**Fundamentals Of Particle And Fluid Solid Processing**
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**Lecture - 55**
**Fluid – solid transport (Contd.)**

Hello everyone and welcome back once again in the class of Fundamentals of Particle and Fluid Solid Processing.

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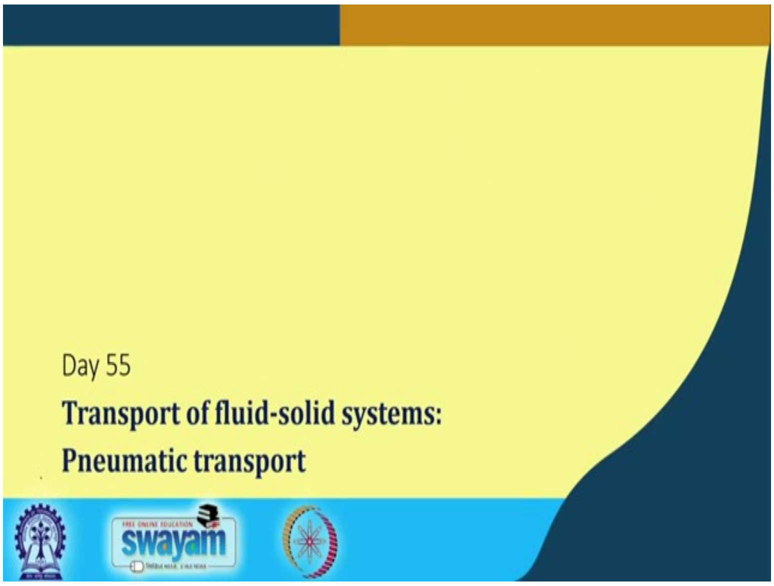


We were discussing about the pneumatic transport that we introduced in the last class. We have seen two different flow regime that is the dense phase flow and the dilute phase flow, how to demarcate between these two in case of horizontal flow and the vertical flow in by determining the choking velocity and the saltation velocity. Now, we will see a more generic description that how to calculate the pressure drop.

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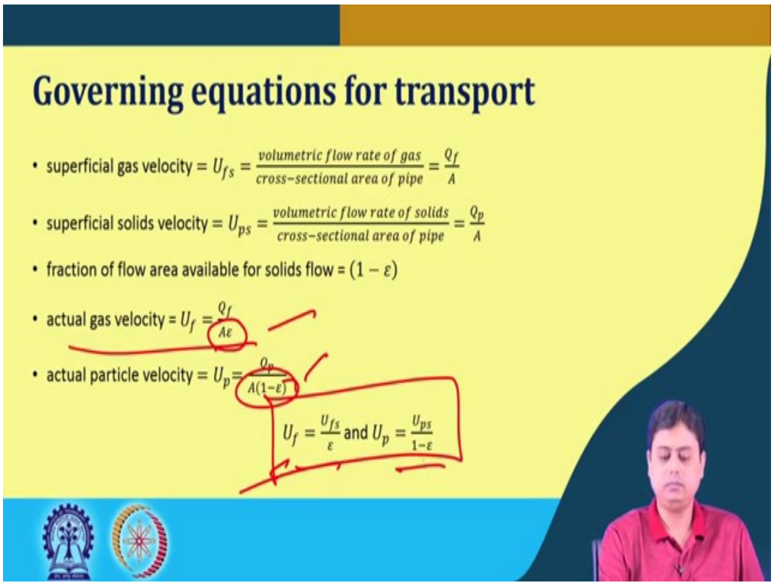


So, before that let us introduce some of the known parameters that we know, but still say to refresh our memory few definitions which will govern the transport of the solid and the fluid in this case the gaseous phase. So, usually we say the superficial gas velocity which is designated as $U_{fs}$ is

$$U_{fs} = \frac{volumetric\ flow\ rate\ of\ gas}{cross-sectional\ area\ of\ pipe} = \frac{Q_f}{A}$$

