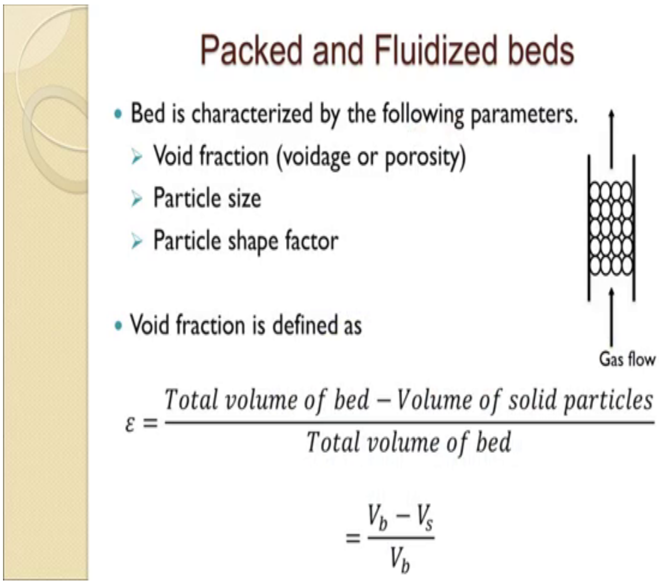
Iron Making
Prof. Govind S Gupta
Department of Materials Engineering
Indian Institute of Science, Bangalore

Lecture - 14
Iron Making

We talked about the pressure drop packed bed and where we you are familiar with a safe factor and other thing.

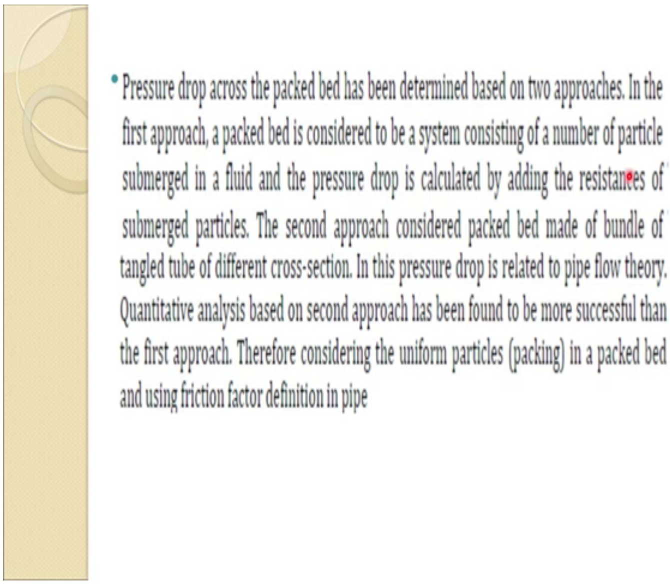
(Refer Slide Time: 00:33)



$$\varepsilon = \frac{Total\ volume\ of\ bed - Volume\ of\ solid\ particles}{Total\ volume\ of\ bed} = \frac{V_b - V_s}{V_b}$$

So, when we do replies the case gas from the packing in the container, there is a resistance offered by these particles to the gas flow packed bed. The resistance is offered by these particles to the gas flow. So, you will get if you measure the pressures here and here, you will see there is a pressure drop in this one which is the birth against this resistance.

(Refer Slide Time: 01:13)



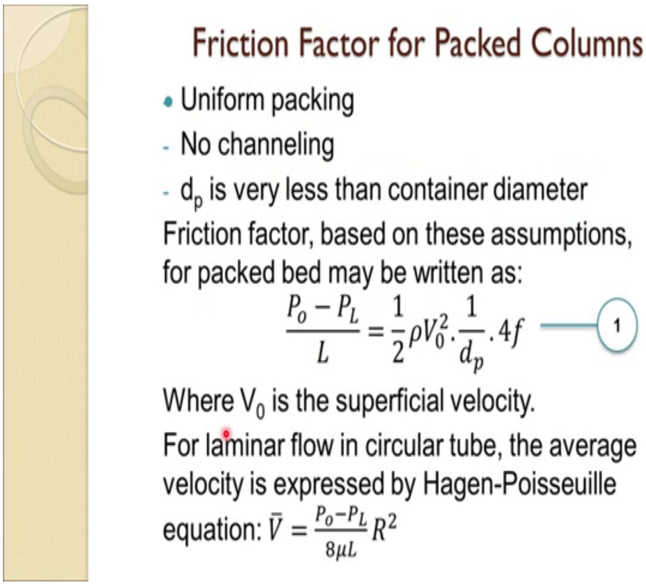
So, this is the one which one has to measure it in a packed bed. So, pressure drop across the packed bed has been determined based on 2 approaches. So, in the first approach a packed bed is considered to be a system consisting of a number of particle submerged in a fluid and the pressure drop is calculated by adding the resistance says a submerged particle.

