Mechanical Unit Operations
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Lecture 35 - Centrifugal Separations - 2

Welcome to the MOOCs course Mechanical Unit Operations, the title of this lecture is centrifugal operations part 2. In the previous lecture on centrifugal separations we have seen a basic, few basic concepts of centrifugal separations. We have also seen the importance of the neutral zone and then we have also discussed few types of centrifugal separation equipment. This lecture we will be discussing working principles of the centrifugal separation and then the few problems. Then we also see a few details about the cyclone separators as well as the hydrocyclones.

Principles of centrifugal sedimentation: let us assume that you have a solution which is having a few particles, fine particles. And, then the separation of those particles by sedimentation settling is going to take a long time. Under such conditions what you do, you prefer to go for a kind of centrifugal sedimentation. So, for such kind of solutions if you are doing a kind of a separation by centrifugation then let us assume the schematic is like this:

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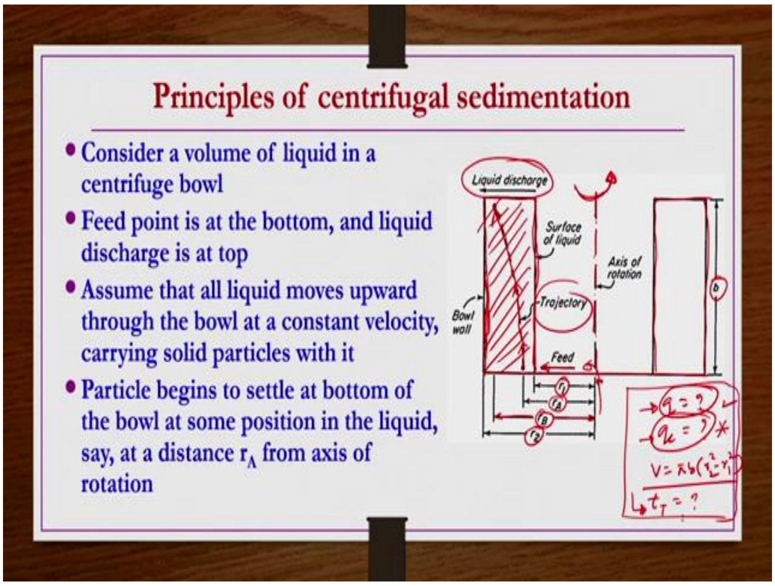

So, we have a kind of a centrifugal bowl of the size like this. The centrifugal ball height is b and then radius is r_2. And this is the central axis or the axis of rotation of this bowl. So, assume this bowl is rotating with the central axis, central axis is axis of rotation. And then feed is entering from the bottom like this and then clear liquid is discharged from the top continuously from here as shown here in the picture. Now, whatever the feed is coming in that is having particles also.

Those particles, the small particles, fine particles we are separating centrifugal force, by applying centrifugal force this bowl is rotating at certain angular velocity. So, now what we are doing, we are taking the feed and then allowing this feed to enter from the bottom. And then we are rotating it so that the clear liquid surface we can see here. So the liquid surface is of radius r_1 so when we centrifuge it, so if you rotate it very high speeds, what happens? The liquid surface will form a kind of almost concentric cylindrical surface like that we have already seen here in a previous lecture.

So, that liquid surface, surface of liquid is at r_1 distance from the axis of rotation or from the central axis. Now, this feed that is entering at the bottom and then assume that the (bottom) the liquid is travelling upward, travelling upward. So, this feed is liquid feed is also having a particle. And then whatever the particles are there, they try to settle towards the wall and then being separated from the liquid, that is what the purpose. Let us assume a particle at this location r_A, r_A is the distance from the axis of rotation. At that particular point particle is there.

And, then this liquid within the centrifugal bowl, what happen? The feed is continuously coming and then the liquid is also continuously going out, it is a kind of continuous process. So, there is a kind of a residence time for the liquid. So, within that residence time of liquid the particle let us assume it reaches some other location, that location is at distance r_B from axis of rotation. So, now this residence time is going to limit the separation. So, within this residence time if $r_B = r_2$ then particle will be hitting the wall of the bowl and being separated.

