Fundamentals Of Particle And Fluid Solid Processing
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Lecture - 40
Centrifugal Separation (Contd.)

Hello everyone and once again, welcome back to the class of Fundamentals of Particle and Fluid Solid Processing. So, we were discussing about Centrifugal Separation. We have seen several problems that was dealt with the concept of Stokes number, Euler's number, the Cyclones Separators in parallel; how to find the equi-probable cut size; how to find the size distribution provided the feed size distributions and one of the outlet stream size distribution are given.

We have seen four-five problems related to that till the last class and I mentioned that all this concept that actually has been discussed for the gas cyclone.

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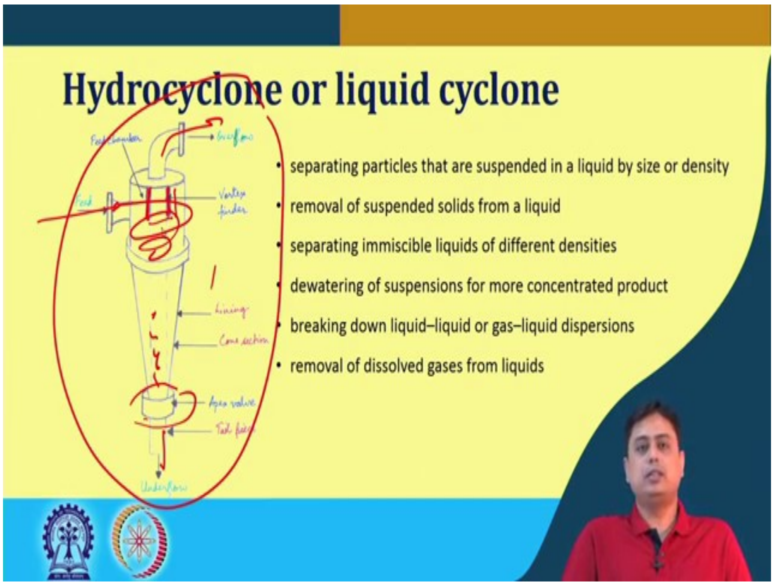

Now, the similar concept actually applies to the Hydrocyclone or the liquid cyclone as well. So, it has a similar geometry, where we have the feed chamber. The feed comes in with a very high velocity and goes tangential to this inlet, to this conical cylindrical section. We have this overflow and this is the vortex finder which actually intrudes into the cylindrical section.

So, this the depth from the top surface, it comes. It is one of the design parameter in both the cases; be it the gas cyclone or the liquid cyclone. And, this is the conical section, we have and this is the valve that is there and this is the under flow where the solid particles are collected and this is the overflow sections like the water or the liquid phase is being withdrawn along with that some final particles also escapes.

So, all the concepts that we have discussed it applies similarly in this hydrocyclone or the liquid cyclone; that means, when the fluid phase is the liquid phase, it is called the hydro cyclone and when it was the gaseous phase, it was the gas cyclone. So, the applications of these hydrocyclones or the family of hydrocyclones, finds extensive use in separating particles that are suspended in liquids by its size or the density.

So, if there is a range of particles having different sizes and densities that can be separated in this hydro clock hydro cyclones. Overall the removal of suspended solids is also done with these hydro cyclones. It also is used for separating immiscible liquids of different densities. It is used in dewatering of suspensions to make it more concentrated product as a demulsifier or say breaking down liquid-liquid or gas-liquid dispersions. It is used and also it is sometimes used in the removal of dissolved gases from the liquid.

So, in that case what happens? This gas phase creates the inner vortexes and it escapes. So, these are the applications and the design consideration; all the calculations remain same as of the gas cyclone separator.