The second approach considered packed bed mat of bundle of tangle tube of different cross section in this pressure drop is related to pipe flow theory quantitative analysis based on second approach has been found to be more successful than the first approach the therefore, considering the uniform particle packing in a packed bed and using friction factor definition in pipe we can define the pressure drop. So, when we say this particle submerged in a fluid. So, mostly the drag forces weight and buoyancy forces based on that you calculate the pressure drop and this is a very standard were stocked low and other thing with the law in Reynolds number you might have read about it.

And similarly about the pipe flow this is another theory through with the press using that one can predict the pressure drop in the packed bed. So, in the pipe flow as such it is a smooth flow which you are aware of Hagen Poisseuille for the equation, but in this one.

Because it is going through a tortuous path it is travelling the fluid or either a gas or liquid. So, it is not the simple pipe flow theory, but you can apply the pipe flow theory correcting this conduct tortures path of it and this is found to be more satisfactory lee given pressure drop and then the submerged particle. So, I would be talking little about the second theory.

(Refer Slide Time: 03:46)



So, write on that we define one friction factor under these assumptions uniform packing no channelling and the particle diameter is less than the con quite less than the container diameter usually should be at least 1 by 12th of containers diameter minimum.

So, friction factor we define usually there, there are resistance forces which are acting on the particle when any fluid is flowing and usually you group them some of them you are unable to quantify and that is the one which you say about the friction factor and the force which is acting on this packing or on a particle or something usually is can be written five an empirical way. So, this is usually the force equal to characteristic kinetic energy characteristic area into friction factor this is the normal way you represent any friction factor. So, in this case, when we are talking about the to flow and this is actually a force this is the kinetic energy and when this is written actually in short form this is the characteristic area and this is the friction factor.

So, few things have been cancelled out. So, force is nothing actually the pressure. So, pressure drop per unit length or divided by the length of the packing a packed bed and you can correlate this. So, where V naught is the superficial gas velocity and we had talked about superficial get superficial gas velocity we come over go back to this if there is no particle in this tube or cylinder. So, whatever velocity of the gas is having here that is the one which we call the superficial gas velocity we will come back to this again and for laminar flow in a circular tube the average velocity is expressed by Hagen Poisseuille equation which I believe you might be aware of that and this is true only under laminar flow. So, we are trying to get this friction factor correlation for packed bed column on this laminar flow.

(Refer Slide Time: 07:08)

Representing R in terms of hydraulic radius, and if the tube is not circular then,

$$\bar{V} = \frac{P_0 - P_L}{2\mu L} R_h^2$$

R_h in terms of void fraction and wetted surface is expressed as:

$$R_h = \frac{\frac{volume\ of\ void}{volume\ of\ bed}}{\frac{wetted\ surface}{volume\ of\ bed}} = \frac{\varepsilon}{a}$$

And a is related to specific surface (total particle surface area/volume of particle) as

$$a = a_v(1 - \varepsilon)$$

So, this is the average velocity. So, which the R is the radius of the tube which can be represented in terms of hydraulic radius which usually you put it, your cross sectional area divided by the wetted perimeter sort of rate if you represent in a hydraulic radius form and this hydraulic radius in terms of void fraction can we define a volume of the void divided by volume of the bed and then divided by the wetted surface divided by the volume of the bed. So, volume of the void is epsilon and wetted surface is a. So, a is also related is related to specific surface that the total particle surface area divided by volume of particle this comes out to these.