Superficial solids velocity similarly is,

$$U_{ps} = \frac{volumetric\ flow\ rate\ of\ solids}{cross-sectional\ area\ of\ pipe} = \frac{Q_p}{A}$$

Now, say this solids concentration or the amount of solids once it is there in the system, the void space that is occupied by the gas phase is $\varepsilon$ that is the void space of the pipe, because that is the empty space that the gas phase can occupy and can flow through those area. So, that means, the fraction of flow rate available for solids to flow is $(1-\varepsilon)$. And then the actual gas velocity is the superficial velocity divided by the porosity or the void is respective void is if I say the respective volume fraction.

$$U_f = \frac{U_{fs}}{\varepsilon} \text{ and } U_p = \frac{U_{ps}}{1-\varepsilon}$$

This is a relation we knew or even if you look at the actual gas velocity expression. It is the flow volumetric flow rate of the fluid divided by the area, which is available for that fluid to flow. The area available for gaseous phase to flow is $A\varepsilon$. The area available for solids to flow is $A(1-\varepsilon)$, so that these are the actual velocities, or in other words the relation between the actual velocity and the superficial velocities are these that is the superficial velocity divided by the void is or the respective volume fraction is the actual velocity.

$$\text{actual gas velocity } = U_f = \frac{Q_f}{A\varepsilon}$$

$$\text{actual particle velocity¿ } U_p = \frac{Q_p}{A(1-\varepsilon)}$$

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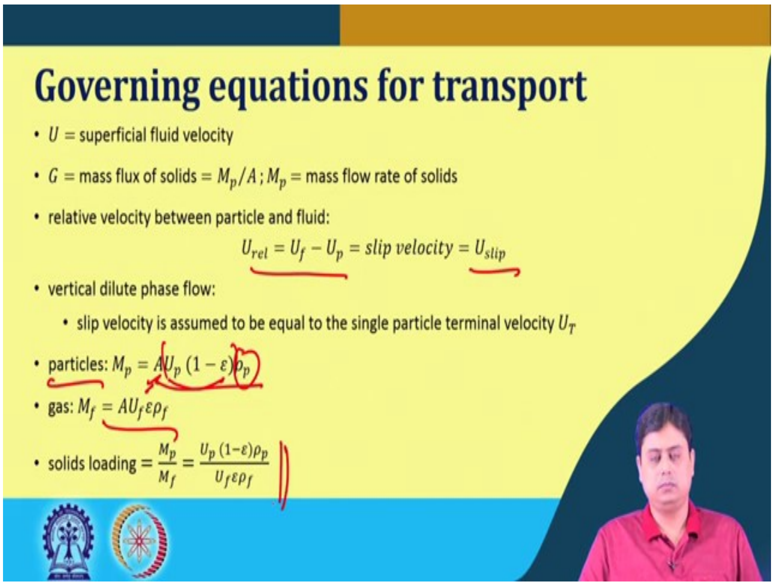


So, in most cases, the common nomenclature that is followed in fluidized bed or in this kind of transport that $U$ typically says it is a superficial gas velocity. So, if you remember that may be the coming $U_{ps}$ the forth coming slides will be mentioning this, the superficial velocity as simple $U$. The mass flux of the solid that we have seen its nomenclature as $G$ in the last class as well which is the mass flow rate of the solids divided by the cross sectional area of the flow $M_p/A$.

Now, there would be the relative velocity between the particles, the solid particles in suspension and the air or the gas phase. That if you say as a relative velocity then it is defined as

$$U_{rel} = U_f - U_p = slip\,velocity = U_{slip}$$

We say this is the $U_{slip}$. Now, in case of vertical arrangement of the dilute phase transport, the slip velocity is mostly are very often assumed to be equal to that of the single particle terminal velocity, helps us to estimate several parameters. Now, if you write the continuity equations, then we see that for particles, the mass flow rate of the solids is

$$M_p = A U_p (1-\varepsilon) \rho_p$$

the cross sectional area, its available flow area multiplied by the actual velocity multiplied by its density.