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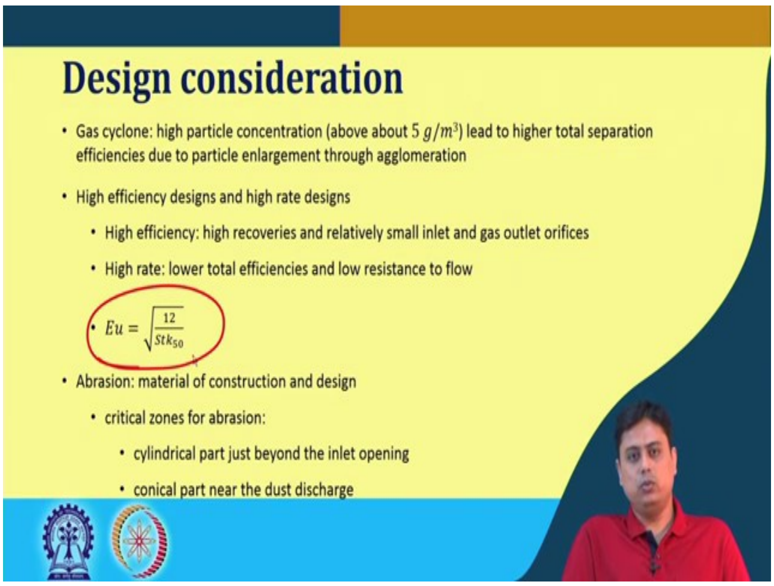

Now, when it comes to the design of these cyclone separators, there are some guidelines which we have listed here. We will quickly go through this. These are some the things that are here are logical and few things that we have already discussed. So, for example, the Gas cyclone; we mentioned that in case of high particle concentrations that is above 5 g/m^3, it leads to total higher separations or higher efficiency due to the particle enlargement that can happen due to the agglomeration of the particles.

So, if the surface properties of the particle that are suspended in the fluid or in the gas phase are such that it can quickly agglomerate. Then, the size enlargement can happen. It can stick to one another each with the other surfaces and the size enlargement happens and if that happens the separation becomes easier. So, the higher total separation efficiency can be achieved in such case because if the suspensions the there is high particle concentration. So, distance between the particles gets closer.

The cyclone the separators in general can be of two types. We have to choose appropriately or wisely depending on where it is being used. For example, the broad category of these separators, cyclone separators are either of high efficiency design or say high throughput handling design or say the high rate designs. One gives us very low size cut or the cut size and the other can handle a large throughput or the large volume of the flow rate.

So, quite naturally the high efficiency designs provide high recovery of the solid particle or the coarser particles and relatively small inlet and gas outlet orifices are there. So that means, the resistance to flow is higher. On the contrary high rate designs can handle this large volume of flow rate because there is low resistance to flow, but it results in lower total efficiency. So, based on your requirement or on the requirement, this has to be chosen wisely.

Now, we have already talked about the importance of Euler number and the Stokes number. There are some empirical relations that are available to relate these two numbers. Now, the Euler number deals with the overall pressure drop. Stokes number deals with the cut size. So, if such direct correlations are available, it makes the life more easier or the design consideration much easier and one of such empirical relation is like this. This is the approximation.

$$Eu = \sqrt{\frac{12}{Stk_{50}}}$$

So, what happens here? The Euler number at the numerator, you have the Δp and the Stokes number at the numerator you have the cut size that is a square. So, which means if this Δp value increases the cut size decreases; that means, with a higher pressure drop, you can naturally achieve a lower value of the cut size. So, this has to be balanced as per the affordable pressure drop that you can have and the cut size or the purity that you want.

The other important consideration since this is there is a very high flow rate or high velocities are involved, particles are involved in the fluid phase. So, the abrasion of the material of its construction that has to be wisely chosen. The stainless steel materials that has typically used, sometimes rubbery materials used because there are two mainly main critical zones, where this abrasion happens more rigorously or more these are the prone to the abrasion. One is the cylindrical part just beyond the inlet opening and the other is the conical part near the dust discharge.

Because, here in this portion is just the high velocity fluids are entering and is creating the vortex and at here, at this position the direction changes. So, these positions are more prone to this abrasion. So, the design or the construction material has to be chosen for their design very wisely.

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There are chances of solid attritions. In fact, that happens the particle breakage can happen and this happens logically more in the case of larger particles. The solid-solid interaction happens, the particle impact happens which with each other. So, the particle breakage happens. But how it influences the performance? It is still under the research category; so, but logically larger particles are more likely to be affected than the finer particles due to this influence. The important, the other important rather parameter that has to be considered during this design of the large scale operation is the blockage.

Now, this cyclone cone rapidly fills up with the dust because that is the collection zone. So, if that happens very rapidly, the pressure drop goes very high and the efficiency also falls. Because we now we have if you remember that pressure drop versus flow rate along with the efficiency curve, you remember there was an operation zone; appropriate operation zone and theoretically, although it should increase the efficiency, but practically the efficiency sharply falls.

