Chemical Reaction Engineering 2 (Heterogeneous Reactors)
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Lecture 37
Fluidized Bed Reactor Design Part 2

How to you make air conditioners noiseless? This is supposed to be split AC I say, no it is not window it is only split I think it is better than supposed to be better than split, split will not give as said window when compared to window, central AC if you put you will not have any noise start, okay. I think yesterday what we have discussed about fluidized beds you remember a little bit? Come to the class I say, okay mentally, okay. So we have discussed the definition of fluidization and, types means what types we have discussed regimes and all that we have discussed, good.

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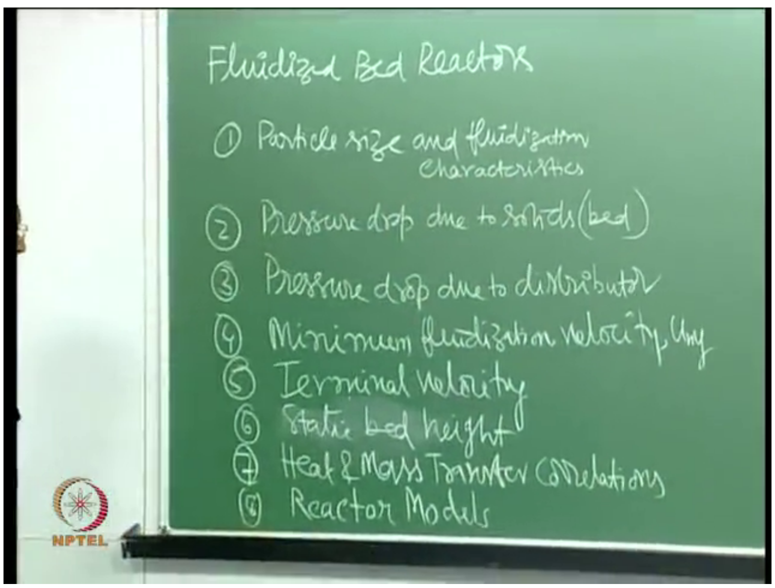

Now to designed fluidized bed rectors what are the parameters we should know, that is what what we are going to list here, number 1 is particles size and fluidization characteristics, number 2 is pressure drop due to solids or sometimes we can also say bed pressure drop due to solids in the bed, okay so number 3 is pressure drop due to distributor plate or distributor and number 4 is minimum fluidization velocity, number 5 terminal velocity, 6, bed height I think I will write here static bed height, 7, heat and mass transfer correlations, the last one 8 is, difficult to write, reactor models reactor models.

See how many things we should know and actually this is a full course if you teach all of them one by one deeply, good? But I think all the points we will just touch and this we have to go a little bit deeper just to develop the model, so you need to find out what are the particles that can be used for fluidization what kind of fluidization you get if you use different size of the particles that is 1, number 2 is that the pressure drop how much maximum pressure drop that will be there for the solids, okay that is one. Then you have the distributor to support the solids, right?

So what is the maximum pressure drop this distributor plate should have? How do you design this distributor plate that is very important, so then you know like for example what is the free area we allow when we have the distributor plate you have perforations and what is the area is it 100 percent, 100 percent means same column, column diameter so then 50 percent, 70 percent, 80 percent, 30 percent how much you go for free area so that is what you have to also find out and that correspondingly gives you the pressure drop that is the one.

Then we have the minimum fluidization velocity I think I better write here this symbol umf, right? So that is starting point of the fluidization then we have terminal velocity of the solids actually it does not have any meaning you know here terminal velocity we are talking about single particle terminal velocity where in the bed you have lots of other particles. So in the part in the presence of other particles definitely these terminal velocity will be different but even then we would like to have an idea what is the maximum you know upper side what you can go but sometimes even plus or minus 100 times you will go around that velocity, okay because multi particles systems even now it is very difficult to characterize and there is no theory where you can get all the solutions using you know from first principles and also closed form solution, closed form solution means correctly you are having the solution you have the nice equation and when you solve it as a differential equation (())(6:51) example you will get a nice solution all that is not possible for multi particle systems and that too in the presence of some other fluid either gas or liquid. So then you have this static bed height, what is the bed height to start with you have to take you know we discussed that hp height of the packed bed before fluidization what it should be, how many times L by d for example or how many times d if I take 1 meter diameter how many times I can go as packed bed static bed before starting fluidization 2 times, 5 times, 10 times, okay so that also is important for us.

