

Lec 15: Two-phase flow through packed bed

Hello everybody. Welcome to this massive open online course on solid fluid operations. Today we will discuss the two-phase flow through the packed bed. In the previous lecture we discussed the single-phase flow through the packed bed, and we also were learning about different fundamentals of the flow phenomena through this packed condition or packed bed. There, we learned what is Darcy's law, there we learned what the Kozeny-Carman equation is. We also learned the general expression for the fluid flow phenomena for estimating this frictional pressure drop when both the laminar and turbulent conditions prevail. And also we were actually discussing the different characteristics factors of the solid particles and also flow phenomena whenever it will be flowing through the packed bed.

We are describing about the Ergun equation based on which you can calculate what will be the frictional pressure drop within a flow regime of laminar as well as turbulent flow. There are two forces we are discussing that one is viscous force another one is called inertia force. So both the forces whenever it will be acting then how that frictional pressure drop can be calculated that is actually given by Ergun, is general expression containing that viscous effect and inertia effect. So that we have discussed in the previous lecture.

Now in this lecture we will be discussing about the two phase flow instead of single phase flow. There are many applications in industry where this two phase flow will be flowing through the packed bed and there some process output will be there. There will be some reactions when suppose gas and liquid will be reacting in a packing condition or in presence of solid particles or in a catalyst particles there. So there are some examples of course are there that we have shown different applications of the packed bed in the previous lecture when single phase flow will be there. So in that case here also you will see that for two phase flow there are several applications which is being actually carried out in packed bed of that catalyst particles.

Now here are some examples given here metals like nickel, palladium, platinum as a powder or on support of metal oxides that is chromium oxide which is being used actually as a catalyst and it is actually used in a packed condition for carrying out that reaction between olefin and hydrogen. So which would be giving you that paraffin and also metal catalyst like copper, nickel and platinum which are being used for reactions like hydrogenation reaction example like acetone will be reacting with hydrogen in presence of this metal catalyst and which will be giving you that product of isopropanol. And also other applications like oxidation of hydrocarbons, oxidation of carbon monoxide which will also being done in presence of catalyst particle in a packing condition. Also metal oxide support vanadium pentoxide that also being used as a catalyst particle in a packed condition for that production of phthalic anhydride from the naphthalene. That means naphthalene to be oxidized to give this phthalic anhydride in presence of vanadium pentoxide as a catalyst particle.

And also you will see that mixed oxide of iron and molybdenum those are also being used for the reaction of methanol and oxygen which will give you the formaldehyde with carbon monoxide and water. And iron oxide or metal sulfides like water and carbon monoxide which will give you that hydrogen and carbon dioxide. And also you will see that there are several other reactions that are being done in packed bed condition. So basically we are seeing here that two phase flow one is the liquid another is gas. So gas and liquid both will be flowing through the packing condition instead of single phase flow.

Now you will see that mostly that in industry whenever this gas liquid flow will be carrying out in a packing condition. So that may be in different mode this happened like co-current both the gas and liquid will be flowing upward. Even co-current downward also there will be that gas and liquid flow. Also counter current operation also will be there. And you will see that most of the applications that is being done in the down flow condition where trickle flow condition will be prevailed there.

So that is called trickle bed reactor. There gas and liquid both would be flowing from the top of the column which will be flowing downward to the bottom. In that case it is actually happened just by flow of laminar condition of that gas and liquid. And also it is advantageous because there is a less back mixing will be reduced whenever it will be flowing both the gas and liquid will be flowing downward there. So there was a co-current flow of that gas and liquid usually downward through packed bed is used for catalytic chemical reaction between components of the fluids.

So in that case the catalyst usually being some active substances supported upon that granular ceramic material which I have shown some example of that catalyst there. Such arrangements are known as trickle reactors, trickle bed reactors. So here these are some trickle bed reactors the pictures are there and also you will see that the trickle bed reactor is fixed bed reactor with two phase flow. In that case liquid phase and gas phase flow will be co-currently downward through a fixed bed of catalyst. In this case the study of hydrodynamics of trickle bed reactor is required to evaluate the reactor performance, size and energetic requirements.

