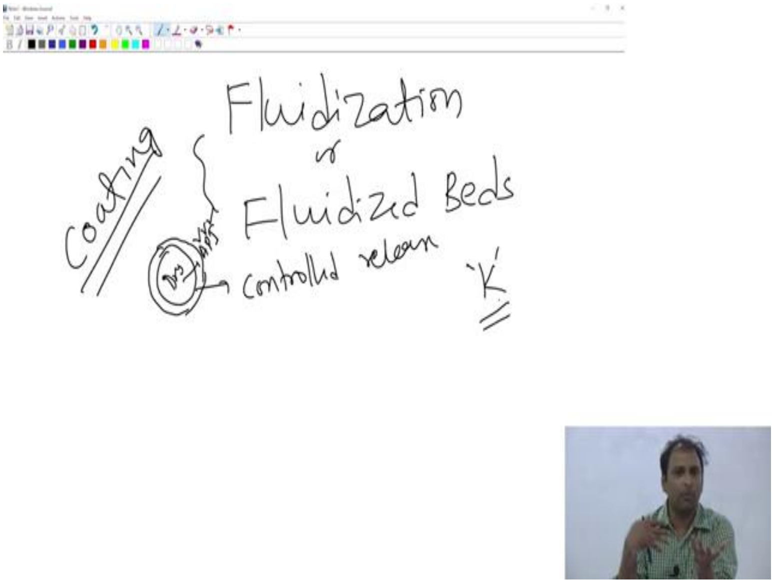
Fluid Mechanics
Prof. Madivala G. Basavaraj
Department of Chemical Engineering
Indian Institute of Technology, Madras

Lecture – 45
Fluidized bed

So, we are going to talk about a new topic which is; what is called as Fluidization, ok, or what I call as Fluidized beds.

(Refer Slide Time: 00:21)



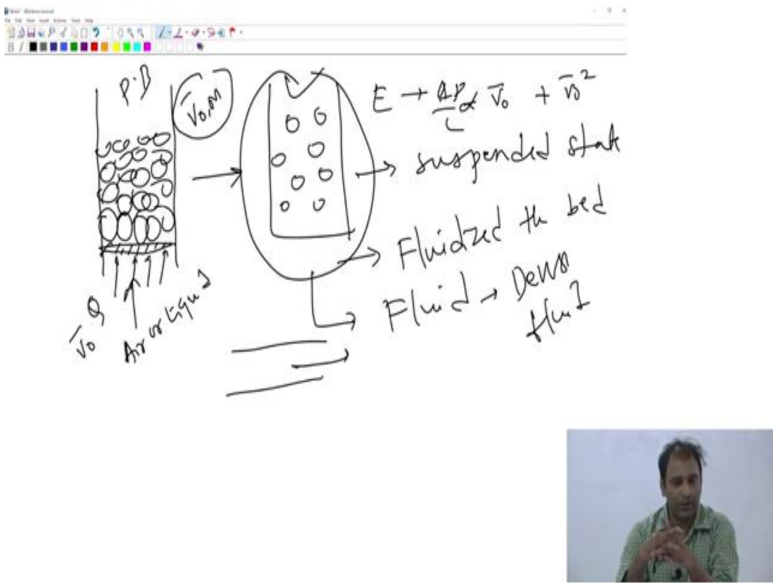
Again, like packed bed call you know packed columns fluidized bed concept is again is something that is again used for you know solid liquid or solid fluid contact, and it has a lot of applications in the industry. One of the example that I showed in the previous class was looking at what is called as a fluidized bed coating, ok. If you have say some particles in the fluid. So, I was talking about the application in coatings where if you really want to have a like say you have a solid particle.

Say, it could be say for example, a drug particle or something was a API, which is a active pharmaceutical ingredient, and if you want to coat it with a thin layer of you know some other material. And that some other material could be it can be a material which is kind of taste masking because you know a lot of you know like say paracetamol if you take it as a little sour like now it is a little bitter, ok.

So, I can have a coating of some other material which is a inert material which you can consume like maybe a starch layer for example, right. It could be used in the case of taste masking or you could also have a case where I would like to have a layer of something on the particle surface which may help in what is called as a controlled release, ok. That means somebody takes a pill and you would like to have that drug released into the body over extended period of time, ok.