If $r_B < r_2$ then that will be carried away along with the liquid. So, that separation will not place. So, separation of the particle is now based on the whatever the liquid residence time. So, we have to provide a specific volumetric rate so that to get a required separation. So, how much this volumetric flow rate, that we have to get. So for that we need to know volume of the liquid, so the volume of the liquid is nothing but $\pi b(r_2^2 - r_1^2)$. Because, now this is the liquid, liquid is only in this part.

So, because that is now forming a concentric surface, cylindrical surface within the bowl because of the rotation. So, now the volume of the liquid is nothing but $\pi b(r_2^2 - r_1^2)$. If you know the residence time, let us say t_T then you can know the volumetric flow rate required volumetric flow rate for the separation of the particle. So, for that we have to know, what we do, we do some kind of simplification to get this residence time. And then divide this volume of the liquid by this residence time to get this required flow rate.

And then this required flow rate will also be a function of kind of some kind of a cut diameter. It is not that you provide a kind of flow rate, all the particle will be separated. Because the liquid is having particles of very wide size distribution, not necessary that all the particles that are present in the liquid which we are going to separate by centrifugation, they will not be having a uniform size and shape. So, different shape, different size would be there. So, based on the size distribution we find out the cut diameter of the particles.

Having the diameter smaller than that one, they will be retained in the liquid. The particles having the size larger than that D_{pc} or the cut diameter will be hit to the wall and then they will be separated. So, corresponding to the cut diameter which size particles are the will find a kind of minimum size of the particles that will damn sure be hit in the wall and being separated. So, obviously the particles which are larger than that particular size will also be hitting the wall and then being separated.

So, corresponding to that cut diameter we call it cut diameter, so corresponding to that one also we will find out what is the volumetric flow rate. So, the finally this is what we are going to do, we are going to find out a critical volumetric flow rate kind of thing. So, if you maintain that one, so the particles of certain size or larger will definitely be separated. And then particles of size smaller than that one they will be retained in the liquid. So, that is what we are going to do.

So, that is what we have to do. How much volumetric flow rate we have to provide in a given in a centrifugal bowl so that particle of specified size can be removed and then particles smaller than that specified size will be carried away in the liquid so that we can get the performance. So, this equation will also be applicable in other way also, let us say you have a kind of a liquid which is having particle size let us say 0.1 to 10 micron size, so then if you want like all the particles having size greater than 1 or greater than 1 micron should be separated.

So, then the D_{pc} the cut diameter you can take 1 and then correspondingly you can back calculate what should be the volumetric flow rate that you should provide. Either way you can find out. If you have the fixed volumetric flow rate then what should be the cut diameter above which all the particle will be separated, that way also you can do the calculations. That way also you can use the same equations. So, now what are we going to do here?

We are deriving these equations required equations here and then doing some example problems. Consider a volume of liquid in centrifugal bowl, feed is at the bottom and then liquid discharges is at the top. Assume that all liquid moves upward through the bowl at a constant velocity carrying solid particles with it. But, the trajectory of the particle would be like this because of the centrifugal force, because of the centrifugal force the trajectory of the particle will be like this. Because this trajectory we have already derived, we have derived it as a kind of a paraboloid. So, this kind of the trajectory particle will have.

Particle begins to settle at bottom of the bowl at some position in the liquid say at a distance r_A from axis of rotation.