Or you can think of in this way that the cross sectional area multiplied by the superficial velocity multiplied by the density, $A U_p \rho_p$ is basically the superficial velocity, because if you look at this above expression, the superficial velocity is actual velocity multiplied by $(1-\varepsilon)$. So, similarly for the gas phase the mass flow rate of the air or the gas phase, we can write

$$M_f = A U_f \varepsilon \rho_f$$

So, the parameter solids loading is the ratio of the mass flow rate of solids to the mass flow rate of air which is defined as this.

$$\text{solids loading} ¿ \frac{M_p}{M_f} = \frac{U_p (1-\varepsilon) \rho_p}{U_f \varepsilon \rho_f}$$

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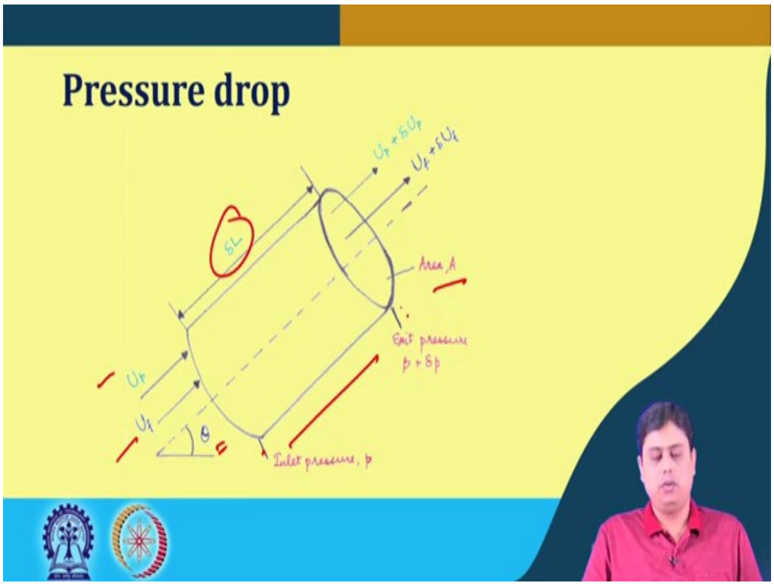


Now, if you look to derive an expression for the pressure drop, because this is what is important we have seen in case of slurry transport, how to estimate the pressure drop in the case of dilute phase transport. Now, here if we consider the similar scenario and irrespective of its orientation, so generic approach can be something like this that say the area available for cross this flow the cross sectional area is A.

We take a pipe section of length $\delta L$. $U_p$ is the particle velocity, $U_f$ is the fluid velocity, these are the actual velocity. So, there would be the pressure difference of $\delta P$. And this section is inclined with the horizontal plane with the angle of $\theta$. So, we try to now write the pressure drop expression for this entry, this inlet and the outlet.

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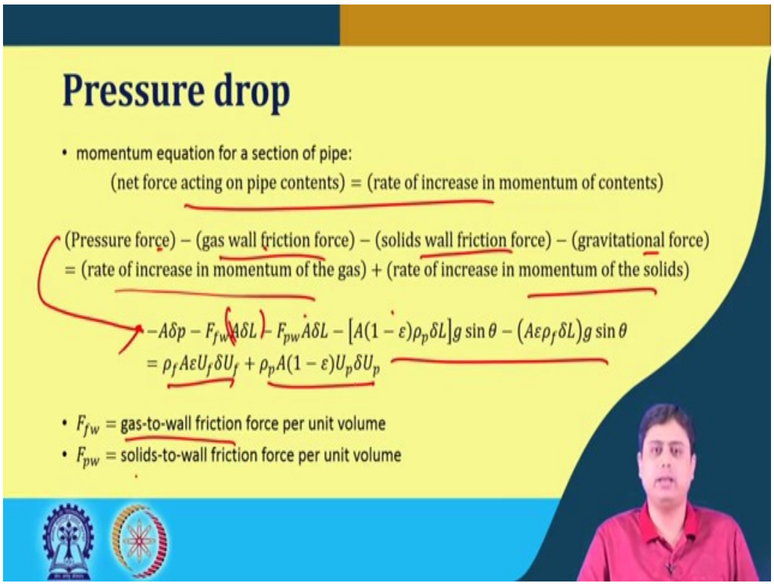


