Fundamentals Of Particle And Fluid Solid Processing
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Lecture - 51
Fluid – solid transport

Hello everyone. And welcome back with a another new section in the subject that is Fundamentals of Particle and Fluid Solid Processing. Today we will be discussing on transport of Fluid solid systems.

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Now, till now we have seen several aspects of these particles that is starting from its size determination study. And then we have seen its separation how particle moves in a fluid or how a fluid moves around a particle. We have seen how sediments can be separated or say the particle fluids can be separated by fluidization by sedimentation by filtration.

Also we have seen how to reduce the particle sizes. We have seen how to enlarge that. Now, today we will see that how the particles and the solids the fluids how do we transport them. Or what are the transport fundamentals the transport mechanism when we try to move particle from one place to other place. Now, as itself just moving the solids or flowing solids we have seen its difficult due to its characteristics.

So, it is typically mixed with another fluid. And now that fluid can be of liquid or can be of gaseous state. Mostly in practice for the gaseous phase, it is the air that is used in order to transport the particles from one place to other. And, such scenarios called the pneumatic conveying or the pneumatic transport of the particle. The other one when the liquid phase is involved in order to move these particles from one place to other.

That is the main component becomes the water; that water is typically our more most widely used liquid phase in the liquid and liquid and the solid system transport. So, and this second one that is when it is involved with water, that kind of transport we see the slurry transport. Now, instead of water that can be of other liquid; now typically as I said mostly used liquid component is the water.

Now today, we will focus on this slurry transport and then we will move on to the pneumatic transport at a later stage. So, which means the transport of fluid solid system we basically have divided in two components further. One when the fluid is gas, that is the pneumatic conveying and when the fluid is liquid we call the slurry transport.

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So, in slurry transport the slurry or we can say that this is a mixture of the liquid and the solid particles. And, this is the I mean broad definition of a slurry. And when this is highly concentrated by the fine particulate materials, this slurry we call as sludge. Now, it has widespread applications, it has immense applications in various areas of mineral transport.

For example, say the coal phosphate and all these industries. Also when they try to transport these coal particles from one place to the other this kind of slurry transport is useful. Also the handling of slurry is involved, when there are the applications of dredging of slants or silts for maintaining the waterways. And there also this sand and water mixture it basically we can call that it is a slurry of sand which has to be handled.

So, it has several applications now as I said mostly the liquid phases water in slurry transport. But there are examples or evidences that the slurries can be of coal oil or coal methanol fuel this kind of slurry are also there in application. But mostly it is the water that happens to be the liquid phase. Now, when we transport the slurry or transport the particles in terms of slurry now there the fluid property typically changes.

That fluid property means the water property or the original fluid property without the particles it has its own characteristics, but when certain concentration of slurry is mixed or. So, and certain concentration of fine particulate solids are mixed within the it then it its characteristics also changes. And in order to calculate or estimate the pressure drop, when it flows through pipe we need a one common parameter or the vital parameter that what is the density of the slurry?

Now this density can be obtained in couple of forms. So, typically it is used as the slurry or the mixture density, which is calculated in terms of the volume fraction of the solids. So, here if C_v is the volume fraction of the solids, then this slurry density or the mixture density is calculated in this form.

$$\rho_m = C_v \rho_s + \left(1 - C_v\right) \rho_f$$

Where ρ_s is the density of the solid particles of the material and ρ_f is the density of the fluid and as I said in this case the liquid phase.

So, based on this expression, we can find out that what is the mixture density? In terms of say mass fraction instead of this volume fraction, we can also obtain such expression which would look like in this form.

$$\frac{1}{\rho_m} = \frac{C_w}{\rho_s} + \frac{(1 - C\,\dot{c}\,\dot{c}\,w)}{\rho_f}\,\dot{c}$$

Where this C_w stands for the mass fractions of the particulate solid; so by this way also we can find out what is the mixture density. So, either for a slurry either we can know what is the mass fraction of the particulates or the volume fraction of the particulates. Based on any of this information, we can obtain its mixture density. Now when this slurry flows it flows in different regimes depending on the feed rate or the superficial velocity.

Now, also this slurry we can understand this solid particles are basically immiscible. That are suspended in the liquid phase and it should ideally be remain suspended while it flows which means there are chances that depending on the sizes of these particles since these are immiscible. If you remember our concept on its falling time to the bottom surface of a pipe to the travel path or the travel distance that it travel in between that time ok.

