Chemical Reaction Engineering 2 (Heterogeneous Reactors)

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Lecture 38

Fluidized Bed Reactor Design Part 3

We will start now, right? So in the last class I have drawn the fluidized bed with manometer and all that, right?

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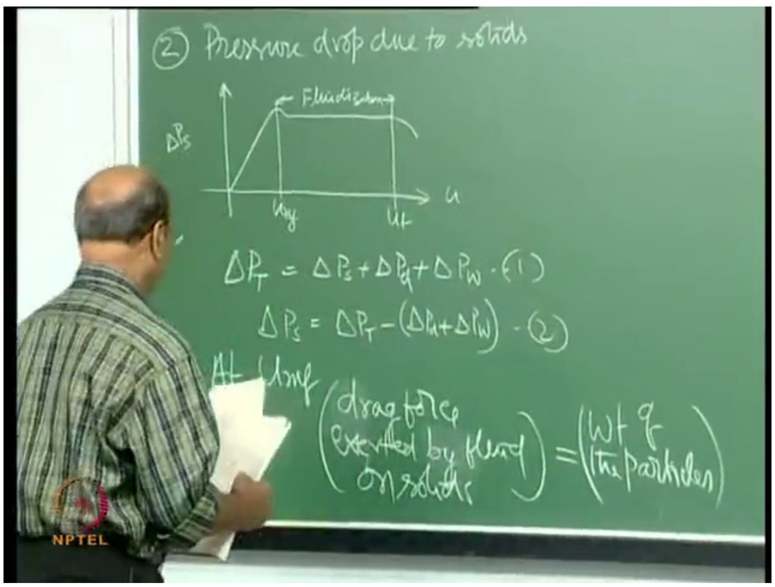

Plus we also have that delta p graph, right? These two, so now delta p graph I have to still draw this is second item no pressure drop due to solids so fluidization, okay this is the graph what we have also drawn and I have given the diagram where how to measure the pressure drop, right? So the total pressure drop which you measure directly from the manometer is delta Pt equal to delta Ps plus delta Pd plus walls usually walls are neglected but anyway we will keep that delta Ps equal to delta Pt minus delta Pd plus delta Pw, okay the equation numbers you have?

So this is the first equation right? First one this is second equation, okay. So what we measure is this and before taking the actual delta P measurement with solids without solids you have to measure the pressure drop you know in the picture I do not want to draw it again in the picture before putting the solids you have only walls walls are there walls and distributor plate, okay you just measure at various velocities what will be the delta P and then correspondingly you subtract from every pressure, okay from every for every flow rate you can subtract these values and then you will get this and when you plot this only the pressure drop after fluidization will be constant otherwise as I mentioned in the last class also it will be there will be slight increase in the pressure drop due to the distributor plate walls will not contribute much, okay but distributor plate will have tremendous pressure drop you know I hope you remember your (())(3:24) orifice equation to measure pressure drop.

See we have single orifice where you measure the pressure drops, okay and convert that into flow rates, okay. So the same u square also will come here so that is why pressure drop will tremendously increase as the velocity is increasing that we have to subtract that one has to be very clear. So once I have this then we have to find out is it I mean is there an equation which we can also derive for finding out the pressure drop due to solids, okay is there an equation there is an equation very simple very good equation because weight per unit area is pressure drop and at minimum fluidization velocity the entire bed is supported by the drag force, so the drag force and then weight of the solids if you are able to balance you are going to get the equation, right?

So that equation you will check with the experimental data, so that equation is at minimum fluidization velocity at umf that means at the point of fluidization you have a drag force exerted by fluid by solids exerted by fluid on solids exerted by fluid on solids this must be equal to weight of the particles which is nothing but you know m into g mass into acceleration due to gravity, okay that you just remember, okay.

So now this drag force, how do you measure drag force? How do you measure it what you are telling is calculation Stokes law will give you calculated value, right? Cd equal to 24 by nre, okay not nri nre nri is different, okay or re simply, how do you measure? Is there any measurement possible for drag force? How do you measure friction? You have done with no through pipes how do you measure friction Kaviya? Always Kaviya first attack just now you are coming? Take rest, Shekher how do you measure? How do you measure velocity change I change velocity what you do you measure, Moody’s chart you measure, you read you do not measure measuring is doing experiment I say, but how do you measure energy loss, right?

Student: Total energy minus kinetic energy.

Professor: How do I measure total energy minus kinetic energy? Measurement I am asking, where did you calculate, measure the pressure drop I say see this seems to be very simple questions, no they are not simple questions I think you do not have any idea at all I know I how to measure the pressure drop drag force or friction factor or friction because you cannot directly put something there and then measure it no it is only indirect measurement which is used I mean which is measured by pressure, okay even here we do the same thing drag force I think you know we do not really think beyond certain point I do not know anyway I can if I go there time will go, okay.

So the drag force is measured in terms of pressure drop, okay.

