Fluidization Engineering

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Lecture - 28
Mass transfer in fluidized bed-Gas-liquid-solid system

Welcome to massive open online course on Fluidization Engineering. So, today's lecture on mass transfer in fluidized bed in gas liquid and solid system. So, in the previous lecture, we have discussed about the mass transfer phenomena in case of gas solid fluidized bed system. So, they are we have seen that the mass transfer mechanism or mass extent of mass transfer or rate of mass transfer depends on different factors like flow rate and particle size and also the physical properties of the system. And also they are whether the particles are porous or non porous and if the particles are adsorbing the partic[le] adsorbing the gaseous components they are on its surface or not.

So, based on fluids that mass transfer characteristics would be changing; based on that particle characteristics; not only that that in case of bubbling fluidized bed that we have seen that due to the solid movement surrounding the bubbles and also the region of cloud surrounding the bubbles that may govern the mass transfer they are. And it is seen that that interchange of that gas will give you the extent of mass transfer inside the gas solid fluidized bed and here in this lecture, we will see that whether that mechanism will be there or not and or if gas liquid both will be there in presence of solid then how that mass transfer will be happening here.

So, here instead of 2 phase, we will be considering that 3 phase and then you will see that interface between this gas liquid and liquid solid even gas solids will be there and through which that mass transfer may happen. In this case, the mass transfer phenomena will be depending on the phase characteristics as well as the holdup of the phases inside the bed and the what is that mixing characteristics of the phases inside the fluidized bed now of course you will see that. ah

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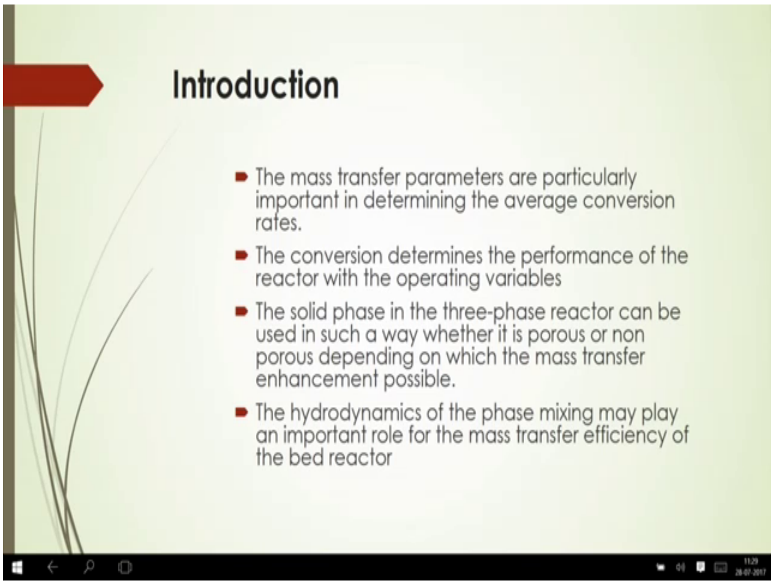

This will be the determining factor for the average conversion rates in fluidized bed and then that conversion determines the performance of the fluidized bed reactor with different operating variables. And in the 3 phase solid 3 phase fluidized bed reactor, the solid phase can be used in such way that whether this solids will be porous or non porous that depending on which the mass transfer enhancement may possible because of the there will be some adsorbing phenomena of the solid particles there.

Of course, the main important factor whatever we have discussed earlier also before starting this mass transfer phenomena and said the fluidized bed of this phenomena that any reactor whenever you are using the performance of the reactor, you have to know the hydrodynamics characteristics of that particular phases whatever flows of that phases inside the bed is happened.

So, hydrodynamics of the phase basically mixing characteristics flow pattern; that change that mass transfer rate.

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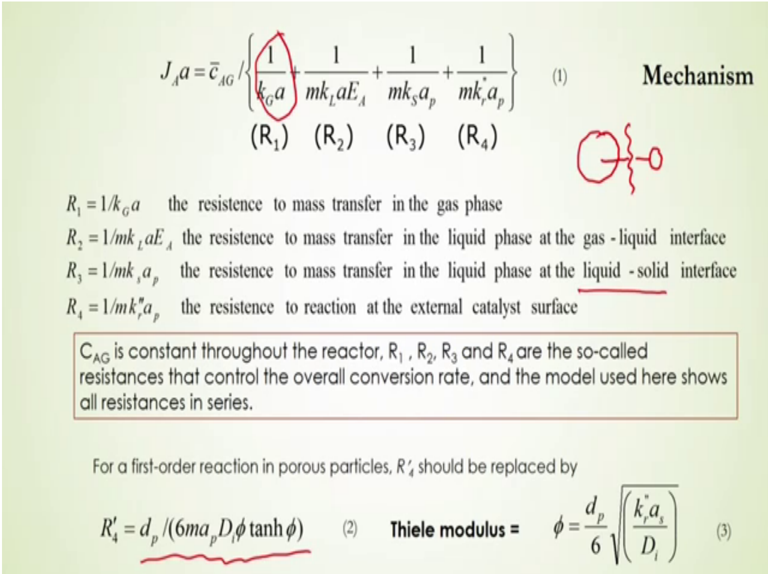

And said the fluidized bed we know that mechanism of that 2 phase theory of mass transfer characteristics they are. So, here you see if you see that the that equation 1 here one mechanism that; what does it mean that J that would be equal to C A G bar by 1 by k G a plus 1 by m to k L a if E A plus 1 by m k S a p plus 1 by m k double dashed r a p; what does it mean? Actually this; why we should write in this equation? They are in fluidized bed for 3 phase operation for mass transfer mechanism, of course, it is the things that if you are considering the component a is transferring from one phase to another phase, then you can say what should be that rate of mass transfer they are.

So, if we consider that rate of mass transfer is that J A J into A, then it will be is equal to 1 like this; of course, whenever transferring up component from 1 phase to another phase, there will be certain resistance to transfer from one phase to another phase. Now what are those resistances here this resistances are represented by this R 1 R 2 R 3 and R 4 what is this R 1 r one is that is 1 by k G a; this 1 by k G a denotes the resistance to mass transfer in the gaseous phase here and R 2 is 1 by m k L a E A; the resistances here to mass transfer in the liquid phase at the gas liquid interface.

So, here gas to gas liquid interface and then what is then 1 by m k S a p, the resistance to mass transfer in the liquid phase at the liquid solid interface. So, first here gas to liquid then liquid to solid. So, there will be interface between liquid solid here also and then R 4; another resistance, it is called the resistance to reaction and the external catalyst surface there. So, we are aware of the resistance of the mass transfer whenever the component is transferring from one phase to another phase like from gas phase to the solid phase here. So, what are those barrier or resistance that the cross that is called here one is gas to liquid interface, then liquid to solid interface and then solid phase there. So, initially, it will come from gas phase like if it is suppose, this gas phase and then gas phase to the here liquid phase and then this is liquid phase liquid phase to that it will go to the solid phase there and then it will be there of the remaining part again it will be the gas phase or solid phase like this.

So, there may be barrier of that gas liquid solid interface they are. So, this mass transfer rate J A can be represented by this resistance in terms of resistance that is called C A G by this is one that is called by R 1 plus R 2 plus R 3 plus R 4. So, in this way this mass transfer rate can be expressed in case of 3 phase fluidized bed system and here; in this case, C A G bar is the constant concentration of the component in the gas phase throughout the reactor and R 1 R 2, R 3 and R 4 are the so called resistances that control the overall conversion rate and the model used here shows the all resistance in series here because it will come as R 1 plus R 2 plus R 3 whenever their mass transfer from the gaseous phase to other phases to their interfaces.

For first order reaction, you will see that generally in case of porous particles and some specific example for that the first order reaction then r dashed that is R 4 should be replaced by the r dash four here this R dashed 4 will be represented by this equation d p by 6 m a p D i phi into tan h phi here this phi is called this Thiele modulus who should be depending on that particle size and also rate of reaction. They are inside the bed also there were surface area of the surface and molecular diffusivity of the component i. So, in this case this for first order reaction, you will see that this R 4 that this resistance should be represented by in terms of particle diameter and Thiele modulus.

So, from this I think rate of mass transfer you will be able to know what extent of mass transfer in the fluidized bed for 3 phase system is going on and there is the mechanism; that means, here now all the phases whenever, it will be crossing then there will be some resistance there liquid phase gas phase and gas liquid solid liquid and the solid phase resistance on you they are see this picture.

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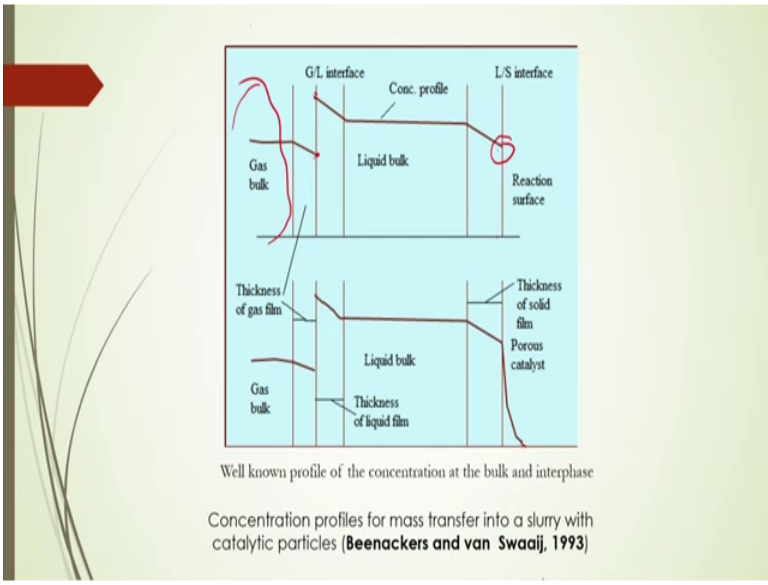

Here this is well known profile of concentration at the bulk and the interface whenever there will be mass transfer or inside the gas liquid solid systems. So, in this case you see that here if we see that this concentration profile this is the gas bulk phase in this case, the concentration will be almost remain constant and after that you will see in the very adjacent to that interfaces of that gas liquid; that means, very thin film of the gas between this liquid and gas, then there will be certain change of concentration. Here, it will decrease and at the interface there would be certain concentration and at the interface there will be some equilibrium of that concentration of gas out of the liquid here in the liquid.

So, here it will be the liquid concentration and gas concentration that would be at equilibrium condition here that would be related some equilibrium constant and after that you will see whenever it will move to the liquid and very adjacent to this gas liquid interface very thin film of liquid, whenever it will pass through this thin film, then here again the concentration will decreases because resistance is high and then after that in the liquid phase there will be constant of concentration they are profile for that component a. Again if we consider that solid phase here that here liquid solid interface, in this case, you will see that the at the solid surface there will be reaction surface and adjacent to this solid surface that is liquid solid interface, there will be thin film that concentration will be decreasing and then here again at the surface the solid surface there will be reaction take place there.

So, this is the profile concentration profile when the component would be reacting with some of the reactant and how the mass transfer is happened in the fluidized bed there and another profile here, if suppose there is porous catalyst is used, then what will happen this had this the solid surface the solid surface; what this the concentration profile will be exponentially decreasing with the; that means, thickness from the surface to the solid.

So, this mechanism or concentration profile is shown first by Beenackers and Van Swaaji; 1993. So, from this mechanism, we can infer what should be the actually mass transfer mechanism and what should be the concentration of the component which is transferring from one phase to another phase by changing its concentration from its phase layer to the another phase.

