimum value or at Sherwood number is equal to 2.0; even when the particle is exposed to a stationary gas; that means, u or Reynolds number equals to 0.

And d psh is nothing, but that non spherical particle diameter here may be spherical or non spherical particle will be inside the bed. So, generally the d sph has been taken as the non spherical particle or spherical particles d sph can be replaced by the screen size d p as of the state by the Kunii and Levenspiel 1991. So, this is basically that here the particle size will be as d p here whatever it is that you have to consider.

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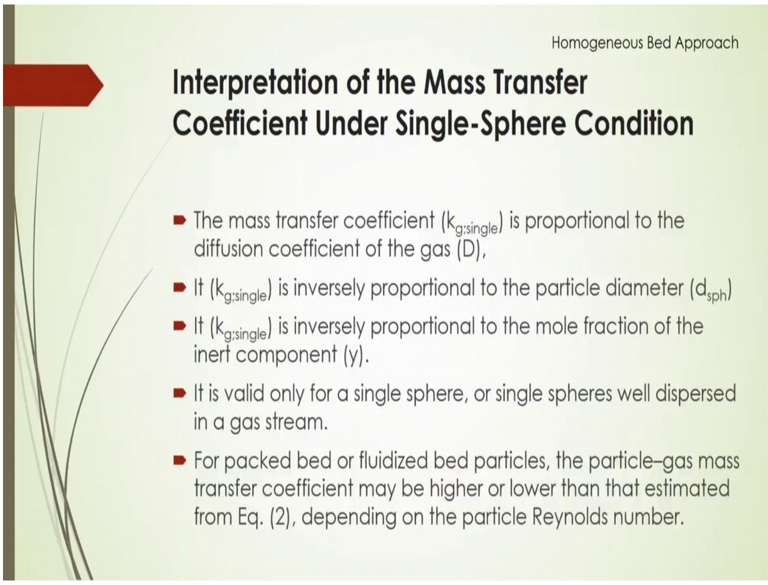

Now, the mass transfer coefficient for the single particle in the fluidized bed is proportional to the diffusion coefficient of the gas D. And ; that means, here if the diffusion coefficient of the gas increases then mass transfer coefficient from the particle to the gas will be increased and if particle diameter increased, then you will see that the mass transfer coefficient of the single particle will be decreased. That means, here the mass transfer coefficient for the single particle is inversely proportional to the particle diameter.

Now, again you can say that this single particle mass transfer coefficient will be inversely proportional to the mole fraction of the inert component in the bed. And it is valid only for a single sphere if there are more than one particles, then you cannot use these correlations to predict the mass transfer coefficient they are in the fluidized bed. Of course, that this fluidized this particle should be well dispersed in the gas system they are then only you can see that for the particle how from the particle how mass transfer is happened inside the bed.

For packed bed or fluidized bed particles, the particle gas mass transfer coefficient may be a higher or lower that estimated from equation 2 that depends on the particle Reynolds number; So, here very important that this particle gas mass transfer coefficient that depends on the operating conditions.

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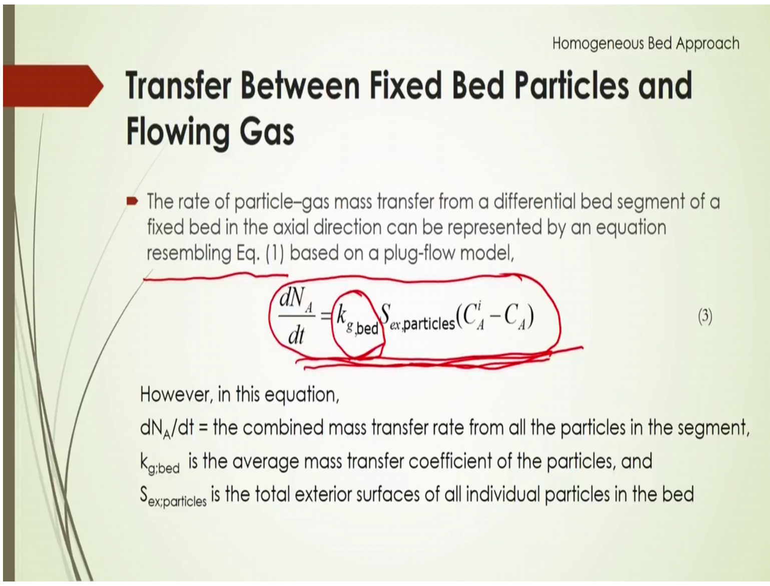

And the rate of particle gas mass transfer from a differential bed segments of a fixed bed in the axial direction that can be represented by the equation that is similar to that equation 1 based on a plug flow model that will be here.

So, this is basically for the fixed bed that is particles are not moving whereas, gaseous moving in that case this mass transfer phenomena also can be governed by this equation here. Now, in this case k g bed is the mass transfer coefficient of that gas in this case for the fixed bed condition. However, in this equation you will see that d N A by d t the combined mass transfer rate from all the particles in the segment will be there.

Because here fixed bed here not only one particle will be there, more than one particles. So, for a particular segment in the fluidized bed you can say more than one particle from there. And mass transfer will be considered here not only from the single particle the mass transfer will be from the all the particles there in the fluidized bed. And k g bed is the overall you can say that average mass transfer coefficients of the particles and S e X that particles is the total exterior surfaces of all individual particles in the bed.

So, here the surface area will not be only single particle that all the surface area for all particles will be considered inside the bed. As per Kunii and Levenspiel 1991; this exterior surface area of that particle should be for that fixed bed condition will be is equal to V into segment.

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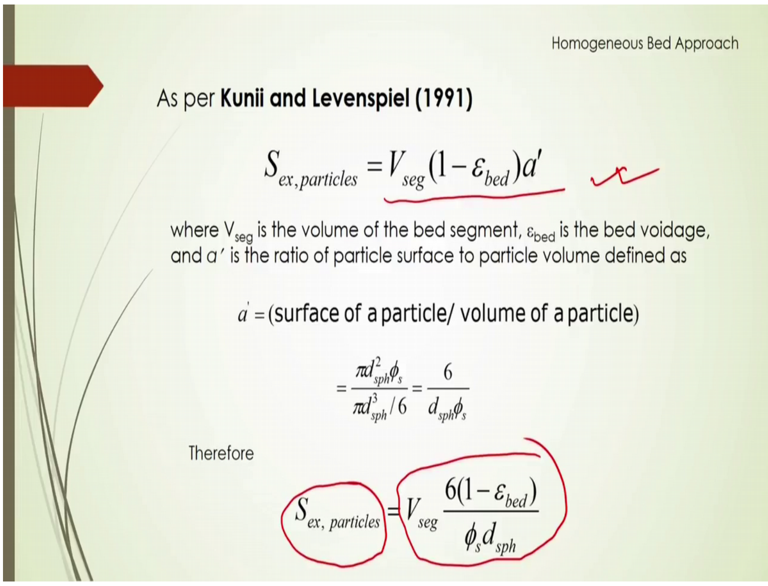

That means, that volume of that segment of that particular fluidized fixed bed that into 1 minus epsilon bed epsilon bed is equal to the porosity of the bed into a dash a dash here a dashed is called the specific interfacial area which is defined as surface of the particle divided by the volume of the particle here, where V segment is the volume of that bed segments.

And this then after substituting this specific interfacial area and in the equation here, then you can say what will be the exterior particle surface in the bed that will be is equal to here that V seg into 6 into 1 minus epsilon bed divided by phi into d d p.

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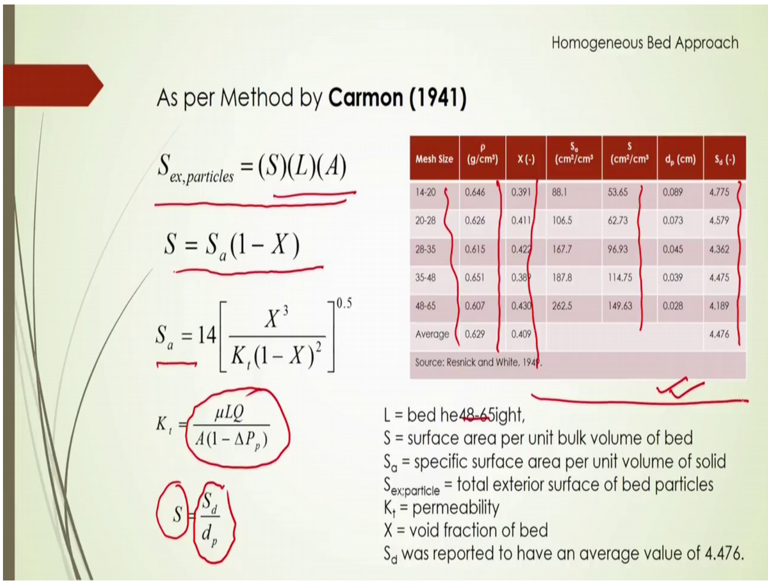

Now, there are several methods to find out this exterior particle surfaces for Carmon 1941; they have given one method to find out the exterior particle surface there. So, they have taken or they have suggested that that exterior particle surface will be is equal to S into L into A; whereas, S is equal to S a into 1 minus X.