What people do is they make this coating and you know you can play with a coating material you know I can maybe work with you know again the concept that permeability we talked about, right, yesterday, that comes into picture, depending upon you know how porous the membranes are you know I can basically control the amount of release that happens over a period of time, ok. So, there are a lot of applications of you know fluidization and one application you know is in coating industry where people would like to look at coating of you know some material on a particle for example, ok.

(Refer Slide Time: 02:48)



Now, so we have looked at a packed bed, right. So, packed bed essentially is a long column we said now, there is you know support plate at the bottom something like that, right and you have particles are basically filled in the column, ok. Typically, what happens in the packed bed you know, there is actually a something at the top which basically you know restrains the solid from going, you know if you are using fluid a very very high velocity it could so happen that the particles can be carried away, right. So, to avoid that test basically some structures at the top to continue to have the particles in a packed bed state, ok. Now, if you remove that for the time being, ok, let us say that you know removing that, and what we do is you are letting either air you know or some liquid, into the packed column, what do you think would happen?.

So, I am going to have a uniform you know flow rate through which I am going to let the fluid into the column, again we can talk about you know this either you know the superficial velocity or the actual velocity, right. So, as and when I increase the flow rate of course, your pressure drop is going to go up, right. If you go to Ergun's equation, right, so you have delta P by L which is basically proportional to a term which depends on the velocity plus a term which depends on the velocity square, right. Your; you know the pressure drop is going to go on increasing, ok.

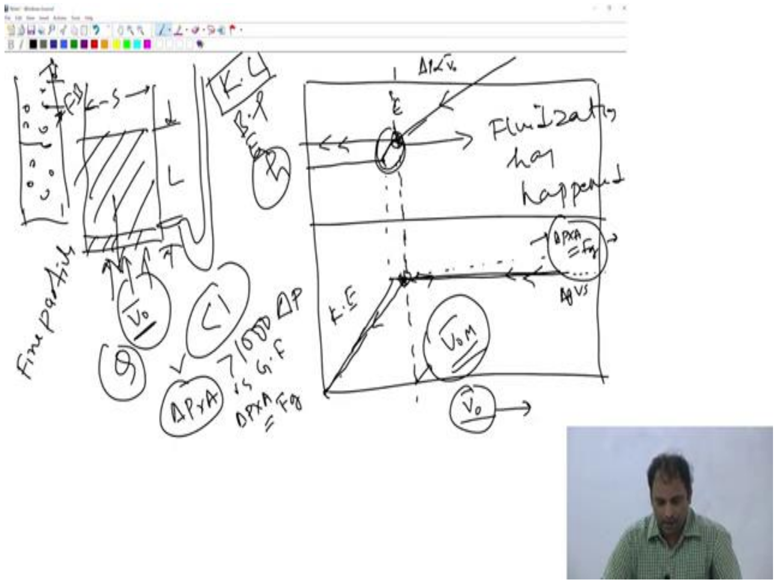
Now, what will happen if you continue to increase the you know fluid flow rate? Right. At some point you are going to reach a state where the particles are going to break contact with each other and they are going to, go to a state where the all the particles are you know a nicely suspended state, ok. So, that is a packed bed, ok. When all the particles go into a suspended state that is when you said you know I have basically what is what I have done is I have basically fluidized the bed, ok. So, fluidization essentially refers to you know start with a, you know packed bed.

So, you know you basically increase your velocity you know enough that all the particles in the bed they essentially break the contact and they kind of you know, so in this state you know the bed essentially behaves like a fluid, ok. The entire fluid particle mixture, it essentially you know behaves like a fluid or you know you if you want to use a more accurate term it will behave as a dense fluid, ok. Dense fluid because you know the of course, that your density is going to be much larger and the fact that you know your particles are there, your viscosity is going to be again higher than the you know the fluid in which they are dispersed, ok.

And so, where I said for all practical purposes it behaves like a fluid you can actually transport you know such a you know fluid particle mixture in a pipe, you can actually use all these you know all the fluid operations that you do, right you know draining of these fluids through valves everything can be done, ok. For all practical purposes this you know fluid particles in a fluidized state behave like a liquid, ok.

Now, one of the questions that people ask you know when you are working with fluidized bed is what should be the minimum velocity, what should be the minimum velocity that I should be using for me to go from a packed state to a fluidized state, ok. That is one of the you know important question. So, we are going to look at some aspects of that, ok.