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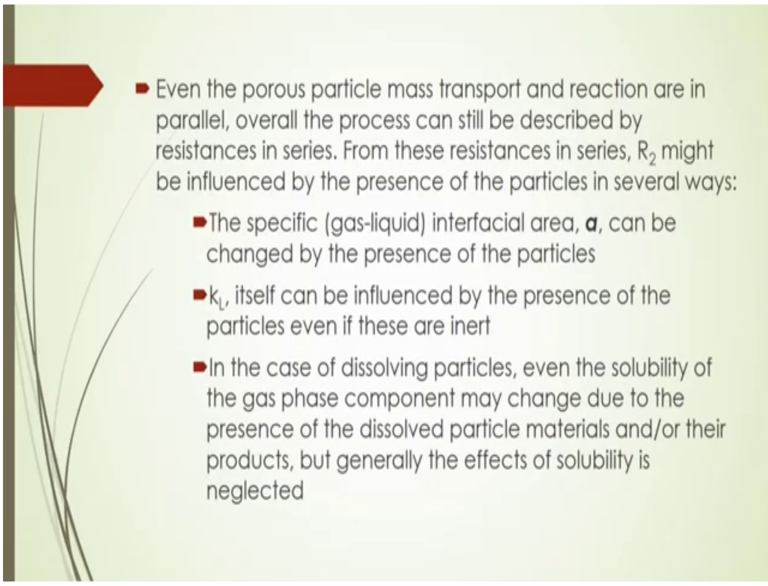

Now, if porous particle mass transport and reaction if there are parallel then overall the process can still be described by the resistance in series. So, from these resistances in series; that R 2 might be influenced by the presence of all particles in several ways. So, the specific gas liquid interfacial area a that can be changed by the presence of the particles there.

Of course, whenever you are going to do any experiment in gas liquid solid fluidized bed suppose in a column from the bottom, if you supply some gas, then what will happen in solid liquid slurry, then you will see, there will be gas liquid solid operation and they are there will be some up holdup of gas inside the bed and then this holdup of gas will be changing with particle are concentration and also size of the particles and then the interfacial area gas liquid interfacial area will be changing in presence of solid particles there and because of fluids, you will see that mass transfer rate will be changing because the mass transfer rate that depends on the interfacial area of gas liquid as well as gas solid.

So, in that case; individual mass transfer coefficient in liquid itself can be influenced by the presence of particles even if these are inert in nature in the case of dissolving particles you will see when the solubility of gas phase component may change due to the products, but generally the effects of solubility is negligible. So, very interesting that the mass transfer rate a depends on that interfacial area of gas and liquid and also gas sorry solid and liquid surface area. So, in 3 phase fluidized bed, you can control or you can change the gas holdup and because of which that interfacial area of gas and liquid and because of which that rate of mass transfer will change in the fluidized bed.

Now, how can I then enhance the mass transfer in the presence of particles.

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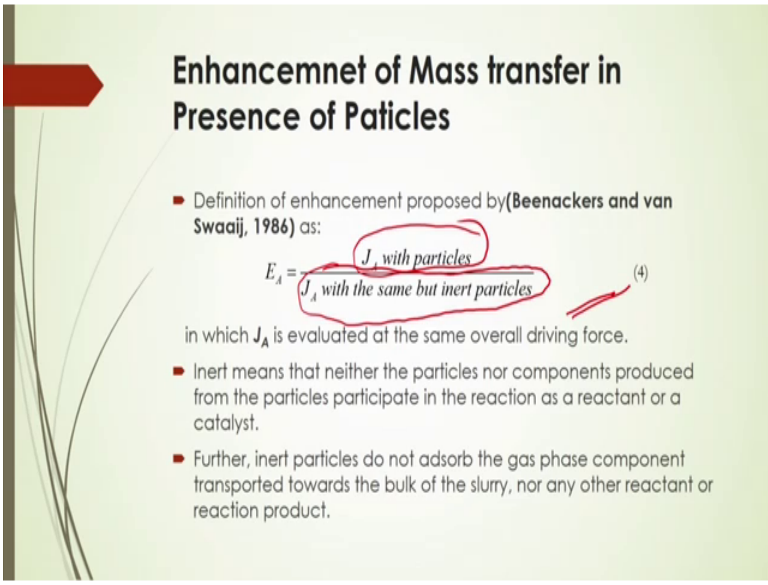

So, now enhancement of mass transfer can be defined first here by equation four that is given by Beenackers and Van Swajji; 1986 that it is defined as that what will be the mass transfer with particles and what will be the mass transfer with the same, but it will be with inert particles in which they is evaluated at the same overall driving force of concentration inert means that neither the particles nor components produced from the particles which are participating in the reaction as reactant or catalyst to there. And also we will see that inert particles do not adsorb for the gas phase component that is transport transported towards the bulk of the slurry nor any other reactant or reaction product there.

So, basically what would be the enhancement of this mass transfer that can be calculated by knowing the mass transfer with particles and mass transfer with the same, but inert particles.

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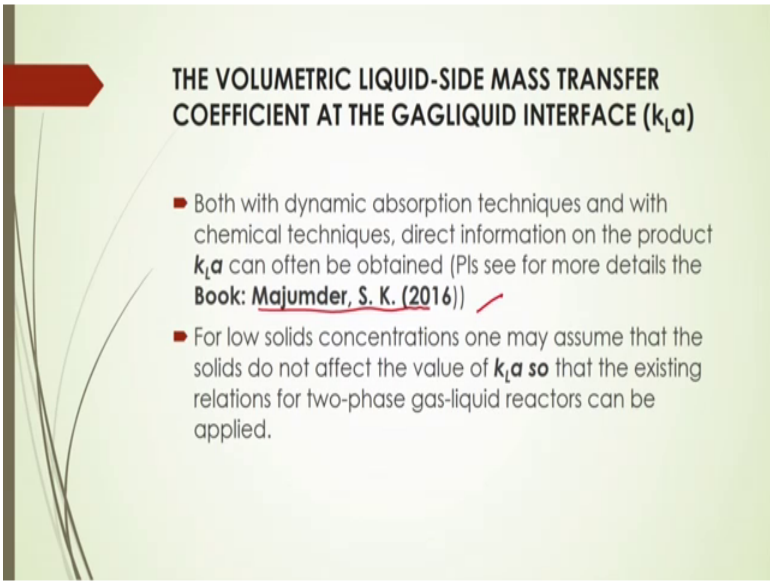

Then said the weight whenever you are talking about the mass transfer rate inside the fluidized bed, we have to know; what should be that rate and how it depends on; of course, from the basic we know already, we have discussed earlier also that the mass transfer rate that depends on concentration differences that is called driving force and also that cross sectional area or you can say that surface area of the interfaces there.

So, if we consider that if this mass transfer is proportional to that concentration difference or driving force then what should be that proportionality constant that proportionality constant can be represented by the mass transfer coefficient. Now this mass transfer coefficient sometimes this whenever you are considering that the mass transfer that concentration difference in the liquid phase. Then it will be liquid side mass transfer coefficient at the gas liquid inter face here.

And if you are considering the gas side then there will be gas side mass transfer coefficient generally it is very easy to estimate the concentration of that component which is transferred in the liquid phase and so, liquid phase mass transfer is very interesting and another important point that that sometimes for individual phases for in; it is very difficult to calculate that. What is that for specific surface area of course that individual what is that a for unit surface a what should be the mass transfer coefficient. Then what should be the overall mass transfer coefficient for the whole reactor and it is actually calculated or estimated by some chemical method or physical method.

They are and both this method physical method or chemical method is described in the books in Majumder S K in 2016 that in details and for further reading we are just suggesting that this can be followed for a mass transfer phenomena how chemically or that physically can be estimated and for low solids concentration one may assume that the solids do not affect the value of mass transfer coefficient that is the overall mass transfer coefficient. So, that the existing relations of 2 phase gas liquid reactors can be applied there.

So, volumetric liquid side mass transfer coefficient at the gas liquid interface k L a that can be that can be calculated by absorption mass theory or by any chemical theory with or without reactions there.

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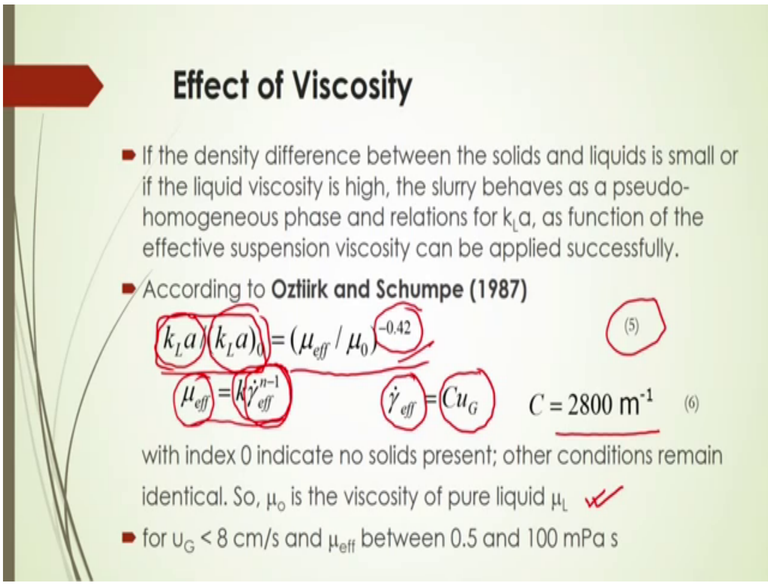

Now, if we change the systems properties inside the fluidized bed, then what will be the rate of mass transfer is there any change or whether it should be enhanced or lower the mass transfer rate there inside the bed, of course; viscosity of the fluidized bed or fluidizing system, they are very important a because the resistance of the mass transfer that depends on the physical properties of the system.

So, if the density difference between the solids and the liquid is small or if the liquid viscosity is very high then the you can say slurry; that means, liquid solid mixture behaves as pseudo of homogeneous space and you can say that relations for that overall mass transfer coefficient as function of the effective suspension viscosity and it can be actually expressed by correlating with that viscosity of course it is based on the experimental data, how we cannot actually predict this by mechanistic way or from the what is that that is called that material balance or some basic principle equations this is not possible, but from the experimental data by empirical correlations that you can correlate how this mass transfer coefficient will be changing with the viscosity.

So, Oztlirk and Schumpe here 1987; they have give suggested one correlations of mass transfer coefficient which will be relative to the mass transfer coefficient of; that means, without solid and how it will be changing in presence of solids and if you add some solid particles. Then of course the slurry viscosity will be changing as Einstein theory that you know that if you increase the solid concentration in the liquid. Then the viscosity of the a slurry will increase. So, according to that if you add some solid particles there will be a change of viscosity. And you will see that reduction of mass transfer would be there.

So, if you do the experiment with and without solid particles you will see that mass transfer coefficient would be that k L a by k L 0, here if you represent it by here these k L a in presence of solid and k L a 0 in presence in without solid particles, then this must this will be will be equals to that ratio of that effective mass trans[fer] effective viscosity of that slurry by the viscosity of the phase without solid 10 to the power minus 0.42.

So, it is seen that that in presence of solid particles this mass transfer coefficient is decreasing exponentially with the power of 0.42 and this mu effective means effective viscosity. Why this effective viscosity effective viscosity means here you see whenever you are adding solid particles to the certain concentration. And you will see there will be change of viscosity inside the bed. And this change of viscosity that is this a slurry viscosity are compared to that only clear liquid; that means, pure liquid only water viscosity, then it will be the effective viscosity there.

So, this effective viscosity generally are represented for the non Newtonian behavior of fluid now slurry generally behaves like non Newtonian fluids that is why in that case here this effective viscosity will be represented by the shear rate here. So, this is a directly proportional to that what is that shear rate here shear rate to the power n minus 1 here to k here k. So, this gamma effective dot; it is directly proportional to this velocity of the gas inside the gas liquid solid fluidized bed c the constant the c constant is equals 2800 meter inverse.

Now interesting that that other conditions remain here identical; so, mu 0 is the viscosity of the pure liquid which is represented as mu L and for u g less than 8 centimeter per second and effective viscosity between 0.5 and 100 Milli Pascal per Milli Pascal second. Then only you can apply this equation number 5 to predict the mass transfer overall mass transfer coefficient in presence of solids that is the effect of viscosity; how this viscosity if you are changing, then how this overall mass transfer coefficient will change inside the bed.