So, this has to be clearly in mind. So, this blockage can happen one of the reason is that rapid fill up of the solids at the conical zone; the mechanical defects any gasket blockage or something like that or say the physical property change of the field during the operations. This physical property like the condensation of water vapor from the gas; if that happens, this leads to some sticky material ok. If the surface property of the solid particles are such that it sticks to a together ok, it forms agglomeration big chunks of solids forms together. In that case it can blockage is block some of the portions of this flow zone.

The other important the or in fact, the very important parameter is the solid discharge design. That we have mentioned that this blockage in this zone that should not happen because this directly relates with the solid discharge zone. The solid discharge zone should not be should not have any leakage because if this is this operation is happening under pressure. Then, what happens? Any outward leakage although can increase the efficiency, but then the solids actually or it can be pollutants it actually contaminates the nearby atmosphere or if it this operation is happening under vacuum, then any inward leakage that what happens?

The particles that are being deposited can be re-entrained in the cycling zone. We have discussed the cyclones in parallel; how we can effectively use such configuration to reduce the cut size, to reduce the flow rate if it is evenly distributed during solution of several problems. The cyclones also can be used in series, that one after another and in that case the first cyclone would be of minimum to low efficiency or design. It should be able to handle high throughput and stage wise, you can increase the purity of the suspension or the particle laden gas stage by in a step manner.

So, the consecutive ones after the first one should be of high efficiency design and the initial the first one can be of high rate handling design. So, these are some practical consideration that are typically done or should be done and that brings this end of this cyclone thing. So, if you remember on the first class, we mentioned that this centrifugal field can be introduced in two-way; either by introducing high velocity fluid tangentially into this cylindrical section creating a stable vortex or the equipment itself is rotating; that means, the centrifuge.

The example is the centrifuge that it rotates and if there is the very low or insignificant amount of relative slip between the liquid and the solid wall, the liquid also moves at a speed of this rotating vessel or the bowl.

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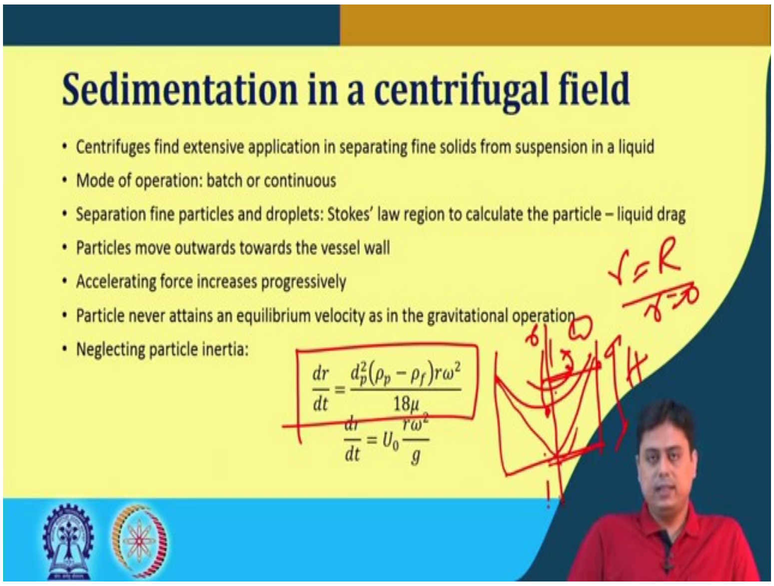

So, Sedimentation in centrifugal field this actually employs the second operation that is the second application of centrifugal field that here the centrifuges are basically used to enhance the sedimentation rate that are happening typically in gravitational condition. So, to enhance that settling rate, this actually finds extensive applications in separating fine solids from suspension of a liquid. Now, it can be operated in batch mode or with appropriate or say associated accessories, it can be operated in continuous mode as well.

So, the separation of fine particles and droplets, since this is happening or this is warranted here, typically the calculation of particle liquid drag involves the consideration that Stokes law region is valid. Then, basically it is compares the relative terminal velocity again and this separation can happen. So, here also you can understand the typical example of having a centrifuge in applications is that when we rotate a bowl and there is water inside that. So, this free surface of the liquid also takes a certain form and that form is typically like this.