(Refer Slide Time: 06:39)



Again, we will take the same picture. So, I have a column, there is a support plane at the bottom you know I have a packed bed, ok. There is some pressure drop tapings here, ok. I am going to measure the pressure drop, and you know it is an open column. So, I do not have the, you know the support plate at the top, right. And we can look at, so say that again the cross sectional area of the you know column is S you know and the initial length that you had was say L, ok, L is the length of the packed bed that you begin with, ok. What will happen if I start increasing the volumetric flow rate, right, so or the not M anymore. So, I am just going to write it as, right. So, I have a fluid that is coming with some you know flow rate Q and there is a corresponding you know the superficial velocity through which it is going into the column.

So, I would like to look at you know a couple of parameters, ok. One is how does the height of the packed bed change as a function of you know V 0 bar that is the superficial velocity and I would also like to look at how does and I would also like to look at what is the how does a delta P change is a function of you know the V 0 bar, ok. So, what do you think would happen? So, I have you know packed bed. Some you know height or some length L, ok. I have a fluid; it could be air or liquid coming into the column, ok. I slowly go on increasing the flow rate or the superficial velocity I would like to look at how does delta P vary as a function of V 0 bar and h vary as a function of again V 0 bar.

So, of course, you know your it will depend on you know under what conditions I am doing the experiment, right. Do I have you know what is a Reynolds number is it, is the Reynolds number less than 1 or is the Reynolds number more than 1000, depending upon that I would have to either look at Kozeny-Carman equation, or a Burke Plummer equation or a Ergun's equation and I can basically plot how does the pressure drop way is a function of you know V 0 bar, right.

If you assume that you are working with very fine particles, ok; that means, you know the size of the particle that you have in the column is smaller. Of course, you know I would have to be I will be working in the range where you Reynolds number is less than 1, therefore, your pressure variation is basically captured by the Kozeny-Carman equation during which you know if I go on increasing V 0 bar of course, my pressure drop is going to go linearly, right, because you know we this pressure drop is proportional to you know it is, right its it goes linearly as V 0, yeah, correct.

Yeah, top is free to move, but this will happen as long as this continues to remain as a packed bed, ok. I am only looking at the initial stage where the in spite of the fact that I am slowly changing the flow rate, all the particles in the bed are intact there is practically no change in their rearrangement, there is no rearrangement as such. The fluid velocity is so low that I can assume it to continue to behave like a packed bed, ok. That is the state I am talking about hm.

Yes, yeah. So, of course, yeah I would have to overcome gravity if I really want to. So, I am still talking about cases where, I am still talking about case where you know the whatever pressure that, whatever you know the force that comes because of the fact that I am applying a particular flow rate that is still lower than you know the whatever the gravity that you know because of which is be you know. So, I can say you know there is a gravitational force that is acting on the entire bed, right.

Now, I would have to offset that, ok. So, I am still in a range where you know your the if I say delta P, right multiplied by area will give me the pressure force, and I would have to worry about what is the strength of that this versus the gravitational force, right. So, if I am lower, right if this is more, right, it will still continue to you know, increase linearly, ok.

So, initially what you will do is you know with the increase in V bar, the your the pressure drop is going to go on increasing linearly, right that is a straight line passing through the origin, ok. Now, if I were to look at the height of the bed, ok, the fact that you know there is no rearrangement in the packed bed, ok, the particles are essentially not moving. Essentially, the height would remain constant, right. There is no essentially, there is no change in the height of the column, right or height of the packed bed you know in sense, right. Now, what will happen? At some point you are going to basically reach a case where the pressure force that is delta P times A is equal to the gravitational force that is acting on the entire bed, ok. And at that point there is going to be some rearrangement and if you increase the velocity past that velocity, there is going to be the some rearrangement because of which the height may change a little bit, ok.

This is a region where you know the particles are going to kind of loosen up, this is a some minor change in the porosity of the bed, ok. And however, the change in the porosity, is kind of offset by the fact that you know there is a small change in the velocity. So, if I what to look at the delta P as a function of V 0 bar beyond that point, it will continue to remain constant, ok. The reason why it appears that you know it is remaining constant is because you are really talking about a very large change in the pressure drop when it is in a fixed bed state, ok.