What is S a? S a is equal to 1 4 into X cube by K t into 1 minus X square to the power 0.5. Whereas, K t is the parameter that will be is equal to is equal to that depends on the pressure drop of the particle there inside the bed. And mu L Q by A into 1 minus delta P p and S this S is equal to the S d by d p. What is this S d? S d is called that S d generally is a parameter which is reported and can be taken as average value of a 4.476 and d p is the particle diameter.

And here L enlarged bed height; bed height bed height and S is equal to surface area per unit bulk volume of the bed. And S is the specific surface area per unit volume of the solid and S ex particles (Refer Time: 23:16) total exterior surface of the bed particles. And K t is equal to permeability whose depends on that pressure drop and then for that X is equal to void friction of the bed.

And it is seen that this S d that parameters u that S is defined as that S d by d p S d how this S d will be changing with respect to particle size; there is the it is given one source from source that how this S d changing with respect to mesh size here. Then also how this S this surface area will be depending on the particle size there and also what is that

X value and what is the density of the particle; based on who is this S d value can be calculated.

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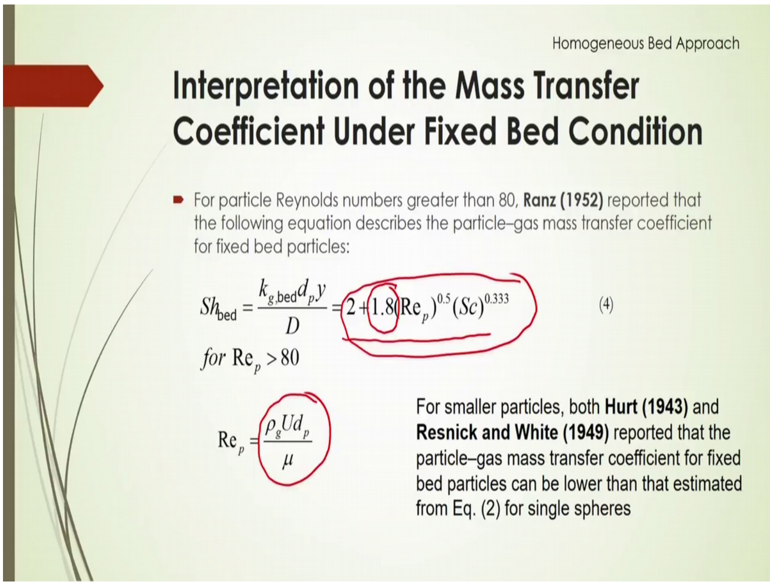

For particle Reynolds number if it is greater than 80 range 1952 reported that the following equation describes the particle gas mass transfer coefficient for fixed bed particles here. So, Sh bed fixed bed particles it will be is equal to 2 plus 1.8 into Re p to the power 0.5 into smith number to the power 0.333. It is exactly almost you can say the same trail, but here the instead of 0.6; it will come here 1.8.

So, this Re p is defined as here like this. So, for smaller particles both Hurt 1943 and Resnick and White 1949 reported that the particle gas mass transfer for fixed bed particles can be lower than the estimated from equation number 2 that has been given earlier here in this case for single particle.

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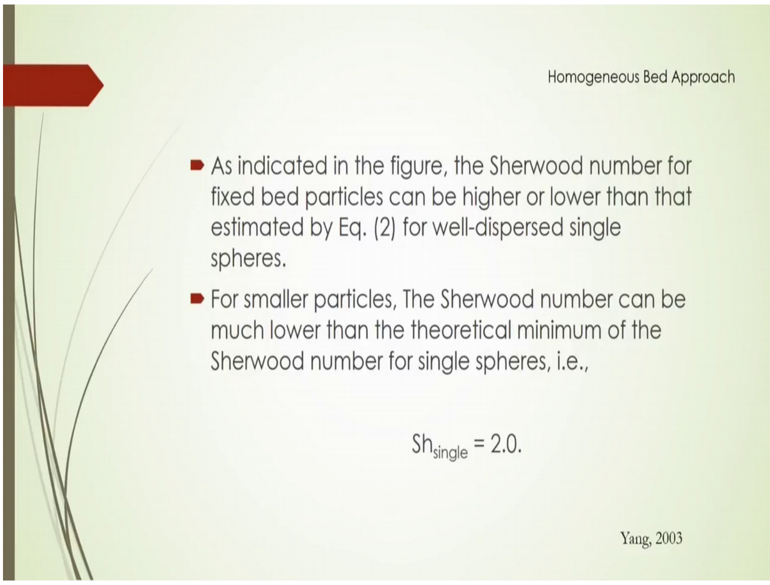

Now, you will see that the Sherwood number for the Sherwood number; Sherwood number for fixed bed particles can be higher or lower.

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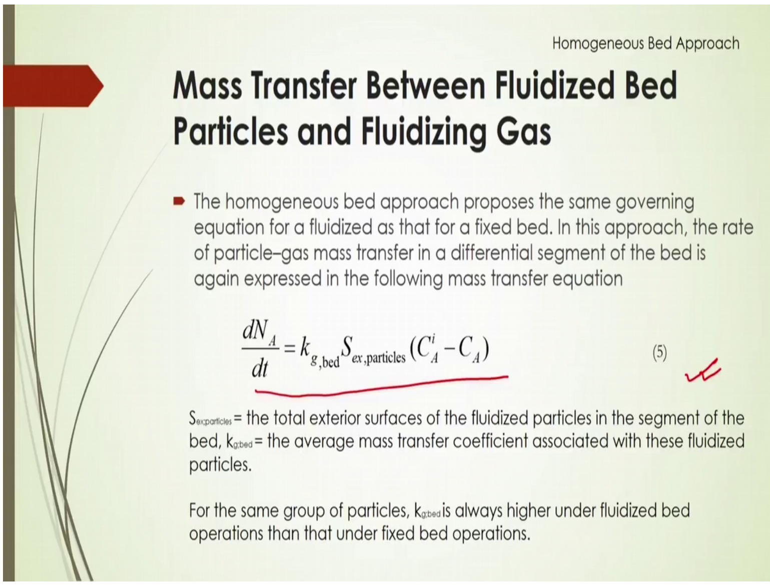

That depends on that depends on; that means several operating conditions here. And that here also will see minimum theoretical value of the Sherwood number will be is equal to 2.0.

Now, what will be the mass transfer then in case of fluidized bed particles and the fluidizing gas. Now, if we apply that homogenous bed approach here for this fluidized bed, then same a governing equation we can we can write here. And in this case the rate of particle gas mass transfer in a differential segment of the fluidized bed is again can be expressed in the following mass transfer equation like this here.

The similar way for that fixed bed here in this case particles will be moving whereas, in the fixed the particles are not moving. And also in this in the single particle case they are also particle may move or may not move there. So, in that case the how the mass transfer coefficient happens and in this fluidized bed how the mass transfer coefficient will be happening?

So, in this case both gas and particles should be moving; then the mass transfer rate can be expressed by this equation number 5. In this case again you will see that S ex particles that will represent the total exterior surface of the fluidized particles in the particular segments which are considered. And k will see g bed here it is ; it is actually denoted for the mass transfer coefficient associated those fluidized bed particles. And for the same group of particles you will see that k g bed is always higher under the fluidized bed operations then that under fixed rate operations.

So, very interesting that whether you are using same group of particles or not that depends very important here. If you are using A type particle that is gildered A type particles orbited particles you will see there will be different mass transfer coefficient compared to the gildered C type or d type particles there.

So, depends on the group of the particles. So, if you are using that same group of particles in fluidized bed operation and fixed bed operation and if you compare the mass transfer, you will see that for the same group of particles these mass transfer coefficients in the bed will be always higher under fluidized bed operations compared to that fixed bed operations.