(Refer Slide Time: 08:13)

Specific surface can be defined in terms of mean particle diameter: $D_p = \frac{6}{a_v}$

And $V_0 = \bar{V}\varepsilon$

On combining these equations, we get,

$$V_0 = \frac{P_o - P_L}{2\mu L} R_h^2 \varepsilon = \frac{P_0 - P_L}{2\mu L} \cdot \frac{\varepsilon^3}{a^2}$$

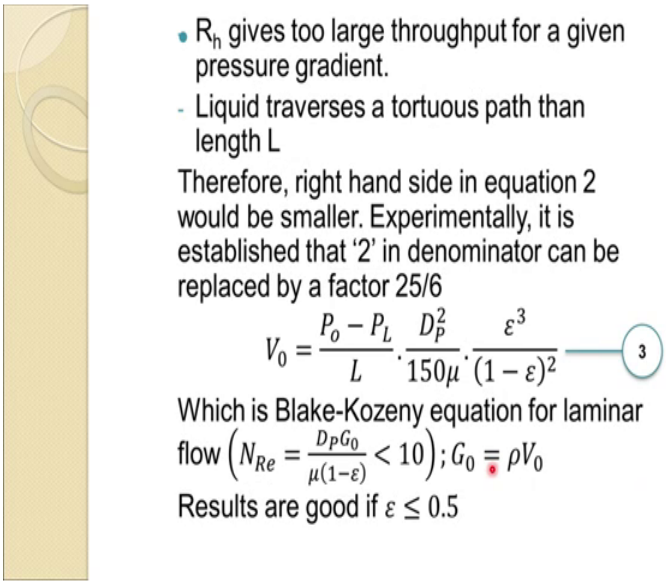
$$= \frac{P_o - P_L}{2\mu L a_v^2} \cdot \frac{\varepsilon^3}{(1-\varepsilon)^2}$$

Or,

$$V_0 = \frac{P_o - P_L}{L} \cdot \frac{D_P^2}{2(36\mu)} \cdot \frac{\varepsilon^3}{(1-\varepsilon)^2} \quad (2)$$

And this specific surface also defined in terms of mean particle diameter which is 6 by a V and where what we said about superficial gas velocity. So, when the particles is this is the average velocity and this is the void fraction. So, it be multiplied this or actually divide the superficial velocity with the void fraction you will get the interest resale velocity um. So, this V actually the interstitial velocity here V bar. So, now, will be combined these definition of all these and put it into this equation. So, what essentially we get it is this equation and were again, now a you define it in terms of these and mean particle diameter then you will get this equation and finally, these in mean particle diameter you put it you get this equation for in terms of superficial velocity.

(Refer Slide Time: 09:52)



So, one can get the superficial velocity from this equation however when experimentally you measure R it is found that R s the hydraulic radius gives too large throughput for a given pressure gradient. So, liquid travis traverses a tortuous path then the length L which we discussed length L that is a packed weight length. So, therefore, right hand side in this eq equation do would be smaller. So, experimentally it is established that 2 in the denominator can be replaced by a factor of 25 by 6.

So, once you replace this factor by 25 by 6 comes to this and this equation actually known as Blake-Kozeny equation for laminar flow and the Reynolds number is defined as particle diameters and it is a mass velocity which is rho the density of the gas and superficial gas velocity and void fraction viscosity of the case. So, Reynolds number should be less than 10, then you can get the pressure drop across the bed using this correlation a result is good when a void fraction is less than or equal to 0.5.

(Refer Slide Time: 11:27)

From this, bed friction factor comes:

$$f = \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot \frac{75}{D_p\left(\frac{G_0}{\mu}\right)}$$

For turbulent flow in tubes, friction factor becomes a function of roughness only.