So whenever you are going to design some trickle bed reactor you have to know what will be the hydrodynamics inside that trickle bed reactor, how that liquid or gas will be distributed inside that trickle bed reactor, whether it will be laminar flow or turbulent flow, whether it will be co-currently or counter-currently or whether there will be uniform mixing inside the bed or not. Also you have to know what will be the energy requirement for that, what will be the frictional resistance whenever fluid will be flowing through the bed and how that frictional resistance can be assessed all those informations to be known to you before going to design that trickle bed reactor or packed bed reactor. So already we know that some equations for single phase flow that is Darcy's equation, Hagen-Poiseuille's equation which is to be used for deriving that Kozeny-Carman equation even that Ergun equation. So here also whenever the trickle bed reactor will be considering when liquid and

gas both will be flowing downward, so in that case what will be the frictional pressure drop and what will be the frictional pressure drop for individual phases and if that frictional pressure drop for individual phases then what will be the two-phase frictional pressure drop that can be assessed based on the single phase frictional pressure drop. So this hydrodynamic behaviour inside the packed bed to be known.

So in that case mainly that flow regime hold up means what will be the volume fraction of liquid and volume fraction of gas, how it will be distributed throughout the bed that is also very important point there and also frictional pressure drop. These are the important factors which will be governing that operation of that trickle bed reactor. And here some example that I have shown you will see that whenever we are talking about that gas and liquid will be flowing through the conduit or bed there will be certain you know flow map or flow regime or flow condition which will give you that certain fashion of that flow inside the bed. For co-current downward flow of liquid and gas through a bed of solid particles that will be flowing exhibiting or that will be showing you that four types of regime that can be distinguished those flow regimes are like called trickle flow that means their gas will be continuous whereas liquid may be distributed phase. And then pulse flow there you will see that unstable regime with partly gas continuous and partly liquid continuous this is called pulse flow.

And then dispersed bubble flow there you will see the whenever gas will be distributed through the voids of that packing or packed bed there formation of bubbles will be there. So the bubbly flow will be there at a certain flow condition. And then spray flow so there you will see that gas and liquid will be flowing but gas here continuous but liquid will be highly dispersed flow that means here liquid will be dispersed flow that means as a droplet flow it will be there. So there are four special types of flow regime we can expect from this trickle bed reactor at different flow conditions it is called trickle flow and then second is pulse flow third is dispersed bubble flow and fourth one is spray flow. So these are called hydrodynamics that means it is how that flow phenomena occurs inside the bed.

Now you will see that when that trickle flow when that bubble flow when that pulse flow and spray flow will happen at what condition. So there will be a certain limitation for that you cannot increase that liquid velocity or gas velocity beyond a certain regime so that you will not be able to have that type of flow regime. So to get that a special type of flow regime is within a range of operating condition you will see that if you are having that superficial velocity and then superficial gas velocity. Here in this picture there is a map shown where you will see that with respect to liquid velocity what should be the gas velocity to be followed so that you can get a special flow regime. To get that trickle flow that means their gas will be continuous whereas superficial liquid that means liquid will not be continuous there.

So in that case what will be the regime to get this. So here this trickle flow regime will be showing in this regime where this superficial liquid velocity will be less than 10 to the

power of minus 2 meter per second where the superficial gas velocity will be less than 1 meter per second. So within this range of superficial liquid velocity and gas velocity you can expect that will be a trickle flow and beyond this regime that means superficial liquid velocity greater than 10 to the power minus 2 meter per second you will see that you can expect that their bubble flow within this range of superficial gas velocity of 0 to 1 meter per second. Also even you will see that you can get the pulse flow there beyond this certain range of this. So you can expect this within this range at any point if you consider for this is you know a specific value of superficial liquid velocity and the superficial gas velocity then you can say that there will be a pulse flow.