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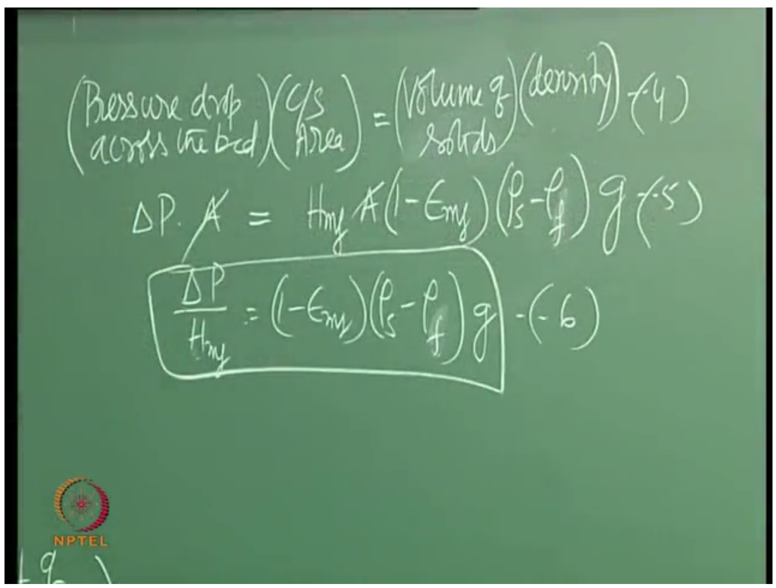

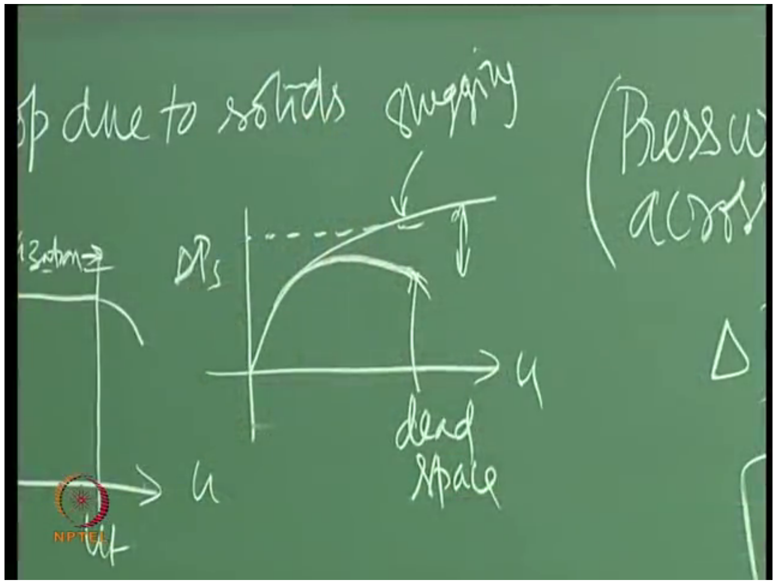

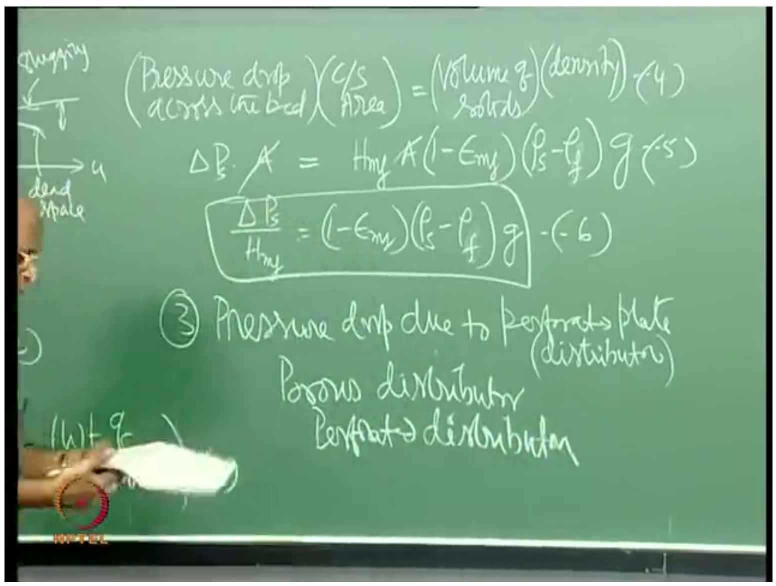

So when I write the equation again of course in terms of words this will be pressure drop across the bed in fact I gave you clue how do you measure friction factor, right? Friction factor all of you would have done the experiments maybe Savita would have not done, okay and Kalpana what should I call you Kalpana or Sarojini, okay Kalpana would have not done but all others would have done it, Rachit you have done it no, seems like, okay anyway.

So pressure drop across the bed and of course the cross sectional area that will there and, okay this length I do not know maybe cross sectional area equal to because drag force no weight of the bed, okay it is nothing but of course weight of the bed mass into gravity, how do you calculate mass of the bed? Volume of the bed I know and then density, okay. So volume of bed and density and this density is the apparent density because already you have some other fluid and the solids would have lost some weight, correct no because of the buoyancy, okay into of course g is there, okay. So this is the one if I write the equation this will be delta P and cross sectional area is A and volume of the bed is nothing but actually volume of the bed means here only what you are balancing is solids, right?

So volume of the bed means we are talking about I think better write beds means we fill the entire bed solids. So I have some the volume of the bed into 1 minus epsilon of that will be weight of the solids, okay where epsilon is the wide edge so that is what so that will be if I take what did I I did not put anything there no, okay let me put that one as hmf because we are talking about minimum fluidization velocity, right? Into cross sectional area that is the volume into 1 minus epsilon mf because everything at minimum fluidization velocity, right? This multiplied by density which is nothing but rho g or rho f to be general for liquid also that is possible and into g it is very simple only.