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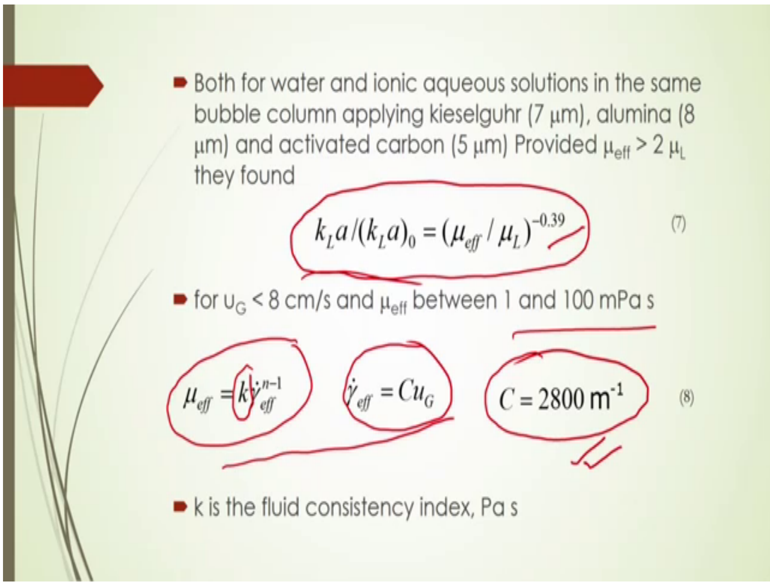

And if you are using that ionic aqueous solutions in the fluidized bed then you will see that as per the bubble column reactor then for the water and ionic aqueous solutions and if you are using that Kieselguhr with small particles of 7 micrometer. And also alumina or activated carbon of various fine particles like 8 micro micrometer or 5 micrometer particle size in that case, you will see that a it is seen that viscosity that is the effective viscosity because those are non Newtonian fluid this effective viscosity would be 2 times of that water viscosity they are.

So, in that case; it is seen that for this ionic aqueous solutions that the overall mass transfer coefficient in presence of these solid particles would be changing with exponentially with the coefficient of 0.39 and for gas velocity less than 8 centimeter per second and effective viscosity 1 to 100 Milli Pascal second and this mu effective and this shear rate effective shear rate those are related to this gas velocity and then this proportionality constant with this gas velocity will be represented by this c and we should be equals to 2800 that already been considered earlier. And here important point is that this k; k is called that fluid consistency index that as per non Newtonian fluid behavior it is expressed.

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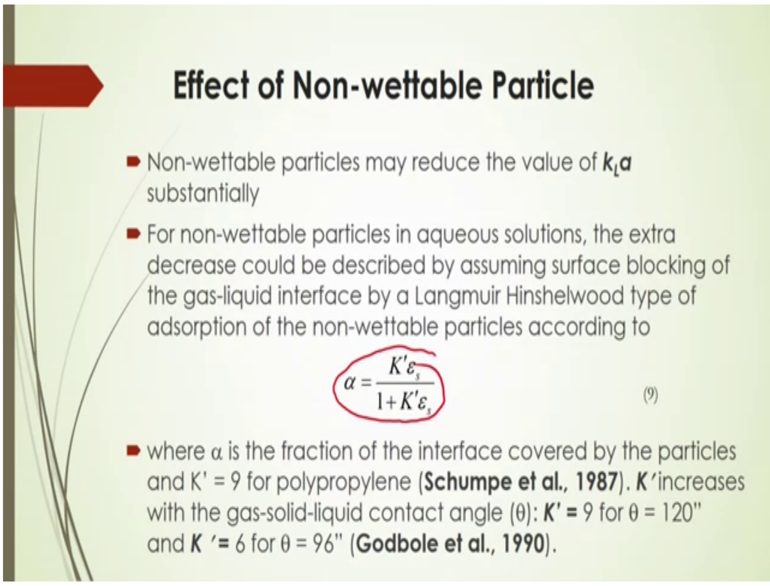

Now, if is there any non-wettable particle there inside or not; so, non-wettable particles may reduce the value of a overall mass transfer coefficient there. So, for non-wettable particles in aqueous solutions, the extra decrease could be described by assuming surface blocking of the gas liquid interface by Langmuir; you can say that Hinshlwood type of adsorption of the non-wettable particle according to this equation 9 here.

So, here this is alpha is called that fraction of the interface that would be covered by the particles and k dashed is generally the constants it is taken or it can be observed experimentally would be equals to nine for polypropylene that is given by Schumpe et al; 1987, whereas, this k dashed may increase with the gas liquid solid contact angle and this k dashed is equal to 9 for theta is equal to 120 and k dashed is equal to 6 for theta is equal to 96 degree.

So, in that case, we can have that if there is any wettable particles or non-wettable particles; how this mass transport rate will be changing there. So, it is seen that that mass transfer coefficient may decrease if there is non-wettable particles are used their inside the bed.

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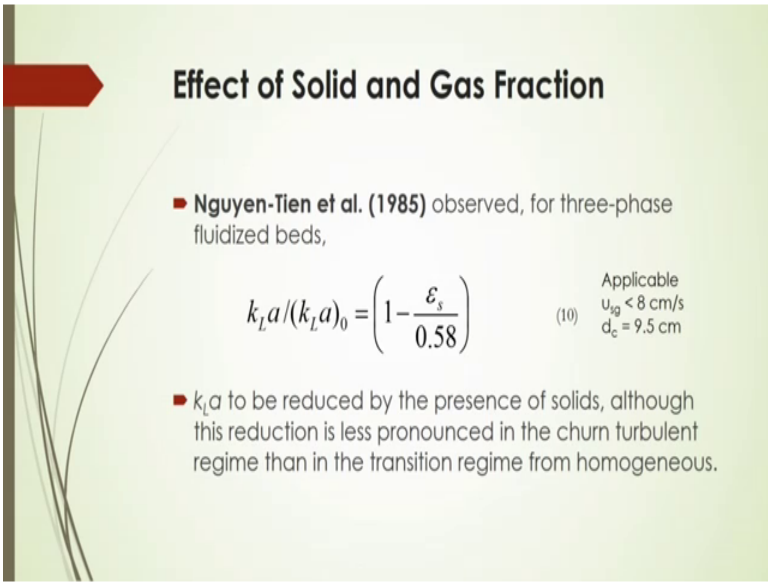

Now, effect of solids and gas fraction. Now very interesting that for 3 phase fluidized bed you will see that how much solids are being used for that mass transfer operation that is very important. So, fraction of the solid inside the bed that is very important. So, that depends that that affects that mass transfer coefficient there.

So, mass transfer coefficient to be reduced by the presence of solids although this reduction is less pronounced in the churn turbulent condition of the fluidized bed system. So, equation 10 can be used to calculate the mass transfer coefficient with certain concentration of the solid fraction inside the bed within gas velocity less than 8 centimeter per second and the column diameter is less than 9.5 centimeter.

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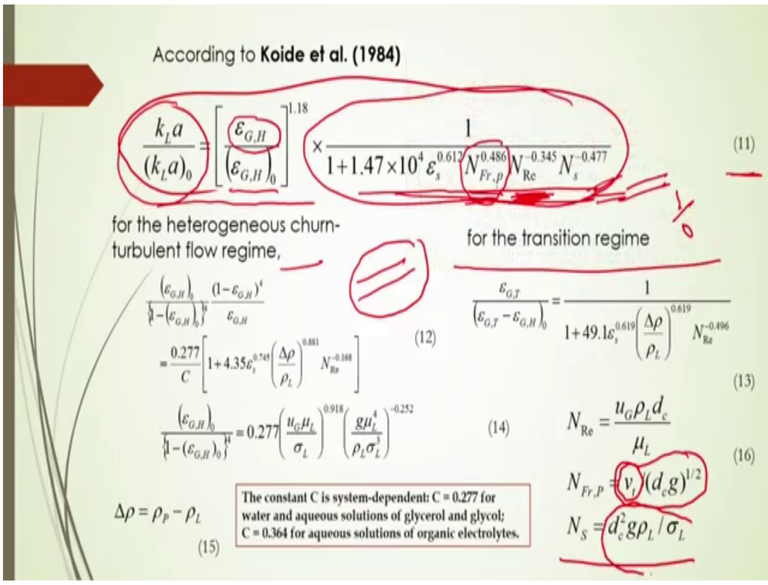

Now, according to Koide et al, 1984, they have suggested their own correlations from their own experimental observations. And they have developed one correlations in terms of Froude number, Reynolds number and also you can say that there will be some other are called this is called here N S that is here this called transition number. Here this turbulent flow regimes churn turbulent flow regimes this numbers of this Froude and the Reynolds number will be changing because of the gas holdup; how it will be changing in this gas liquid solid fluidized based system.

Now, you will see that heterogeneous churn turbulent flow regimes this gas holdup in presence of solids will be changing because of the change of viscosity whenever you are adding some solid inside the bed and because of which you can get the change of mass transfer coefficient inside the bed and then d r c equation 11, how it is related this epsilon G H is called that gas hold up gas hold up at this churn heterogeneous churn turbulent flow regimes and this a epsilon G H 0 is called that gas hold up at; there will be no actually that churn turbulent regime; that means, c this laminar flow regime. So, in that case, what should be the gas holdup and how this gas holdup will change this mass transfer coefficient?

Now, without actually changing any fluid velocity, then Reynolds number will be zero. So, in that case you will see that this part this Reynolds number will be zero; that means, here mass transfer coefficient will be in presence of solids will be 0 there whereas, in case of Froude number there you will see that if I change the terminal velocity of the; that means, this terminal velocity of the solid particles they are without having any gas velocity without having any gas velocity without having any liquid velocity; that means, in the steel gas liquid solid medium they are only solid particles will be just settling down with terminal velocity. So, at that terminal velocity condition what will happen you have to change this what is that Reynolds number that will be considered at here 0. So, in that case k L will because to 0.

But in this case, if you are considered that there will be no flow then you cannot here consider this Reynolds number there will be certain change of; that means, here that what is that Froude number we are according to the definition of this Froude number. So, because of which there will be change of mass transfer coefficient. So, according to this equation eleven if we here do this Reynolds number is equal to 0. This part this part will be is equal to what infinite; that means, here ultimate; it will be is equal to this part; what will be the value here 1 by N R e; 1 by N R e is equal to 1 by N R e means here this is Reynolds number if it is 0 then 1 by 0; that means, infinity.

So, here what does it mean; that means, infinity; infinity here by infinity, then 1 by 1 plus infinity; that means, 0; that means, 0 here. So, at a terminal velocity at a certain terminal velocity there will be 0 mass transfer parallely also. So, this is totally complex phenomena at this churn turbulent condition there. So, and you cannot apply this equation only for this heterogeneous churn turbulent flow regime. So, this equations is applied total equation is applied for the transition regimes also. So, here churn turbulent heterogeneous churn turbulent and the transition regime that is just entering to that heterogeneous churn turbulent flow regimes.

So, in that conditions all those portion will be included here. So, this is basically the empirical correlations not like that that you will get the directly the just substitution of this, what is that parameter here you will get directly that equation. So, there will be certain range of applicability of this equation and for he see you will be able to calculate. So, you cannot consider here that Reynolds number to be is equal to 0. So, that that mass transfer will be is equal to infinity that is also not possible here. So, there will be certain range of applicability of this correlation and this here N S is very interesting that this N S will give you that for the system properties, you will see that if is there N S surface tension change inside the bed or not if you are adding some surfactant of course there may surface tension will change.

So, accordingly that mass transfer coefficient also will change. So, that that will give you the variation of by changing this N S here.

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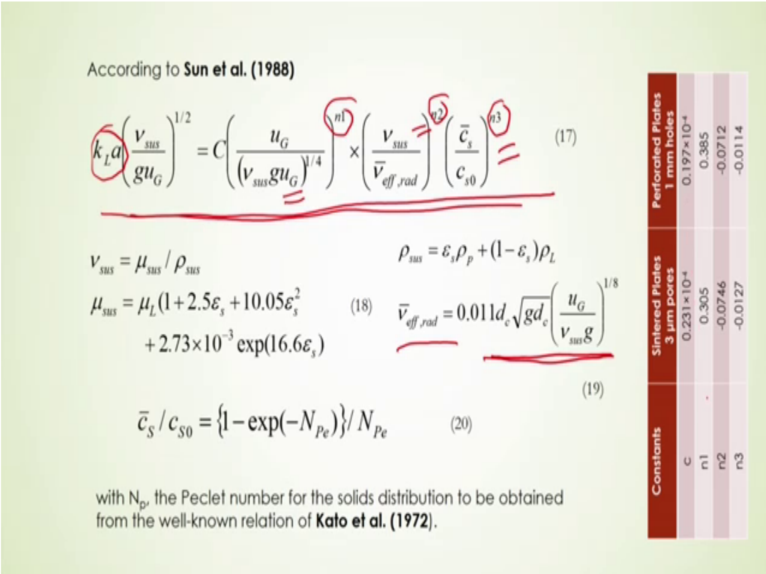

Now, according to Sun et al; 1988; they have given another equations to actually predict the mass transfer coefficient in gas liquid solid systems. So, they have given what should be the what is that what should be the effective viscosity of the suspension. And what will be the consumption of the solid and what should be the what if the you can say that effective , you can say, it is called that kinetic viscosity of the fluid inside the bed. So, that. So, that will affect that overall mass transfer coefficient here.