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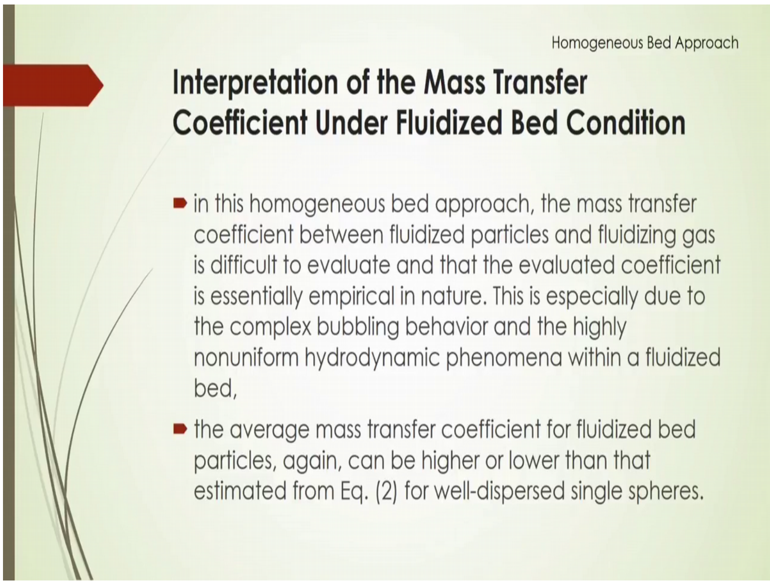

Now, in this case homogenous fluidized bed approached; the mass transfer coefficient between fluidized particles and fluidizing gas is very difficult to evaluate and that the evaluated coefficient is essentially; it will be empirical in lesser. This is because you know that there are several operating conditions that effects the mass transfer phenomena inside the fluidized bed.

So, that is why it is very difficult to actually obtain the mass transfer coefficient in the fluidized bed from the mechanistic model. So, generally empirical model are generally developed to represent the mass transfer coefficient inside the fluidized bed um. And this is especially due to the complex bubbling behavior or other you can say several particle size distributions inside the bed; bubbling behavior, flow pattern and the highly momentum you can say non uniform a hydrodynamic parameter or you can say hydrodynamic phenomena inside the fluidized bed that affect the mass transfer coefficient inside the bed.

The average mass transfer coefficient for this fluidized bed particles again can be higher or lower then that estimated from the equation 2 for well dispersed single spheres. So, it depends on how well or what will be the intensity of the mixing of the particles there inside the bed; that that is why we have already told about that what extent of mixing or what would be the mixing phenomena of the particles inside the bed that of course, you have to move because those things will affect the mass transfer behavior inside the bed.

So, average mass transfer coefficient that depends on how well the particles will be mixing inside the bed.

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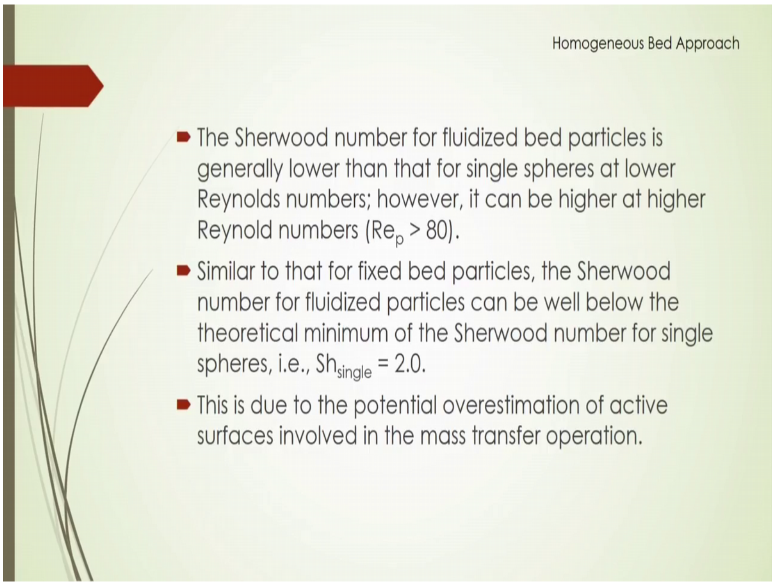

And the Sherwood number for this fluidized bed particles is generally lower than that or the single spheres at lower Reynolds number. In this case you will see for Reynolds number the particles will not be moving by inside the bloke bed that intensely and mixing will not be there inside the bed. And there will be no back mixing that is why sometimes you see for the lower a Reynolds number, this number fluidized bed would be sometime some extent lower; that means, the mass transfer coefficient is some extent to lower.

And it can be higher at higher Reynolds number because they are what will happen that case the well mixing phenomena will be inside the bed and back mixing sometimes some extent will be used there at higher flow rate. And that is why if Reynolds number of the particle is greater than 80; it is seen that that the mass transfer coefficient inside the bed will be increased relative to that single particle fluidized bed.

And similar to that fixed bed particles the Sherwood number for the fluidized particles can be well below the theoretical minimum of the Sherwood number for single sphere that is Sh is the single that will be is equal to 2 here. And this is because of the potential over estimation of the active surfaces of which are involving the mass transfer operation.

And in bubbling fluidized bed you will see that most of the particles are expected to stay in the immersion phases with some concentration that is C i a at equilibrium with C A in the emulsion gas. So, and most of the particles here may does be considered as the inert from the mass transfer point and mass transfer point of view and because they do not contribute to the significant amount of mass transfer to the bubbling gas.

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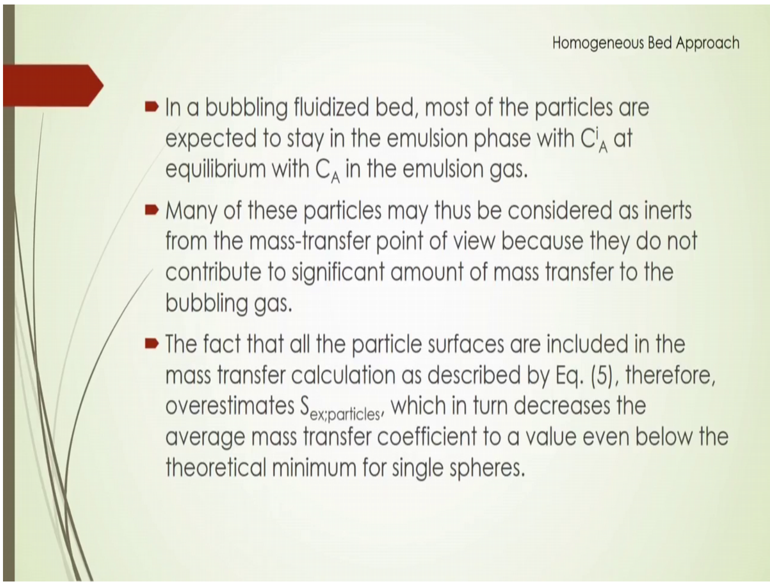

And the fact that all the particles surfaces are included in the mass transfer calculation that is described in equation number 5; therefore, over estimates that exterior surfaces of the particle which in turn decreases the average mass transfer coefficient to the value even below the theoretical minimum for the single spheres.

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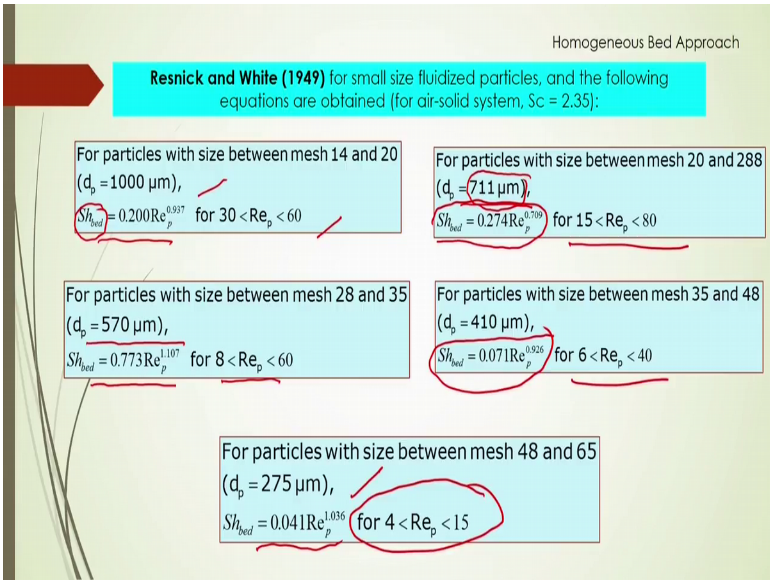

And for fluidized bed what should be the mass transfer coefficients; how it can be predicted empirically or Resnick and White 1949 for small sized fluidized particle and the they have given some equations for the mass transfer coefficient or empirical equations to predict the mass transfer coefficient here is shown in slides.