So, this in this relative sense, if the particle size is big enough or say it is highly concentrated or say has a certain concentration. And the hindered settling happens before it moves to its destination then those particles will settle. So, which means the slurry can be transported in different flow regimes. Ideally, if we if this slurry is made for transportation then these particles should be suspended all the time.

So, that it can be efficiently carried till its destination. So, based on this idea or this observation, this slurry transport has been categorized or has been divided in three flow regimes. One is the homogenous flow, in which there is a uniform distribution of particles over the pipe cross section or say the flow cross section. So, when it flows through the pipe so, this contains the solid particles the fluid is flowing.

So, at a certain cross section for homogeneous case, if this is the cross sectional view there should be a uniform distribution of the particles. Or say there should not be any concentration gradient in this cross section. If that happens we typically say this is the homogeneous flow. And then the particles should settle very slowly and as I said ideally it should remain in suspension.

So, in this category these kind of slurries are also called the non settling slurries; because by the time it settles it reaches its destination. So that means, in the flow region or the in the flow path it is not settling. So, the flow properties, in this case are basically dictated by the solids. Its rheological properties are dictated by the concentration or the type type of the solids.

So, these slurries are the slurries that has high concentration and finer particles say less than 75 μm in that range. These kind of slurries exhibit this homogeneous flow behavior. Now with a fixed particle or a given particle size, if we increase its concentration the solids concentration the flow tends to be homogeneous in nature. It becomes more homogeneous suspension.

Examples of this homogeneous flow or the homogeneous flow regime that behave in this homogenous flow is the sewage sludge drilling muds, detergent slurries, fine coal slurries, paper pulp suspension. These typically does not this does not settle quickly the particles. And it flows along with the bulk motion of the fluid or the liquid and typically there is a uniform distribution of the particle all over its cross section.
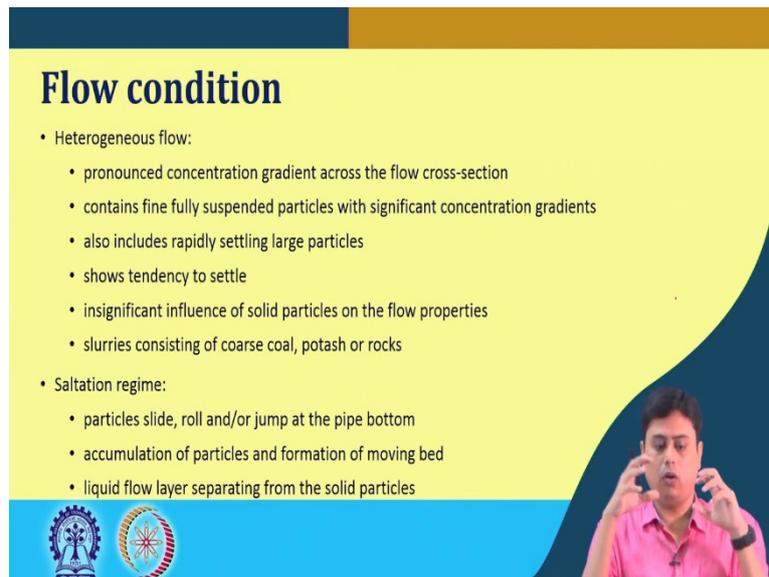
So, these are the characteristics of homogeneous flow. In case of heterogeneous flow on the, unlike this homogeneous case; there would be a pronounced concentration gradient across the flow cross section, which in homogeneous case was supposed to be uniform cross section uniform gradient. Or there should not be any gradient there is a uniform distribution.

In this case there is a pronounced concentration gradient across the flow area. Now it contains fine fully suspended particles, with significant concentration gradients as well as rapidly settling large particles. Because, now we understand that why we have covered this settling phenomena before we came to this flow behavior; because we know the terminal settling velocities it is its dependency on the particle diameter.

So, if the particle size increases, it rapidly falls. Now this heterogeneous flow contains this both range of particles one is fully suspended very fine particles. But it will have a significant concentration gradient along the flow area or pipe cross section as well as it will have rapidly settling large particles. So, disc in this kind of flow regime or this kind of flow shows the tendency of particle settling at the bottom of the pipe or the bottom of the surface or the bottom of the conveying system.