So, this empirical correlation of equation 17 also will be used to calculate the mass transfer coefficient in terms of what is that concentration of the solid what is that kinetic viscosity of the suspension gas velocity and this effective kinematic viscosity of the fluid can be calculated by this equation number 18 and here this n 3, n 2 and n 1 all those are coefficient that can be obtained from this what is that from this table this datas are given here.

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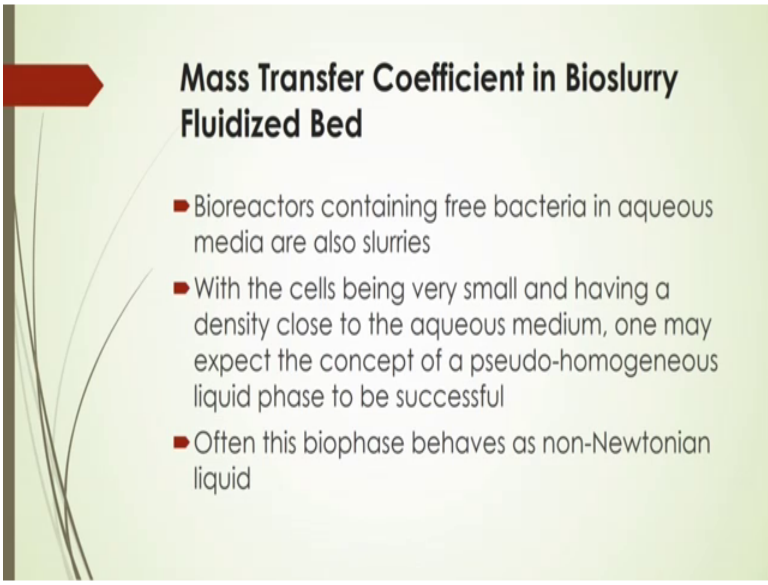

Now, mass transfer coefficient in bioslurry fluidized bed what is that now bio reactors containing that you know that you can do that at experiment with free bacteria in aqueous media that bacteria in aqueous media can be considered as slurry here with the cell being very small and having density close to the aqueous medium one may expect the concept of pseudo homogeneous liquid phase to be.

That will be successful, and often you can see that this bio phase behaves as a non Newtonian liquid inside the fluid. And if you are if you are changing this fluid properties by adding this bacteria; that means, slurry concentration will change other properties of the fluid also changed and because of which you can see that the change of mass transfer coefficient also will change you can use that correlations previously whatever given there to predict to the mass transfer curve and or calculate the mass transfer coefficients in the bed.

Now, you will see that Kawase and Moo-Young; they have done several experiment.

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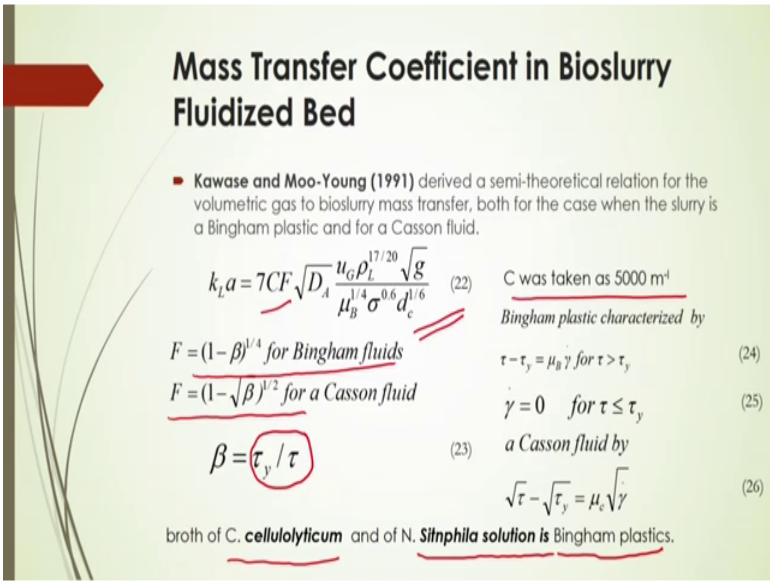

And they have suggested the same empirical correlations for the volumetric gas to bio slurry mass transfer both for that case when the slurry is Bingham plastic and for the what is that Casson fluids there. So, by equation twenty 2 can be used to calculate the mass transfer coefficient for that what is that Bingham plastic fluid and they have done the experiment with this micro organisms.

And there is slurries of these microorganisms that behave like that Bingham plastics fluids and accordingly they developed this correlations 22 to represents the mass transfer coefficient here you will see some coefficient C and F C can be taken as 500 meter to the power minus 1 and F should be is equal to one minus beta to the power 1 by 4 for Bingham fluids and F to be is equals one minus root over beta to the power half for Casson fluids and this beta is nothing, but the shear stress in the y direction to the shear stress overall shear stress there.

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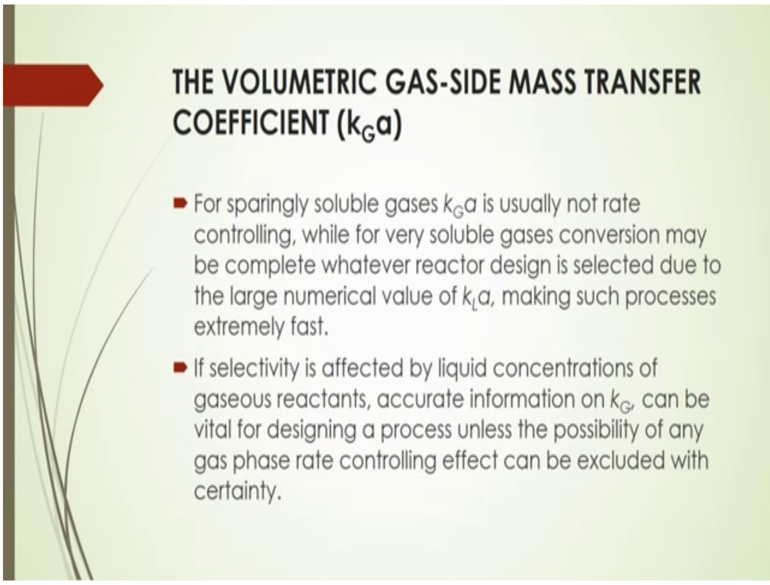

The volumetric gas side mass transfer coefficient that is represented by k G a. Now if you have that the gas whatever is being used that are sparingly soluble inside the bed and it is not a usually the rate controlling and if you are using that it could be for very soluble gases conversion may be complete whatever reactor design is selected that due to due to the what is that large the numerical values of k L a making such processes extremely that fast.

So, in that case of selectivity is affected by the liquid concentrations of gaseous reactants and which may give the accurate information of the mass transfer coefficient of gas whose can be vital for the designing of the processes and of course you will see that based on that possibility of any gas phase rate controlling effect which can be excluded with certain phenomena.

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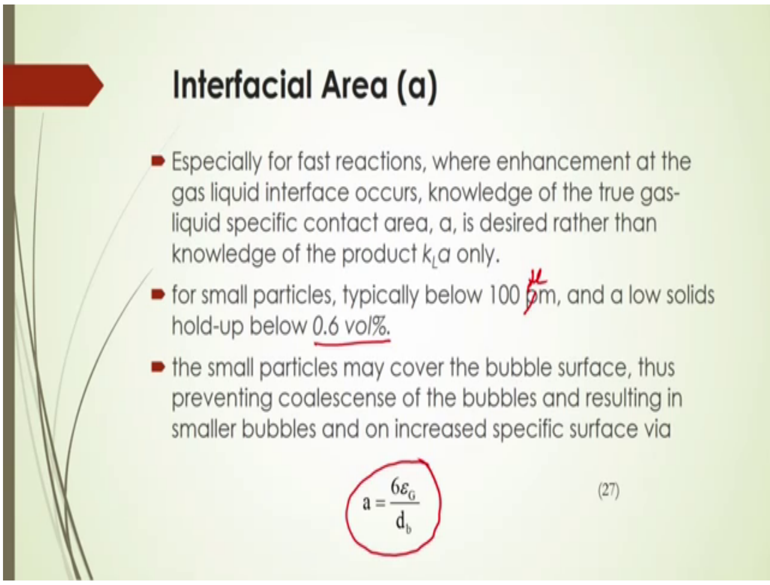

And in this case, whenever you are considering that gas phase mass transfer coefficient one important point is that. Suppose there is a gas liquid solid mass fluidized bed and gas is distributed as dispersed phase or bubbles and then for fast reactions the enhancement at the gas liquid interface, here in this case bubble surface to the liquid interface, then that case knowledge of the true gas liquid specific contact area that is denoted by a would be required and that will give you the more actually information about the mass transfer coefficient of overall mass transfer coefficient.

So, here a is the specific interfacial area now if we produce more finer bubbles inside the fluidized bed then you will see that you will get more interfacial area and then more overall mass transfer coefficient and of course, more mass transfer rate. They are inside the bed for small particles typically below 100 micrometer hundred micrometer here 100 micrometer and low solids hold up below 0.6 volume percent, then small particles may cover the bubble surface thus prevailing the coalitions of the bubbles and resulting in smaller bubbles and on increased specific surface area. So, in that case, the specific surface area will be represented by this equation number 27.

Now, this specific interfacial area is depends on the what is that particle a size. Now if you are considering that gas phase to the liquid phase mass transfer of course, you have to consider the bubble size there. Now what is the bubble size that is D B that you have to first obtain by certain method may be the photographic method will be the useful one.

Otherwise, you can consider other that p i v method and other you can say that conductivity probe method to calculate it or to find out the bubble size, once you know that bubble size, then what should be the interfacial area you can calculate.

Now, for this you need further information about the gas hold up inside the bed how to calculate that to gasholder how to estimate that gas holdup we have already discussed above data this earlier also that you can calculate this or you can estimate this gasholder by phase isolation method or you can estimate this gasholder by what is that conductivity method and there are other various several methods to find out this gasholder method and I think the phase isolation method is very easier to calculate for overall gas hold up if you know that this overall gas hold up, then equation 27 will give you the interfacial area of the bubble therefore, take taking part to calculate the or to estimate the mass transfer overall mass transfer coefficient.

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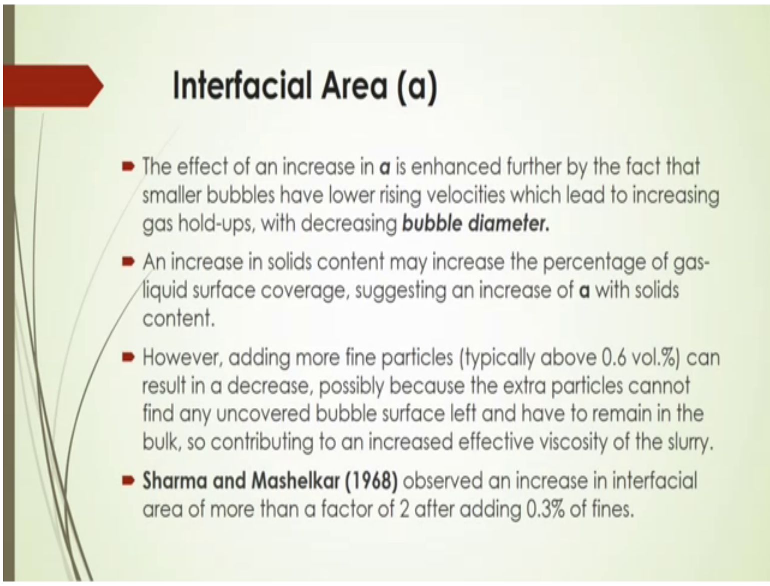

And the effect of any increasing interfacial area is enhanced further by the fact that smaller bubbles have lower rising velocities which lead to increasing gas holdups with decreasing bubble diameter very interesting that of course, This holdup or bubble size depends on that physical properties of the system and also heat flow inside the bed fluid flow sometimes changed the kinetic energy and the momentum exchange between the phases and because of fluids that there will be breakup or bubbles are qualities of bubbles. And there will be net change of bubble inside the bed will be there.