Therefore air solid system they have measured and they have considered that smith number is equal to 2.35. And based on that they have given this correlation Sh Reynolds number of the particle is in the range of 30 to 60 and particle diameter is 1000 micrometer, then the Sherwood number or; that means, mass transfer coefficient can be calculated from this relation.

Whereas, if particle diameter is little bit slower that lower that 1000 then; that means, 711 micrometer then Sherwood number to be calculated from this equation. This equation when; that means, Reynolds number will be within the range of 15 to 60; similarly for particle diameter of 570 micrometer then mass transfer coefficient within the range of Reynolds number of 8 to 60; this mass transfer coefficient can be calculated.

And for Reynolds number 6 to 40 for this particle and particle diameter of 410 micrometer the Sherwood number to be calculated and in this way from which this mass transfer coefficient can be calculated. Similarly for very small particles here 275 micrometer particles and the Reynolds number if it is very low; that means, 4 to 15, then Sherwood number to be calculated from this condition.

So, from these equations you will be able to calculate what should be the mass transfer coefficient and the fluidized bed even I am suggesting you to develop your correlations from the experimental data, from your sophisticated experimental data. Nowadays they have actually used their experimental data to develop these correlations. And they have done their experiment by their with within a certain operating range, but you can do the experiment in fluidized bed mass transfer experiment also you can do.

And changing different operating conditions you can also have the mass transfer coefficient data based on the different operating conditions and by the dimensional analysis and you can have different correlations based on your experimental data. And this function this mass transfer coefficient then can be represented by different I think non dimensional groups by dimensional wises.

And that functionality can be actually analyzed by your experimental data by least square method or you can say multiple linear regression method to develop this type of correlation.

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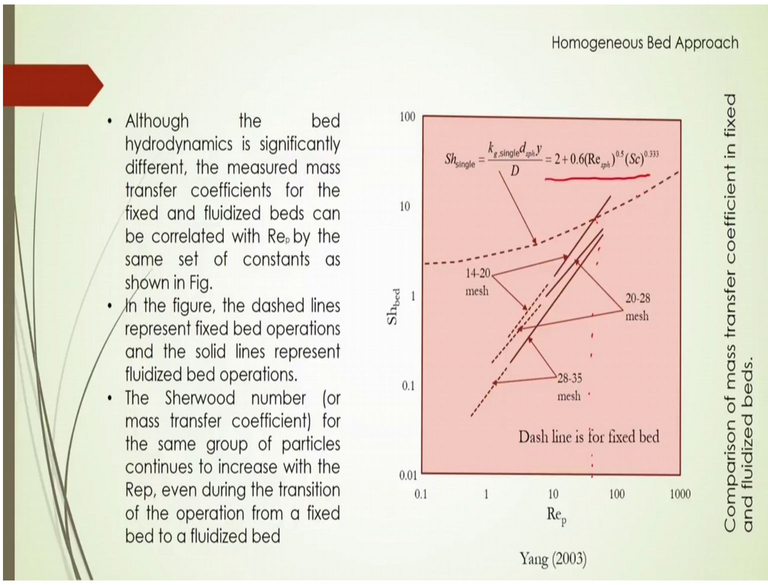

Here seen this figure Yang 2003 he has given one chart here for comparison of mass transfer coefficient in fixed bed and fluidized bed here. You will see that in this figure dashed line is for fixed bed operating condition and this year this dash line here for single particle operating condition.

Now single particle bed here the mass transfer coefficient or Sherwood number can be represented by this equation that already we have shown. And for fixed bed you will see that mass transfer coefficient would be lower than this single particle whereas, the fluidized bed you will see after a certain Reynolds number here; you will see less greater than 80; you will see that the mass transfer coefficient will be beneficiated or higher than the fixed bed condition and single particle fluidized bed.

So, in the fluidized bed it is already it will be it will be higher only for the Reynolds number is greater than 80. Whereas, if it is less than 80 then the mass transfer coefficient will be lower. So, in that case fluidized bed operation will not be beneficial compared to the fixed bed operation. It is also observed that or it is reported that the bed hydrodynamics is the main important parameter which governs or which effects the mass transfer coefficient for the fixed bed and the fluidized bed operation.

You will see that Sherwood number will be more higher in case of single particle there. Because there will be no interaction of the solid particles or in the other solid particles, even with the bubbles they are inside the bed. So, whenever you are considering fluidized bed; so, bubbling fluidized bed there may be interaction between solid and bubble and solid and other solids and that is why sometimes these mass transfer coefficient will be lowering within a certain range of Reynolds number.

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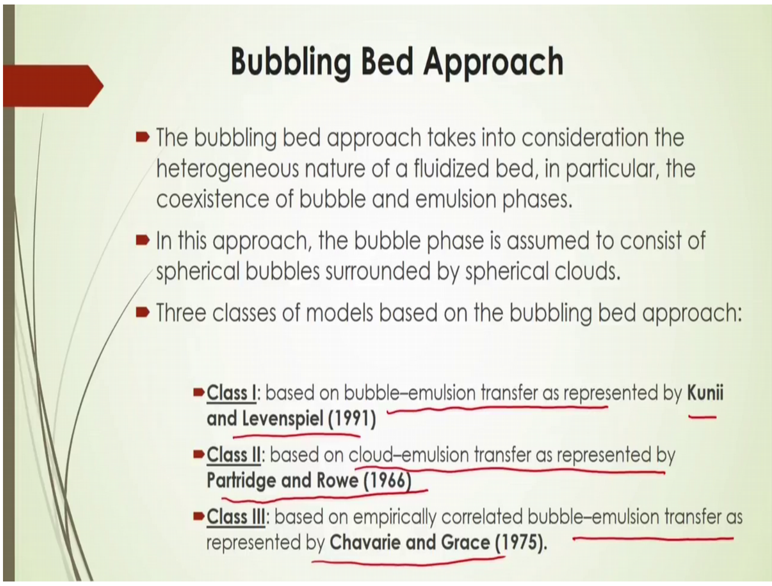

Now, bubbling bed approach; what is that bubbling bed approach? The bubbling bed approach takes the consideration that we told that already there should be two phases; one would be the bubble phase another would be the emulsion phase.

So, generally the three classes of models based on the bubbling bed approach can be divided. One is based on bubble emulsion transfer as represented by Kunii and Levenspiel; another is called the cloud emulsion transfer as represented by Partridge and Rowe and the class III based on the empirically correlated bubble emulsion transfer as represented by Chavarie and Grace.

So, this bubbling bed approach will be actually considered here the phenomena of the bubble emulsion interaction even cloud is there any cloud surrounding this bubble that also include there.

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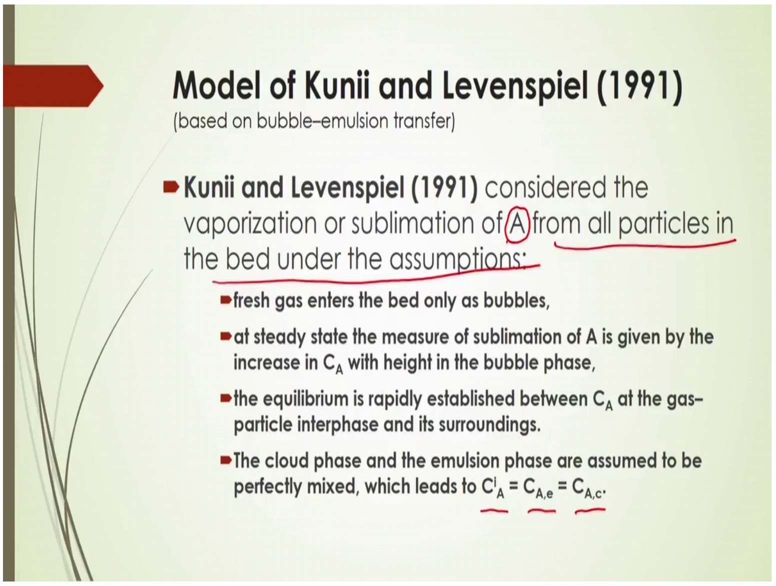

Now, based on that Kunii Levenspiel bubble emulsion transfer approach; there they considered that vaporization or sublimation of A; component A from all particles in the bed under the upon assumptions here. They assumed that fresh gas enters the bed only as bubbles at steady state the measure of sublimation of A is given by the increase in C A with height in the bubble of phase. And the equilibrium is rapidly established between concentration of that component A of the gas particle interface and its surroundings.