Then you have heat and mass transfer correlations both will take place I think you know during reaction you have either exothermic reaction or endothermic reaction so heat transfer will automatically come into picture catalytic reaction so mass transfer again comes into picture so that the due to diffusion the reactant gases have to go into the catalyst get reacted, come out all that things, okay.

So that is what is heat and mass transfer correlations what we have then finally we have the reactor model, okay what kind of reactor models we have ideally? Only two flow systems p of r and m of r, okay so we have to also see which one is more suitable here either p of r or m of r or both that is what, that is what is the overall picture I think I have to complete all this in 2, 3 classes.

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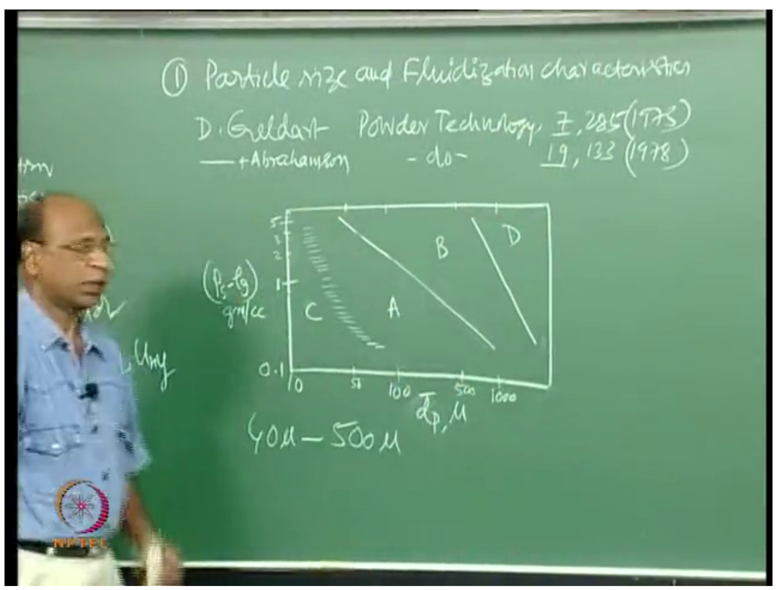