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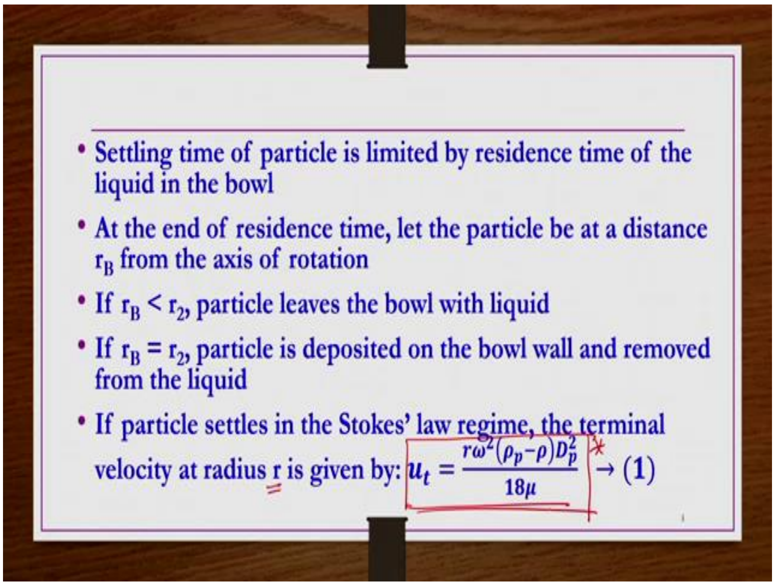

Settling time of particle is limited by residence time of the liquid in the bowl. At the end of the residence time, let the particle be at a distance r_B from the axis of rotation. If $r_B < r_2$ then particle leaves the bowl with liquid. Separation will not take place, if $r_B = r_2$ then particle is deposited on the bowl wall and removed from the liquid. So, this r_A and r_B we are taking to different locations within the column of the liquid. That is from r_1 to r_2 distance between r_1 to r_2 distance we have taken this so arbitrary position so that we can do calculations.

But we do not know what are these r_A, r_B values, indeed we do not want. We wanted to makes sure the particles are within this range between r_1 to r_2 distance only so that we can do the calculation and then we can find out the required volumetric flow rate.

Let us assume particles settle in the Stokes' law regime, then the terminal velocity at radius r is nothing but $u_t = \frac{r\omega^2 \Delta\rho D_p^2}{18\mu}$. This we have already derived in the flow past particle system kind of thing, those things when we have done, we have done settling velocity of particles under the gravity as well as under the centrifugal field, those things we have done. So, under Stokes regime if the particles are settling due to the centrifugal field then the velocity is given by this expression.

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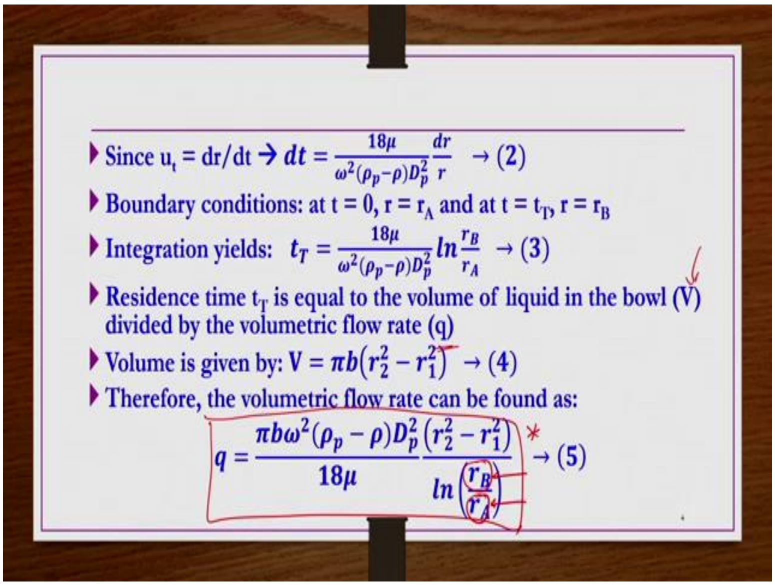

Now, u_t is nothing but $\frac{dr}{dt}$, r is the position where the settling velocity we are calculating. So, then from here we can write $dt = \frac{18\mu}{r\omega^2\rho D_p^2} \times \frac{dr}{r}$. Why are we writing? Because we wanted to find out the residence time of the liquid, so the time we have to find out here. So, now the important thing is the boundary condition, what are the boundary conditions? So, then at entry point particles we have seen, we have assumed like that they are at r_A positions.