We get,

$$\frac{P_0 - P_L}{L} = \frac{1}{D} \cdot \frac{1}{2} \rho \bar{V}^2 . 4f_0 = 6f_0 \cdot \frac{1}{D_p} \cdot \frac{1}{2} \rho V_0^2 \cdot \frac{1-\varepsilon}{\varepsilon^3} \quad (4)$$

From experimental data, $6f_0 = 3.50$

$$\frac{P_0 - P_L}{L} = 3.50 \frac{1}{D} \cdot \frac{1}{2} \rho V_0^2 \cdot \frac{1-\epsilon}{\epsilon^3} \quad (5)$$

This is known as Blake-Plummer equation for turbulent flow $\frac{D_p G_0}{\mu} . (1-\varepsilon)^{-1} > 1000$

Now, many in many cases turbulent flow prevails, now it be before that if we rearrange this equation and compare with our this equation. Now we can define the friction factor. So, friction factor comes by comparing these about this. So, this is the friction factor through the tube and for turbulent flow the friction factor becomes a function of roughness only. So, for turbulent flow again to define the sort of terms the force kinetic energy characteristic area and the friction factor and you substitute the value in terms of the parameter which we defined earlier this finally, you get it this equation for the pressure drop and that is known at Blake Plummer equation.

So, and this is applicable when the Reynolds number is greater than 1000 degree sorry 1000. So, this is the Reynolds number as usual as we defined in the laminar flow and similarly you can rearrange this equation, you can define the friction factor for this case and for this case the friction factor comes to this.

(Refer Slide Time: 12:54)

Friction factor is given by

$$f = 0.875\frac{1-\varepsilon}{\varepsilon^3}$$

On combining equations 3 and 5, we get,

$$\frac{P_o - P_L}{L} = \frac{150\mu V_0}{D_P^2}\cdot\frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{1.75\rho V_0^2(1-\varepsilon)}{D_P\varepsilon^2} \quad (6)$$

This is known as Ergun equation. In dimensionless group form,

$$\left[\frac{(P_o - P_L)\rho}{G_0^2}\right]\cdot\left[\frac{D_P}{L}\right]\cdot\left[\frac{\varepsilon^3}{1-\varepsilon}\right] = 150.\frac{1-\varepsilon}{D_P\left(\frac{G_0}{\mu}\right)} + 1.75$$

So, now if we combine both the equation because in many situation in the packed bed like in the blast furnace do you have both the term the you have laminar flow some places you have also turbulent one. So, if you combine both the terms, you can get the total pressure drop across the packing and that keeps this equation is also known the Ergen equation and you can put this one in the dimensionless form also in various form this can be written dimensionless or Reynolds number and like that.

(Refer Slide Time: 13:49)

Example 7.2.1 Calculate the pressure drop for a laboratory scale packed bed, through which air is being passed, for the following conditions:

column diameter,	0.2 m	ε_v,	0.45
column height,	1.5 m	volumetric gas flow rate,	0.04 m^3/s
particle diameter,	0.01 m	viscosity of air,	1.85×10^{-5} kg/ms
ϕ_s,	0.85	density of air,	1.21 kg/m^3

And using this equation we can find out the pressure drop or in terms of universe blast furnace. So, this is one example. So, calculate the pressure drop for a laboratory scale packed bed through which air is being passed for the following condition. So, column diameter is 0.2 column height is 0.5 particle diameter. So, this column id is a packing height and particle diameter is 0.01 meter safe factor of the particle is point eight five and void fraction of the packing bed is point four five volumetric gas flow rate is 0.04 meter cube per second.

So, it is a volumetric gas flow rate viscosity of the earth is given and density of the air is given. So, you have to find out the pressure drop. So, essentially if you substitute the value in this what you need new particle diameter is given or length is given void fraction is given you need the velocity which is not given so that from these data you can easily find it out because the volumetric gas flow rate is given.

So, this poly metric gas flow rate if you divide with the area of the container or area of the packed bed, then you can get the required velocity. So, the linear velocity. So, 0.04 is the volumetric flow rate meter cube per second and because it is a packed with cylindrical packed bed diameter and height is given. So, pi R square.

(Refer Slide Time: 15:39)

SOLUTION The linear velocity U_0 is given as

$$\frac{0.04}{(0.2)^2 3.14/4} = 1.27 \quad \text{m/s}$$

Then using Eq. (7.2.3) we have

$$\Delta P = 1.5\left[150\frac{(1-0.45)^2}{(0.45)^3} \times \frac{1.85 \times 10^{-5} \times 1.27}{(0.85 \times 0.01)^2} + 1.75\frac{1-0.45}{(0.45)^3} \times \frac{1.21 \times (1.27)^2}{0.85 \times 0.01}\right]$$