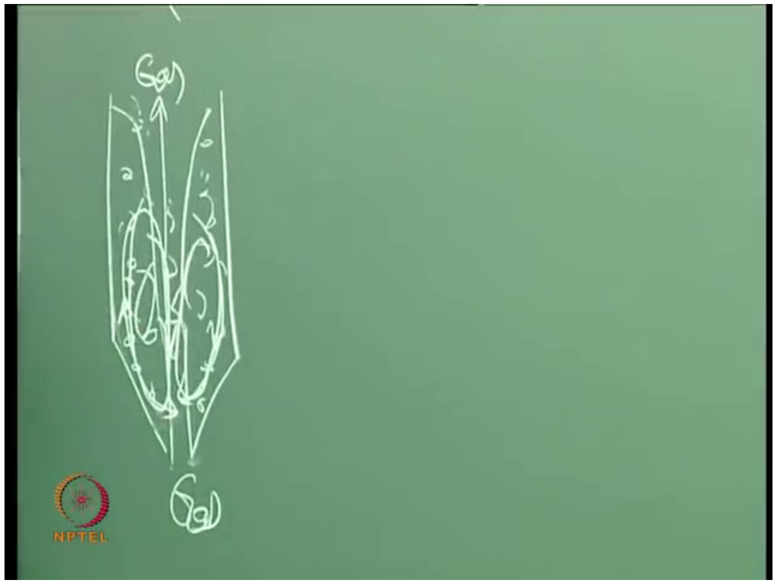

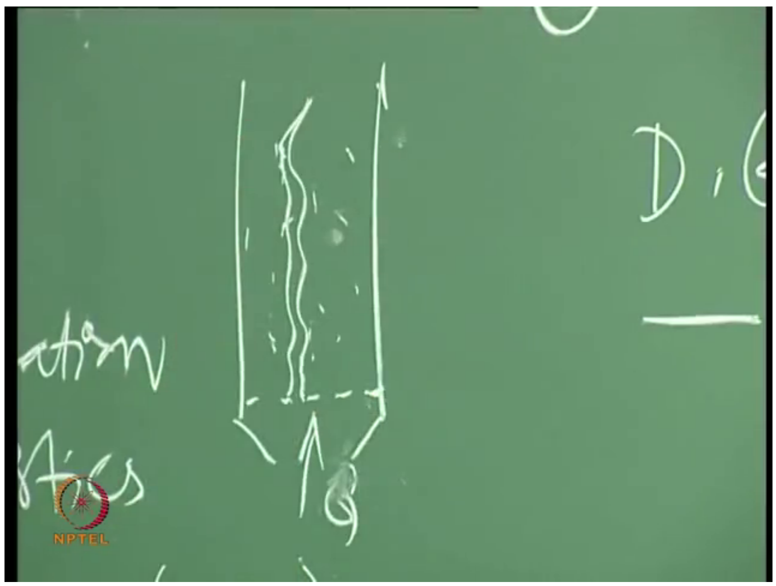

So that is why first let us state this parameter particle size and fluidization characteristics, lot of you know all these things are mainly empirical and many researchers try to find out what kind of fluidization you get if I take for example 10 micron particles, 100 micron particles, 1000 micron particles, 10000 micron particles, okay generally beyond that we do not go beyond 1 micron 1 mm particle itself beyond that we do not go 1000 microns but still there are large scale fluidization particles where particularly fluidized bed combustion they use around 5 to 6 mm whole particles because they cannot go to very fine powder it is go to very fine powder all the energy what they produced in the thermal power plant will used for crushing because tons and tons of coal has to be crushed to very fine powder means, okay.

So that is why practically they found that around 5 to 6 mm size coal combustion for coal combustion, so I think beyond that normally we do not use the fluidization operation that is the maximum, right? And if you want to use beyond that also some kind of good contact then what we call it as spouted beds, spouts the bed you know heavy large amount of I mean large diameter particles will spout rather than entire bed moving that I think also I will mention when you are talking about this.

So that is why many people tried and then they try to give the good fluidization for good fluidization means where you have smooth uniform fluidization like particulate fluidization particulate fluidization is good fluidization, why? Because inter particle distance is same everywhere that means all particles are uniformly distributed in the bed nice things happening, okay like western society where discipline is there, okay to some extent there is discipline there not like our traffic and all that but whereas here in the real aggregative fluidization excellent representation of India, chaos you cannot find out suddenly there may be bubbles you know suddenly there maybe bubbles bursting, suddenly there maybe bubbles starting and in between there are good ordered people in between somewhere this corner, one this corner, the other corner is one so that kind of chaos will be going on.

So that is why some of them try to put this information in terms dimensionless numbers obvious first dimensional number dimensionless number that will come is Reynolds number, very good good guess, so afterwards that only we know next one? Next number you tell me, Savita, Sherwood number will not come here you know this is for fluidization characteristics Sherwood number will come in this step you are playing chess thinking 10 steps ahead, okay you are talking about only that particle and fluidization characteristics where we are not talking about heat transfer, mass transfer anything, any other number? You see I told you know actually I am a good person why do you scold me I do not no I think all the time my guess and I am very good psychologist I say I can easy find out how the students mind will work, you see how much time you are taking to give second dimensionless number in fluidization it is a fluid particle system, porosity is not a number no it is just a parameter dimensionless number, Archimedes number is one, other than that for fluidization, 2 I think you would never heard of what is called Froude number u square by gdp, what does that tell you Froude number? This is my problem I say once I start discussing (())(12:21) goes, goes goes, okay what is the definition of Froude number?