Whereas at any point in this region you can say that what would be the superficial liquid velocity and what with the superficial gas velocity only based on those liquid and gas velocity you can expect this bubbly flow here. Whereas to get the spray flow you have to control the liquid velocity very low that means less than 0.01 meter per second and superficial gas velocity will be higher than 1 meter per second then only you can expect that spray flow. Whereas bubble flow it will be a smaller than 1 meter per second but it will be high liquid velocity at around 0.

1 meter per second. So this is the case that for trickle bed reactor what will be the flow transition. Here special packed bed we are considering this trickle bed reactor because this reactor are being used for that catalytic cracking in industry especially for having that you know less back mixing as well as that more uniform liquid and gas distribution within this flow regime. So that is why this bed is more expected to utilized. Now mostly that flow regimes are detected by visual observation through transparent column wall in laboratory scale experiment. And however other techniques can be used like electro conductivity, thermal conductivity, pressure drop measurements and even variation in mass transfer coefficient those methods also can be used to get this type of flow regimes.

And also you have to remember that the trickle flow you will see that in the case of trickle flow the catalyst particle tends to be covered by a film of liquid of varying thickness whereas gas tends to flow through interstitial space which is not occupied by the liquid. And also this normal regime of trickle flow is mainly determined by a superficial velocity of liquid and gas both. And the transition between these two regimes is characterized by sudden increase in two phase frictional pressure drop. So that is why you have to know what will be the frictional pressure drop. So based on which you can mark it on whether it will be that bubbly flow or a spray flow or you can there the trickle flow.

So that demarcation can be obtained based on that two phase frictional pressure drop. So how to calculate that two phase frictional pressure drop or how to assess that frictional pressure drop there. You can measure that two phase frictional pressure drop just by different techniques either that pressure transducer, substituted instrument you can use even modern techniques also you can use to measure that frictional pressure drop. From the laboratory experiment you can use that simply manometer also you can use that two

phase frictional pressure drop what will be there in the trickle blade also. I think in your laboratory also you are doing this type of experiment in trickle blade reactor there what will be the frictional pressure drop how to measure it and also how to assess this frictional pressure drop.

Once that frictional pressure drop by experimental measurements you have to assess it. Now there are several methods to assess this either by correlation method or by other you know that stochastic method or you can say some mechanistic method by which you can assess this frictional pressure drop. You will see that one of the important method based on which you can assess this two phase frictional pressure drop whenever fluid will be flowing through the packed bed or that any conduit there if there is a two phase flow there. So here this is called actually Lockhart-Martinelli method and Lockhart-Martinelli in 1949 they have given a certain concept based on which that this frictional pressure drop of the two phase flow can be assessed. So that concept or that model of that Lockhart-Martinelli in 1949 still being used which is known as Lockhart-Martinelli model.

So this model is mostly used as a recognized tool to describe the two phase frictional pressure drop in different process equipment. So it is called Lockhart-Martinelli model you have to remember it. So in this case you will see that this is basically a method of two phase frictional pressure drop multiplier. Here one multiplier to be considered which is very popular method to assess the frictional pressure drop in the packed bed. What is that actually? So according to that model of that Lockhart-Martinelli given in 1949 the two phase frictional pressure drop in a packed bed is a function of single phase frictional pressure drop.

So this is the concept that two phase frictional pressure drop will be certain factor multiply each to the single phase frictional pressure drop. So single phase frictional pressure drop if you multiply by a certain factor then it will give you that two phase frictional pressure drop. This is the concept. So that is why the by which factor you are multiplying this single phase frictional pressure drop either liquid or gas that factor will be called as multiplier that will be called as multiplier or it is called frictional pressure drop multiplier. So this can be expressed by this here this equation.

So ΔP_{fTP} here basically the frictional pressure drop f for frictional ΔP pressure drop and here P, P means here TP, TP means here two phase frictional pressure drop that will be is equal to ϕL^2 into ΔP_{fSL} .