i.e.,

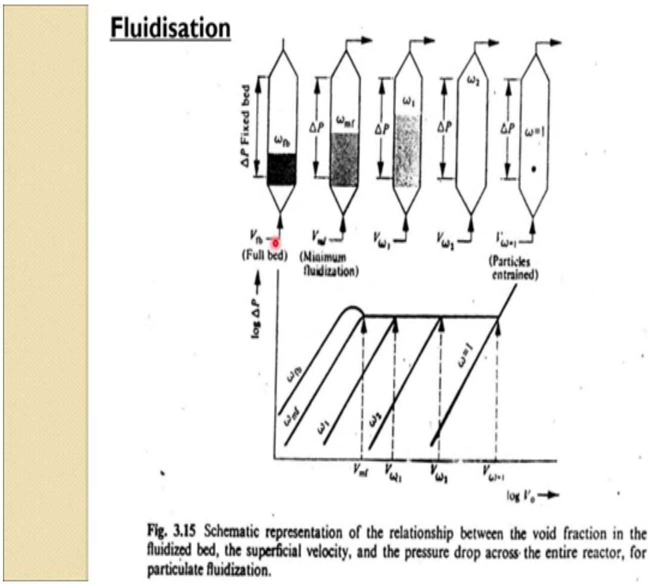
$$\Delta P = 1.5[243 + 2430] = 3.99 \times 10^3 \quad \text{N/m}^2$$

So, 0.2. So, this is a diameter by pi d square. So, that gives you the velocity 1.27 meter per second seems a reasonable velocity and if you put this value into the equation of a he here V naught is appearing here and here and you will see. So, all other values are given.

So, 1.27 1.27 square. So, your pressure drop comes around 3.99 into 10 to the power 3 Newton per meter square.

So, that sort of pressure drops you can get it in the blast furnace actually you can do have various measurement devices. So, by which you measure the pressure drop across the layer or across the view some distance. So, once we know the pressure drop we can do the back calculation and we can know the velocity wha what sort of velocity is prevailed a dead pressure drop and we can know whether this velocity is higher or lower that way one can assess the performance of the blast furnace.

(Refer Slide Time: 17:14)



Now, we will we would be applying all these principles what we have talked to explain the blast furnace phenomena; so one about the pressure drop another which is quite prevalent in blast furnace about the fluidization. So, again you have to understand this term fluidization and what is the meaning of it and what is it. So, you are now familiar about the packed bed packed bed it is a where the particles are packed in a container. So, now, suppose you have this packed bed which is some length and you are sending the air from the bottom and its coming out from the top; so, as you keep on increasing the way fluid velocity here.

So, in the starting it is a offering quite a big resistance to the gas flow. So, pressure drop would be there and it you keep on increasing the velocity more and more resistant would be felt by these by the gas and this particle or the bed will expand when you are putting more and more air. So, this is sort of it you are increasing the velocity pressure drop is there creases and when and this bed expands.

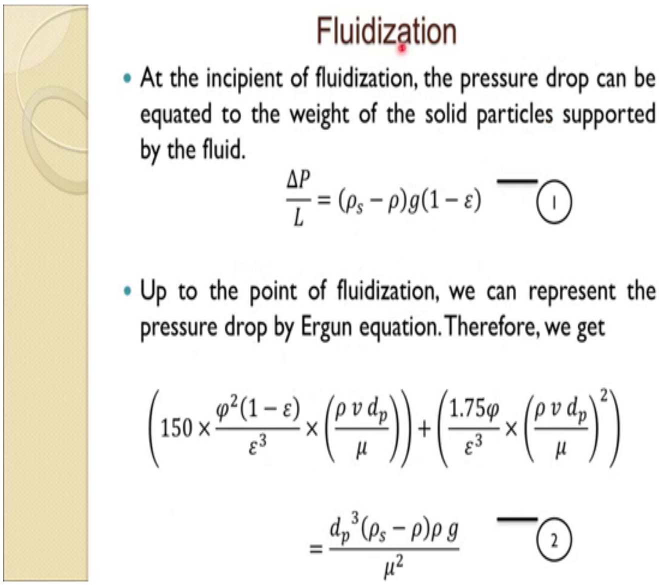
So, if one particular velocity what you will find the bed is sort of fully expanded and particle in one way they are separated to each other and that is where we called this situation like a minimum fluidization where the particle are separated to each other and they are sort of. So, particle weight and the force which is acting on the particle to drake gas or the pressure drop the they are equal under this condition and the velocity of the gas at under this condition is known as the minimum fluidization velocity and the void fraction related to that condition when the particle are separated called the minimum fluidization void fraction.