Equation to be effective I do not ask Archimedes number, okay because no one can tell definitely, can you tell Narsima Reddy? Equation tell me, no into there only divided by divided by u square that will come anyway when you are discussing about minimum fluidization velocity Froude number is another number which will come, okay same of course friction factor as a dimensionless number also people use no.

So all these things will come and people try to characterize in terms of those numbers Froude number is u square by gdp the last squared divided by g, g is the (())(13:19) gravity dp is the diameter of the particle that will tell us inertial upon gravitational or buoyancy also you can say, okay so that is the kind of thing what we have but they were not very successful then there was a person called Geldart so from then onwards it is called Gerart classification of solids, okay so he published a paper in powder technology we have page number 7, sorry this is not page number I want to write page number and saying, okay. So this is volume 7 285 page number 1973 and again they modified this with another person called (())(14:18) maybe he speech this scholar, okay Abrahamson son of Abraham, okay.

So this is Geldart plus Abrahamson so these two people again published in the same that is after 5 years I think no, 1978, okay. So this is volume number 19 page number 133 1978 so they slightly modified the old graphs and then get slightly more reasonable because it is an empirical observation this is very popular because straight forward and easy to use that is why all our research must be very simple as simple as possible but not simpler like, who said that, Einstein your morals should be as simple as possible but not simpler it is wonderful statement no, good.

So they have made this one as simple as possible in the beginning but I think next one they did not it is not simpler a little bit complicated in the sense that some updating because it mainly empirical observation they do experiments, observe, record there is no theory behind this, okay. So what they did was everything we have put in the form of a graph if you draw the graph you will get some experience about this and you will also know how to draw the straight lines this is rho s minus rho g normally expressed as grams per cc, okay one can also express in kgs and this side we have d bar p in microns, okay microns so that is one and then this kl changes here from 10 we have here somewhere 100, here 1000, okay approximately 100 this is log scale this side and then this side the density difference this is mainly for gas solid only, okay 0.1 to 0.1 somewhere here this is 1 0.11 so, okay this maybe 2, 3, 5 normally decreases no, okay log scale initially this one will be larger than smaller, smaller like that it goes actually it will be 6, 7 like that, okay good.

So this is the scale what we have and then they put their data in this format like divide the regions it will start, okay this side also I have to put approximately, so this again this maybe 50 this is also 50 then somewhere here I have 500 so this is only just approximately plotting this is 50, 100 it starts somewhere here this is a kind of diffusive region, not so much I will tell you what is this later all this is one region then we have 1000 starting from here, okay this is a this is one region then we have, okay good.

So first draw the lines approximately like that you know till 1000 ncr it may start around 50 here or slightly inside 50 so this also may start around this is 500 somewhere in between like this, okay. So then what he calls is this he calls as group A, this he calls as group B, this he calls as group C and this group D, okay. So now we have to see first of all what is this group C, group A, group D and all that, right?

So group C particles are the cohesive particles you can see they are smaller size fine size see here even around maybe 20 microns, 50 microns less than 50 microns under in general it is less than 100 microns but this boundaries are not exact I think you know they put all the data and then try to interpret but I think I will also give you some sizes later but generally when you have small particles you have cohesive powders, one example is talcum powder what you put everyday morning, okay.

If you have talcum powder will be around 1 micron, 10 microns less than that very fine powder. So that is an example of cohesive powder, so that means when you have that kind of powders you know as the size is becoming smaller and smaller the surface energy is more they come together stick to the surface very difficult to fluidize. That means the drag force which you are going to use to left the entire bed may not be sufficient sometimes to break the entire particle forces that is why you will get uniform fluidization some part the particles may fluidize where you have slightly loosened you know structure there in some other parts it may not, so that is why very difficult to fluidize is group C particles.