Even you will see there will be change of gas hold up because of those variables and you will get our interfacial area. So, interfacial area depends on what that may be that system properties may be that flow properties may be what is that the geometric variables also inside the bed and an increase in solid content also may increase or decrease the gas liquid surface gamma rays or you can say surface area in that case.

So, an increase in solid content may increase the percentage of gas liquid surface area suggesting an increase of my interfacial area with solid content there. However, adding more fine particles typically above 0.6 volume percent that may results in decrease possibly because of extra particle that sometimes, cannot find any uncovered bubble surface that is left and also have to remain in the bulk. So, bulk; so, that it contribute to the increasing of effective viscosity of the slurry.

So, in that case there may be change of specific interfacial area and also increase in interfacial area will be more than factor of 2 after adding up 0 point 3 percent of fines that is stated by Sharma and Mashelkar; 1968 here.

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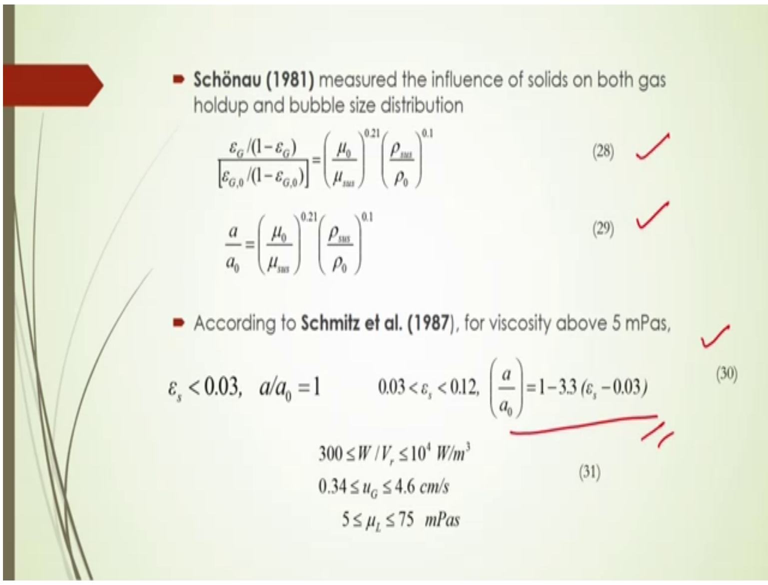

And Schonau; 1981 measured the influence of solids on both gas hold up and bubble size distribution and they have developed correlations respective correlations as given in equation 28 and 29 according to Schmitz et al 1987 for viscosity about 5 Milli Pascal second, they have given that they have given correlations there for interfacial area specific interfacial area in terms of solid concentration or you can say solid fraction inside the bed as this here a by a 0 is equal to 1 minus 3.3 into epsilon s minus 0.03. From this equation, you can calculate, what will be the specific interfacial area in presence of solid. If its fraction is some extent, there if it is less than fraction is less than 0.03, then you can calculate from this equation and a 0 is the specific interfacial area for is there know what is that solid fraction they are inside the bed.

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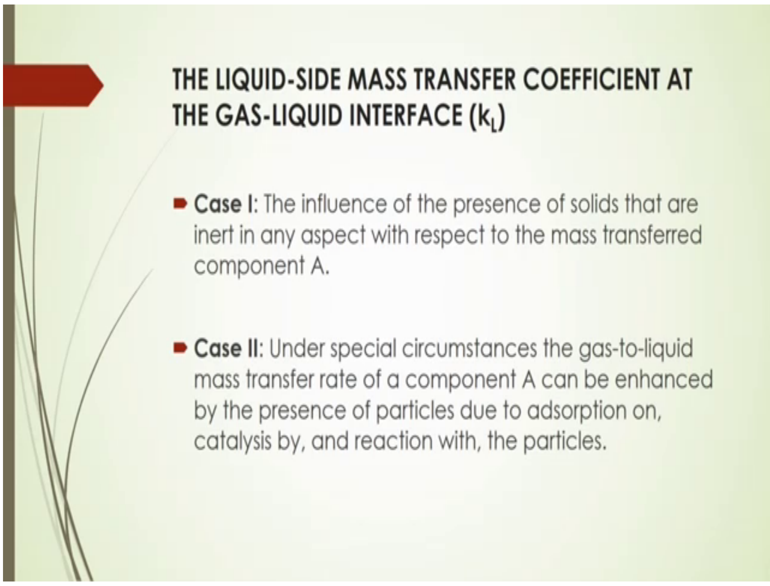

And liquid side mass transfer coefficient at the gas liquid interface k L here this is very interesting that this k L with the individual mass transfer coefficient not this overall mass transfer coefficient here the influence of the presence of solids that are inert in any aspect with respect to the must transferred component. Here whereas, other cases you will see that under special circumstances the gas to liquid mass transfer rate of component that can be enhanced by the presence of particles. Because of the adsorption on what is that catalyst surfaces are or the reaction with the particle set its surface.

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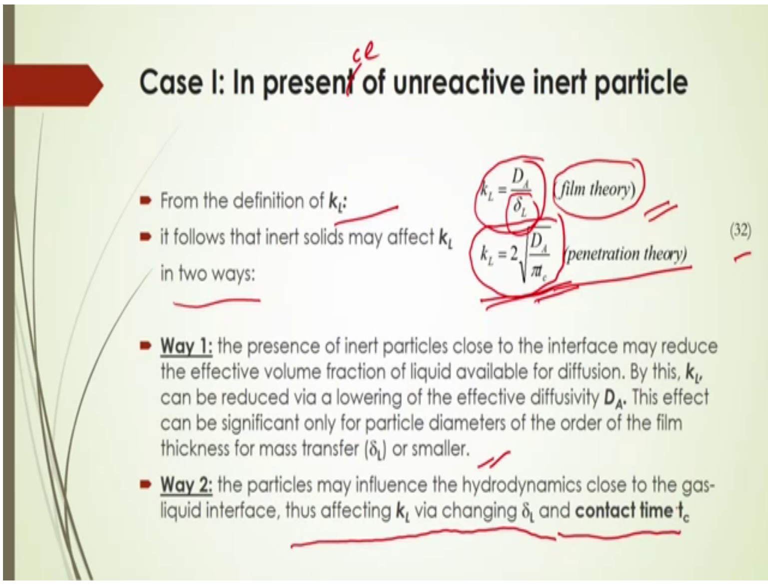

Now, in present in present of what is the presence of unreactive inert particles, here, we can see that from the definition of what is that k L individual mass transfer coefficient? If we apply that film theory, they are that k L should be is equal to what is that d a by delta L what is D A? D A is the diffusion coefficient and delta L is called the film thickness in the liquid side and it follows that inert solids may affect this k L in 2 ways and here way one and way 2 here the presence of inert particles close to the interface may reduce the effective volume fraction of the liquid available for diffusion by this k L can be reduced via a lowering of the effective diffusivity that is D A. This effect can be significant only for particle diameters of the order of the film thickness for mass transfer delta L or even are smaller.

So, in this way you can calculate what should be the of this individual mass transfer coefficient by this film theory otherwise penetration theory also you can apply there to calculate this mass transfer individual mass transfer coefficient by equation thirty 2 here given this k L is equal to 2 into root over d a by pi t c here. So, in this case what they expose time of that what is that what is that contact time of that gas solid or what is that liquid solid interface there and that depends on. So, this is called that contact time t c now this contact time.

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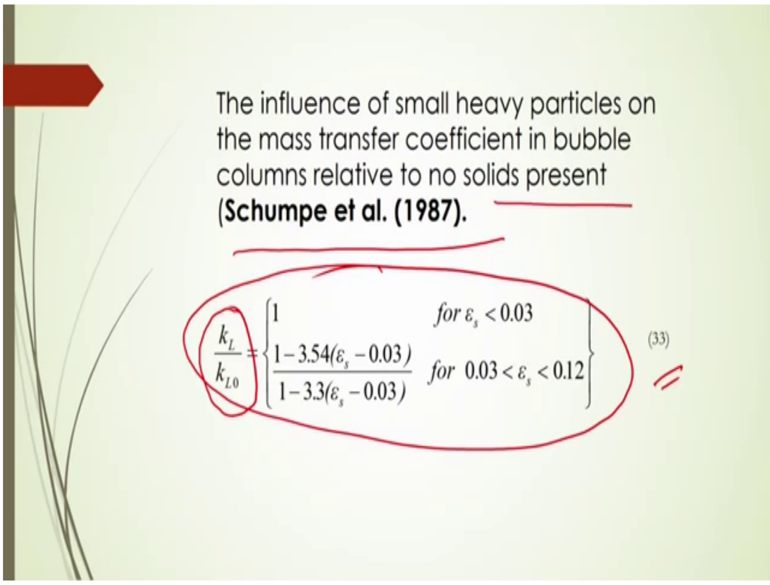

How to calculate that contact time? It will be discussed later on. So, another way that we have to discuss that the particles may influence the hydrodynamics are close to the gas liquid interface. Thus, affecting k L via changing this film thickness and the contact time by this penetration q e the influence of small heavy particles on the mass transfer coefficient in bubble columns relative to no solid present here Schumpe et al; 1987, they have given these empirical correlations to calculate this mass transfer coefficients without solids there.

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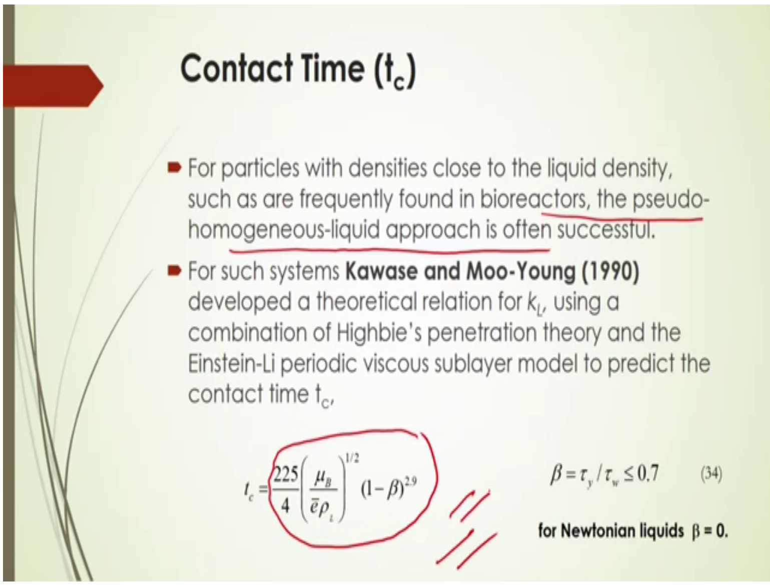

So, based on this equation, you will be able to calculate; what will be the individual mass transfer coefficients in presence of; that means, if you know that solid fractions inside the bed now for particles to densities close to the fluid density such as are frequently found in bio reactors the pseudo homogeneous liquid approach is often successful in this case. So, for such systems Kawase and Moo-Young; 1990, they have developed one theoretical relationships for that individual mass transfer coefficient using the combination of highbies penetration theory and the Einstein Li periodic viscous Sublayer model to predict the contact time there.

So, this contact time that depends on what very interesting that this contact time will be depending on the viscosity of the basic fluid and also the energy dissipation in the fluidized bed there. So, by this equation that is equation thirty four you can use; what should be the contact time for that.