The cloud phase and the emulsion phase are assumed to be the perfectly mixture which leads C A i is equal to C A e that will be is equal to C A c here; what is C A i? The concentration of A at the interface and C A is the concentration of A or component A in the emulsion and concentration of component A in the cloud phase.

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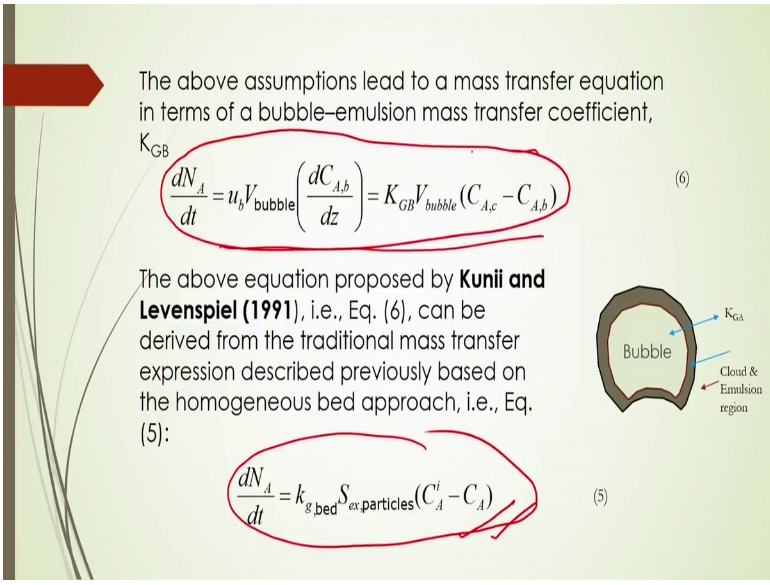

Now, these assumptions lead to the mass transfer equation in terms of bubble emulsion mass transfer coefficient which can be expressed by this equation number 6. Now the above equation of course, proposed by this Kunii Levenspiel and can be derived from that traditional mass transfer expression that is described previously based on the homogenous bed approach there in equation number 5.

So, based on this equation you can derive this equation for this here for bubble emulsion mass transfer coefficient.

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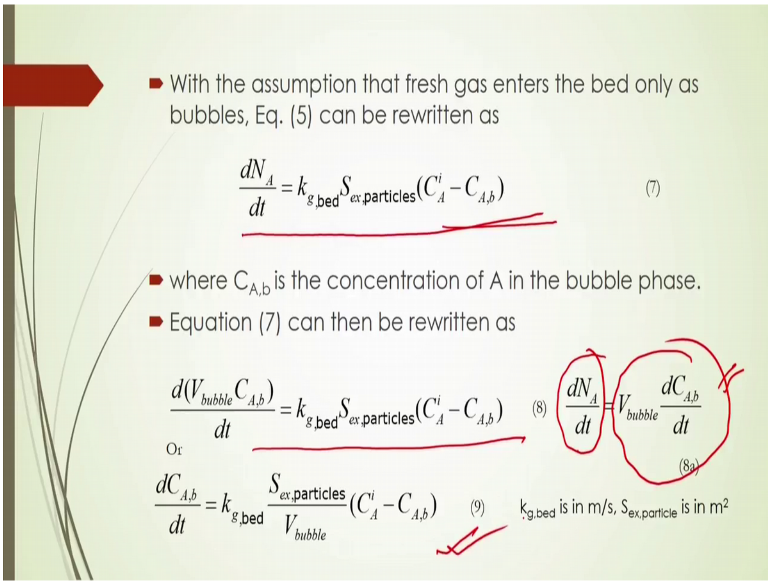

With the assumption that fresh gas enters to the bed only as bubbles equation 5, then can be rewritten as here d N A by d t equal to k g into bed into S ex particles into C A i minus C A b here. Now C A b is the concentration of component A in the bubble phase, then equation 7 can be rewritten and can be represented by this equation number 8. And from this you can say that d N A by d t can be represented by this bubble volume also, this V volume this d C A b by d V in terms of concentration of that component in bubble phase.

So, if you express this equation number 7 in terms of concentration instead of number of moles, then you will get this equation number 0.

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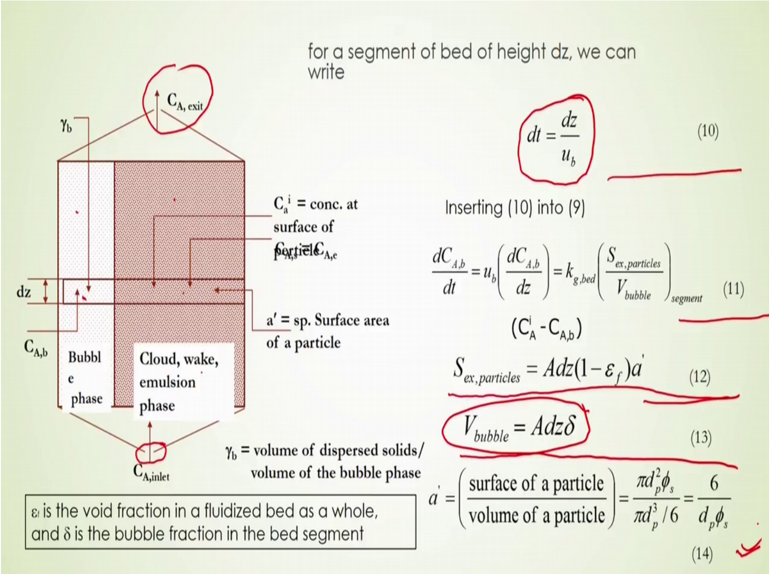

Now, you see I see here this figure there are two phases one is bubble phase, the total fluidized bed is segmented into or you can say that divided into two parts C r one is called that bubble phase and this is called the emulsion phase and emulsion include the cloud wake emulsion phase here and bubble phase here.

So, here C A inlet from this region inlet and this is the C outlet or exit you can say and this gamma b gamma b gamma b is nothing, but volume of dispersed solid for volume of bubble phase is there any small amount of particles there in the bubble phase or not that can be represented by gamma. And this the segment of the fluidized bed in which you will see some portion will be the bubble phase some portion will be the emulsion phase.

And in this region you will see you can represented the C A i is equal to the concentration at surface and here and then what will happen that a dash to the specific surface area of the particle and d z and C A b it is the here the what should be the concentration of the component in the bubble phase there.

So, if we a consider here for a segment of bed of height d z then you can write here d t will is equal to d z by u b. Now if you substitute this equation 10 that is d t is equal to d z by u b in equation number 9, then you can get equation number 11 here. And S ex external surface area of the particle or exterior surface area of the particle can be represented by this equation number 12. And this then it will be is equal to V bubble is equal to that will be equal to A into d z into delta and a dash can be defined as by equation number 14.

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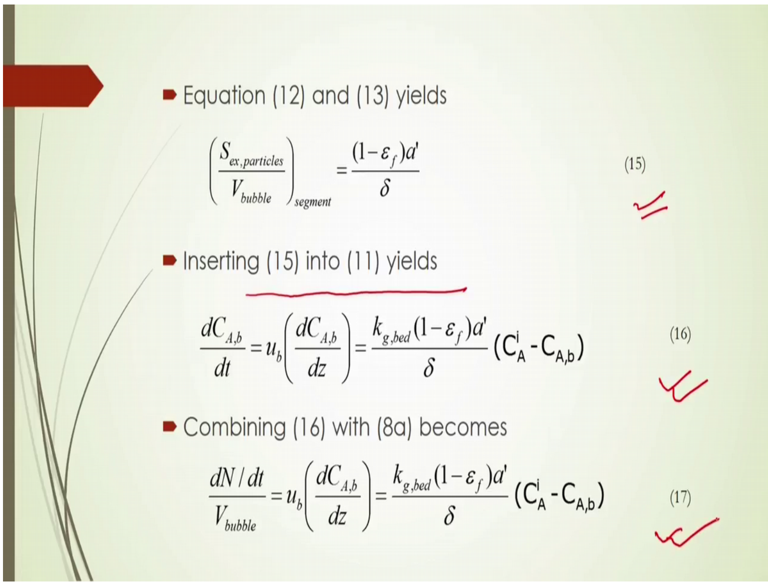

After substitution of this equation in equation number 11; then you can get here equation 15; inserting this 15 into 11 yields this final equation 16. And combining this 16 and 8 a, then will become equation number 7 and in after simplification.