So then we have delta P by hmf is 1 minus epsilon mf rho f into g so this equation if I write this also numbers 3, 4, 5, 6 this is called the fluidization equation, okay. So can I calculate from this the pressure drop? Almost equal to, yes you are right exactly so that is what I thought of asking you but yourself asked and then answered that is right. So at minimum fluidization velocity we know that the bed is almost packed so that is why accept that a little bit of change and some people who will like to take that because there are lot of errors involved in this measurements because first of all your solids are not uniformly a one size particles because always you sieves in reality, right?

Sieves will have some in passing through some retaining on so you will have always a little bit of distribution and that is the starting point for all the errors in fluidization bed and 1 minus epsilon also many times we take as packed bed porosity of if there is already measured value available because some people in the literature some values are available that epsilon mf you can take so that is available rho s I know because solids which I am taking I know rho f I know whether I am taking liquid or gas and the densities we know and g you know we can calculate delta P provided we know the hf, okay or hmf, hmf is nothing but again, Abhinav? Same thing when you take that as packed porosity that also will be packed bed height, so that will be the one, good.

So you can calculate this in fact every time, so this will give you an idea, so I told you sometime back I think it was Anurag who was asking me the pressure drops are in a fluidized bed may be higher than the packed bed. See the maximum pressure drop what you get is only this (())(13:17) due to solids, right? But distributor will have you know always increasing pressure drop as you go with that one but the same thing is also possible for packed bed, packed bed also has the distributor plate, right? But there is slight difference between packed bed distributor plate and this distributor plate only in surface in free area, which one will me more? Which one will be less? Free area for the distributor see you have to Abhinav you have to support the solids right so you have a perforated plate with holes, okay.

So for packed bed we use also we have to use perforated plate otherwise fluid cannot enter no, yes and for fluidized bed also you have to use, free area in your opinion in which bed less free area in which bed more free area, more free area means more amount of liquid can go through or fluid can go through less free area means very less, why? Answer is right.

Student: Because you always anyways lot of (())(14:20) in the bed you cannot keep low free area on the plate and add another pressure drop in the system.

Professor: Exactly not that is the reason but I think anything something more, it is not that because already bed has pressure drop so let me reduce the pressure drop here the same thing we can also do here, right? The same thing we can also do here but, in packed bed plug flow will automatically come because of even bed presence because the bed presence will make the profile almost horizontal the presence of bed itself. That is why that is a good thing that we why we say for packed bed when do you get plug flow or when do you get turbulence you know almost flat velocity profile, what is a Reynolds numbers I told you already this and whereas for tubular flow single tube without anything inside it will be 40000, 50000 to get almost velocity profile, okay.

So that is why, okay so that is not a problem but you know what Shekhar said is right you will use more for packed bed, okay not only to reduce the pressure drop to allow more and more throughput but if I use very large free area for fluidization, fluidization itself will not take place it need some pressure drop that means it needs some jet activity through the pores the fluids should come like jets, okay so that will actually lift the entire bed, for example you can take cloth you know filter cloths are there you can take cloth fix it and also you can fluidize you will never get fluidization you can get mesh what your mother is using you know to make flower and all that what we are also sieves here.

So if you put just sieves you will not get fluidization you will get fluidization much much higher velocity, okay so that is why the actually the design next point is actually the pressure drop due to the perforated plate itself how much pressure drop you allow you should allow, okay. So that is why this is pressure drop S I have been using pressure drop due to solids so this equation which we have to use for measuring the I mean for calculating pressure drop and then it is very simple also particularly if I have gas phase this is almost 0 when compared to this solids.

So it is actually delta Ps you know that equation is becomes even then it is not much complicated so one can easily calculate what will be delta Ps and normally what we do is when you are doing this experiment we also draw this line where it is actual actually where that line is, okay because I can calculate no delta Ps I can calculate from there so delta Ps value I just draw there just for my reference, right? If this curves shows me something like this you know this is the pressure drop this is delta Ps this is u let me say that I have like this what do you say about this graph, is there anything wrong with the fluidized bed? That means not fluidization all the particles are not supported by the fluid only some particles are fluidized some particles are fluidizing that is very important point you can find out really you know that means the other part will be dead space there is no use of that, right?

And sometimes you may get also some kind of you know like this like this that also may go up even if you plot, for example exactly delta Ps removing your pressure drop due to distributor plate even then you will get some times this may be difficult for you this may be due to this slightly increasing and in fact it is not constant it will be fluctuating up and down that pressure drop that is because of slugging so this may be due to dead space that means all the particles have not fluidized and this is due to slugging, what happens during slugging? The entire cross sectional area is occupied by the gas and solids above they are just pushed up, right? So then the pressure drop may be more there because entire thing is just pushed up, right? And that generally very narrow cross sectional area, right?

So at that time when it goes up and then all the solids can be at one pint if they cannot be supported the slug will break and then entire bed will fall, at that time pressure drop will be fluctuating up and down. So the simple things one can see from the graphs and then find out what is the disease for this particular fluidized bed it is like doctors you know they will ask you to take some bp test or some other test and then they see the results or graphs and then find out whether what disease you have.

Similarly you are also doctors for the reactors or any equipment you can just find out by drawing or by looking at the you know some measurements and then find out whether something wrong with that or it is beautifully fluidizing. So all this simple things will be there when you just plot this, okay good. So the next point is this is fine this is the equation this you do not please forget I think it is very for the people who have gone through fluidization you should remember this equation it is not very difficult to remember it is just weight of the bed, okay supported by the gas, okay so that is this in terms of pressure drop this is the equation.