So, in this case it has been seen there is insignificant influence of the particle on the bulk property of the flow. Unlike the homogeneous case, where its rheology was depending on the solids, but here the solids does not have much influence on the flow properties of this heterogeneous flow. The examples are of this case is the slurries consisting course coal

portage rocks so; that means, size gets bigger and bigger it tries to settle at the bottom of the conveying system.

So, this is the homogeneous regime then the heterogeneous regime. And, then we have saltation regime in slide transport. So, here what happens in this saltation regime the particle slides rolls jumps at the bottom of the pipe, which means the particle has already settled some of the particles are settled and fluid stream is flowing. So, there is a clear segregation or the clear distinction between the liquid bulk liquid flow.

And there is a moving bed of particulates and during its motion the particle jumps rolls and slides along the bottom surface of the pipe. So that means, there is accumulation of particles and formation of a moving bed at the bottom portion of the conveying equipment or the conveying system. This regime we call the saltation regime in slurry transport.

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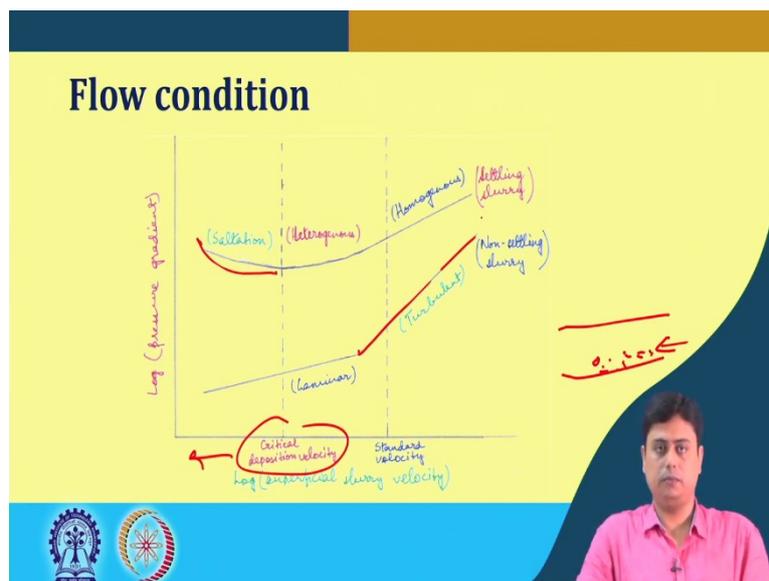
So, if we look at the flow regime map. So, that map would look like something similar to this schematic that is shown here. Now, in this case this schematic also important from the point of pressure drop calculation; because this is one of the prime concern in moving the slurry from one place to other. This is the mechanical energy requirement that is dictated by this pressure drop that will happen when this transport is taking place.

So, such kind of information can be obtained from the log plot of the pressure gradient. And the slurry transport velocity or the superficial slight velocity, which is again the volumetric

flow rate divided by the cross sectional area of flow is the superficial slurry velocity. So, in this case these two lines are shown one for the settling slurries and other for the non settling slurry.

So, by now we know the settling slurry means when the particle settles at the bottom. So, in such case say the flow is happening now we will start from a say at a high velocity. Say at first we understand from this direction that we have had a very high velocity and the slurry was moving. There was a liquid bulk motion of the liquid and at the bottom there is a moving bed of the settle particles.

That amount of the particles at the bottom would be lesser in this case because of its high velocity bulk velocity of the liquid. Now for that we need a critical velocity called the standard velocity. If the velocity is beyond or above or say the higher than the standard velocity then this not this settling slurry behaves as if a homogeneous flow. That means, this is at a very high velocity all the settle particles basically against it suspended due to its kinetic motion.

And the cross section would apparently look like that it has an even distribution of the solid particles. So, the point is that this relative concept that the time it reaches a certain distance. And the time it takes to settle within that time, if it reaches a certain distance; that means, it can remain suspended for a longer time and that happens here.

Once we increase the bulk velocity to a greater extent, then the settling time in which it was falling by that time it would travel a long distance. With that concept, it creates a homogeneous mixture or homogeneous flow. But below this standard velocity there is the evidence of heterogeneous flow which means again here there is a concentration gradient across the cross section the particles settles rapidly it creates a layer of particles.

And if we further go below another value called the critical deposition velocity; the particles deposits basically. So, in order so this is the scenario say the particles nearer to the bottom surface. And there is a sufficient concentration gradient along this surface. So, if we go below a certain velocity, which is called the critical deposition velocity these particles basically settles.