So, if you now try to write this, the essence is that the momentum equation for this section of the pipe is basically

$$(net\ force\ acting\ on\ pipe\ contents) = (rate\ of\ increase \in momentum\ of\ contents)$$

this is a balance we write for the momentum equation. So, net force that is acting on the pipe content and which is equals to the rate of increase of the momentum of the content. Now, the net force that is acting on a pipe content is the pressure drop minus the frictional forces and the gravitational force.

$$(Pressure\ force) - (gas\ wall\ friction\ force) - (solids\ wall\ friction\ force) - (gravitational\ force) = (rate\ of\ increase \in$$

So, the frictional forces are the gas and wall friction force, solids and wall friction force as well as the gravitational force. This is the net force that is acting on that element of the content that is that $dL$ length and the cross sectional area $A$ of that pipe section which is equals to the rate of increase in the momentum of gas and the rate of increase in momentum of the solids, because the content is basically the gas and the solid particle. So, we can individually write this rate of increase for both the cases.

So, now, if we try to write each and every element, each and every component is shown here,

$$-A\delta p - F_{fw}A\delta L - F_{pw}A\delta L - [A(1-\varepsilon)\rho_p\delta L]g\sin\theta - (A\varepsilon\rho_f\delta L)g\sin\theta = \rho_f A\varepsilon U_f\delta U_f + \rho_p A(1-\varepsilon)U_p\delta U_p$$

the respective part, where this $F_{fw}$ is the gas to wall friction force per unit volume that is multiplied by the volume amount gives us the frictional force due to the gas and wall interaction. So, similarly this all the components can be explained this $F_{pw}$ stands for the particle and wall for the solids and wall friction, this force per unit volume.

So, by doing so, and this is the gravitational force that is acting on the gas and the solid content which is the rate of increase of the momentum of gas plus the rate of increase of momentum of solids as you mean the gas density remains constant and the void is remains constant. If we integrate this expression, we can find the $\delta p$ for the $p_2 - p_1$, $p_{outlet} - p_{inlet}$.

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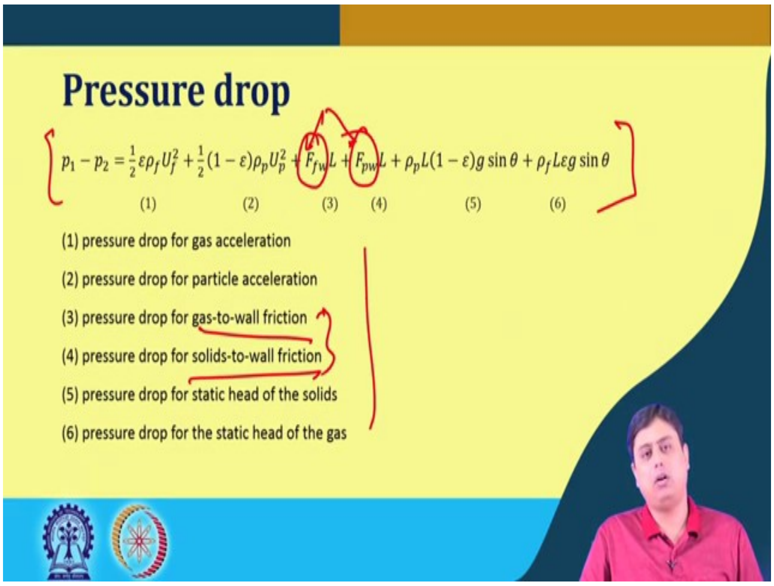