So, at t is equals to 0 particle is at r_A position, so at t is equals to 0 r is equals to nothing but r_A and then by the end of the residence time of the liquid the particle has to reach r_B that is the condition we have taken. So, at $t = t_T$; $r = r_B$, t_T is nothing but residence time of the liquid, so this is what we have. Now, you integrate equation number 2 and then substitute this boundary condition. So, integration of dt is nothing but t, so applying this boundary conditions 0 to t_T we have t_T and then right hand side $\frac{dr}{r}$ is nothing but $\ln r$.

So, applying the boundary conditions r_A and r_B for t=0 and t=t_T we have $\frac{\ln r_B}{\ln r_A}$. Rest all other terms are independent of t and then r. Residence time t_T is equal to the volume of liquid in the bowl divided by the volumetric flow rate. So, volumetric flow rate we do not know, we have to find out. So, if we find out volume that we already have seen V is nothing but $\pi b(r_2^2 - r_1^2)$. So, that V if you divide by this residence time then we get the volumetric flow rate, then we get the required volumetric flow rate.

So, volume is given by $\pi b(r_2^2 - r_1^2)$. Therefore volumetric flow rate can be found as $\frac{V}{t_T}$ when do this $\frac{V}{t_T}$ and then simplify, rearrange this equation like this then you get volumetric flow rate. Then you get volumetric flow rate like this, so $q = \frac{\pi b \omega^2(\rho_p - \rho)D_p^2(r_2^2 - r_1^2)}{18\mu \frac{\ln r_B}{\ln r_A}}$. So, now this equation though we have a kind of expression for the volumetric flow rate, it is not useful because this r_B and then r_A are the kind of arbitrary locations, r_A is towards the liquid surface and then r_B is towards the centrifugal bowl wall. So, this but they are not equal to r_1 or r_2 respectively. So, then this equation can be useful only when we know what is r_A and what is r_B. So, for that we do some kind of analysis now.

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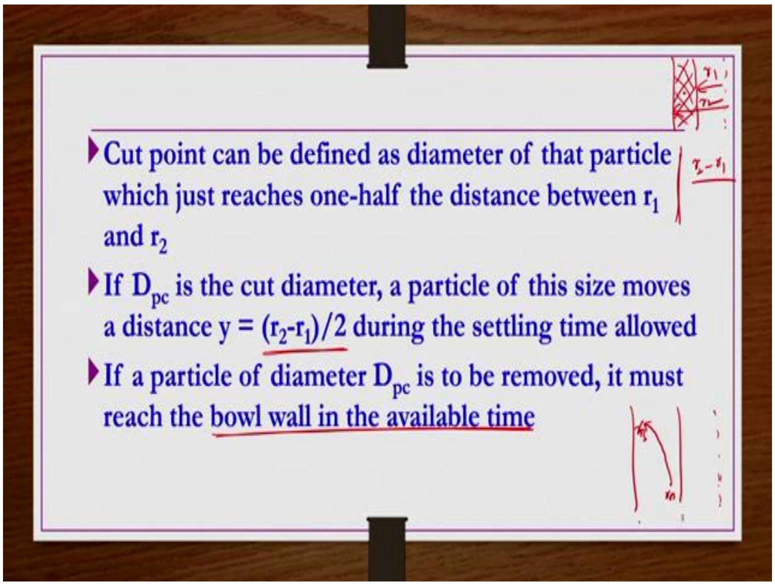

So, let us define cut point as a diameter of that particle which just reaches the one-half the distance between r_1 and r_2. So, we define a kind of cut diameter of the particle so that whatever the particles larger than that cut diameter can be hitting the wall and then being separated. Less than that size may be going out along with the liquid without being separated. So, that cut diameter let us assume that is that particle whichever cut diameter particle let us say D_{pc} we taken the cut diameter of that particles which is being hitting the walls.

So, that reaches one-half the distance between r_1 and r_2 So whatever the r_1, r_2 are there, r_1 is nothing but the distance from the axis of rotation to liquid surface and then r_2 is nothing but the bowl radius. So, that is the r_1, r_2 distance whatever it is covering that is $r_2 - r_1$ is nothing but the thickness of the liquid surface. Half of that distance if the particle is reaching within the residence time of this liquid then that particle is going to be separated.