And once it settles we have seen the saltation regime; that means, now these particles along as it flows it rolls its slips its jumps over one another. So, which means in order to keep the

particles suspended, we require critical deposition velocity. And we have to operate above of this velocity or higher than this velocity. Then the particles are not deposited on the surface it is flowing with the bulk fluid, but with a concentration gradient across the cross sectional area.

At a further higher velocity which is called the standard velocity above which we have the settling slurries behaving as of homogeneous slurry homogeneous flow. In case of non settling slurry, there is no point of discussing any saltation regime; because it is not settling. So, there is a two clear flow regime we observe one is the laminar flow the other one is the turbulent regime.

Now in both the cases we can see that the pressure drop usually increases as we increase the superficial velocity. But in the case of settling slurries, what happens once we reach the saltation regime the pressure drop further increases. If we go beyond or say below the critical deposition velocity the pressure drop in the settling cases increases; because if the particles has settled at the bottom.

Now, it requires higher pressure drop for its movement it is not for the suspended in the fluid cross section area. But in case of non settling slurry, there is a sharp gradient or sharp change in gradient, when the flow moves from laminar to turbulent. Such sharp distinction is not observed in case of settling slurries.

So, by such graph we can have the pressure drop information and which is basically related with the superficial slurry velocity. And this schematic also depicts the different regimes, that is there in case of slurry transport.

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So, now in order to have a model or to calculate its pressure drop and all other hydrodynamic parameter we need certain rheological models. Like, in fluid dynamics we have seen there are several viscosity models are there. So, here typically all the models for the rheology this slurry transport are based on the continuum fluid models. And that actually is valid when the solid particles settles very slowly.

Or say it remains suspended till it reaches its destination of a longer time. Homogeneous slurry is one of the extreme or the limiting factor of this slurry transport; because in this case all the particles are basically suspended and reverse settles basically, it has a uniform cross section as well. Uniform concentration grade, it that does not change in the direction of the flow as well.

So, in this case Newtonian and non-Newtonian flow behaviors can be observed and several fluid, say slurries are there which exhibits the Newtonian as well as the non Newtonian flow behavior. But mostly, the slurries exhibit non Newtonian behavior that also depends on the solids concentration in the slurry.

So, in the higher solids concentration; that means, when the slurry is homogeneous; I mean; because for a given particular size as we increase the concentration it becomes more homogeneous. So, on that note when we try to model or when we try to estimate this kind of slurry, we typically assume that this is a single phase flow with the mixture properties.

And its characteristics are completely different from the original liquid; original liquid means when it was without any solid particles. Now we have seen in Newtonian fluids in laminar flow, the expression between the shear stress and the shear rate which gives us the Newton's law of viscosity.

$$\tau = \mu \dot{\gamma}$$

Now the similar concept also applies here if it behaves as Newtonian slurry.

Now in this case; that means, we have a linear relation between the shear stress and the shear rate. And, if we plot this graph of shear stress and shear rate shear stress or the strain rate the slope of the line gives us the viscosity of this slurry. So, in this case as we increase the strain the shear rate shear stress increases.

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Now, in dilute suspensions of fined particles, this kind of slurry basically behaves as Newtonian fluid. And in order to obtain its viscosity, there is a theoretical relation proposed by Einstein which says that for lower than 2 % of the volume fraction of the solids in a slurry, which contains uniform spherical particles the viscosity can be obtained from Einstein relation which is given as this expression.

$$\mu_r = \frac{\mu_m}{\mu_f} = 1 + 2.5\,C_v$$

Where this μ_m is the slurry viscosity and μ_f is the single phase fluid viscosity; that means, the original liquid viscosity. And, C_v stands for the volume fraction of the solids. This ratio of μ_m and μ_f is called the relative viscosity. So, it specifically applies in the range, when there is a very dilute suspension the solids concentration is lesser than 2 % volume concentration and it consists of uniform spherical particles.

But in most of the cases this these criteria's are not satisfied. So, in case of non spherical particles and a higher concentration there has been a significant deviation from the predictions by this expression of the viscosity of this mixture viscosity. So, basically what we have covered till now is that we have introduced the slurry transport its different flow regime.

And how the behavior of this slurry can be estimated firstly; by estimating its viscosity. And the rheological model, the governing equations typically assumes that the slurry is continuum. So, we will be discussing this further in our next class and in detail. Till then I thank you for your attention and will see you continuing with this discussion in the next class.

Thank you.