And group A particles are exactly I do not know whether you have seen the catalyst or not FCC catalyst is one of the very good examples there that will vary around 100 microns FCC catalyst I will tell you I think I will also tell you then group B particles as you do not have to write that I will tell you notes group B particles just listen there group B particles are like sand particles this is an example, okay so that you will have some idea group B means sand particles and this is the region where all the laboratories in the world people like us who work in fluidization we take always only sand as fluidizing medium, why? You will get good fluidization and bubbles are also they are fast bubbles and all that will come there but characterizable bubbles all that can happen here to some extent here, okay.

So that is why if you go to the literature and try to see either heat and mass transfer coefficients or fluidization a minimum fluidization terminal velocities or whatever you know even pressure drops everything if you go and see the literature 99 percent of the papers will be dealing with only sand, okay.

If they want to increase the diameter, sorry density for example sand density how much? I will ask Abhinav, Abhinav what would be sand density? Not a bad guess still, that is okay kg per meter cube I understood but is it correct? Is it higher or lower, higher? Renita you have any idea, around 2000, okay I think Prabhuv will tell 2500, 1800, okay it is 2600 you see this time you have missed it always you are trying to go in the middle part but this time I think you are tripped I say that is why I asked you when she said 2000, when he said 3000 I said Prabhuv is the best bet to get the answer.

So 2600, okay so to see the effect of density sometimes we use slightly higher density like you know steel balls where you have around iron ore, iron ore will be around 4, 4.7 that means 4700 or 5000, okay kgs per meter cube all that. So those things we would have used but most of the time people love to use this particles or this particles this particles again this side, okay this is the boundary this side particles are better and this side when you are coming to the conceive side again fluidization maybe difficult, okay.

So now please take this I will give you notes you know quickly, group C we will start with group C we can now write group C, okay underline this particles are very cohesive and fine powders so usually around 10 microns, 20 microns like that, okay normal fluidization is extremely difficult for the solids because inter particle forces are greater than those inter particle porses are greater than those resulting from the action of gas normally dag force, right? Or greater than those resulting from the action of gas full stop there. Face powder that is talcum powder what I said face powder flour maze flour and all that flour and starch, starch powder are typical of these solids, okay now next one group B, sorry group A we are moving this way group A, okay.

Group A particles are aeratable aeration you like aeration aeratable are materials having a small mean particle size and or low particle density having a small mean particle size and slash r low particle density in the bracket (less than approximately 1400 kg peter cube), okay full stop there. The solids fluidized easily with smooth fluidization at low gas velocities and controlled bubbling with small bubbles at higher gas velocities, okay full stop. FCC catalyst is representative of these solids those are the typical powders actually there is lot of range here but still we are somewhere around here those are the good representation of group A, okay next one.

Group B the particles are sand like with size range of 40 micro meters to microns I just microns I just write sometimes microns m also one can write to 500 micrometers look that is the normal size range but there you can see more than that also these are the typical group, okay sand like particles with size range of 40 microns to 500 microns and density range of 1400 to 4000 kg per meter cube, these solids fluidized well with vigorous bubbling action and bubbles that grow large, okay particles are similar to sand like particles whatever particles you get similar to sand, next one is group D these particles are spoutable, large and dense in fact not large large and or dense combinations spoutable, large and slash or dense, okay full stop.

D beds of this solids are difficult to fluidize, you know static bed if you take 5 or 6 for example, okay L by d d beds of these solids are difficult to fluidize full stop. They behave erratically giving they behaving erratically giving large exploding bubbles with severe channeling or spouting behavior if the gas distribution is very uneven, okay full stop. Drying grains and peas, okay roasting of coffee beans, gasifying coals and some roasting metal ores are examples of this group. For this group shallow beds are preferred, okay shallow beds are spouting, spouting beds are preferred for this group shallow beds or spouting or spouted beds are preferred, understood no? Good, okay.

So this graph was generated mainly at room temperature, okay and varying because velocity is not told there, right? It is only the density difference and average size of the particle, okay. So normally the flow through the beds are varied from 1 umf to 10 umf you know for the generation of this graph, okay so that is one that is why it is highly empirical later of course I think in this paper or in this paper maybe they also given equations here and also equation for this but there is no equation here because this is a band where you have that error too much this side or that side.