So, if D_{pc} is the cut diameter, particle of this size moves a distance $\frac{r_2-r_1}{2}$ during the settling time allowed as per this definition. So, distance between r_1 and r_2 is nothing but $r_2 - r_1$ according to schematic. So, schematic this is the center of axis, this is the liquid surface so this is r_1 and then this is bowl radius r_2. So, now D_{pc} is reaching half the distance of this whatever the r_2 minus, distance between r_2 and r_1. Distance between r_2 and r_1 is nothing but this liquid surface distance that is nothing but $r_2 - r_1$.

We are taking this particle D_{pc} based on the this distance that half of this distance that particle is reaching within the liquid residence time. So, that is $\frac{r_2-r_1}{2}$ distance that particle is reaching within the residence time of liquid, that is if D_{pc} is the cut diameter a particle of this size moves a distance $\frac{r_2-r_1}{2}$ during the settling time allowed. If a particle of diameter D_{pc} is to be removed, it must reach the bowl wall in the available time. Within the available time, what is the available time? It is nothing but the liquid residence time.

So, within that time this particle has to reach the wall of the bowl. That is it has to reach the r_2 distance, that means r_B has to be equals to r_2. r_B is nothing but that is the one by the, as per the analysis r_B is the distance like you now we have this liquid surface I am drawing again here. So, this is r_A position somewhere and then this is r_B position. The particle is moving in this direction like this, so within the residence time this r_B like particle has to hit the wall, so that means r_B has to become r_2, then only the particle separation will take place.

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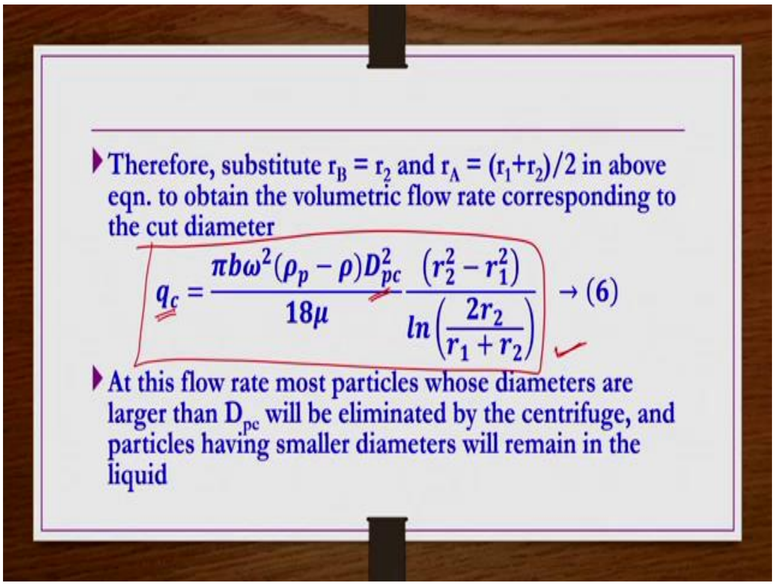

So, therefore r_B has to be r_2 and then r_A has to be nothing but $\frac{r_2+r_1}{2}$ because we taken half the distance. r_A should be $\frac{r_2+r_1}{2}$ in above equation so that whatever the q expression that we have developed in that q expression wherever r_B is there you replace r_B by r_2 and then wherever r_A is there, that r_A you replace by $\frac{r_2+r_1}{2}$. Then we have the volumetric flow rate of the expression like this. And, then this volumetric flow rate we call it q_c because this volumetric flow rate corresponding to cut diameter.

Since, it is corresponding to the cut diameter the volumetric flow rate has to be q_c and then d has to be replaced by D_{pc}. Now, this one actually $r_B \ln\frac{r_B}{r_A}$, so r_B is r_2 and then r_A is nothing but $\frac{r_2+r_1}{2}$. So then $ln\left(\frac{2r_2}{r_2+r_1}\right)$. Now, in this equation everything is known for us, liquid interface in general is known, we can calculate even if it is not known. Bowl radius is known, bowl height is known, rotational speed is known, densities of a particle and then liquid we know, particle cut diameter we are deciding.