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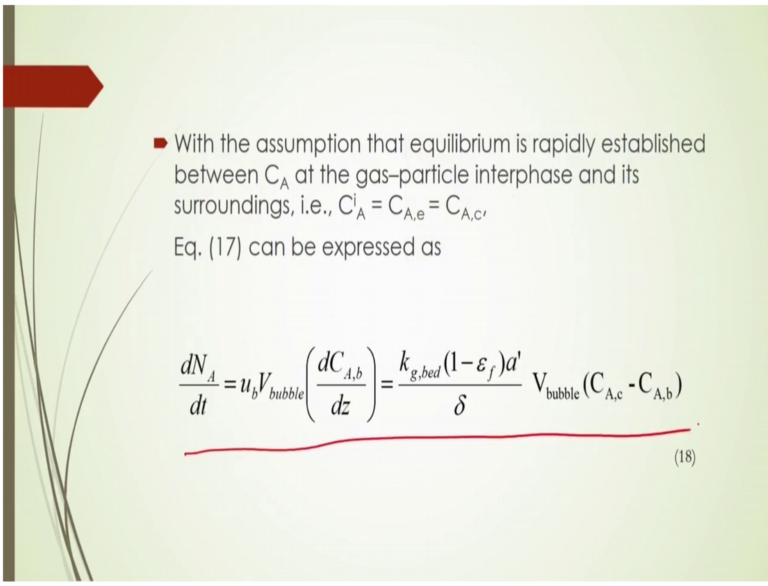

And then again with the assumption that equilibrium will be there if this equilibrium will be readily or rapidly established between C A at the gas particle interface and its surrounding that is C A i that will be is equal to C A e and that will be equal to C A c; then equation 17 can be expressed by this equation number 18.

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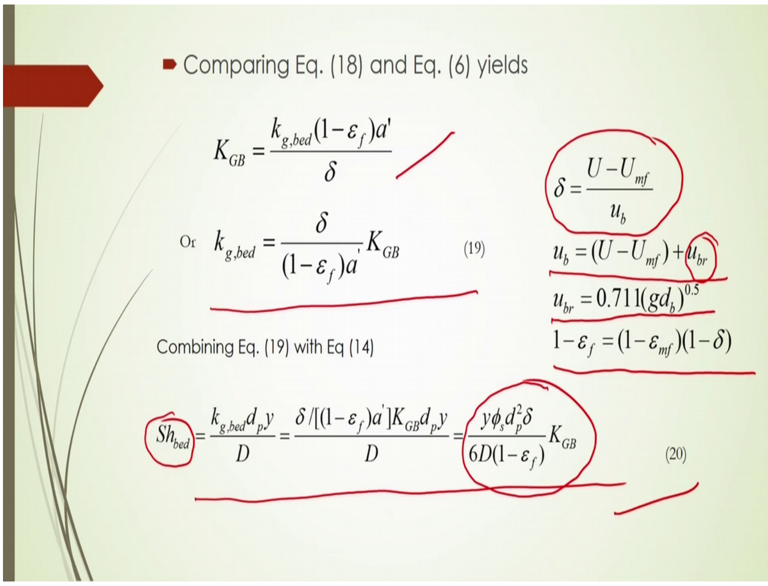

Now, combining equation 18 and 16 that will yield this k g b that will be is equal to k g bed into 1 minus epsilon f into a dash by delta, where delta would be is equal to u minus u m f by u b that already we have described in earlier lectures regarding apart from the bubble fraction in the bubble fluidized bed. And what would be the u b; that means, bubble rise velocity there that depends on the gas velocity minimum fluidization and the bubbles rise velocity; this bubble rise velocity to be calculated by this equation that depends on the bubble diameter and then we are porosity of the fluid inside the bed will be there.

So, by this equation number 19; you will be able to calculate what should be the bed mass transfer coefficient there. Now, combining this equation number 19 and with the equation number 14; you can say Sh bed that is Sherwood number of the bed will be representing by this equation number here; that is y phi S d p square delta by 6 d into 1 minus epsilon f into k g b this is equation number 20; which can be easily find out once you know that diffusion coefficient of the gaseous medium and the porosity of the bed and the what would be the bubble phase fraction particle diameter and mass transfer coefficient there.

So, this by this equation of Sherwood number you will be able to express what should be the mass transfer coefficient in the fluidized bed; when both particles and gas should be moving inside the bed

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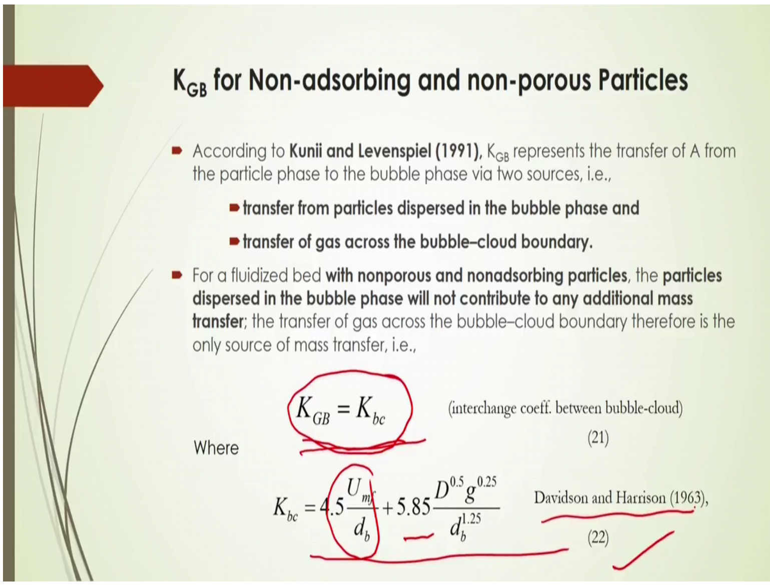

Now if suppose there is a condition that there will be no adsorption of gas inside the bed and non porous particles. So, according to that Kunii and Levenspiel K GB represents the transfer of A from the particle phase to the bubble phase via two sources one is transferred from particles dispersed in the bubble phase and transfer of gas across the bubble cloud boundary.

Now, I think we have already discussed about that there is a cloud surrounding the bubbling fluidized bed and how bubbles are moving rising along with that cloud and the wake region. Now, for a fluidized bed its non porous and the non adsorbing particles is there; the particle dispersed in the bubble phase should not contribute to any additional mass transfer. So, that is why the transfer of gas across the particle cloud boundary therefore, in the only source of mass transfer inside the bed.

So, there will be that transfer coefficient with the K GB is equal to K b C here. So, there will be; so, in that case it is important that if that there will be or that particles (Refer Time: 50:00) additional mass transfer coefficient. So, this you can say that K GB is equal to K bc ; that means, here interest the mass transfer coefficient that contributes by the inter sense coefficient of the component from this bubble to cloud.

So, at this K bc will be is equal to the intersence coefficient will be is equal to 4.5 into U m f by d b plus 5.85 into D to the power 0.5 g to the power 0.25 by d b to the power 1.25 that has already given earlier in lecture. So, it is given by Davidson and Harrison model.

So, once you know that transfer coefficient of that bubble to cloud then here for non absorbing and the non porous particles; you can directly calculate what should be the mass transfer coefficient inside the bubble fluidizing bed. Now, the inter sense coefficient K bc consider the combined effects of true flow of gas q and the mass transfer coefficient between bubble and cloud.