So the next point is pressure drop due to perforated plate, how much pressure drop we can give for the plate, right? So the next point if I write here 2, 3 no 3 pressure drop due to perforated plate or distributor of course if you go deeper and deeper there will be lot of discussion about the distributor itself because that is the starting point for any fluidization and also solid particles so that is why solid particles have been characterized into Geldart's A, B, C, D groups then at least we will have an idea what kind of fluidization we may expect and here distributors various distributors have been used they used simplest one is perforated plate, okay then they can also use bubble caps, you know bubble caps? Prabhuv? Bubble cap distributors, how they look like?

Student: Sir I think there is a hole and there is a cap on top of it when the fluid comes it has to open the cap and then goes through.

Professor: It will not open the cap, it goes through that it will not open the cap is permanent so it will take the tortuous path like this and then again comes out, why do they require that?

Student: More time to interact with.

Professor: Not because of that, it is not because of more contact time, more contact time you can go to packed beds, think some more where do they put their bubble caps, other one is sieve plate, right? Even for distillations sieve plates they use, so why they do not prefer sieve plates but think you know sieve plates will give you more much more bubble you know interaction because small small sieves no sieve means the perforations are smaller you generate large amount of bubbles vapor flowing through that so you will have more surface area more transfer but still we put sometimes bubble caps, anyone I think any idea? Why do you need more pressure drop there actually we should have less pressure drop there no in distillations column I am telling you, (()) (23:00) any idea? How can you operate I think in fact that gives much more pressure drop at high velocities, how can that avoid (())(23:13)?

Student: Because when the gas contacts with liquid it will push the liquid aside.

Professor: Okay when you have bubble cap how this liquid is coming I am talking about distillation how the liquid is coming how the gas is going, where is the gas going where is the liquid going because liquid has to come down from top plate to the bottom plate, gas has to go from bottom plate to top plate to the down comer, okay. So there is always a way through the down comer so liquid will come down there it comes through the down comer that is not a problem, for that sieve plate is better because sieve plate contains lot small small holes, right?

So when vapor is going through that it generates large number of small bubbles, contact (()) (24:07) some extent, okay it is not mainly contact time you heard of dumping weeping, and what is the problem with sieve plates? To avoid weeping to make liquid happy you know because it should not weep no it should not weep so to make it happy you put bubble caps, now what will happen happily it will go through the down comers because you have to provide down comers when you put the bubble cap otherwise if you have sieve plates the liquid has to come through the same sieves gas also has to go through the same sieves so wonderful information is also there on that because sometimes even stabilities due to interaction between the bubbles and then liquid also may happen interaction I have seen I have not used for distillation for some other column turbulent bed contractor I have used and I also used perforated plates and then when liquid is coming from the top and under some conditions the entire liquid will be moving like this inside the bed our diameter was 10 inches slightly bigger column, okay it will be.

Now if you imagine this kind of movement in the industry where they have 2 meters diameter, okay it will have tremendous pressure the entire column also may be moving this way that way if you are not properly supporting it, okay. So that is because the interaction between this bubbles to liquid to avoid that for happy smooth flow bubble caps are better or sieve plates with down comers also are there, okay but sieve plates with down comers still it is not good because some of the liquid is definitely coming through the sieves you cannot avoid that, same problem here why we need why some people use distributor with bubble caps is to avoid solids flow here perforations are perforated plate is the best one sieve plate is the best one.

And sometimes what we do is over the sieve plate we will put mesh very fine mesh so that it will not create any pressure drop but it will not allow solids to fall through when they are falling through it may block even sieves so then you have that you know that hole totally not used for the flow then you have the dead space and like more if you have more dead space it will create you see everything is important you know when you are designing any equipment, okay.

So that is why the general thumb rule is of course there are many many thumb rules for distributed design I am talking about this is one bubble caps can be used, sieve plates can be used and also there is porous distributors which normally we never use for distillation or absorption we do not use because pressure drop will be tremendous, okay porous you have seen the porous distributors it is like membranes porous distributor what they do is they take very fine powder and then compress it as a plate they use copper shots, okay they can also use lead shots they do not use copper shots are very frequently used alumina, glass you should have seen this I think you would have not noticed it that when you are doing in physical chemistry lab they use for filtration you know sometimes not the filter paper but times they use the glass frit they call that is porous distributor that is what exactly the same thing is used and that frit has given porosity you can ask for 10 percent, 20 percent, 30 percent that frits I mean what you have seen maybe 1 inch very small one what you have done in the chemistry laboratory, okay.

So that is what what I am telling you that also can be used that is very widely used because we need some kind of pressure drop across the distributor for fluidization that only gives sufficient energy because that will increase the you know the flow rate velocity, okay velocity and what you are calling minimum fluidization velocity is the superficial velocity only we are not talking about each and every point what is the velocity you know interstitial velocity we are not talking, why? Because we cannot measure that very accurately same thing even with packed bed, okay in packed beds we use whether distillation column or any other use for packed beds when you are using packed bed for process we never use interstitial velocity, why? Because across any cross section the wide edge itself varies, right?

So that means somewhere I have slightly more velocity, somewhere I have less velocity all this I can never take into consideration for the design even though we take another average average of all this wide edge and sometimes we calculate and then to tell people that this is the actual velocity going through the packed bed is superficial velocity divided by epsilon wide edge that will give me the interstitial velocity, okay that is only for some kind of you know satisfaction that okay I am also able to know what is now the interstitial velocity other than that if you look into many correlations most of the correlation will not give you this epsilon in the correlation Reynolds number they give for packed beds.