Viscosity and everything is known, so then you can know what should be the volumetric flow rate that you should provide so that this particle having size D_{pc} or greater should be hitting the wall and being separated. At this flow rate most particles whose diameters are larger than D_{pc} will be eliminated by the centrifugal force. Because on those particle the size is slightly bigger than this cut of diameter, so there they will be having or they will be moving more towards the wall.

So, there is a possibility on the chances that these particles whose size is more than D_{pc} will be hitting the wall is more and then being separated by settling at the bottom. So, whereas the particles having smaller than D_{pc} diameter will remain in the liquid without being separated. So, now let us say as I mentioned already one example, if you have 0.1 to 10 microns size particles in a liquid solution and then you have a fixed dimension bowl centrifugal bowl. And, then if you wanted separate the particles whose size is 1 micron or more, what should be the volumetric flow rate that you should provide to the inlet feed, you can calculate from here.

So, here in D_{pc} you substitute 1 micron 1 x 10^{-6} m. And, then correspondingly the density viscosity of all these things you substitute and then calculate the volumetric flow rate. So, whatever this q_c that you get if you provide that q_c value for the feed flow rate then all the particles which are having 1 micron or more size will be separated. But, the particle size having less than 1 micron will be remaining with the liquid as in the overflow.

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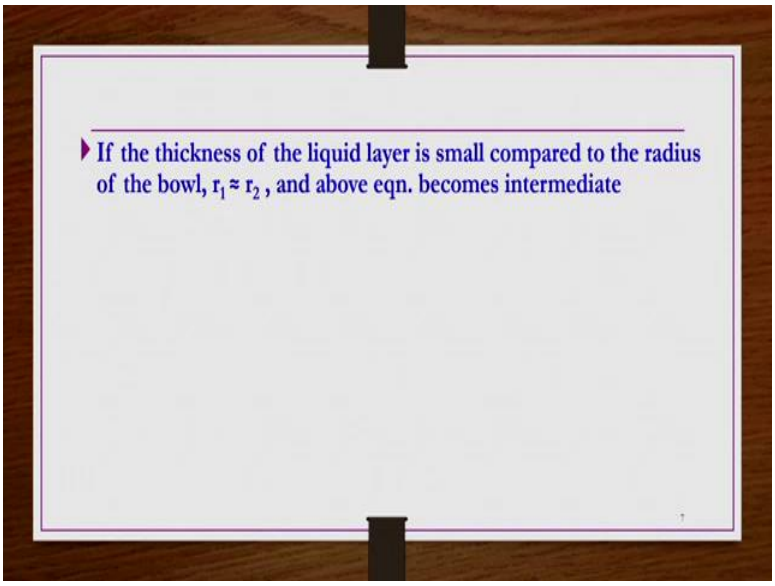