Here the Equation

$$\Delta P_{fTP} = \phi_l^2 \Delta P_{f,sl} \Delta P_{fTP} = \phi_g^2 \Delta P_{f,sg}$$

ϕL^2 is basically the multiplier that means the factor by which you are multiplying with that single phase pressure drop this is basically ΔP_{fSL} . ΔP means pressure drop f for frictional here suffix SL means single phase here liquid, S for single phase L for

liquid, TP here two phase. So two phase frictional pressure drop will be is equal to phi L square into delta P f SL. So this is for if the frictional pressure drop of single liquid through that packed bed and if you multiply it by phi L square then you will get two phase frictional pressure drop.

Either way you can say that if the single phase frictional pressure drop of gas and if you multiply by a multiplier which is called as phi G square here based on gas. This is also multiplier phi G square or phi L square. Phi L square basically for liquid and phi G square for gas. So in this case also you can get that two phase frictional pressure drop. So by these two equation you can easily assess what will be the two phase frictional pressure drop once the single phase frictional pressure drop either for liquid or gas.

So phi is called the two phase frictional multiplier not the sphericity here. And then the author introduced a new parameter which is called X or denoted by X it is called parameter that is called Lockhart-Martinelli parameter. The authors they are given another parameter it is called X which is called Lockhart-Martinelli parameter. This is called X, X is called Lockhart-Martinelli parameter. So the parameter X will be relating to the single phase pressure drop for liquid and gas as if each fluid will be flowing alone in the packed bed and which can be defined by this equation.

So X is basically what is that phi G by phi L that means ratio of this frictional multiplier of gas and liquid or it is defined as what is that root over delta PF by delta L that means friction or pressure drop gradient for single phase liquid divided by friction or pressure drop gradient based on superficial gas velocity.

Here the Equation(s)

$$X = \frac{\phi_g}{\phi_l} = \sqrt{\frac{\left(\frac{\Delta P_f}{\Delta L}\right)_{sl}}{\left(\frac{\Delta P_f}{\Delta L}\right)_{sg}}}$$

So this is called X it is called Lockhart-Martinelli parameter X. Now this single phase pressure drop can be calculated from the Ergun equation. Now you have to know that what will be the single phase frictional pressure drop that you have already learned in your previous lecture that how to calculate the friction or pressure drop for the single phase flow. So that you can calculate by the Ergun equation.

Here the Equation

$$\frac{\Delta P_{f,s}}{\Delta L} = \frac{150(1-\epsilon_f)^2 \mu_f u_f}{\epsilon_f^3 \phi_p^2 d_p^2} + 1.75 \frac{(1-\epsilon_f) \rho_f u_f^2}{\epsilon_f^3 \phi_p d_p}$$

Once that all parameters viscosity, velocity and particle diameter even sphericity even a void fraction of the liquid. So there itself you can easily calculate that frictional pressure drop. So once that frictional pressure drop either by gas or liquid then what will be the

multiplier? That multiplier can be then calculated from the experimental data. that total two phase frictional pressure drop of experimental data and the frictional pressure drop of single phase flow by Ergun equation then if you divide it you will see that what will be the multiplier.

You can calculate easily multiplier. Now this multiplier how it will be related with the Lockhart-Martinelli parameter. Chisholm, 1967 developed the equations in terms of the Lockhart-Martinelli correlating groups for the frictional pressure gradient during the flow of gas liquid mixture in the bed. So in terms of Lockhart-Martinelli parameter here we can say parameter that means X which will be actually relating some physical properties of the group itself as well as that some other characteristic factor of solid how it will be intact all those things and also it will be depending on the frictional pressure drop of individual phase. So we can say that frictional or two phase pressure drop multiplier or frictional pressure drop multiplier which will be function of Lockhart-Martinelli parameter that can be equal to 1 plus C by X plus 1 by X square. So this relationship or correlation is given by C.

Scholl 1967. Similarly for phi G square that fx will be equal to 1 plus Cx plus X square where C is a parameter that can be obtained from the experimental data by knowing that phi L value phi L is what?