And, that expression would be something this one,

$$p_1 - p_2 = \frac{1}{2}\varepsilon\rho_f U_f^2 + \frac{1}{2}(1-\varepsilon)\rho_p U_p^2 + F_{fw}L + F_{pw}L + \rho_p L(1-\varepsilon)g\sin\theta + \rho_f L\varepsilon g\sin\theta$$

where we have all the individual component on the right hand side explained that the first term is the pressure drop due to gas acceleration. Second term is the pressure drop due to particle acceleration. Third term the pressure drop due to gas or the fluid and the wall interactions of the friction; fourth term pressure drop due to the particle wall friction. Fifth term is the pressure drop due to static head of the solids, and sixth term is a pressure drop resulting from the static head of the gas of the fluid.

So, these are what we also started with. And this we can see that it is indeed the case. Now, this expression can be applied for any pipe transport irrespective of its orientation provided we know this friction forces these two that means the gas wall friction and solid wall friction, because other quantities we typically know from the operating condition or from the measurement. So, depending on these two values or analysis of these two values, we can apply it for any orientation of the pipeline network having this pneumatic transfer or even we can apply this kind of balance for the slurry transport as well.

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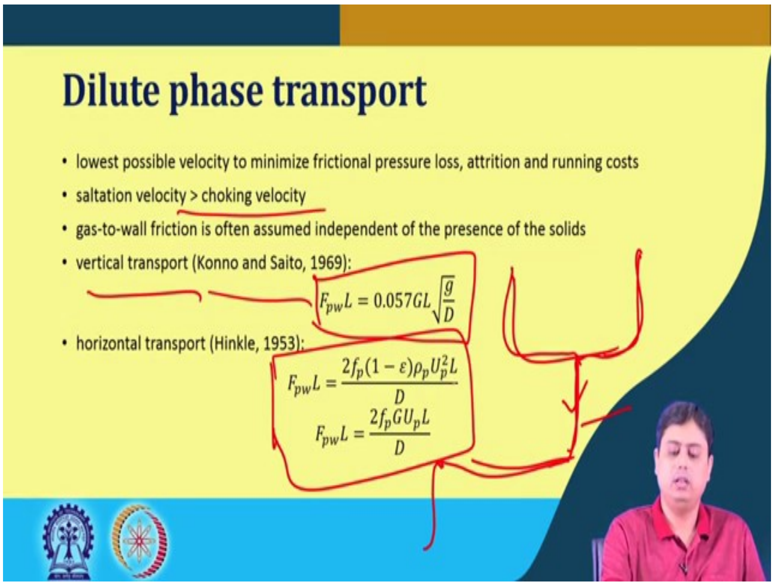


So, now the point come that how to have this dilute phase transport efficiently. So, it is always desirable to operate that with the lowest possible velocity to minimize the frictional pressure drop, to direct reduce the attrition, to reduce or to minimize the running cost. And for any particular size of the solid size and fixed pipe diameter, the saltation velocity is always higher than the choking velocity so which means we have to avoid so when we construct the pipeline network that would consists of horizontal component as well as the vertical component.

So, several pipeline networks will be formed that that this phase is coming here, going there, some phases coming here, if it is combined again flowing in horizontal direction, again going in the vertical direction. So, when this kind of network is there, the pipeline network. While selecting the appropriate operating velocity we have to remember this scenario, saltation velocity occurs in horizontal case, choking velocity occurs in particle case. So, which means we have to avoid by any cost this saltation velocity. We have to operate this on the higher side of the saltation velocity, so that both the velocities can be taken care off or we can avoid the choking velocity for obvious relation.

Now, in case of dilute phase transport, this gas to wall friction is often assume to be independent of presence of the solids. Because while calculating or analyzing these two parameters ($F_{pw}$ and $F_{fw}$), the consideration has to be made that whether this gas wall friction is dependent of the solid particles or not for the presence of the solid particles or not. So, in case of dilute phase transport, this is assumed to be independent of the presence. And then again there are several correlations available to find out what is those friction forces that the particle wall as well as the gas wall frictions.