Of course we know that you know with the increase in the velocity of the you know the fluid with which I am letting the fluid into the column, the frictional force are going to increase, right. However, that change, that small increase that you would ideally see, it is not seen because you know the in this range the pressure drop is much larger. Therefore, essentially if you were to plot delta P versus V 0 bar you will essentially get a straight line in the initial stage and for you know it will remain more or less constant beyond a particular stage yeah, right.

Yeah. So, of course, you know when it goes to the fluidized state you know you do not have any contact between the particles anymore, ok. So, whatever losses that comes because of the fact you know there are of course, there is a fluid particle contact area because of which there is definitely going to be some losses, ok. But those losses are basically very negligible compared to the loss that would happen when they are in a packed state, ok.

Now, beyond this point if you go on increasing the V 0, you know the superficial velocity your height would go linearly with V 0 bar, ok. So, that means, beyond this point your bed is going to continue to expand, and there is going to be a linear increase in the height of the bed as a function of time, ok. Now, when I say height of the bed, I am talking about height of the fluidized bed, right, not the packed bed anymore because all the particles have lost contact, ok. Then in a fluidized state and beyond this point is when I said you know there is a fluidization has happened, ok.

Now, when people reverse the flow, ok; so, now, this is the point where I said this is the point where your delta P multiplied by A is equal to your Fg, ok. That is the point where you know, where the pressure drop across the bed, ok, the pressure force basically counterbalanced by the net gravitational force there is acting on the bed, ok.

Now, if you reverse the flow, what is going to happen is it is going to trace this path back, ok, but however, this the drop in the pressure drop starts to happen a little earlier than what happen you know, what happened earlier, so your pressure drop for the decreasing case is going to be something like this. So, if I were to redraw this let me just do that quickly, ok. So, I am going to draw that that is your a linear variation in the beginning, ok, that is when you are increasing. When you are decreasing, so the decrease starts happening from here and then it becomes 0,

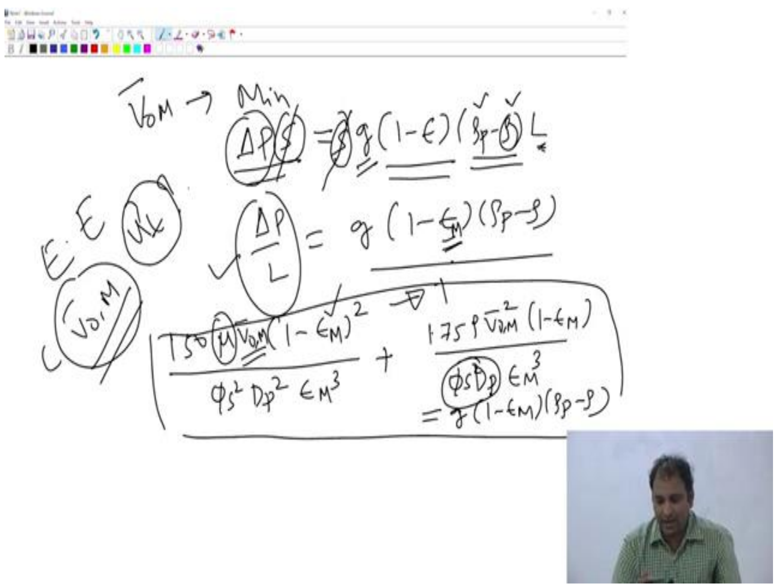
And if you look at the way the height changes as a function of you know V 0 bar, so that constant height you basically get here. That is because of the fact you know there is a subtle variation in the porosity that will happen you know in the case of you know when you are expanding the bed, ok. So, all I am trying to say is you know the porosity, at in the beginning, or the porosity of the packed bed when I started off with. And the porosity of the bed, when I trace back there is a subtle change in the porosity, that subtle change in the porosity is what leads to these minor changes, but however, otherwise the behavior is exactly very similar, yeah, right. What is that? This is the height of the fluidized bed. So. So, what is that?

I mean so, whether it is a, ok; so, his question is that you know I have a column here, right. Now, I have fluidized the bed, so there are going to be particles everywhere, right. Now, you know he is asking a question as to you know is there a range over which you know there is a you know, basically I am talking about the interface between you know the fluidized bed and you know the clear fluid, right. If you look at in that context is that very sharp, it will depend on you know what kind of particle are you working with, ok.