Here the Equation(s)

$$\varphi_l^2 = f(X) = \left(1 + \frac{C}{X} + \frac{1}{X^2}\right)\varphi_g^2 = f(X) = (1 + CX + X^2)$$

Phi L is simply that multiplier that can be obtained from the measured frictional pressure drop divided by the single phase frictional pressure drop. Then you will get phi L. So once that phi L and already what is the X value then you will be able to find out what will be the C value after substitution of that. So in this case then phi L square can be related with the X that means Lockhart-Martinelli parameter and here C is a Scholl constant. The parameter C depends on the experimental conditions whether the liquid and gas phases are laminar or turbulent flow.

If suppose gas and liquid both are laminar then the C value will be is equal to 5 whereas it will be applicable only that Reynolds number will be less than 1000. When this liquid and gas both will be like this turbulent and laminar respectively then the C value will be is equal to 10 where the Reynolds number will be Reynolds number for liquid will be greater than 2000 and Reynolds number for the gas it will be is equal to less than 1000. If suppose liquid will be laminar flow whereas gas flow will be turbulent that means higher superficial gas velocity in that case the C value will be is equal to 12 whereas this Reynolds number for the liquid will be less than thousands and gas Reynolds number will be greater than 2000. But both the phases will be turbulent in that case the value of C will be is equal to 20 and Reynolds number in this case will be defined as 2000s it will be greater than 2000s for based on that liquid and gas Reynolds number will be greater than 2000s where Reynolds

number for liquid and gas it will be defined by this equation. So we understood here that two-phase frictional pressure drop will be some multiplier or multiplication factor of single phase liquid or gas pressure drop and this multiplier will be related to the Lockhart-Martinelli parameter and that Lockhart-Martinelli parameter or single parameter which is related to the multiplier that is suggested by Sissom and that Sissom constant is depending on the flow condition either laminar or turbulent based on that flow condition we are getting different value of Sissom constant.

Now to calculate that single phase frictional pressure drop even gas phase frictional pressure drop you have to know what will be the volume fraction of the liquid and gas inside the bed. To calculate the volume fraction you have to know what will be the volume of the liquid in that packed bed and volume of gas and liquid solid mixture inside the bed. So that will be like this. Similarly epsilon the volume of gas divided by volume of gas liquid solid in the bed that will be V_g by V_t and epsilon is this solid volume fraction that means total volume of solid by volume of gas liquid solid in the bed. So that can be obtained from the mass of the solid that is mass divided by density of the solid you will get the volume of the solid and divided by total volume that will give you the volume fraction of the solid. Here the Equation(s)

$$\epsilon_l = \frac{\text{Volume of liquid}}{\text{Volume of gas-liquid-solid in the bed}} = \frac{V_l}{V_t}$$

$$\epsilon_g = \frac{\text{Volume of gas}}{\text{Volume of gas-liquid-solid in the bed}} = \frac{V_g}{V_t}$$

$$\epsilon_s = \frac{\text{Total volume of solid}}{\text{Volume of gas-liquid-solid in the bed}} = \frac{M_s / \rho_s}{V_t}$$

$$\epsilon_l + \epsilon_g + \epsilon_s = 1$$

Now these three volume fraction that means liquid gas and solid will give you the summation of one. So here this trickle bed from the top liquid and gas both will be flowing downward and this is the trickle bed that means solid catalyst bed that is liquid plus packed solid here and it will be coming out downward that gas and liquid both will be flowing downward and here in the separator that gas will be separated out. So in this way you can calculate what will be the volume fraction of liquid volume fraction of gas and volume fraction of solid and from which you will be able to calculate single phase frictional pressure drop based on argon equation. Now you will see that we are talking about that frictional multiplier that is a function of Lockhart-Montanelli parameter. You will see how they are related if you increase the x value that means frictional pressure drop of that liquid it will be increased then you will see that they are ϕ_L will be increasing whereas that ϕ_G will be decreasing when that you will see that this frictional pressure drop will be lower based on the liquid.

So in this case you will see that this profile is here that ϕ_L and ϕ_G how it will be related to the two phase Lockhart-Montanelli parameter. So here for different flow condition turbulent, turbulent, laminar, turbulent, turbulent laminar and laminar, laminar flow condition these are the different values you can get from this graph. Similarly for liquid multiplier this profile you can have this profile exponentially decreasing for this liquid profile with respect to Lockhart-Montanelli parameter. Let us do an example based on this theory.