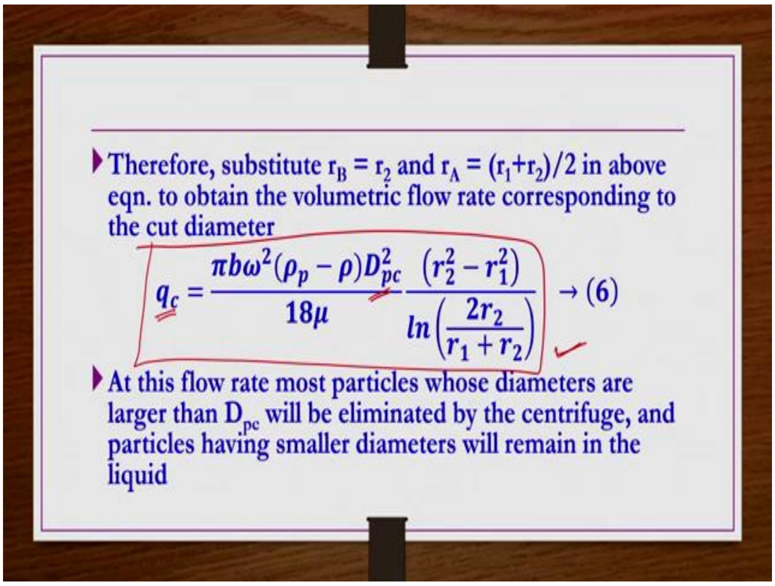

If the thickness of the liquid layer is small compared to the radius of the bowl, $r_1 = r_2$ approximately equals to r_2. Because, in general industrial centrifuges they rotate at very high rotational speed like 15,000-25,000 rpm et cetera. Under such kind of high velocities the liquid, more and more liquid is being pushed towards the wall. And, then this liquid interphase is almost close to the wall of the bowl. So, that is r_1 is approximately r_2, so under such conditions the same equation whatever q_c expression that we have derived we can, under those conditions what will happen?

If you substitute here, $r_1 = r_2$ approximately what will happen? Like let us say, in the case where we have a kind of r_1 is close to r_2 that is possible in many industrial applications. So, if you substitute here so this is going to be 0. $(r_2^2 - r_1^2)$ is going to be very very small because r_1 is close to the r_2 value anyway. Rate, it is going to be very small and then you are going to get unreliable values here or very small flow rate you may get it. So, how to overcome such situation and then develop appropriate volumetric flow rate equation, so that we are going to see now.

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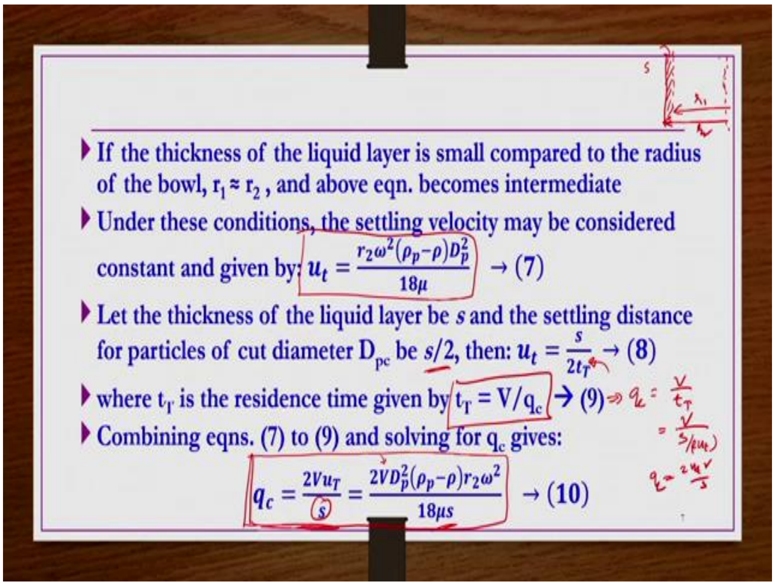

So, under such conditions if r_1 is approximately close to r_2 so then whatever the settling velocity of the particle is there within the centrifugal field, that can be written as $u_t = \frac{r_2\omega^2\rho D_p^2}{18\mu}$. Earlier, we have written r here, r we have written which is nothing but, in between some location between r_2 and r_1 within the liquid layer, that is within the liquid layer. Some location that we have taken and written previous equation and derived it. Now, in the case in the present case, the second case r_1 is approximately r_2.

So, then there is no point taking position in between these two because they are close to each other, so directly we can take r_2. Why r_2, why not r_1? Because want the particles to be separated by being hitting on the wall of the bowl. Because of that one that size r_2 we are taking it rather than r_1. So, u_t for such conditions where r_1 is approximately equals to r_2 we can write it as $\frac{r_2\omega^2\rho D_p^2}{18\mu}$. And, let us say thickness of the liquid layer, now this thickness of the liquid layer is very thin. If you draw here, now here we are very having very thin layer like this.

So, if this is a kind of axis of rotation or central axis, so this is your r1 and then this is your r_2, compared to r_2, r_1 is not very small, it is very close to each other. So, under such condition the thickness of this liquid layer is also very small, so rather writing $r_2 - r_1$ you just designate some values s. So, now if the liquid layer thickness is s then the settling distance for the particles of cut diameter D_{pc} should be nothing but $\frac{s}{2}$. Simply, as in the previous case we have done $\frac{r_2-r_1}{2}$.