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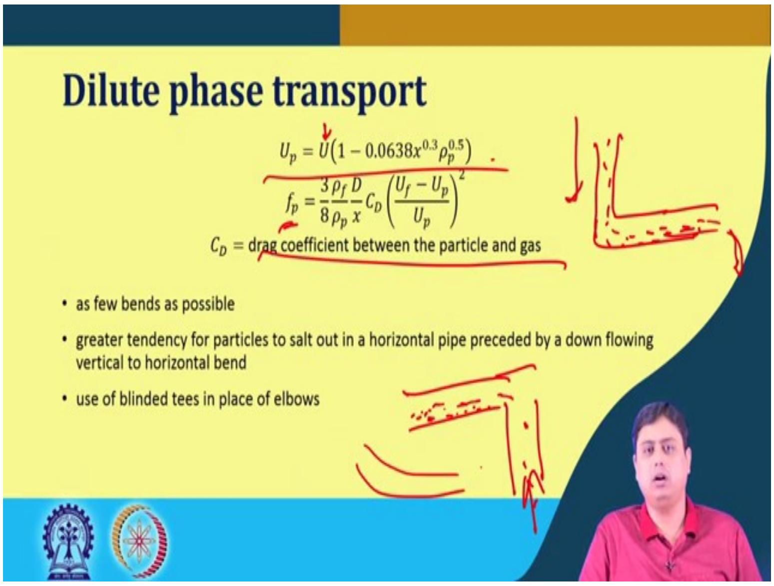


Now, in case of dilute phase transport as it is compared to be I mean considered to be independent of the solids that is present there. So, in vertical transport of this dilute phase thing, so we have these expressions from the literature.

$$F_{pw}L = 0.057\,GL\sqrt{\frac{g}{D}}$$

And, in case of horizontal transport, we have this expression

$$F_{pw}L = \frac{2f_p(1-\varepsilon)\rho_p U_p^2 L}{D}$$

when this equation is expressed in terms of mass flux, it reduces to this expression.

$$F_{pw}L = \frac{2 f_p G U_p L}{D}$$

So, from this expression, we can find out that what is the particle wall friction force in case of vertical as well as in case of horizontal transport.

Now, here this $U_p$ has to be calculated, and that also comes from this correlation,

$$U_p = U\left(1 - 0.0638\, x^{0.3} \rho_p^{0.5}\right)$$

where again if you remember we mention thus $U$ is a superficial velocity, $U_p$ is the particle velocity, actual velocity, because these are difficult to determine we can easily determine the superficial velocity, but not the actual velocities. So, this is what is given in such case. And we can find out the friction factor for such case where $C_D$ is a drag coefficient between the particle and the gas phase.

$$f_p = \frac{3}{8}\frac{\rho_f}{\rho_p}\frac{D}{x} C_D \left(\frac{U_f - U_p}{U_p}\right)^2$$

So, the point is that there are several correlations, and we have to choose appropriately or in suitable manner that fits our working condition that we have mentioned or emphasized during the slurry transport calculations as well. Similar to that here also we have to apply the similar strategy. Now, in case of transport in a pipeline network, it is desirable that there will be as few bends as possible. If we now consider that, we know everything now it is being transported this dilute phase using transported. So, there has to be as few bends as possible, because this bends would create more pressure would create the requirement of more pressure drop.

So, and this bends also creates the detrimental effect to the velocities for example, there is a greater tendency of the particles to settle or sort out in a horizontal pipe that is preceded by down flowing vertical to horizontal bend. So, such say if a pipeline network is something like this, the particles are coming like in such a manner or even in the other direction you can think of the flow is happening something like this. So, the solid particles will be salting here for a longer period in such cases, or even here when it comes it would try to settle here or in fact would settle, and it would take a longer time to again coming back to the circulation loop. So, it is to be avoided.