Here a trickle bed reactor of diameter it is 0.08 meter is operating for a catalytic gas like ethylene oxide liquid water reaction at a gas superficial velocity 0.005 meter per second and a liquid superficial velocity of 0.015 meter per second with catalyst to produce ethylene glycol the diameter of particle density is 10,490 kg per meter cube used in the reactor which is 0.

002 meter of sphericity of 0.86. The effective length of the bed is 1.5 meter the mass of the particle used is 20 kg in this case you have to find out what is the two phase frictional pressure drop per unit effective length and viscosity of the liquid and gas are given also the densities of the liquid and gas are given here. Now in this case then you have to find out what are the two phase frictional pressure drop per unit effective length. Now how to solve this you have to calculate first density of the gas that is given density of the liquid it is given density of the particle also given to you viscosity of the gas is given to you viscosity of the liquid also given to you what is the particle diameter this is also given to you what is the bed diameter this is also given ϕ that means the sphere sphericity of the particle 0.86 mass of the particle 20 kg volume of the catalyst also it is given I think 0.

019 this is volume of catalyst that you have to calculate because mass by density of the catalyst particle that you will get that volume of the catalyst then you have to calculate a volume of reactor that diameter of the reactor is given so volume of the reactor it will be coming like this void fraction ϵ_f it is you know 0.75 I think it is given to you ϵ_f also you can calculate from that earlier equation here ϵ_f that is given here volume of liquid by volume of gas liquid solid in the bed so that void fraction of bed and gas velocity it is given to you liquid velocity also given to you gas volume fraction it is also given to you and then liquid volume fraction that you can calculate and then what is the frictional pressure drop based on Ergun equation that you can calculate to becoming like this frictional pressure drop based on gas that also can be calculated from the Ergun equation you can calculate it x that means Lockard-Mantenelli parameter that means once that frictional pressure drop for individual phases then you can easily calculate what will be the x value that means root over of $\Delta P_f L$ by $\Delta P_g L$ like this. Then you will see that Reynolds number you can calculate it is coming less than 1000 Reynolds number for gas it is also coming less than 1000 that means your condition is laminar laminar so flow pattern is laminar laminar so Sisson flow constant C that will be is equal to 5 then what will be the you know ϕ_L^2 ϕ_L^2 can be calculated here based on that formula given here ϕ_L^2 that means $1 + C$ by x plus 1 by x square here so this is ϕ_L^2 is

equal to what $1 + Cx + 1/x^2$ so based on this you can calculate what will be the ΦL^2 once that ΦL^2 you will be able to calculate what will be the frictional pressure drop for two phase flow that will be basically that ΦL^2 into $\Delta P_f SL$. So here it will be like this divided by L per unit length so it will be like this per unit length. So this you have already calculated I think here it will be by unit length this one this will be like this and then this one known to you and then this one is known to you now you have calculated so what will be the final two phase frictional pressure drop.

So from these you will get that it is around 20,949.28 Newton per meter cube. So here whatever problem is given you just summarize it and then finally you just calculate it in this way. So I think you understood this problem based on this theory so in this lecture what we have learned we learned that what is the Lockhart-Martinelli model and based on which how that two phase frictional pressure drop is related to the single phase frictional pressure drop and the relating factor is called multiplier also this multiplier is related to the ratio of single phase frictional pressure drop of liquid to the single phase frictional pressure drop of gas and the relation is given by Seisholm 1967 whereas this correlation will be a constant it is called Seisholm constant and this Seisholm constant C is related to the flow condition whether this gas and liquid both will be laminar or turbulent and also for that single phase frictional pressure drop will be calculated based on that Ergun equation. So I think you understood this concept of Lockhart-Martinelli model. In the next lecture we will try to start different module like mixing of solids so there we will discuss about how that solid will be mixing with another type of solid and what will be the assessing criteria for having good mixing and non-uniform mixing like this. So thank you have a nice day.