So that is why it is drawn like this here at least the boundary is sharp but with again difference between A, B and all that this gives a beautiful idea for example if you have from the process normally you have a process, okay mining for example you took from mining coal particles for example for gasification and all of them are approximately 7 mm, okay will you know some idea of fluidization what kind of fluidization you are going to get from this information, correct no that is what what we have discussed till now, right? So if I have 7 mm or 8 mm or sometimes we dry paddy, paddy here only but in other countries they also dry wheat and all that roasting of beans, okay.

So all these are large particles so then the moment I have that kind of particles which is the starting point then I will know maybe I will have this kind of fluidization for me so I better go for shallow beds shallow beds means very shallow it is if L by d is 0.4 or 0.5 or 0.2 that is shallow bed, why? Because here for large particles if you have very deep beds fluidization is very difficult and when you are pushing the gas more and more for getting fluidization suddenly they explode because you will get exploding bubbles channeling may occur, particles maybe throughing here and there very high aggregative fluidization which is not uniform fluidization, right?

So that is the reason why you will have an idea, okay when I have group D particles let me go for spouting, spouting is another very nice operation in fact spotting beds alone there is a book also they do like this they have a cone and they have the particles this is gas reduction, okay so this will go like this pushing the particles this is gas of course some amount will percolate also through the bed so you see here it goes like this, it goes like this and some of the particles are caught and again coming here circulations, okay you do not have uniform exposure of each and every particle but on the average if you take because of the circulations this is the circulation what you have circulation will be like this, so circulation will be like this because of those circulations you will have good drying characteristics but you see here advantage is I do not have to use that kind of very high gas velocities because that spot only I have to manage where like umf you have here spouting velocity, what is the minimum spouting velocity where this circulation start, okay got Shekhar I like your fountain exactly like your fountain where these solids are going to this and then near the wall you have the sliding mechanism so the entire bed moves like this this entire bed moves like this then on the whole you have exposure for the hot gas if it is drying operation, okay good.

So that is the one that is called spouted bed we are not talking about that we are talking about in case you want to use a fluidized bed then go for only shallow bed, shallow bed means if the diameter is 1 foot diameter probably you have to use only 4 inches, 5 inches, 6 inches then you will not have time or we will not have time gas will not have time to become a big bubble, easily it will come out that is the reason, okay good.

So that is one the moment you know that you are in B group B then we know that it is sand like particles good fluidization but see the bubbling is vigorous here, here it is exploding bubbles, here it is vigoring bubbles vigorous bubbles and here small and smooth bubbles which you prefer this or this or this, this one because small number of large not small number of large number of small bubbles you will get many good far as because that is how the contacting between solids and gas will improve.

So that is why we have that is why this gives a wonderful picture for us of course there is a lot discussion again correctly how the fluidization take place and all that we cannot go and I can tell you for example 1 here in the cohesive powders when you want to fluidize for example flower for drying purposes flower, or what is other one we have? Starch powder, so what happens is when you are using that talcum powder you have the distributor like this then you are sending the gas here you have the powder that is very fun powder, so most of the times snakes will form here, what are the snakes? This one because of the inter particle forces if there is a weak structure inside so this will start this goes like this that is a snake if you put like this, okay like this.

So like that here there may be another snake but if you go on doing that all the snakes will become one because they (())(34:48) together and then you have the fluidization but that fluidization all the powder may be thrown out. So that is way you can have a bigger cross section like that even though they fall again come back again, okay safe so that is why. So this kind of possibilities are there if you have cohesive powders so that is why that is very difficult to fluidize now with Nano technology this people are now trying to use fluidized beds Nano technology, Nano powders Nano sized powders, okay and even of course Japan has done wonderful work on this particular when we have cohesive powders they used very nice techniques, okay one technique is vibrating the bed, so the moment you start vibrating the bed the entire bed you know with nice vibrations then snakes will not form, what is that you are trying to do only you are trying to loosen the powder by shaking, right? When you are shaking like this the inter particle forces will be gone, right? So then easy to fluidize.