So most of the times they use only superficial velocity because which is easily measureable so that is the reason why superficial velocity cannot be because it is not simply manageable you cannot and that also varies from point to point everywhere in the bed unless you go for what are called structured packings I do not know whether you have heard of them or not, random (()) (29:55) what normally we do in industry is random packings just take the solids and then just dump it but there are structured packings where I mean whatever you know like this like this like this also no like this and then you put the entire column with that you know maybe 1 meter, 1 meter, 1 meter and then given diameter maybe 1 meter diameter total maybe 20 meters.

So for every 1 meter you put one piece and that is connected and you can see very beautiful structure in those packings those industrially this structured packings are also available, what is the use of structured packing is that I know very clearly what is the surface area I am going to get that is all more clarity random packing I do not know unless you measure it and every time you change packing every time it changes, right? So that is the reason why random packings we use, okay.

So the pressure drop due to perforated plate we will take just two plates commonly used, one is the sieve plate perforated plate and the other one is porous plate porous distributor and perforated plate distributor let me write that porous distributor and perforated distributor these two are widely used, okay.

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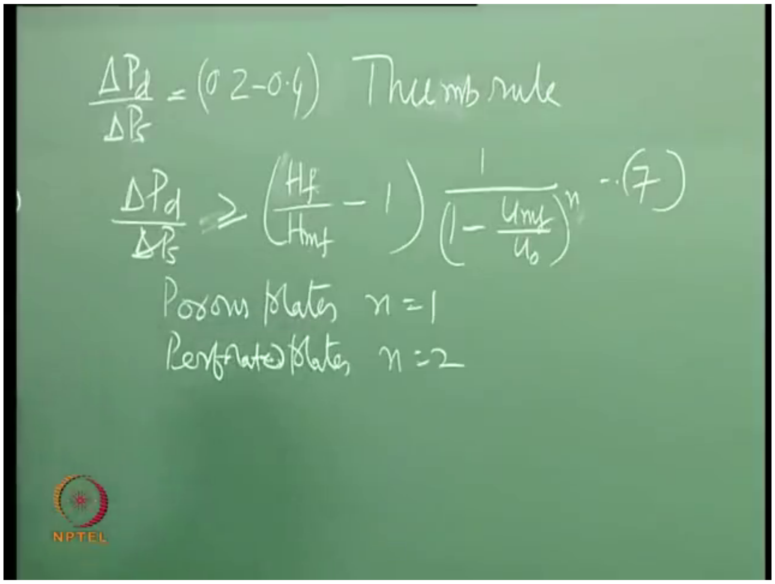

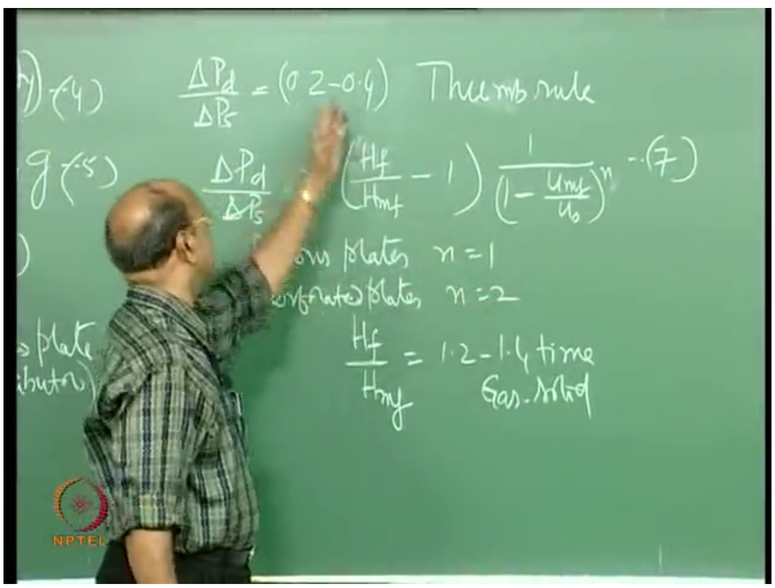

I think there are some thumb rules where the pressure drop should be around 0.2 to 0.4 of delta Ps that is the general thumb rule delta Ps by delta Pv one of the oldest thumb rules is that 0.2 to 0.4 of delta, okay that is all, sorry the other one sorry this is delta Pd, delta Pd by delta Ps, okay this is what normally the thumb rule.

So this thumb rule was observed only by experiments, so you get good fluidization when you use this kind of values, that means the pressure drop should be 20 percent of pressure drop due to solids which you can estimate from this you can calculate from this and I do not know whether you have designed, who taught you process equipment design? Who? As he given the perforated plate design? No, that is simple one I think I will tell him I think he also maybe semester is over at least for you juniors you know perforated plate design also is an very beautiful design, okay how do you choose the diameter of the perforation itself how many perforation should be there, how many perforations will be there automatically comes once you know the diameter of the perforation and once you know the total free area, that fixes but what do you put I think he is the pitch weather a triangular pitch or square pitch, so what do you prefer generally? Why? Where is heat transfer there? It is only to allow it is only he remembers that for heat exchangers so trying to extend, very good nothing wrong, you can accommodate more number of perforation per unit area that is the reason why we go for that, okay.

So the same thing even for heat exchangers but that is not good because when you for heat exchangers when you talk about cleaning square pitch is better because you will have at least some more space in between so where you can clean it and then you know once in a while you have to clean it otherwise it will be fouling and all that, so heat exchanger may not be there after some time.