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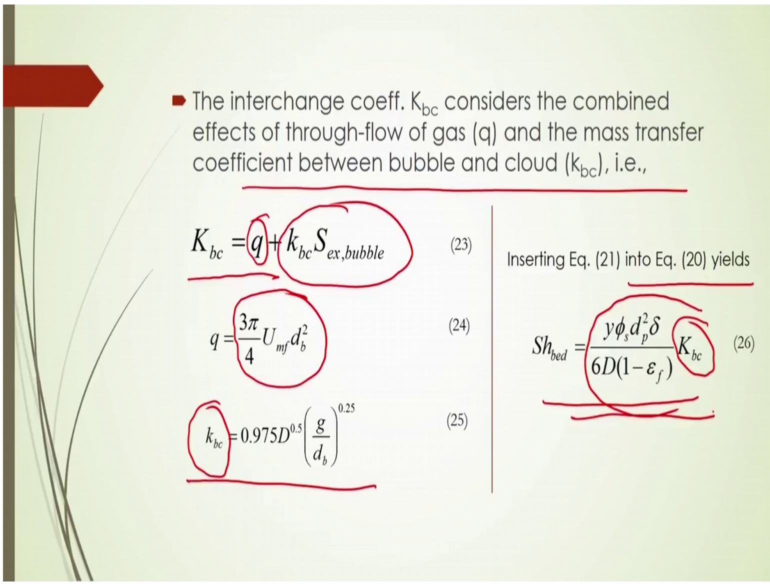

So, in that case K bc will be is equal to q plus K bc into S ex bubble; this q that already we have discussed that will be is equal to 3 pi by 4 into U m f into d b square. So, this K bc will be is equal to what? This 0.975 into D to the power 0.5 g by d b; so, this K bc depends on the mass transfer coefficient, bubble to cloud depends on the diffusivity of the gas and also the size of the bubble inside the bed.

Now, inserting equation number this 21 into 20; that yields finally, this equation 26 of the substitution of this K bc here. So, K bc is important here; we know that K bc then what should be the Sherwood number of the fluidized bed for mass transfer coefficient.

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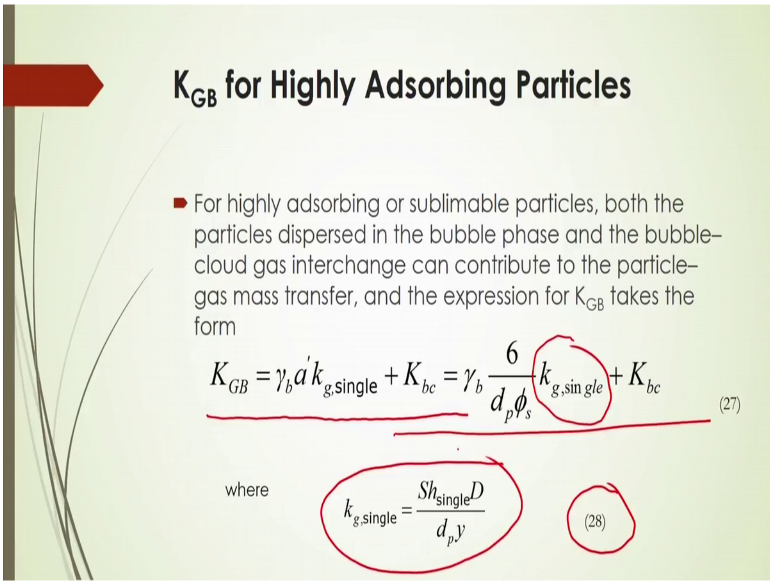

Now if there is a highly adsorbing particle sensor inside the bed, then what should be the mass transfer coefficient? For highly absorbing a bed or you can say sublimable particles both the particles dispersed in the bubble phase and the bubble cloud gas inter sense, then can contribute to the particle gas mass transfer. And the expression for K GB that takes place form this in the form of this equation here K GB is equal to gamma b into a dash into k g into single plus K bc.

So, this equation number 27 can be used for the analysis or you can say predicting the mass transfer coefficient for the highly absorbing particles. And here, very important that this mass transfer coefficient is expressed by the single single particle mass transfer coefficient inside the bed yeah; so, this equation 28 is expressed for the single particle mass transfer coefficient inside the bed.

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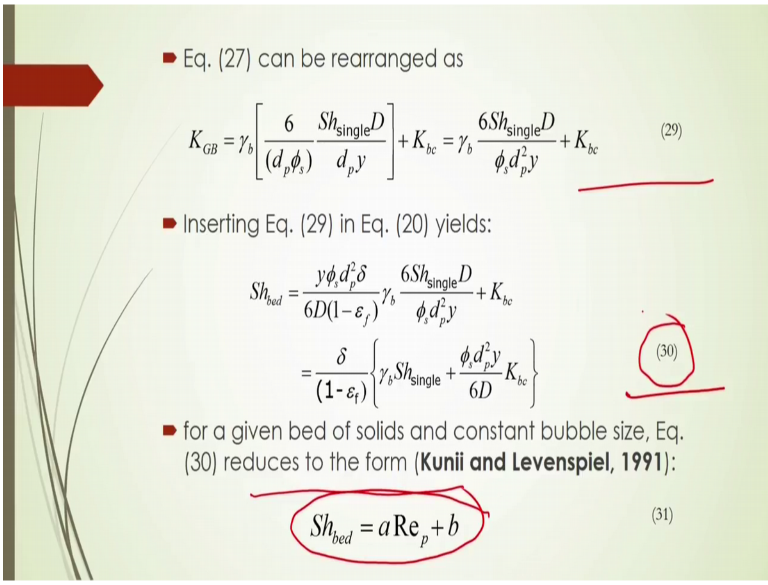

Now, in question 27 can be rearranged as here by question 29 and inserting this equation 29 in equation 20, it will give you the equation number 30. So, for a given bed of solids and constant bubble size equation 30 reduces to form simple here Sherwood number obeyed that would be equal to a into Re p plus b, where a and b are the respective parameters as per simplification of this equation 30.

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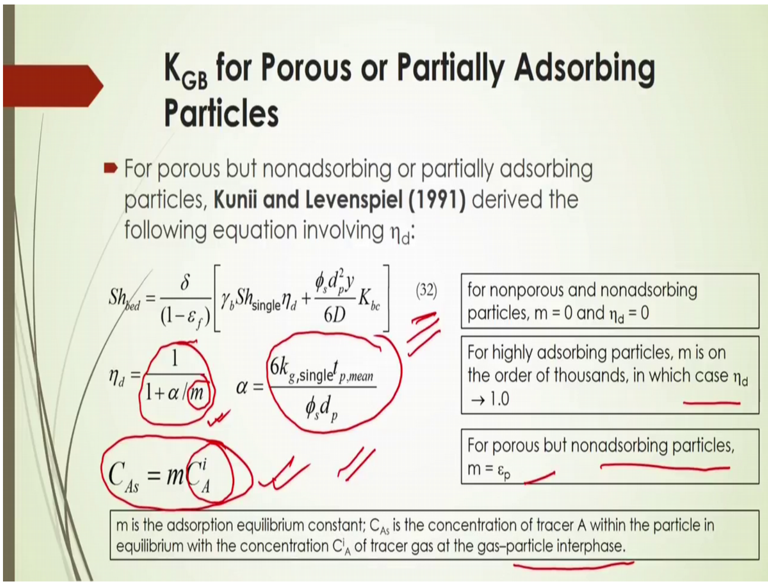

For porous or partially adsorbing particles here porous, but non adsorbing or partially adsorbing particles Kunii and Levenspiel 1991 derived the following equations here given by equation number 32; they have given this equation in terms of efficiency of the adsorption there. So, here this eta d this is represented by 1 by 1 plus alpha m. Here alpha is the parameter which is a function of the particle diameter and the single particle mass transfer coefficient. And also what will be the exposure time of that particle said the bed for mass transfer there.

And here a very interesting point that m is one parameter that is called equilibrium constant. Here this equilibrium constant that what will be that surface concentration of that component A and what is the relation that surface concentration to that interface component concentration there, you can say that it will be represented by this equation and C as are in the concentration of the tracer A or you can say component a within the particle here and in the equilibrium with the concentration C i A at the gas particle interface.

So, by this equation 32, you will be able to calculate if there is a porous, but non absorbing particles or partially absorbing particles are there, you can express the mass transfer coefficient in the fluidized bed by this equation 32. Now for non porous and non absorbing particles m should be is equal to 0 and then hence the eta d should be is equal to 0. And for highly absorbing particles m is on the order of thousands in which case eta d tends to 1, for porous, but non adsorbing particles m should be is equal to epsilon p.

So, after substitution of this eta d and m value for different operating conditions then you will be able to calculate what will be the mass transfer coefficient whether; the particles will adsorb the component or non adsorbed in the particles or you can say partially adsorb the particle. So, whether it is porous or non porous; so, equation 32; you can finally, use for your mass transfer expression in the fluidized bed to predict the mass transfer coefficient inside the bed.