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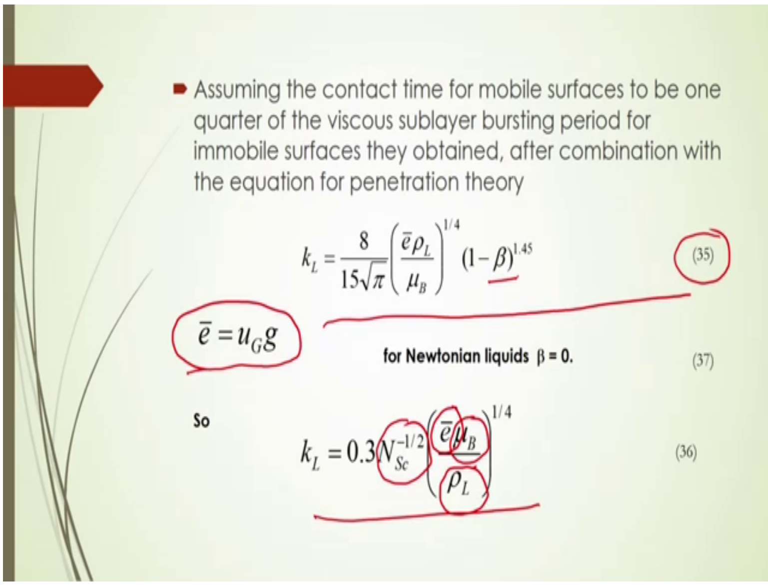

Now assume the contact time for mobile surfaces to be one quarter of the viscous sublayer, then of course busting period for the immobile surfaces they sometimes an effect, they are actually the surface exchange or you can say that surface mobility and because of which that; there will be some change of what is that mass transfer coefficient and of course, the energy distribution between energy distribution during that; what is that flow they are and this energy distribution depends on that how what will be the rate of gas inside the fluidized bed and that energy distribution denoted by this e bar that will be is equal to u G into g.

So, equation 35 can be used to calculate the individual mass transfer coefficient this individual mass transfer coefficient then depends on this what are that here, this density of the liquid viscosity of the base liquid and then what is the energy dissipation and also the Schmitz number; there and this equation 35 is the general equation that can be used for Newtonian and non Newtonian liquid, but for Newtonian liquid you have to consider that beta will be equals to 0.

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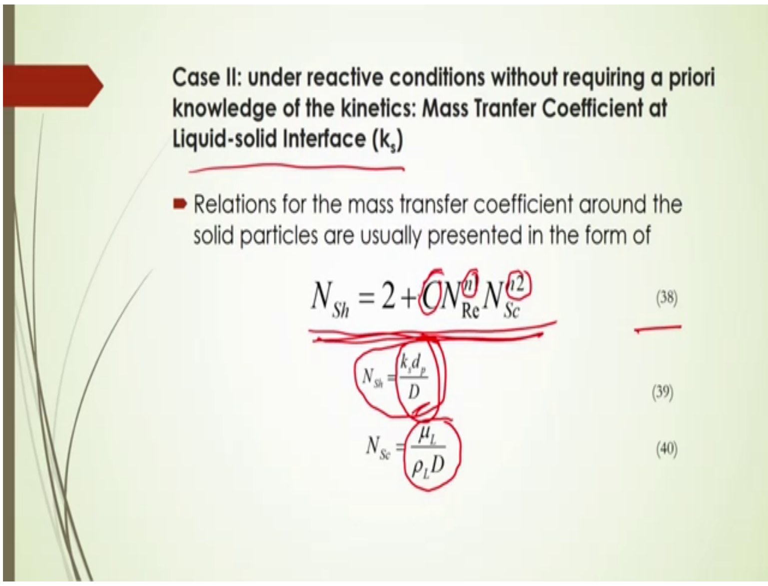

Now, case 2 under reactive conditions without requiring priori knowledge of the kinetics there; so, in that case mass transfer coefficient at liquids on its surface can be expressed by this equation number 38; this equation 38 will give you the what is that mass transfer coefficient of that liquid solid interface this N S h; that means, here shear root number is denoted by that k s d p by D. Here k s is the what is that liquid solid interface mass transfer coefficient d p is the particle diameter and D; this D is called the diffusive the coefficient or diffusion coefficient and the Schmitz number is defined as that mu L by rho L into D.

Here this were C and N 1 into are the constants that can be obtained from the experimental data you can do one experiment and then find out the different results with different variables and make this equation and feed this equation that with your experimental data and find out the coefficient C N 1 and N 2.

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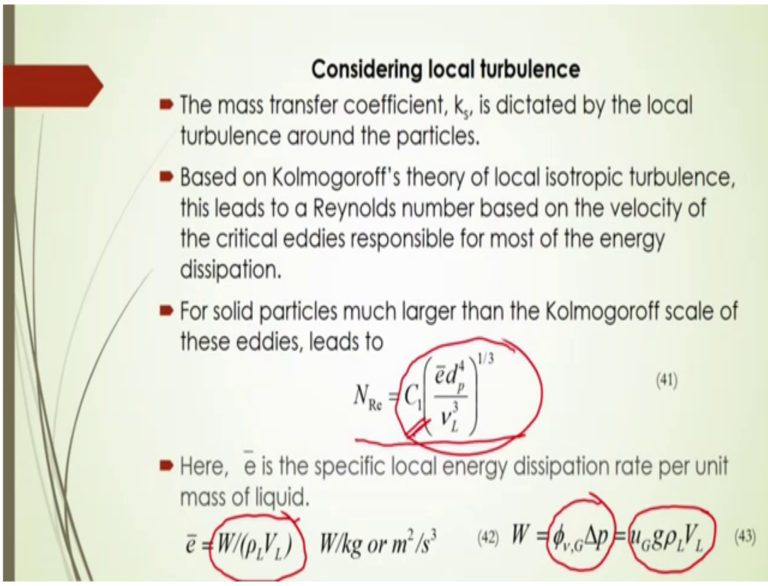

and if you are considering that local turbulence inside the bed then the mass transfer coefficient of course, this liquid solid surface then of course, would be affected by this turbulence.

Now, this turbulence can be considered by the Kolmogoroff's theory for the local turbulence and if you consider that the Kolmogoroff's theory of local isotropic turbulence, then it can be represented by this w by rho L v L whereas, this w is equal to phi v G into delta p; that means, they are what should be the pressure drop inside the bed and otherwise you can calculate it from that velocity of the gas and what is that viscous velocity of the gas and volume of the liquid inside the bed and the density of the liquid and once you know this then it is very easy to calculate what will be the Reynolds number inside the bed are based on this and here one important coefficient is called C 1 which is the this parameter this parameter will give you that the what extent of mass transfer coefficient will be changing inside the bed.

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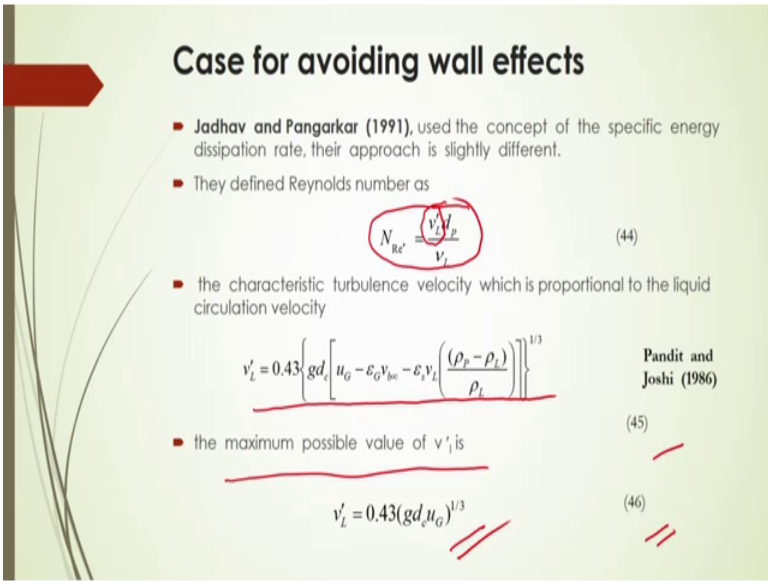

Now, if is there any wall effects inside the bed then of course the Reynolds number will be changing here by this equation forty four you can say in this case, this the velocity of the liquid that will be of course that characterized by the turbulence of velocity that is proportional to the liquid circulation velocity inside the bed. So, as Pandit Joshi, but they have given that theory that whenever liquid is moving inside the bed even gas liquid solid also in bubbling fluidized bed, there will be internal circulation they are and there will be change of liquid velocity that circulation velocity of the fluid that will give you the turbulence inside the bed

So, that turbulence velocity is proportional to the liquid circulation velocity inside the bed that liquid that characteristics turbulence velocity can be represented by this equation number 45 as per Pandit and Joshi; 1986 and in this case the maximum possible value of this what is that liquid circulation velocity will be is equal to this v L dashed which is given in equation number 46.

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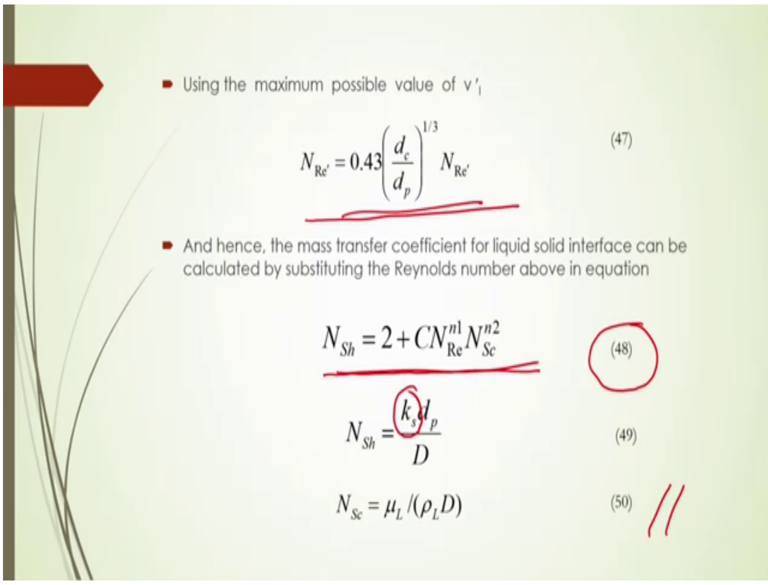

So, once you know this what is that maximum possible value of the circulating velocity of liquid then what should be the modified Reynolds number once you know this modified Reynolds number and if you substitute this equation Reynolds equation for Reynolds number. Here in this equation earlier that equation 38, if we substitute here, then we can get this modified in terms of modified Reynolds number equation number 48.

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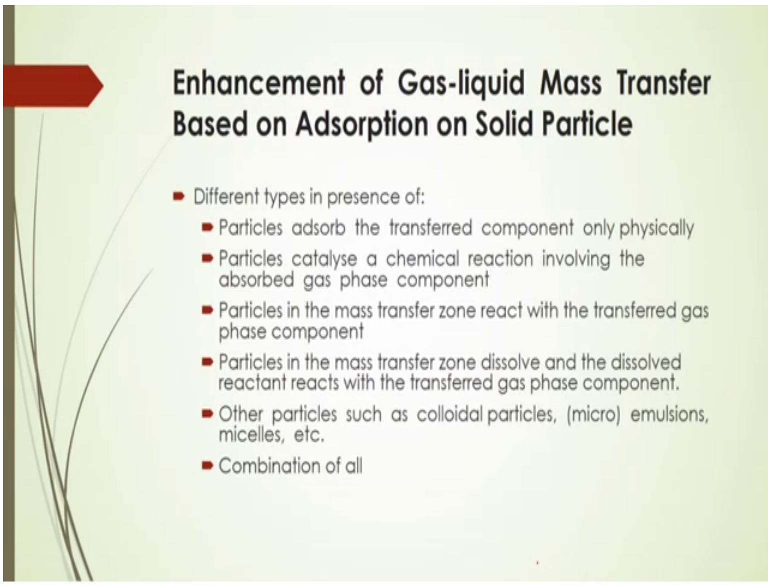

Then after that you can find out what should be the Shorewood number and for which you can calculate what should be the liquid solid to mass transfer coefficient they are in the bed. So, this equation 48 along with this 49 and 50, you can calculate; what should be the mass transfer coefficient for liquid solid side now this enhancement of the gas liquid mass transfer based on adsorption of solids particles. So, is there any adsorption happens in the on the solid particle surface then how this enhancement of the gas liquid mass transfer happens there.