Now, earlier it was thought that gradual or say slope wise change in the bend would help in reducing the attrition or erosion of the pipeline, because this gas and the particles are flowing at very high velocity. But it has been seen by thorough research that use of blinded tees in place of elbows greatly reduces the lifetime of pipeline network.

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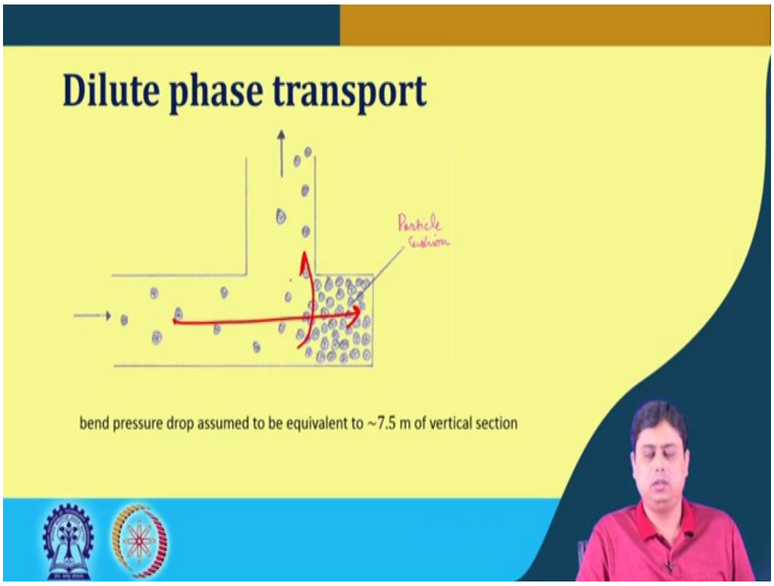


For example, so this is the example of a blinded tee, in case in place of just an elbow. So, here what happens, the effect of cushioning is imparted to the oncoming solid particles. So, some solid particles are gathered in this blinded section they did section. So, particle cushioning effect happens. So, direct hitting of this wall while it is flowing in this direction the changes its direction that attrition, the corrosion, all this things is reduced and greatly reduced.

The lifetime becomes in order of magnitude higher than a simple elbow. So, such kind of design consideration are there, but there is no hard and fast rule for that this comes from the experience, the previous experience, the design experience from the operators. Now, typically thumb rule is that the bend pressure while designing a pipeline network as the bends cannot be avoided, but how to then estimate the overall pressure drop through the network.

A typical guideline is that the bend pressure drop would be almost equivalent to 7.5 m of a vertical section pressure drop with the same kind of particles. And this is then added with the straight section of the pressure drop calculation, because this bends elbows and all these parameters are actual the practical fittings of a pipeline network. So, several such design consideration has to be made in order to have an efficient design of this pipeline network that would be carrying this pneumatic transport.

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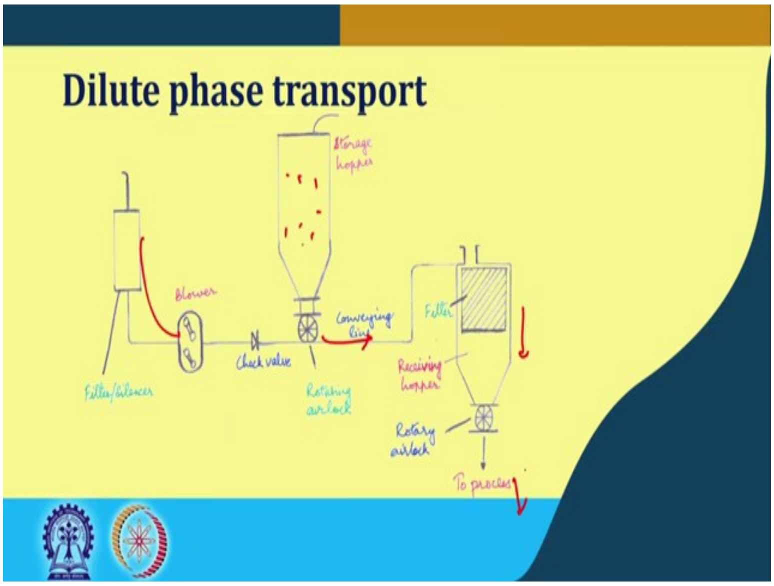