So this is the general thumb rule but I want to take you slightly away from this thumb rule also because later people have used again the derivation is there but anyway I have also not seen that derivation but that equation that is used now later which also comes to this after under special conditions delta Pd by delta Ps should be greater than equal to Hf height of the fluidized bed divided by Hmf at minimum fluidization velocity minus 1 this one is 1 minus umf by u not to the power of n that is the equation if I this is equation 7 when n is a constant.

So this is the equation they try to use and then for porous plates n equal to and for perforated plates n equal to 2 again they do the experiments and then try to find out what is the exponent and all that, okay. So this is slightly some theory you know jet velocities and all that they will take and then they will try to derive this, here of course one should know what is height Hf, Hf is the height of the fluidized bed there are some equations which relates Hmf and Hf, okay beautiful relation is for particulate fluidization, can you imagine that relation we have Hp packed bed and the corresponding porosity is epsilon p, right? Then it has fluidized to certain level where of course packed bed also you can take as mf minimum fluidization velocity, right? Epsilon mf and at some other high velocities you have Hf and epsilon f, what should be the relation between these two?

Student: Hmf by 1 minus (())(36:42).

Professor: Hf equal to, what will happen to 1 minus epsilon f? It is the volume balance, it is the volume balance, right? So when you have the packed bed you have this side when you have almost minimum fluidization velocity Hf into 1 minus epsilon f equal to Hmf into 1 minus epsilon mf that is simply volume balance you know height changes, okay. So that is why one can find out if it is very very good fluidization particulate fluidization that means volume is nicely expanding but in gas solid fluidization that will not work, why? The bubbles will destroy the height and you do not know the bubbles form, where the bubble break so that is why the overall height is not exactly like with this relationship but in the absence of anything we will also take that particular relation what I have told you sometimes we will use that.

So of course this we know umf by u not you know because you calculate umf let us say 1 meter per second you decide in the beginning itself that I want to use 5 meters per second that means 5 times umf, 3 times umf, okay or 20 times umf possible in industry particularly even in 20 time umf also is used very easily in fact most of the times it is 20 to or 10 to 40 times anywhere in between we use industrially, okay because of large amount of solids are there distributor you cannot perfectly design even if you design perfectly the distributor gas flow is not uniform to all these perforation so to somehow you have to fluidize the entire bed so that is why try to use more and more gas, okay.

So that is the reason why you know that kind of long large values are given that range 10 to 40, okay good. So this is the only equation and there is another thumb rule saying that you know if you are very close to umf you just use only 0.15 those are all details I think which we do not have to discuss that, right? This is what you can just remember for porous plates and perforated plates this is the equation which can be used to calculate delta Pd because delta Ps you know from this equation and using delta Pd if it is a perforated distributor there is a specific way of calculating the perforated holes that you have to decide perforated holes, okay then free area you have to decide normally free area we use here around 10 to 15 percent, okay free area good.

So I think this is fine in fact you get this thumb rule if you take this one if you take this ratio Hf by Hmf as 1.2 to 1.4 which is used I mean which is the height you know let me explain Hf by Hmf for many gas solid fluidized beds will be around 1.2 to 1.4 times lmf not able to follow, sorry Hf by Hmf many times in the industry it will be 1.2 to 1.4 times per gas solid beds where you have bubbles and all that it cannot beautifully expand it will expand only when you are going for the velocities beyond table velocities then only starts expanding and comes out of the bed, okay.

So when you have this kind of values you substitute here for perforated plates and you know you will get this thumb rule because originally thumb rules are developed for perforated plates because easiest one is perforated plate so that is the reason and of course people saw that when it is lot of leak is there two perforated plates they put slightly eccentric it is not the same holes but slightly eccentric pressure drop will be tremendous what is the problem there, lot of powder will come and then stay in between these two plates, okay industry is held to run because I think everywhere you will have the problems, good okay.

So that is the one and then next one is Nela what is the next point? This is 3 no, that is 3 4 umf minimum fluidization velocity, how do you find out minimum fluidization velocity? Minimum fluidization velocity umf nice ideas have come you know when you look at this graph, okay I have written here fluidized bed fluidization before that what should I write here, Prabhu? What is that region? Let Prabhuv tell answer, excellent that is the packed bed.

So at this point what is happening? The pressure drop, the pressure drop at this point the packed bed pressure drop must be equal to fluidized bed pressure drop, what is fluidized bed pressure drop? Equation 3, what is packed bed pressure drop? Remember name, Prabhu, Ergun's equation so at the point of minimum fluidization velocity simple we balance the pressure drop this equation and also Ergun's equation, Ergun's equation also has delta P by l or Lp or Hp packed bed, here Hmf equal to Hp because of at the point of minimum fluidization velocity.

So simply we balance this and then that and then and Ergun's equation has velocity terms you have two in fact quadratic equation u and u square, right? So then it is a quadratic equation you solve it and then you will get the minimum fluidization velocity because you are balance it point of minimum fluidization velocity that we will do quickly and before that no one asked me why this particular height and then falling and slightly above and the almost gone static, why no one asked me? Abhinav?

Student: Sir I think the inter particle (())(43:41).

Professor: What will happen at that point? Why is it increasing and then again falling? Right? you are on the correct track.

Student: Particles are attach (())(43:52) when they circulate.

Professor: So it needs a little bit of higher energy to break that inter particle forces and once they are broken then it is easy again so the particles will not have you know the gas need not have that much energy, so that is the reason why it is a little bit falling and then comes down and if you do that if I do the experiment this is I have taken the bed put the solids and then slowly increasing the velocity in this direction from lower value to higher value but I can also do the experiment I can start at the highest value possible, right? Not terminal velocity somewhere here terminal velocity means all the solids will go away, right?