So that is why there is no end for human mind I say, okay but only thing is you have to sit down and then think properly yes so this is what can be done and then that kind of thinking should come first in the mind and then you have do the experiment and prove that your thinking, your hypothesis and what you have done experimentally both are right, if both are right you are great, Abhinav, okay do M. Tech I say beautiful or MS somewhere, you are doing? Good it is very nice, good.

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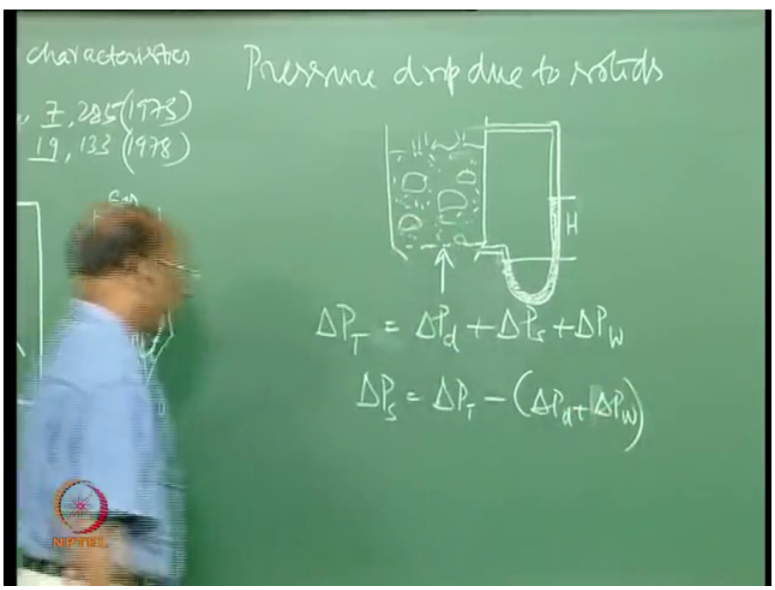