So, if this is the bowl wall as you increase the rotating speed, this free surface at a certain point of time will touch the base depending on the depth of the liquid and the speed the angular momentum of this rotating bowl. So, they what happens? The particles are then moved towards this vessel wall. The accelerating force increases progressively and particle never attains an equilibrium velocity as that happens in case of gravitational operation.

So, in this case if we neglect the particle inertia because we consider the particles to be very fine. So, the inertia effect of the particle if we can neglect, then the velocity of the particle can be written in this form assuming the Stokes law is valid in that region, where r is the radius of its rotation; that means, this r this is a small r.

$$\frac{dr}{dt}=\frac{d_p^2\left(\rho_p-\rho_f\right)r\,\omega^2}{18\,\mu}$$

So, when r is R; that means, it touches the particle touches the wall of the vessel of the centrifuge. When r is equals to 0, it is basically the axis on which it is rotating, its rotational axis.

So, if this is this is the flow field, then what happens is that we can write this expression in terms of single particle terminal velocity.

$$\frac{dr}{dt}=U_0\frac{r\,\omega^2}{g}$$

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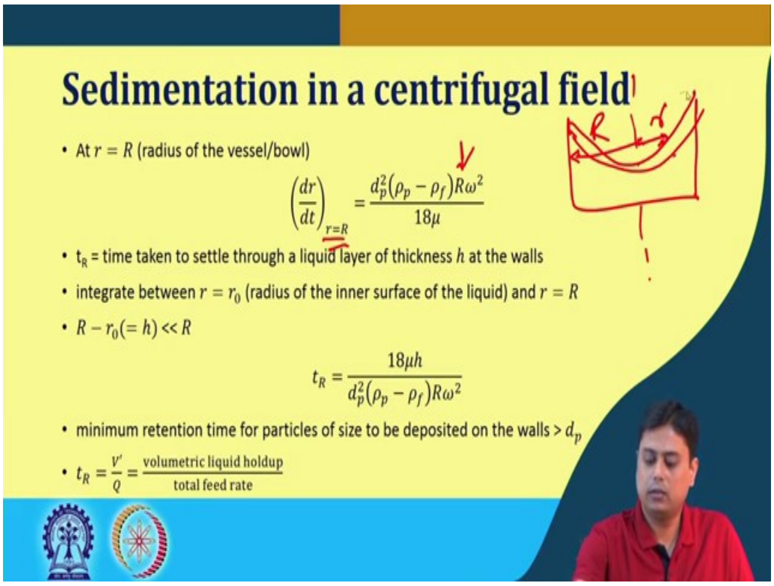

Now, let us say this R as I mentioned the radius of the vessel. So, if this is the vessel, it is rotating on its axis and the free surface takes a form like this. Say particle is here this is R. So, when r is R, it basically the particle hits the wall, impacts a wall. So that means, this expression at R is r. This R is introduced in this place of r.

$$\left(\frac{dr}{dt}\right)_{r=R} = \frac{d_p^2\left(\rho_p - \rho_f\right)R\,\omega^2}{18\,\mu}$$

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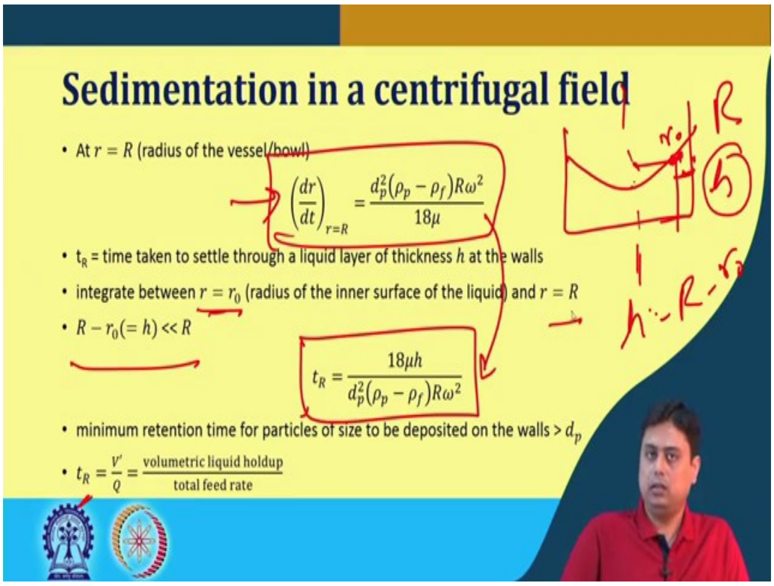

So, we if we now think of a scenario that this is now basically the particle here, if this is my rotating bowl, rotating in this axis and this free surface takes of this form and the particle on this surface is r.