So, different types of you will see that enhancement would be happened that is in presence of sometimes particles will adsorb to the transferred component only physically sometimes, particles analyzed sorry catalyze chemical reaction that will involve the adsorbed gas phase component sometimes particles in the mass transfer zone react with the transferred gas phase component sometimes particles in the mass transfer zone dissolved and the dissolved reactant reacts with the transferred gas phase component.

And you will see most of the cases, there will be adsorption of the components on the surface of the solid particles and reaction will be on the surface of the reactions other particles such as colloidal particles emulsions micelles, etceteras also may change the mass transfer rate inside the fluidized bed and also you will see combination of all these possibilities may enhance the mass transfer inside the fluidized bed.

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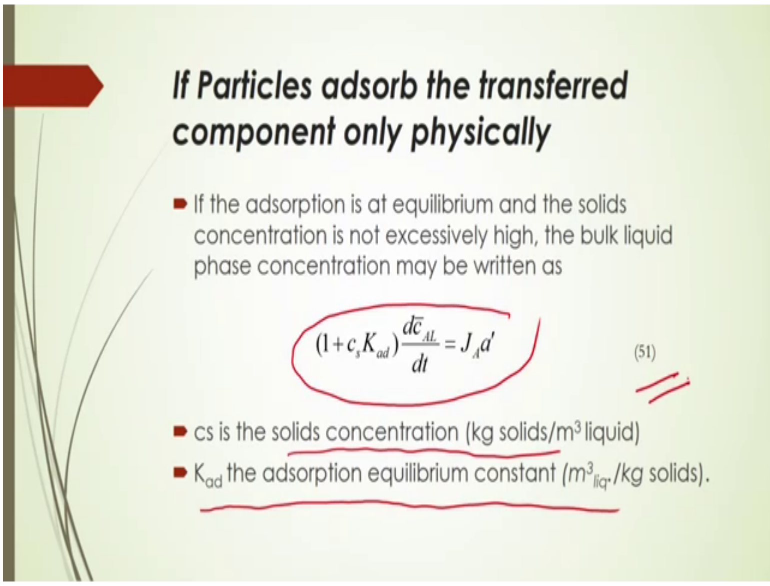

There if particles adsorbed the transferred component only physically, then you can represent this mass transfer rate by this equation 51.

In this case, C s is the solid concentration and D a d is the adsorption equilibrium constant here. So, if the adsorption is at equilibrium and the solids concentration is not excessively high, then bulk liquid phase concentration may be retained by this equation number 51.

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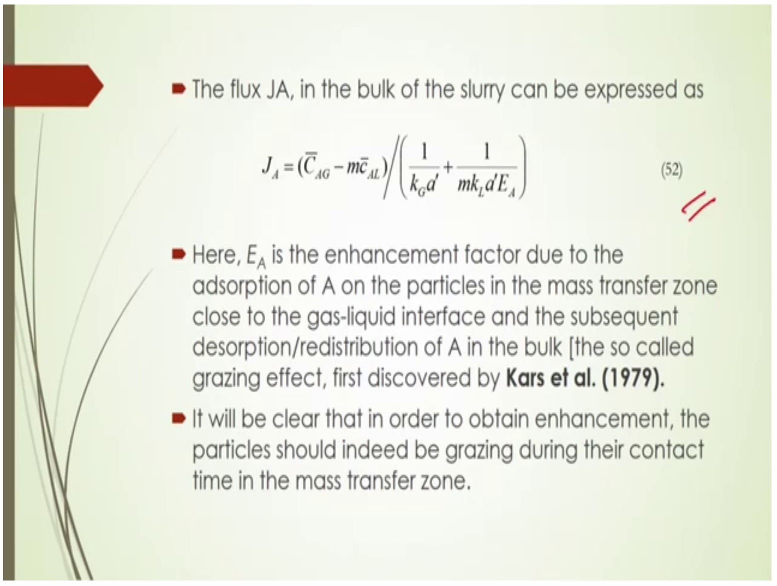

And the flux J A in the bulk of slurry can then be expressed by this equation number 52; here E A is the enhancement factor due to the adsorption of a on the particles in the mass transfer zone that is close to the gas liquid interface and the subsequent desorption or redistribution of in the bulk and also you will see that it will be it will be obvious that in order to obtain the enhancement the particles the particles should indeed grazing during their contact time in the mass transfer zone.

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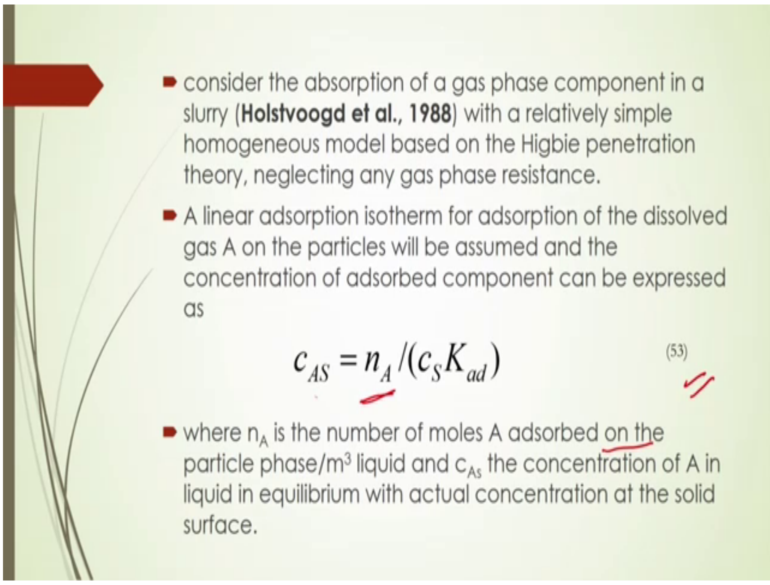

And if you consider the adsorption of gas phase component in slurry with relatively simple homogeneous model based on the Higbie penetration theory and if you neglect any gas phase resistance they are. So, in that case, you will see that there will be certain linear adsorption relationship for the absorption of the dissolved gas on the particles and the concentration of the adsorbed component can be expressed by the equation number fifty 3 here given. So, in this case this n a is the number of moles a adsorbed on the particles and C A S are the concentration of a in the liquid at equilibrium condition and with equal concentration at the solid surface.

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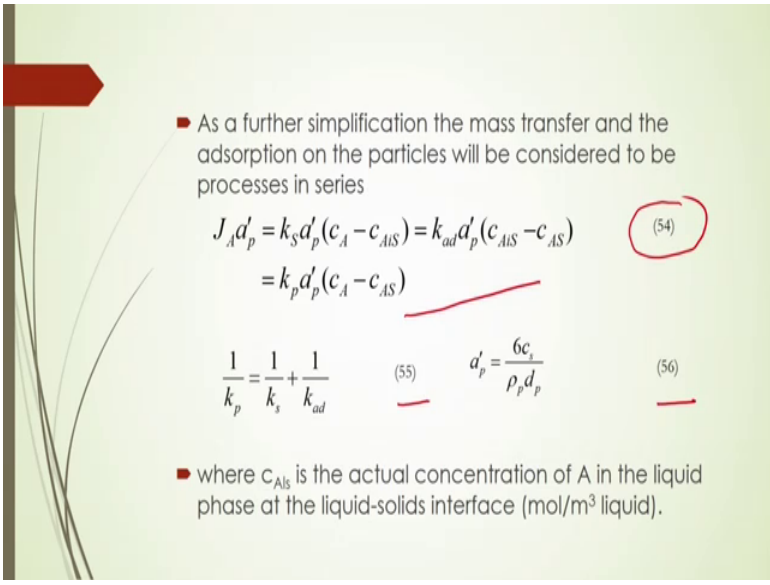

And if we simplify this equation number 52 along with those equation 53 and 51, then we can say that equation number 54 can be obtained and 55 and 56 will give you the overall, what is that mass transfer coefficient for the particles inside the bed and interfacial area for the particles there and in terms of solid concentration.

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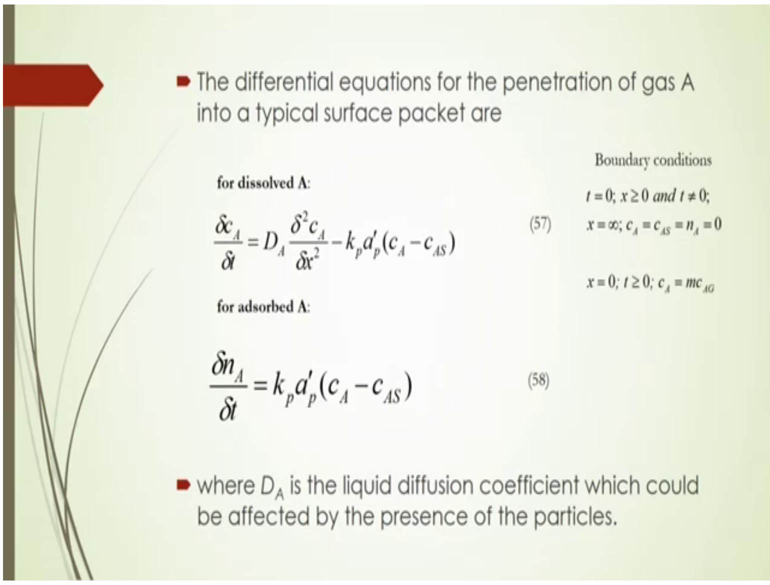

The differential equation for the penetration of gas into typical surface packet that we have already discussed about that surface packet is there is any solid bulk of solids are behaving like that one that is simple what is that bulk of solids that may change that mass transfer rate there and in that case, you will see for dissolve or adsorbed; what should be the mass transfer rate that can be expressed by this equation number 57 and 58 here and the enhancement factor can be calculated based on that then by this equation number 59.

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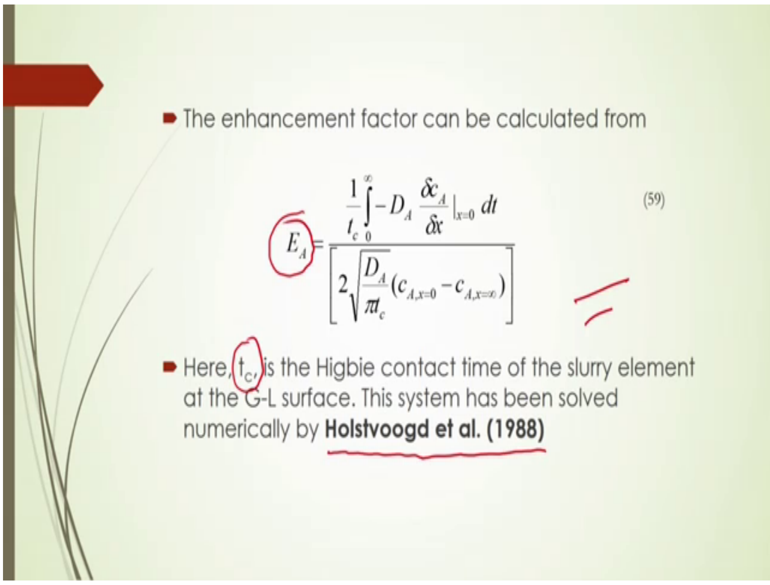

In this case, the contact time is the main important governing factor that which will give you that; how which will give you that enhancement degree of enhancement of the mass transfer inside the bed and these systems has been solved numerically which is given by Holstvoogd et al; 1988 to calculate the enhancement factor based on this contact time and also the change of concentration within very short what is that film thickness.