So somewhere here if I start and then slowly decrease I do not see this, why? Obvious inter particle that forces are not there because you have already broken them in the beginning itself, okay. So take it to higher velocities and then do it then you will get almost like this of course there will be slight (())(45:02) a little bit down, okay but anyway I think you know you will get almost horizontal like this, in the beginning.

Student: That is why (())(45:15).

Professor: That is when you are going in the 0 to smaller velocities to higher velocities, okay that is why, okay not lift the bed why it has to lift the bed? Because all the particles are coming together if each particle is individually present then the gas will exert the drag force on each and every particle so uniformly it will fluidize but when you have normally we use fine powders so it has that surface energy where it will come together and then clean together, so that you have to break before fluidization so that is the reason why it goes slightly above, right?

And this kind of very beautiful points you cannot see particularly by the by this is generally for Geldart A and Geldart B particles, okay if you go to cohesive powders then you cannot exactly find out that nice curve you cannot that is why we do not want to fluidize group C particles cohesive particles absolutely necessary we have to do it, right? So then use either vibrations or some people even use not only vibrations you have this sound ultra sound, ultra sound also breaks this you know the inter particle forces and one can also do that many many techniques can be used, good okay.

So that is what I thought I will just inform you there, liquid solid depends on what kind of not definitely this so much because but still it can have slight peak there also, okay for liquid solid also it is possible, good.

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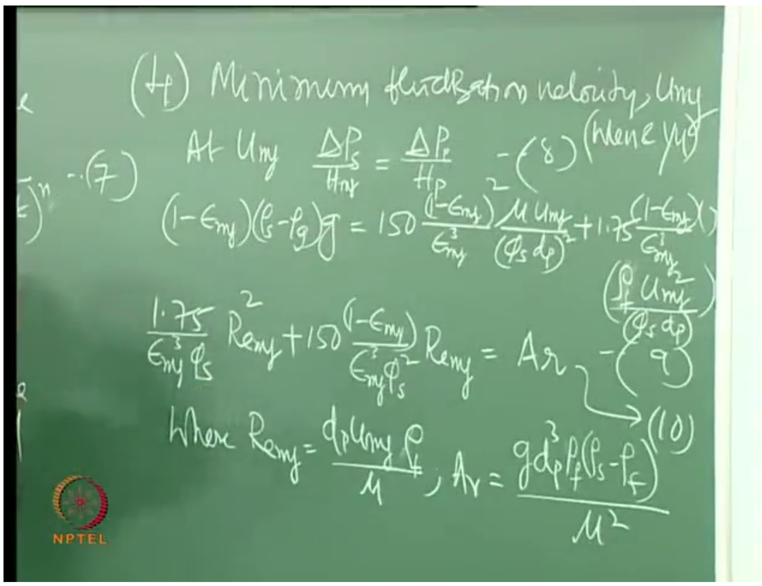