So, basically this distance is the liquid thickness that it has to travel to reach the wall say this distance is h. That means, $R-r_0(¿h)$ the radius of inner surface of the liquid. So, the time it takes to settle through this liquid layer, if this expression has to in has to be integrated in the range of R is equals to r_0; where, r_0 is the radius of inner surface of the liquid and R, where R is the wall.

So, from this position to this position that is this thickness, it has to travel at which time; how much time it would take? If we integrate that and we consider this scenario that this thickness is very small compared to the radius of the bowl or the vessel or the centrifuge equipment, then we derive an expression the retention t_R; R stands for the retention is this one.

$$t_R=\frac{18\mu h}{d_p^2(\rho_p-\rho_f)R\omega^2}$$

So, this time we have derived that this time is required for the particle to travel from the free surface of the liquid, the inner surface to the wall.

So, this can be also thought of that this is the minimum retention time of the particle of size greater than d_p that is required to be deposited on the wall and again, this retention time can be written in terms of volumetric liquid holdup divided by the total flow rate that the volumetric liquid holdup in the bowl and the total feed rate that is there.

$$t_R=\frac{V'}{Q}=\frac{volumetric\ liquid\ holdup}{total\ feed\ rate}$$

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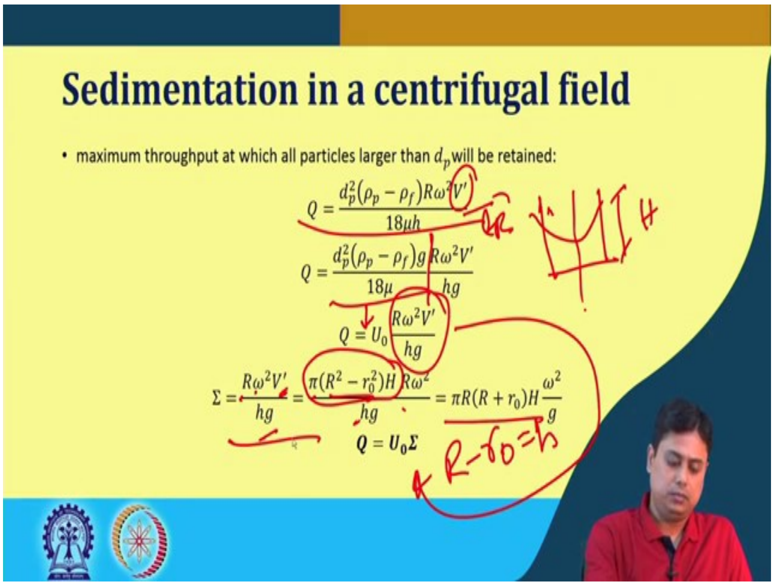

So, which means this t_R; then we can write in terms of this Q. So, the Q becomes this V' divided by t_R which is the expression that we derived.

$$Q = \frac{d_p^2(\rho_p - \rho_f)R\omega^2 V'}{18\mu h}$$

So, this is the maximum throughput at which all particles larger than d_p will be collected in the centrifuge.

$$Q = \frac{d_p^2(\rho_p - \rho_f)g}{18\mu}\frac{R\omega^2 V'}{hg}$$

It will be stuck sticking or hitting the wall and will be collected; which if we separate the variable, we see that

$$U_0 = \frac{d_p^2(\rho_p - \rho_f)g}{18\mu}$$

represents the U_0 the single particle terminal velocity multiplied by a factor.

$$Q = U_0\frac{R\omega^2 V'}{hg}$$

This factor is called the capacity factor of centrifuge. Now, this capacity factor is nothing, but if we expand the V' which is the volumetric holdup of the liquid which is nothing, but

$$V' = \pi\left(R^2 - r_0^2\right)H$$

H is the axial depth of this liquid because this is the volume of that liquid film that it travels

$$\Sigma = \frac{R\omega^2 V'}{hg} = \frac{\pi\left(R^2 - r_0^2\right)HR\omega^2}{hg} = \pi R\left(R + r_0\right)H\frac{\omega^2}{g}$$

So, from this expression, we can also write that Q is basically particle terminal velocity multiplied by the capacity factor of the centrifuge.

$$Q = U_0\Sigma$$

Now, if we look at this expression of this centrifuge capacity factor, we see this actually depends on the centrifuge geometry and its speed rotational speed. This has nothing to do with the particle size or the fluid properties etcetera. It is purely a geometric parameter.