If you really have a perfectly mono dispersed particle I would expect it to be a very sharp interface, ok. But however, if the moment you have a size range, or a poly dispersed sample or you know bi-dispersed sample of course, you know this you know deviation this you know very clear interface is going to be a little bit you know blurred for example, yeah.

So, I am; so, when I said this h, I am in the, so I am basically talking about what is the height up to which the particles are basically suspended in the fluid, that is that height corresponds to, ok.

(Refer Slide Time: 17:44)



Now, what I can do is I can actually get an expression for the minimum fluidization velocity that you know that V 0 M bar, which is the minimum fluidization velocity. And typically what people do is when they do experiments, so this vertical line that I am drawing, the velocity be corresponding to that is what is called as a minimum fluidization velocity, ok. That is if you are increasing the you know your V 0 bar which is the superficial velocity, right, so at some point in the your delta P versus sorry delta P versus V 0 bar, right.

So, at the point where you start decreasing at the point where you are seeing a decrease in the delta P in the second cycle, or at the point where you are seeing a constant height versus V 0 bar in the second cycle, right. Here the first case you start with a fluidized packed bed you go into a fluidized state, ok. In the second cycle you start with a fluidized state and you go back into the packed state, ok. So, this the velocity that correspond to this particular line is what is called as a minimum fluidization velocity.

And one of the way of getting you know expression for that minimum fluidization velocity is that you basically equate the pressure forces, right. So, your delta P times S which is the pressure drop across the packed bed, multiplied by S which is the surface area or the cross section area of the bed, right, that should be equal to the gravitational force. And because of the fact that you know you only have as a fraction of the bed with solids, so 1 minus epsilon is going to give me the fraction of the solid that I have in the bed, right multiplied by rho P minus rho which is the density difference, right. Because you know I would have to worry this is the net gravitational force acting, right. I would have to worry about the rho P minus rho that is the rho of the fluid, right because there is a buoyancy as well, right times g, right.

And so, now, if you look at this; so, if I and times L as well, right your L which is, so if I want to talk in terms of, right is that ok. So, this is there is also S here, right, ok. That is your surface is your cross section area multiplied by length that will give me the volume, ok, right. Multiplied by 1 minus epsilon will give me the volume of the solid that I have in the bed, ok. Multiplied by rho P minus rho is what gives you the net gravitational force, right multiplied by of course, the gravitational constant, right. So, I can get this out, right therefore, I can write delta P by L as g times 1 minus epsilon into rho P minus rho, ok.

$$\Delta PS = Sg(1-\epsilon)(\rho_P - \rho)L$$

$$\frac{\Delta P}{L} = g(1-\epsilon)(\rho_P - \rho)$$

So, when this happens that is when you know you start seeing a variation in the height of the column, right. So, height of the column in you know it was initially constant, the point where I start seeing a you know the increase in the height of the bed, ok, at that point is when you know you have this the pressure force equal to the gravitational force, ok. That is what this expression this expression corresponds to, ok. Now, yeah, right. What is that?

Yeah, no. At the before it is not that is L, right. Correct.

Yeah. So, but you know as I said, right there is only a subtle change in the height, ok. I mean you know you are basically talking about you know a very small fraction, you know. So, practically you can neglect that small difference in the height you know L to be, ok. You are talking about this delta P versus V 0 bar or the other one. Correct.

So, this line, ok. Let me make it clear, right. So, let me just rub this here, let us do that, ok. Your height was constant, right to begin with, ok. There is a small change here, and when you are reversing it back its going to come back like that, right that is your height, ok. So, that point here, and the point where the pressure drop starts falling in the second cycle that should coincide with that and the velocity corresponding to that is what is called as a minimum fluidization velocity.

So, I mean, so people have come up with the different procedures for doing it, ok. So, this is one of the guidelines for doing it. But you know we are going to get an expression for V 0 bar M, ok. Let us look. So, one of the thing that you can do is again you know is there a large variation in the velocity across this, not much, ok. So, I mean you know I would worry about you know whether you choose this or this, if the difference between you know V 0 bar that you would get would be really large you know, but, ok. So, I am basically talking to you about a procedure that is used experimentally for obtaining the you know the minimum fluidization velocity, ok.

So, now, at the minimum fluidization velocity, the epsilon that is a porosity of the bed is typically denoted by epsilon M which is the porosity of the bed at the point of fluidization, ok. And the point when the fluidization starts to occur is typically kind of you know referred by a term called incipient fluidization, ok. That is the point at which the fluidization starts happening, ok.