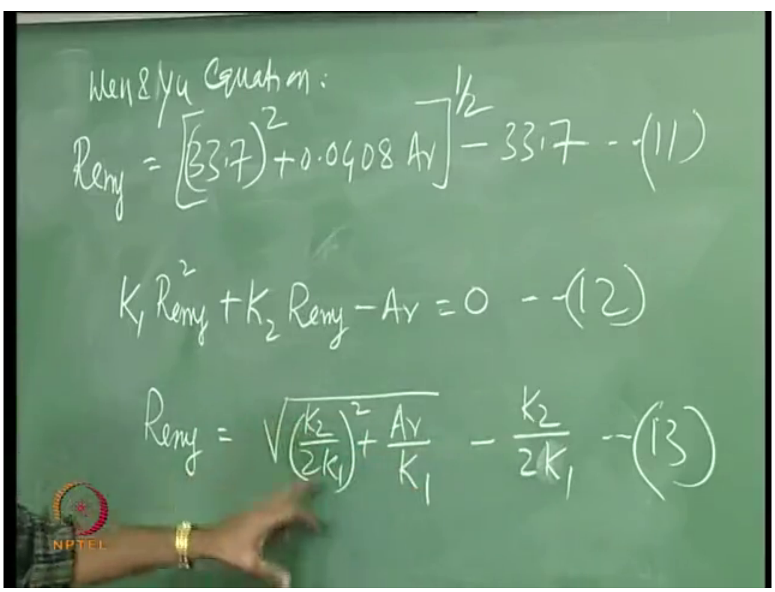

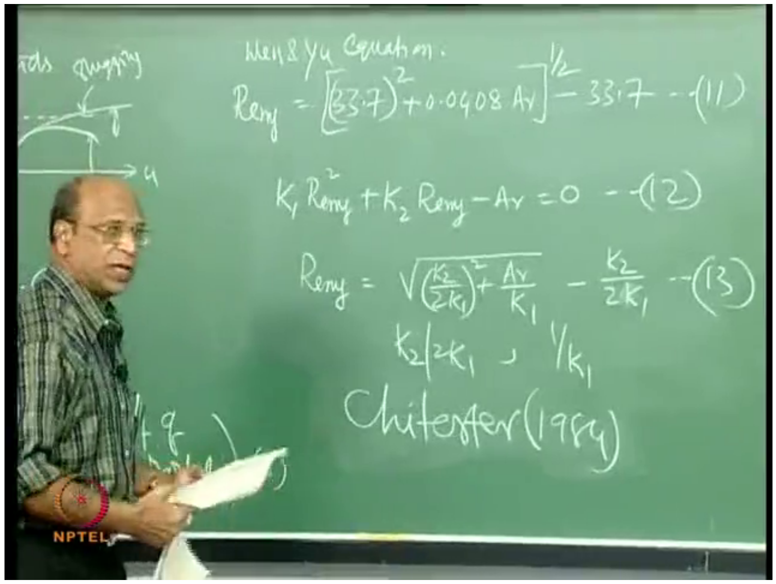

So minimum fluidization velocity at the point of fluidization so I think it is unfair to maybe ask you to remember Ergun's equation so I will just draw here at Umf delta Ps equal to delta P, okay this also I can write per unit length Hmf Hp packed bed at a minimum fluidization velocity, okay where of course we are taking Hmf equal to Hp at that point.

So now I have to write here the Ergun’s equation, okay here delta Ps that familiar equation is 1 minus epsilon Mf rho s rho g into g equal to the other equation is 150 1 minus epsilon m square mf epsilon Mf cubed mu Umf because at Umf we have already balanced this is mu viscosity and phi s by dp whole square, okay that whole square comes and here I have 1.75 again I have here 1 minus epsilon Mf by epsilon Mf cubed how we get these cubes and all that you would have done it no in the derivation Ergun's equation derivation you get here rho, okay I will write here this term rho f rho f Umf square by phi s dp where phi s is sphericity, okay.

So that is the equation and when you rearrange this I may give this derivation to you, okay when I rearrange this what you what do I get is very nice equation 1.75 by epsilon Mf cube phi s Remf square plus 150 1 minus epsilon Mf by epsilon Mf cube phi s square into Remf equal to Archimedes number I have to give the number 7 this is 8 this is 9 this is 10, okay where I have to write Remf equal to dp Umf rho by mu rho f by mu and Archimedes is, Narsima Reddy gdp cubed rho f rho s minus rho f by mu square, okay.

So this is the Reynolds number, sorry Reynolds number and Archimedes number I think I will remove this I think this is first given by a person called Wen and Yu I will also write here Wen and Yu that is why it is called Wen and Yu equation I think 1948 or so, reference okay I do not have here but sometime like that only, so that is the one and there were very smart people you know they were all excellent engineers at that time they want to use the equation as simple as possible, okay.

So that is why what they did was they found out epsilon Mf and phi a square for large number of particles, okay sand, sand you know if you take river sand it will be different it will take if you take see sand it will be different, which one will be more round? River sand or see sand? River sand because river is continuously flowing but there it is only back and forth action, okay and also limited most of the time but there river in Vijaywada may bring sand to Nelur, okay. So during that it is only flowing like this no at the bottom of the river or ganga for example you take we do not know where the sand from Himalayas may be coming to Bay of Bengal particles so that is why it is more round so like that they have taken various particles alumina, copper you know not silver silver is costly zinc and many many materials and they have formulated this group as 1 by phi s epsilon Mf cube is approximately 14 and the other group that is 1 minus epsilon Mf divided by what is that phi s square and epsilon Mf cubed is approximately 11.

So then this constant will become how much? This constant will become how much? This will become, 24.5 and this becomes 1650, correct? So now that is the quadratic equation now which we can easily solve now this is a constant 24.5 multiplied by Remf square using these two, right? And 150 into 11 that is 1650, okay so then if you solve that the equation what you get for minimum fluidization velocity is Remf equal to 33.7 whole square plus 0.0408 Archimedes number this whole thing under square root into 33.7 this is called Wen and Yu equation even know very widely used Wen and Yu equation very widely used for small particles, okay very widely used for small particles.

And you know that delta x people where you know they want to still see whether this is equation correct or can you modify a little bit delta x research normally what we do, okay finding out a little bit of plus side negative side and all that what they did was that they take this as K1 constant, this as K2 another constant and then solve the differential equation in terms of you know K1 and K2, right? In terms of K1 and K2 what you get here is that, okay I mean what I am trying to tell is that this K1 and K2 will be the, okay let me write the corresponding differential equation in terms of K1 and K2 K1 Remf square plus K2 Remf minus Ar equal to 0 number, number is this is 11, okay so this is 12, good.

So if they solve that what they get is Remf equal to square root of K2 by 2 K1 whole square plus Archimedes by K1, okay this one minus K2 by 2 K1 capital, so this is equation number 3 no 13 where now what they did was they took all the data that is available for minimum fluidization velocities because they know Archimedes number, right? And then take this ratios K1, K2 you know we fix this 1 by K1 and K2 by K1 so they try to fit the data using this ratio one ratio is here I have 1 ratio is K2 by 2 K1 other ratio is 1 by K1 that is this and anyway this is 2, okay over.

So now this they try to fix the data like this we have 1, 2, 3, 4, 5, 6, 7 correlations, so all these 7 correlations I think you know the popular correlations this is the first one Wen and Yu for generally small particles there is another one called Chitester, Chitester correlation this is in 1984 if you the actually Chitester is the Phd student where he has his work is only to find out minimum fluidization velocity in the thesis I think he is from France. So for large particles his correlations seems to be better large particles you have not mentioned what is large what is small normally around 100 microns if you have 200, 400 less than 500 microns this seems to be the better one Wen and Yu equation above that Chitester equation seems to be better, okay. So with that I think minimum fluidization velocity is over then I think I have to do tomorrow the remaining parameters, okay.