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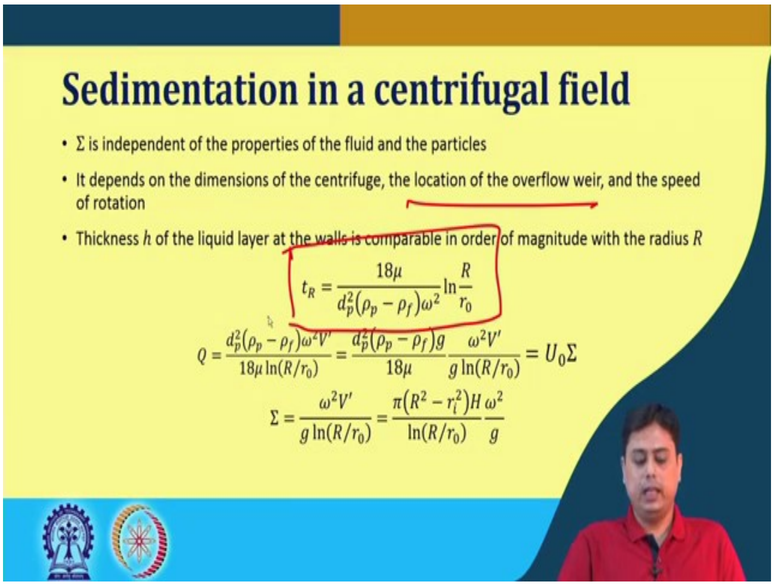

So, this capacity factor is independent of properties of liquid and the particles. It depends on the dimension of the centrifuge, the location of the overflow weir and the angular rotation speed.

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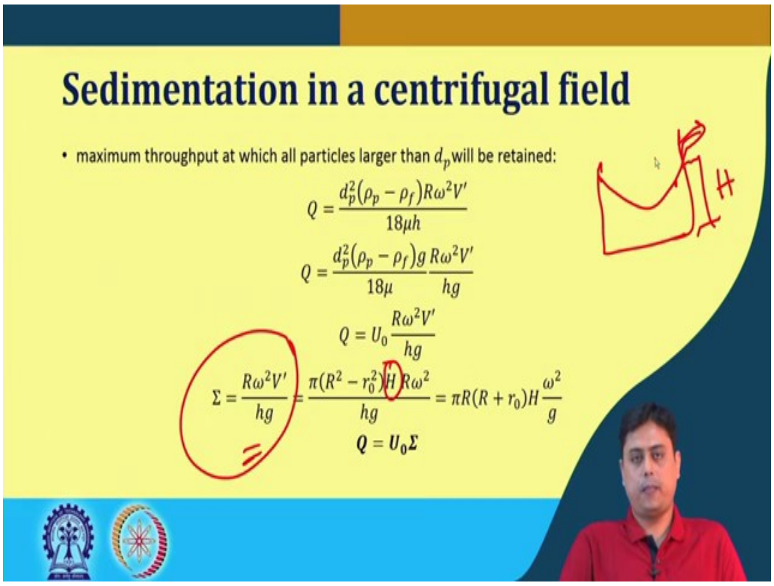

The location of the overflow weir, it indicates this height H; that means, once this fine particle this height H dictates that where the overflow should be going out. So, this is the thing that we can calculate here what is the capacity.