Now, like in slurry transport, we have seen that how it is typically flown or how it is typically conveyed, one of such schematic for the pneumatic transport is shown here. So, here these are the solid particles are stored in a storage hopper, and this is rotary rotating here lock is there. This is the conveying line. Here the blower is there from where the air comes and being pushed in the conveying line along with the solid particles that carries. And at the receiving end of this suspension, it is filtrate using different types of filter that we have seen, and then the particles goes to the process after collecting the particles.

So, it is not that one single stage operation of the filtration can help in separating this suspension there can be multiple stages of the separation or the loop it can goes again and again not the single pass operation. So, all this actually constitutes the whole dilute phase transport line. So, then these details, you can find it again in the encyclopedia or the Perry's handbook.

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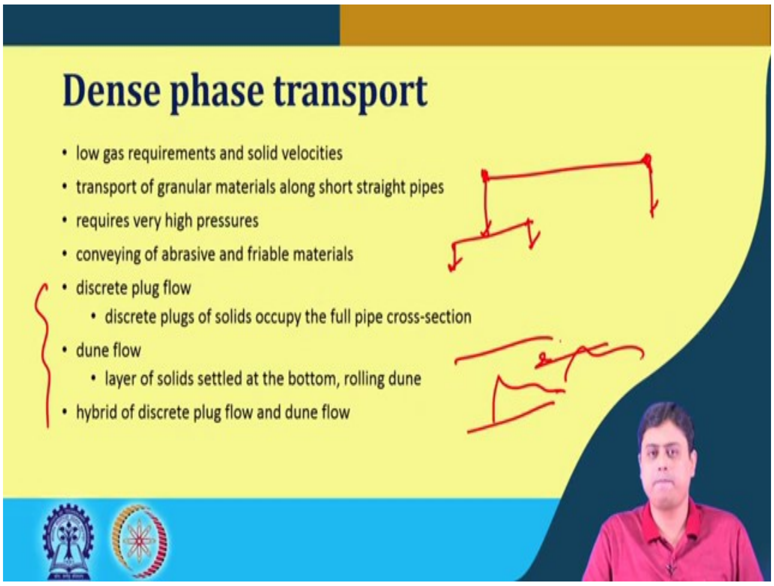


Now, in case of dense phase transport as I a mentioned earlier, the only benefit is that the low gas requirement and the law solid velocity. But it is applied to transport granular material along a short straight pipe, because we can understand the solid particles are settling in this case it requires very high pressure, but it can be useful in converting abrasive or friable materials because the velocities are low. The attrition the correlation and all this things are lower than the dilute phase transport.

In this case, so we have two extreme basically one is the how much the dilute phase transport, one is the discrete dense phase transport. Now, in the dense phase transport, here also we can have two extreme. One is say the homogeneous flow, where whole cross section is basically filled with the solid particles, so kind of a plug flow of solids can happen. And in other case there can be different scenario we call the heterogeneous flow. In this heterogeneous flow can further be classified in this three types, one is the discrete plug flow that means, discrete plugs of solids occupy the whole cross section, the other can be the dune flow the sand dune like that happens. So, here there will be a layer of solid that would settle, and these solid dunes would be rotating and the solid gas phase will flow on top of this. So, there is a rolling movement of the dunes. And in between these, two there is a hybrid movement of the discrete plug flow and the dune flow.

So, this basically gives a overview of types of pneumatic transport starting from the dilute and the dense phase transport, its pros and cons, and a typical overview of the transport line or the total transport organization that can happen in case of dilute phase transport that we have seen. And, this brings to the end of today's lecture, and the next day will be seeing with the father different context.

Till then I thank you for your attention.