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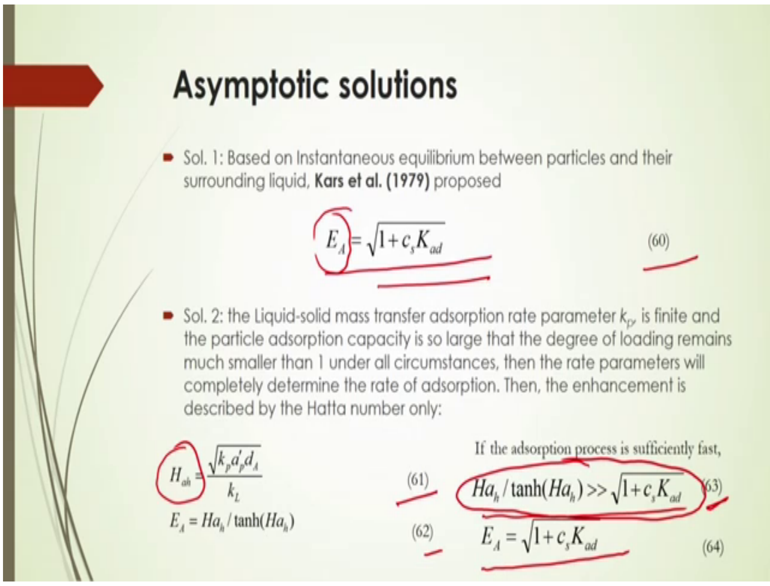

There are several scientific solution are also given for this equation number 59, here equation 60 has given by Kars et al; 1979 based on instantaneous equilibrium between particles and their surrounding liquid here in this case this enhancement factor directly related to this consumption of the solid and also the what is parameter? What is that mass transfer adsorption rate that is k p and here other unknown parameters like equation 61 and 62 that will give you that degree of loading; that means, they are inside the bed and also determine the rate of adsorption and the enhancement and represented by the Hatta number that is h a h this Hatta number and that depends on the reaction kinetics also.

So, that reaction kinetics will give you that if there is the Hatta number criteria is given by 63 is maching, then only you will be able to calculate at that particular condition; what should be the enhancement factor inside the bed.

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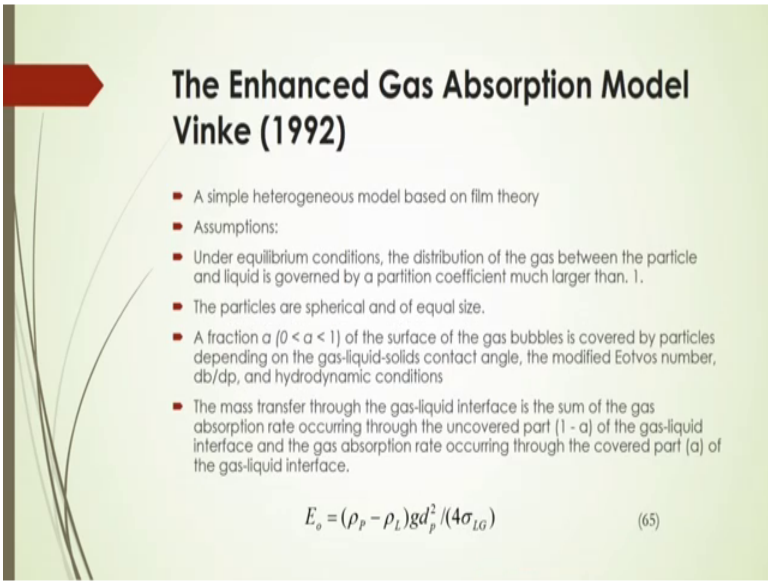

And there are some other there are various other solutions given by different investigators in this case the enhanced gas absorption model are given by Vinke in 1992, I think it will be suggestive to follow this literature to get the enhanced gas absorption model to have this what is that mass transfer enhancement in the gas liquid solid fluidized bed based on the film theory and based on that film theory.

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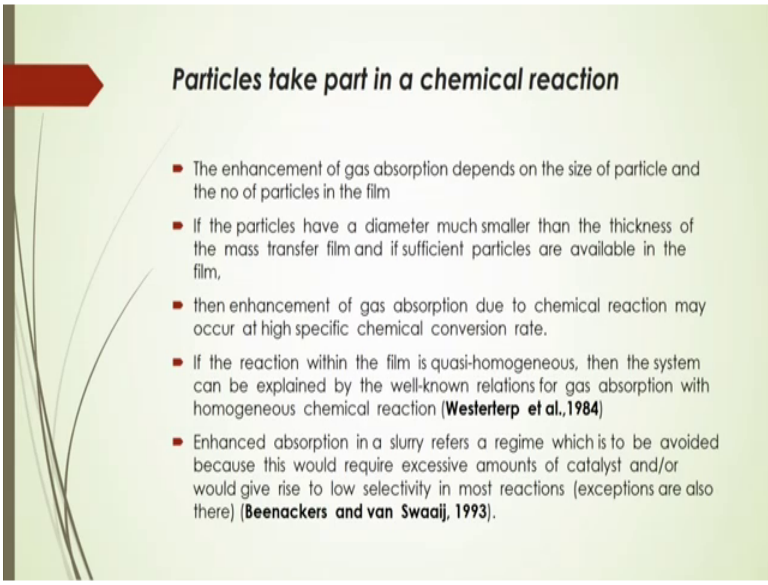

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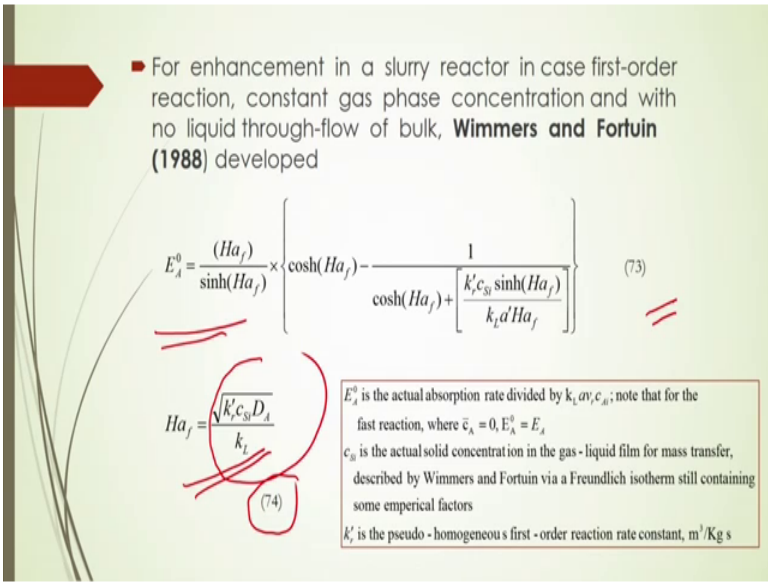

If there are particles take part in chemical reaction Westerterp et al; 1984 they have given some equations; based on that there are experimental results and also the enhancement in slurry reactor in case of first order reaction constant gas phase concentration and with no liquid through flow or bulk Wimmers and Forutin; 1988, they have developed this equation number 73 here and here this Hatta number is represented by this equation number 74.

So, based on these; you can calculate what will be the enhancement of the mass transfer in slurry reactor in case of first order reaction.

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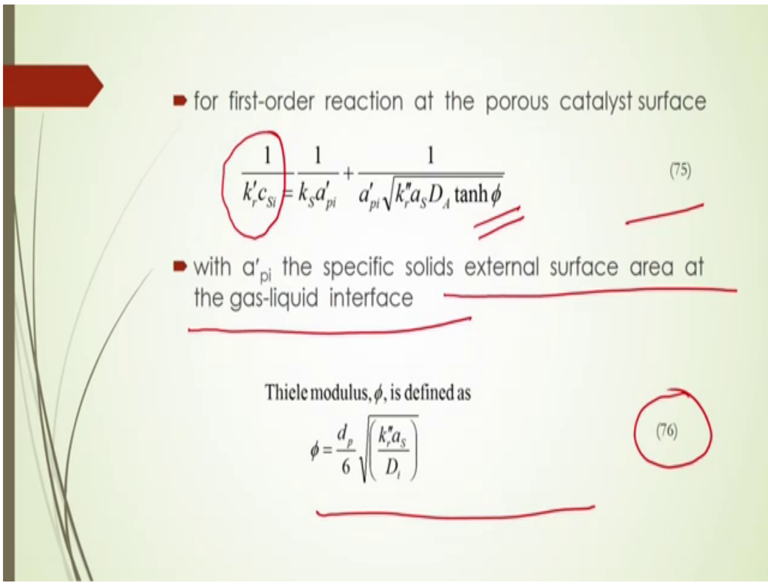

And for first order reaction at the porous catalyst surface, you can represent it by equation number 17; 75 and with a p i the specific solids external surface area at the gas liquid interface, it will be represented by this equation here 76 for this; Thiele modulus and once you know this Thiele modulus here, then what should be the mass transfer coefficients that enhancement factors also they are according to this equation.

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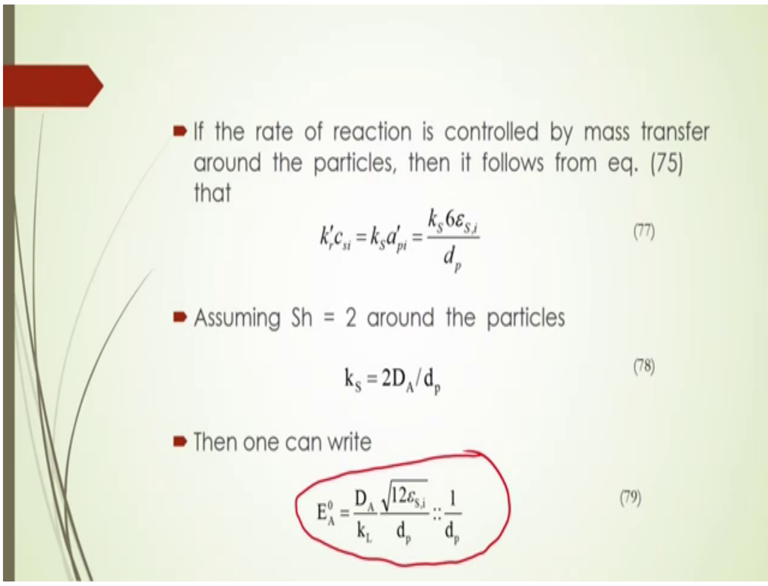

And equation 79, once you substitute this k S value and other what is that rate of reaction this k r; this is controlled by the mass transfer around the particles, then you can get this enhancement factor of mass transfer by this equation number 79.

So, more details about this, I think it will be helpful to study with these references, but here I have given some references to follow further to know more about this mass transfer here.

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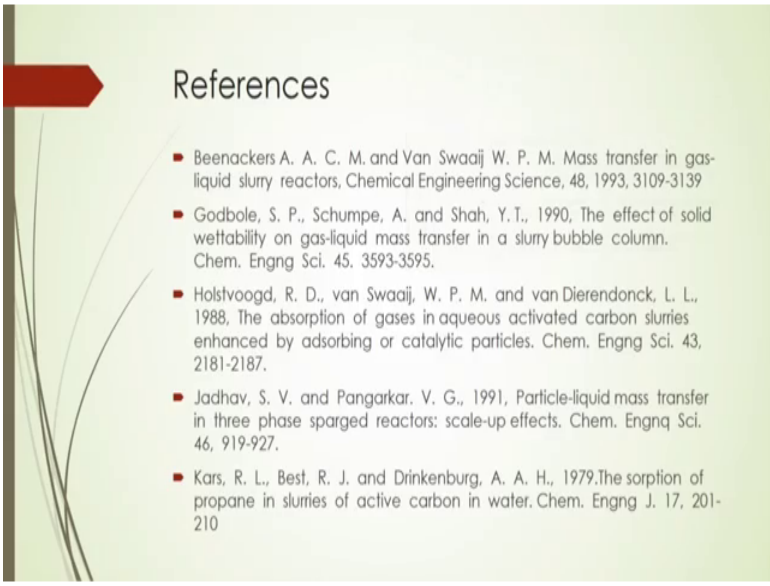

So, it will be better to read more about this for more details of mass transfer phenomena in the gas liquid solid fluidized bed I think in this lecture, we have learned something about what would be the mass transfer rate what would be the mass transfer coefficient what the different correlations and if use their porous or non porous particle. So, they are how enhancement of the solid enhancement of the mass transfer inside the fluidized bed for gas liquid solid system, we have learned and it will be more helpful if you go through this reference more in details so.

Thank you.