Now, what I can do is, I can write an expression for delta P by L from Ergun's equation, ok. I can equate that to this you know the right hand side. So, therefore, what I can do is I can write one fifty times mu V 0 bar, into one minus epsilon M whole square, right divided by phi S square into Dp square into epsilon M cube that was the first term in the Ergun's equation, ok. And 1.75 into rho times V 0, of course, now it is going to be M because it is a minimum fluidization velocity, right. Again M here into 1 minus epsilon M divided by phi S into Dp into epsilon M to the power of 3 should be equal to g times 1 minus epsilon M into rho P minus rho, ok.

$$\frac{150\,\mu\overline{V_{0,M}}(1-\epsilon_M)^2}{\phi_S D_P^2 \epsilon_M^3}+\frac{1.75\rho\overline{V_{0,M}}^2(1-\epsilon_M)}{\phi_s D_P \epsilon_M^3}=g(1-\epsilon)(\rho_P-\rho)$$

Yes, so that is the, so if you can; so you can solve this and you can actually obtain an expression for you know it is a it is quadratic in V 0 bar M, ok. And there are ways by which I can actually calculate what is V and epsilon M you know, if you know the properties of the part that you are working with, basically I can substitute all of that. If you know the you know the fluid that you are using for your operation I can actually calculate what is the V 0 bar M, that is the minimum fluidization velocity. That is the velocity with which I should be operating to achieve a fluidization state, right. Now, it turns out that. Yeah, go ahead. It is a general equation that is applicable for the entire.

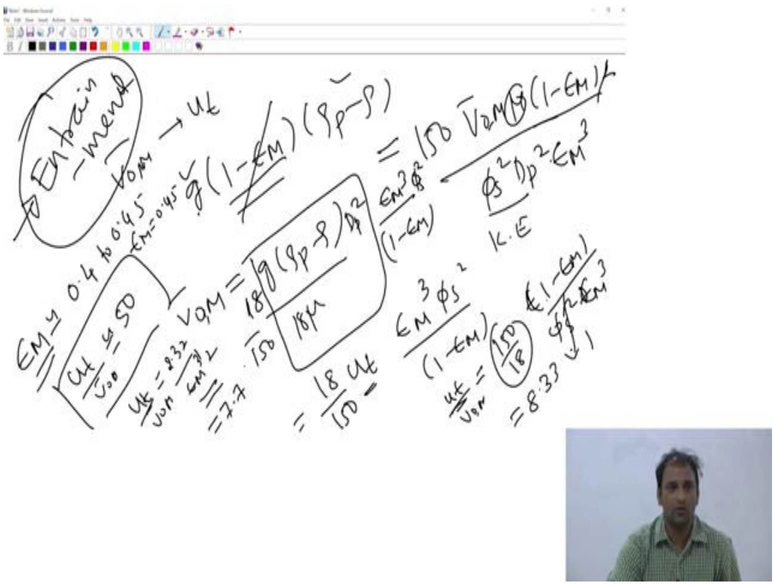
No, no, I you can do that, right its, ok. I mean with this I can actually go back and I can also look at two limiting cases as well, right. All I am trying to say here is you know you can look at a general expression, ok. It is not necessary that you know. So, when I talked about you know the experimental way of you know when I talked about this, right. I just took a simple case of you know how. So, otherwise I would have to maybe you know, so if I did not consider the like say Kozeny-Carman equation, I could still draw this plot, how does the pressure drop change is a function of you know V 0 bar I can you know work it out, right, ok.

I just took a simple case for which you know you have a linear variation. So, you know now, it makes the point clear, ok. It is not necessary that you know I would have to be working with the Reynolds number less than 1, ok. So, now, any more questions? Yeah, ok. Now, what I can do is I can actually go back and take a look at the limiting cases, ok. And I can actually one of the question that people ask is that you know, what should be the typical velocity, ok; what should be the typical value of V 0 bar M compared to the settling velocity?

So, obviously, your V 0 bar M has to be less than the settling velocity, right. If you have a packed bed made up of particles, if I want to fluidize it the velocity that I maintain, ok, the velocity of the fluid that I maintain to have them in a fluidized state it has to be less than the a settling velocity, right otherwise all the particles are going to be carried away in the fluid, right, ok.