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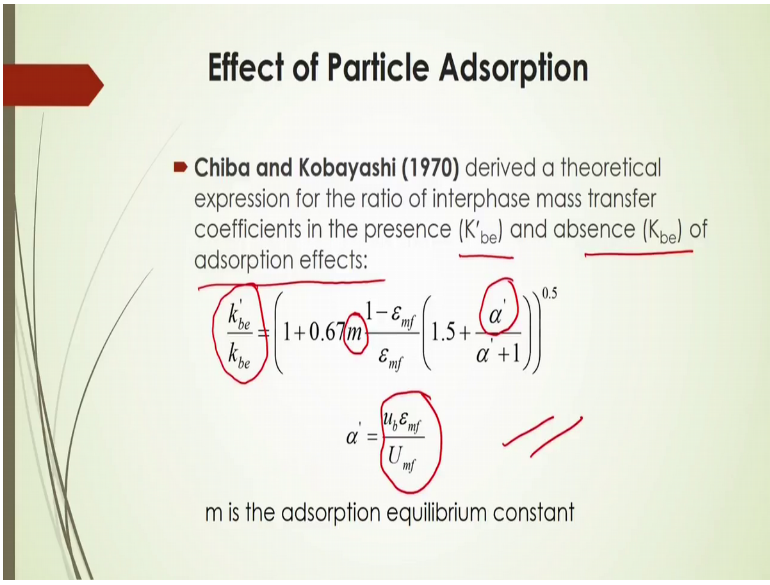

Now, if is there particle adsorption then how the effect of particle adsorption will be there inside the bed; now Chiba and Kobayashi at 1970 derived a theoretical expression for the ratio of interchange; interface mass transfer coefficient in the presence of this K be and absence of K be of adsorption coefficients here.

So, k b e by k k b e dash by k b e that will be represented by this equation here; where alpha dash will be represented by this here one parameter this is important here and m is the adsorption equilibrium coefficient.

So, this is another model how the if there is a adsorption of gas inside the particle.

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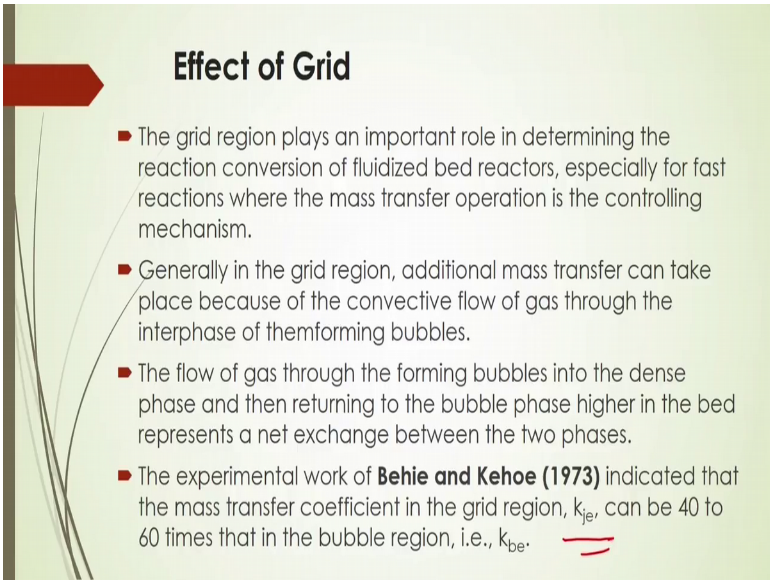

And effect of grid is there any grid effect for the mass transfer or not. The grid region plays an important role in determining the reaction conversion of fluidized bed reactors. Especially for first reactions where the mass transfer equation is the main controlling mechanism. And in the grid region you will see that additional mass transfer may be happened because of the convective flow of gas through the; interface of interface of thermo, you can say interface of that changing of that bubble surface there.

Because you will see that if is there grid then what will happen the velocity inside the bed will be higher; actual velocity inside the bed will be higher. So, because of who is that the change of mass transfer will be there; the flow of gas through the forming bubbles into the dense phase. And then returning to the bubble phase higher in the bed that will represents a net exchange between the two phases.

Now, the experimental work of Behie and Kehoe 1973 you can say that they have indicated that the mass transfer coefficient, the grid region can be 40 to 60 times that in the bubbles region. So, this is very important that; so, grid region will enhance the mass transfer coefficient inside the bed.

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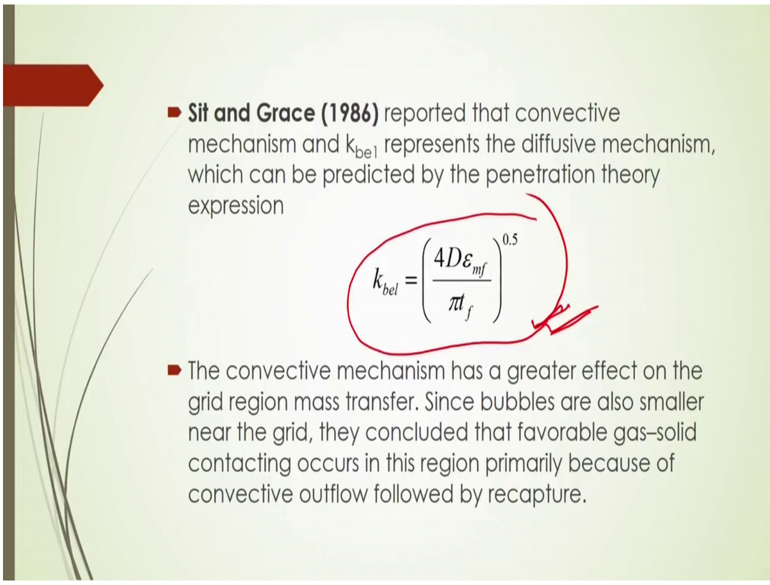

According to Sit and Grace you can say that convective mechanism and k b e a represents the diffusive mechanism which can be predicted to the penetration theory expression by this equation. So, from this k b e l it is called that convective transport mass transfer coefficient inside the bed; though this convective mechanism has a greater effect on the grid region mass transfer.

And since the bubbles are smaller near the grid and they concluded that favorable gas liquid or gas solid a contacting occurs in this region primarily because of convective outflow followed by the recapture.

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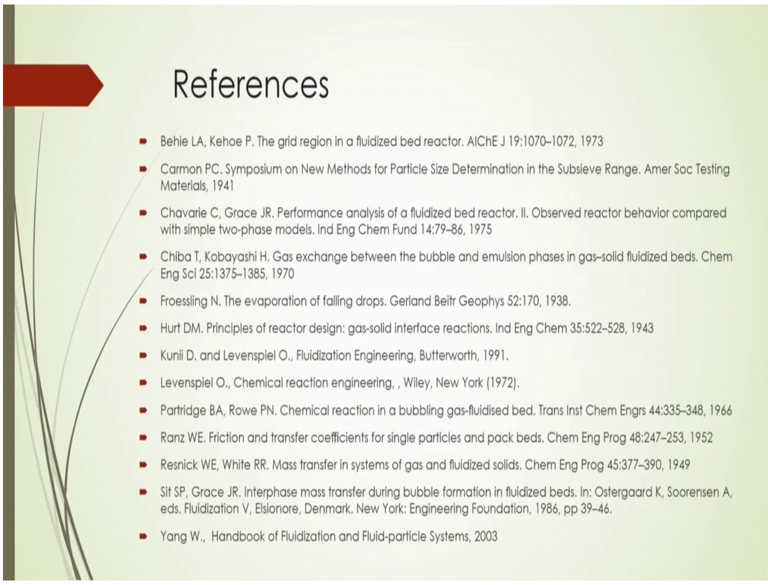

So, I think we have discussed about the mass transfer phenomena inside the bed for what is that for single particle and for that fixed bed conditions and what would be the mass transfer characteristics in bubbling fluidized bed.

And we have seen that bubbling fluidized bed will give you more mass transfer if Reynolds number is greater than 80 even in grid region also that mass transfer coefficient will be more higher. Because there would be a high velocity and also that due to the bubble breakup mole smaller bubbles will be there. And then bubble to the emulsion phase the transfer will be more and also we will see that other phenomena of that mass transfer how it will be changing inside the bed.

And several correlations also developed here to represent or to predict the mass transfer coefficient inside the bubbling fluidized bed. And based on the inter sense coefficient you also will be able to calculate what should be the mass transfer coefficient inside the bed and this is the gaseous solid mass transfer phenomena.

And in the next lecture we will discuss about the gas liquid solid mass transfer phenomena. There of course, you will see that not only here gas and solid will be there, liquid also will take part to enhance the mass transfer coefficient. And more about that mass transfer coefficient will be discussed in the next class and for this gas solid operation and mass transfer mechanism, you can follow more literature this is given in references so.

Thank you for attention.