Now, here the assumption was that this H the thickness that it travels the thickness of the liquid is is very small compared to the dimension of the centrifuge or the radius of the centrifuge. But if that is not the case then that integration of this expression from r 0 to capital R results in this generic expression.

$$t_R = \frac{18\mu}{d_p^2(\rho_p - \rho_f)\omega^2}\ln\frac{R}{r_0}$$

Then again, similar to the previous expression, we write Q as V' divided by this t_R.

$$Q = \frac{d_p^2(\rho_p - \rho_f)\omega^2 V'}{18\mu\ln(R/r_0)} = \frac{d_p^2(\rho_p - \rho_f)g}{18\mu}\frac{\omega^2 V'}{g\ln(R/r_0)} = U_0\Sigma$$

We try to separate out again, we write we try to write deliberately in terms of the single particle terminal velocity and in this case the capacity term becomes this expression.

$$\Sigma = \frac{\omega^2 V'}{g\ln(R/r_0)} = \frac{\pi(R^2 - r_i^2)H}{\ln(R/r_0)}\frac{\omega^2}{g}$$

So, the point is that similar to this for several types of centrifuge such expressions can be derived and can be used for certain calculations.

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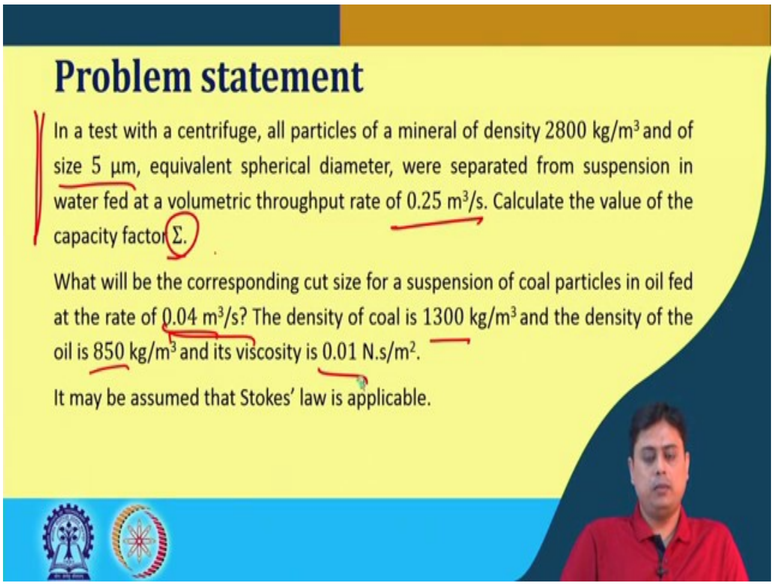

For example, say in a test with a centrifuge all particles of mineral density having 2800 kg/m^3 of size 5 μm that is the equivalent sphere diameter, were separated from suspension of a water at a volumetric throughput rate of 0.25 m^3/s.

So, you have to calculate the capacity factor and the second part is that what would be the corresponding cut size for a suspension of coal particles in oil fed at the rate of 0.05 m^3/s; 0.4 m^3/s. The density of coal is given; the density of oil is given; then the viscosity is also provided. It can be assumed that the Stokes law is applicable.

So, for the first part all the information are given, we have to find out what is the capacity factor. Now, for the same centrifuge, if we now change the feed quality or the feed type from water to oil having coal particles of different densities; then, the question is what would be the cut size or what would be the critical size that it can separate at this given flow rate?

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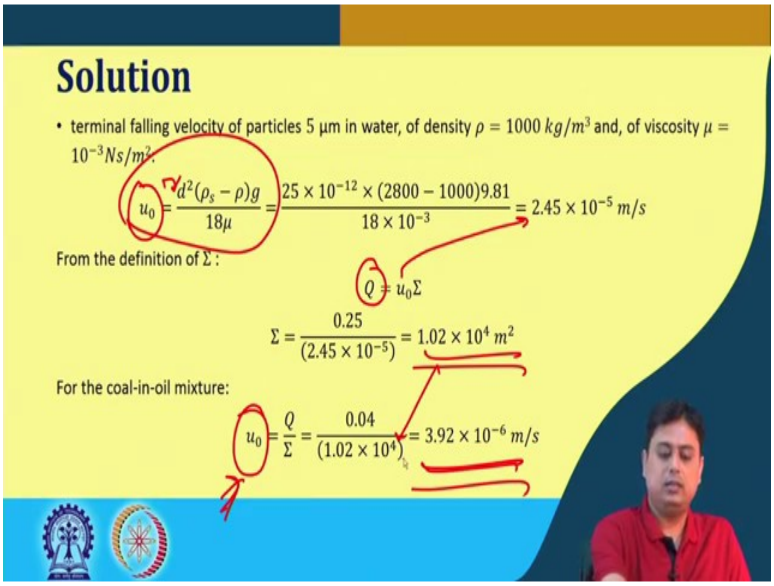