And when you further increase the velocity of the gas beyond that then where expand more particle becomes more and more separated from each other and. In fact, if you keep on increasing and they will start flying out of the bed and that is when they start flying out of the bed of only one particle trap you call sort of a elutriation velocity that time. So, particle are able to escape at that velocity. In fact, using this principle if you have a mixture of the particle of different size you can separate them into individual size and this is one of the very impractical uses to separate the individual sized particle by controlling the velocity at the bottom.

So, because each particle would be having a different elutriation velocity and based on that they can separate the particle and this figure showing how this pressure drop keep on increasing with the velocity, but here you will see there is a hump. So, this is the situation related to minimum fluidization velocity the hump is coming because the particle are interlocked. So, really to make them separate you need a little higher velocity to unlock them before the fluidization can occur.

So, the pressure drop is higher actually before the fluidization occur and once this interlocking and or it overcomes with the all those forces pressure drops because by definition it is each particle they are separate. So, they sort of it now not much resistant they are not locked interlocked with each other and thing. So, pressure drops and that is one which we take it the pressure drop at minimum fluidization velo velocity and that is the velocity also to call the minimum fluidization velocity and the other kind of condition are related to that to keep on increasing. So, this gives you an idea what is the fluidization forty third elutriation velocity and in between things and these all think we would be discussing in the blast furnace description.

(Refer Slide Time: 23:25)



So, now do you understand the fluidization. So, as I said in the incipient fluidization is the one when the pressure drop is equal to the weight of the solid he just suspended that time this is the condition where particle large balance with the pressure drop and they are separated. So, it is a weight of the particle. So, essentially rho s minus rho that is the gas density g, so this is sensing the weight and this is what is the solid content of that 1 1 minus epsilon; so, this at the incipient fluidization; so, up to the point of fluidization.

So, when we say flew just before the incipient fluidization particle are not fluidize it a just and you can express the pressure drop using the Ergun equation. So, till that time the Ergun equation sort of a valid; so, using that up to the point of fluidization. So, we can represent pressure over Ergun equation. So, now, Ergun equation we are writing in terms of Reynolds number here and this is actually a pressure drop which we have substituted here.

And it be so after this equating writing in this form this term become this and if this is actually nothing it is or about Galileo number.

(Refer Slide Time: 25:17)

or

$$\left(150 \times \frac{\varphi^2(1-\varepsilon)}{\varepsilon^3} \times Re_D'\right) + \left(\frac{1.75\varphi}{\varepsilon^3} \times (Re_D')^2\right)$$

$$= \frac{d_p^{\,3}(\rho_s - \rho)\rho\, g}{\mu^2} \quad \text{— (3)}$$

- Wen and Yu have shown that

$$\frac{\varphi^2(1-\varepsilon_{mf})}{\varepsilon_{mf}^{\;3}} \cong 11$$

$$\frac{\varphi}{\varepsilon_{mf}^{\;3}} \cong 14$$

ε_{mf} = void fraction at minimum fluidization.

So, this is your Reynolds number as we have defined this and equated with this. So, putting in terms of Reynolds number then these factors this one is over here at the minimum fluidization velocity, it is shown where is some of the authors that this can be equal to about eleven and similarly the other factor could be about 14, so epsilon m f with the void fraction at minimum fluidization. So, knowing this thing and this is like a Galileo number this. So, you can see this is a quadratic sort of equation which can be solved.

(Refer Slide Time: 26:25)

- From equation 3, we get

$$Re_{D_{mf}}' = \sqrt{33.7^2 + 0.0408\, Ga} - 33.7$$

which is independent of φ and ε_{mf}

- Ga is Galileo number and is defined as

$$Ga = \frac{d_p^{\,3}(\rho_s - \rho)\rho\, g}{\mu^2}$$

$$Re_{D_{mf}}' = \frac{\rho\, U_{mf}\, d_p}{\mu}$$

The Reynolds number this gives you the solution of this in terms of Galileo number Galileo number as we said its this and define here also again. So, this is the your fluid density slowly density particle size and fluid viscosity. So, this is the Reynolds number at minimum fluidization velocity which can be defined in that way.