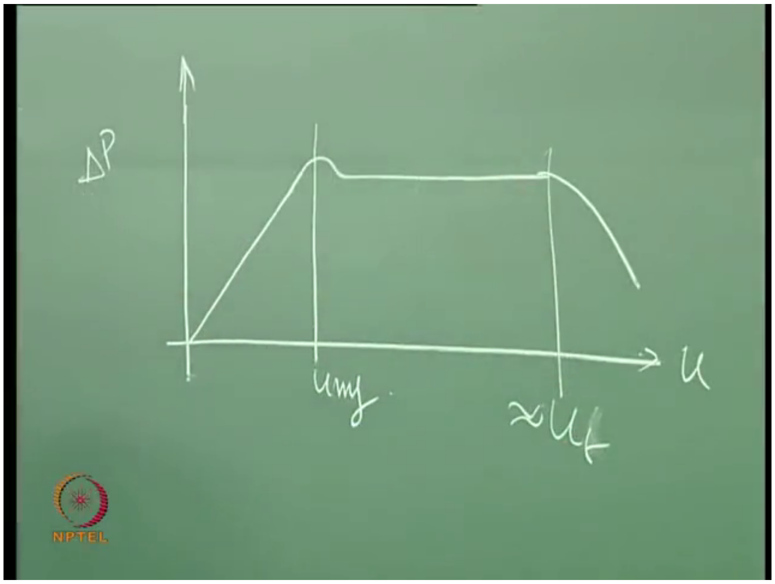

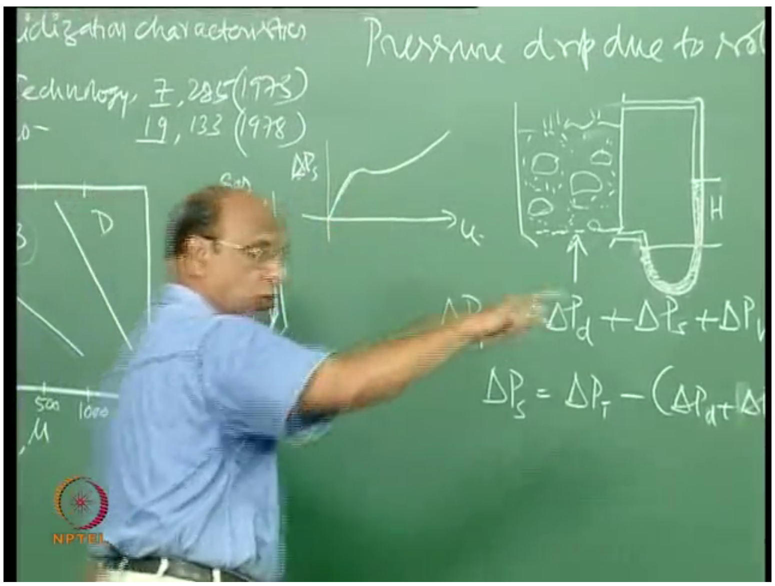

So this is the particle size and fluidization characteristics that is this I think still I can tell many many things about that but all stories we do not have time that much then this first part is over now second one is pressure drop due to solids that is simpler one so let me quickly finish, so here I have to draw the picture for fluidization, okay we have the bubbles somewhere here, then so that is the mano meter then we may have this is the mano meter fluid that is the pressure drop which we can measure, okay pressure drop due to solids we are taking, good.

See, okay what is that you are discussing? You have an experiment definitely the only thing is I am very happy you are able to recollect that you know you have the experiment for fluidized bed only or something else liquid solid, why choice I say packed beds fluidized bed both are important for chemical engineers, why what is the concession, I was giving 12 means 12 all 12 we have 12 experiments at that time, okay good but anyway I think there is no choice between packed bed and fluidized bed both you should know thoroughly because I think packed bed is right hand and fluidized bed is left hand for you, okay good anyway.

So this is what how arranged it is gas solid fluidization same thing even liquid solid also when you measure this you measure the total pressure drop delta Pt total pressure drop through this, okay as delta this one this also gives some pressure drop delta Pd distributor plate pressure drop plus delta Ps because of the solids that is here, okay that is weight divided by per unit area plus I also have delta P walls wall pressure that is what what I measure, okay.

So what I do is before starting the experiment that means before putting the solids inside this then I do the experiment for the same velocities different velocities for the same velocities without any solids, what do I get? I get the pressure drop due to distributor plate and also pressure drop due to wall, so then delta Ps I will subtract, no delta to get delta Ps I subtract delta Pt minus delta Pd plus delta Pw, okay correspondingly if I also plot this when I am doing that experiment Abhinav I think this also you could have done delta P versus u plotting graph, okay initially when I have low flow rates then you there is nothing but packed bed, right?

So you may get a linear graph which is not true all the time, okay and then it will go like this it goes like that but if you do not know this and then if you have plotted this total pressure drop then what you get is this, this is delta P versus u like this I do not know whether you remember your graph whether this way you got that way you got that is the right one this is wrong one, why? Why this wrong one that is right one? This is only which is not fluidized? This also fluidized this is at this point you have fluidization but after that it is continuously increasing pressure drop.

So after fluidization the our theory is that you know because there is no more additional solids so the total weights is constant weight per unit area is your pressure, okay pressure drop must be constant, okay. So that is what is that this will come because without knowing yourself this distributor is there you are measuring the you know actually distributor will contribute much more pressure drop at higher velocities, okay. So that was added to that that is the reason I mean when I was doing that laboratory in charge when I was also conducting those experiments you know for students so this kind of graphs they used to plot then we use to explain no no that is not right you have to subtract the distributor pressure drop and then only you will get almost horizontal like that, okay so this is the one, okay good.

So this is of course at this point what we call it as umf if you go much much beyond this were terminal velocity is come it is pressure drop only we are plotting then what will happen solids will go out, okay then you will get something like this actually this is maybe approximately ut because solids will go out of the system that means total pressure drop is less, right? So this will happen I think I will stop here I have to develop an expression for this I think that I mean (()) (43:52) has become to me also terror, he made me like that Shekhar, want to run? Okay run run, this is delta Ps, okay even though you write here delta Ps this is wrong it should be removed subtracted only this one you have to add, okay you leave.