So, we quickly see that the terminal velocity of this 5 μm particle because this is the particle size for the first part that is given. We can easily calculate the terminal velocity

$$u_0 = \frac{d^2(\rho_s - \rho)g}{18\mu} = \frac{25\times10^{-12}\times(2800-1000)9.81}{18\times10^{-3}} = 2.45\times10^{-5}\,m/s$$

So, this expression gives the particle terminal velocity as 2.45×10^{-5} m/s.

Now, by definition this whole throughput is the particle terminal velocity multiplied by the capacity factor.

$$Q = u_0\Sigma$$

$$\Sigma = \frac{0.25}{(2.45\times10^{-5})} = 1.02\times10^4\,m^2$$

So, the capacity is known and the Q is known, we can is sorry we here the Q is known and the terminal velocity is known. Q is given as we have to handle 0.25 m³/s and we have calculated this u_0.

For the coal-in-oil mixture:

$$u_0 = \frac{Q}{\Sigma} = \frac{0.04}{(1.02\times10^4)} = 3.92\times10^{-6}\,m/s$$

So, we can easily find out what is the capacity factor? Now, same centrifuge is being used, but for a different flow rate of a different feed quality. So, in that case the u_0 will be the flow rate that is desired in the second part which is 0.04 m^3/s divided by this capacity factor gives us the required terminal velocity, that this is required or this will happen this is the minimum requirement.

So, this terminal velocity will be of certain cut size particle and from this expression once again so that means, here we know the u_0; we have to find the u_0, the other parameters are given; so, using 3.92×10^{-6} in this expression and ρ_s as 1300; ρ as 850 and μ as 0.01.

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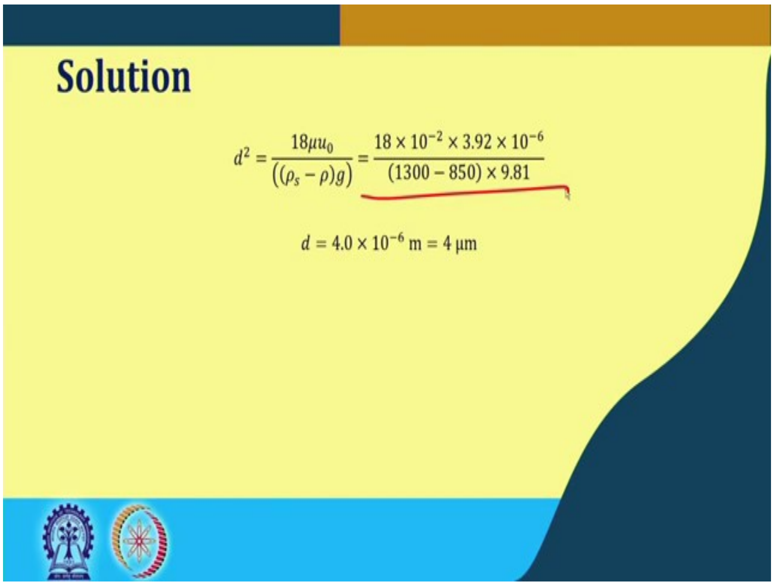

We can have the cut size as 4 μm.

$$d^2 = \frac{18\mu u_0}{((\rho_s - \rho)g)} = \frac{18 \times 10^{-2} \times 3.92 \times 10^{-6}}{(1300 - 850) \times 9.81}$$

$$d = 4.0 \times 10^{-6}\, m = 4\, \mu m$$

So, this would be the cut size if the feed quality changed to oil containing coal particle of known density viscosity and the particle densities. So, I hope this the whole scenario becomes now clearer to you, that we have covered in the centrifugal separation two areas one is (Refer Time: 31:01) stable vortex formation for a stationary equipment. The other is the creation of centrifugal force by rotating the bowl or the vessel itself that is the centrifuge. In both the cases we have seen its operation and its capacity or the efficiency.

With this, I conclude this section here and on the next day, we will be seeing the other section.

Until then, thank you for your attention.