So, once you know Galileo number you can all do know that you know its number now with this correlations you can easily find the minimum fluidization velocity for the particle the part which requires 2 fluidize.

(Refer Slide Time: 27:18)

- In the fluidized condition of the bed, Wen and Yu found a relationship between the friction factor (f) and ε and expressed their results analytically:

$$\varepsilon^{4.7} Ga = 18 Re_D{}' + 2.7 Re_D{}'^{1.687}$$

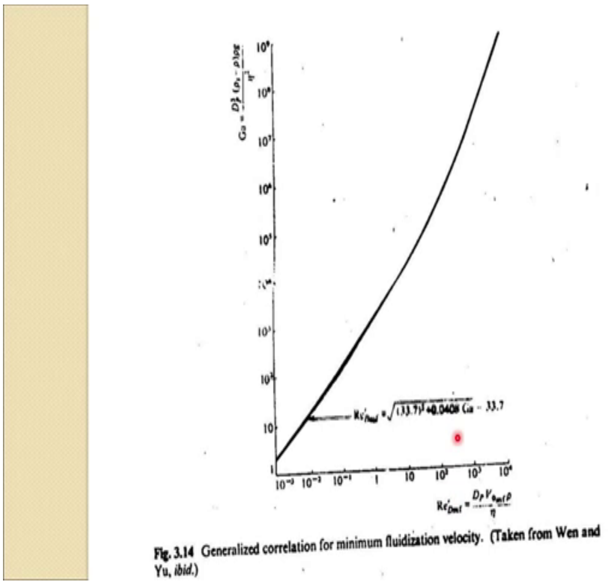
- From this relation, one can calculate the bed voidage for $Re_D{}'$ or for a given bed expansion and particle size, one may calculate the required superficial velocity.
- Finally at ε=1, terminal velocity is reached.

$$V_t = \sqrt{\frac{4}{3} \times \frac{D_p(\rho_s - \rho)g}{\rho f}}$$

So, in the fluidize condition of the bed also the same other found that friction factor and the void fraction can be expressed also in by this relation in there between the Reynolds number and Galileo Reynolds number and Galileo number from this actually you can even calculate the vo void fraction. So, from this relation one can calculate the dead voids for particularly Reynolds numbers or for a given bed expansion and particle size when we calculate the required superficial velocity.

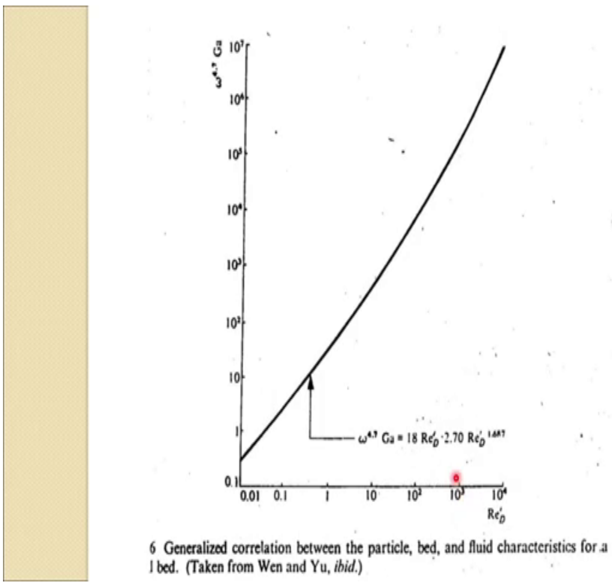
And finally, when the void fraction is one the terminal velocity come to this or like a Lutheran velocities you can say that would be that a lesson for it.

(Refer Slide Time: 28:20)



And in a graphical form these are represented as. So, Reynolds number in terms of minimum fluidization velocity it. So, this is Reynolds number at minimum fluidization and a Galileo number.

(Refer Slide Time: 28:40)



So, if you know one of that think other parameters, you can calculate similarly for the void fraction the same relation it still is put it in the form of graph to get the values. So, from this curve also one can get the value.