We talked about this alliteration, right, ok. If you maintain a fluid velocity such that the superficial velocity, or the velocity with which you are sending the fluid into the column, the moment it becomes larger than the settling velocity the individual particles that make up the column or the fluidized bed, all the particles are going to be carried away, right.

(Refer Slide Time: 27:57)



In fact, we can actually get a estimate of you know how high or how low you know this V 0 bar M should be compared to ut by a very simple analysis. What we are going to do is we are going to look at the first part of you know your. So, this is 150 V 0 bar M into mu 1 minus M whole square divided by your phi s square into Dp square into epsilon M cube, right. That is your Kozeny-Carman equation, right at the point of you know fluidization.

So, therefore, what I can do is I can actually get what is V 0 bar M, right. What I can do is basically if I work this out, what will happen? I have g here, and rho P minus rho, right and then I have this 1 minus epsilon M here, so that gets cancelled with this, ok. I have a term which is 1 minus epsilon M on the right hand side, right that basically comes down. So, let me just do that very quickly, ok.

You are going to have epsilon M cube here multiplied by 1 minus epsilon M, right, ok. And your phi a square into there is going to be Dp square here, right, there will be phi a square, ok. Thus I have got it the other side and there is a mu here. So, mu is going to come to the denominator, right and of course, it is going to be 1 over 150, right. That is going to come to the other side. I can multiply this by 18 and divide by 18, and if I look at this part that is essentially is your settling velocity, right. Your g you know rho P minus rho into Dp square divided by 18 mu that is your ut which is the settling velocity that goes as right your V 0 bar M, there is a minimum fluidization velocity is 18 divided by 150 into ut time epsilon M cube into phi s square divided by 1 minus epsilon M, ok. Therefore, I can say your ut by V 0 bar M, is equal to 150 divided by 18 into, right 1 minus epsilon M divided by phi a square into epsilon M cube, ok, right. This factor sum you know 8.33 or something like that, ok.

$$\frac{u_t}{\overline{V}_{0,M}} = 8.33\frac{(1-\epsilon_M)}{\phi_S^2\epsilon_M^3}$$

Now, if you are working with spherical particles you are, you know your phi S is 1, right. And again there are a lot of experimental data where people have shown that if you are working with spherical particles, it turns out you know the value of epsilon M that people have measured is typically in the range from 0.4 to 0.45 that is a the porosity at the incipient fluidization at the point of fluidization for spherical particles. If I substitute that value your ut by V 0 M comes out to be of the order of 50, ok.

If I substitute for phi S is equal to 1 here you have 8.33 multiplied by 1 minus epsilon M divided by epsilon M cube it turns out that the number that you get is of the order of 50. That means, if I were to work with you know the fluidization I can use any velocity, from the minimum fluidization velocity all the way up to 50 times the minimum fluidization velocity, right.

The moment the velocity becomes more than 50 times the minimum fluidization velocity that is when all the particles are going to be carried along with the fluid and when that happens people call it as what you call the entrainment, ok. When you have a fluid stream that is coming into the packed bed, or into a fluidized bed and if that stream is basically carrying, you know carrying the particles also along with the fluid, that particular you know operation is what is called as a entrainment. And typically you would have to work under conditions where your entrainment is very much not there, right, you know you do not want the particles to be carried out no along, right, ok. So, that is for ut by V 0 bar M of 50, ok.

But if you work around this and if you do exactly a similar analysis for you know the turbulent flow conditions, it turns out that you know ut by V 0 bar M that you get would be of the order of it goes as 2.32 divided by epsilon M to the power of 3 by 2, ok. The similar ratio that ut by V 0 bar M goes as 2.32 divided by epsilon M to the power 3 by 2 you can work it out, right.

All you have to do is you know take out the Burke Plummer part, and then rearrange it in terms of the settling velocity, that is what it comes out to be. And if I do a similar analysis you know for the case of epsilon M to the power of to be 0.45 this ratio comes out to be 7.7, ok. That means, the operating window for the fluidization, you know I can work over a much wider you know range of velocities for the case of laminar flow conditions. However, if I work in a turbulent flow conditions the range of V 0 bar M, you know the velocity that I can use you know without the entrainment happening is basically lower, right. That is what it is going to be yeah.

And we will stop here. We will solve some problems on you know all these concepts on Friday as well as on Monday, yeah.