Now, r_2, r_1 close to each other, so that $r_2 - r_1$whatever the thin layer of liquid is there that we are calling s. So, $\frac{s}{2}$ we are writing, then settling velocity we can rewrite as a kind of that distance $\frac{s}{2}$ divided by the residence time of the liquid, divide that by residence time of the liquid, that $\frac{s}{2}$ divided by t_T that is $\frac{s}{2t_T}$ t_T is nothing but residence time of the liquid within the centrifugal bowl.

Now, form here you know the velocity, so volume is also known, so then we can calculate volumetric flow rate. So, residence time is nothing but volume of the liquid divided by the volumetric flow rate. Or volumetric flow rate is nothing but volume of the liquid divided by t_T. So, now volumetric flow rate from here what we can write, $q_c = \frac{V}{t_T}$ and then $\frac{V}{t_T}$

from this equation number 8 what we can write, we can write it as t_T is equals to nothing but $\frac{s}{2u_t}$. So, that means $\frac{2u_tV}{s}$ we can write it as a kind of volumetric flow rate. When you do this one, so $q_c = \frac{2u_tV}{s}$.

So, V is the volume of the liquid that we are having inside the bowl from which particles are being separated. So, that volume of the liquid V we know, this u_t just now we have written it as $\frac{r_2\omega^2\rho D_p^2}{18\mu s}$, , so this s is there, so this is the volumetric flow rate. If you know the thickness of the liquid layer then you can know volumetric flow rate from this equation as well. So, but this equation is more suitable when you have a kind of very thin liquid layer where r_1 is almost close to r_2.

Now, sigma value scale up, the sigma value is in general used to find out the scale up for the industrial applications. What does it physically indicate? Let us say physical whatever the sigma value that we are going to do, if you get some sigma value that indicates the area of a gravitational tank that should be provided to do the same duty that this centrifugal bowl is doing. So, whatever the separation that you are doing some D_{pc} particles particle size greater than D_{pc} are being all separated by providing some kind of volumetric flow rate, that you are doing in a bowl.

Centrifugal bowl having radius less than 1 meter or something like that, that within small bowl you are doing separation. But, when you do this we are going to do some problems also, we will find out sigma value. The sigma value is going to be order of 10^3 or 10^4 sometimes 10^5 m^2. So, whatever the separation that you are doing in the small centrifugal bowl if you wanted to do the same separation in a gravity sedimentation, you have to have a gravity sedimentation tank of area equal to Σ. Such large tank you should use.

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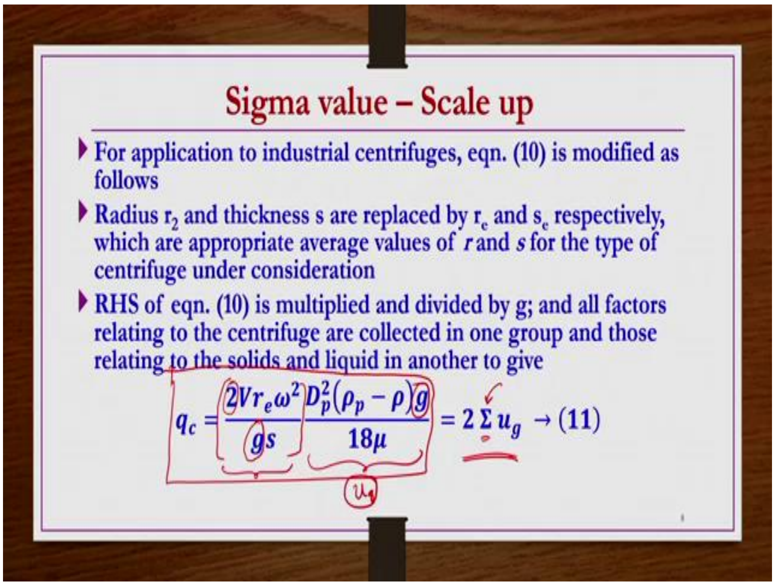

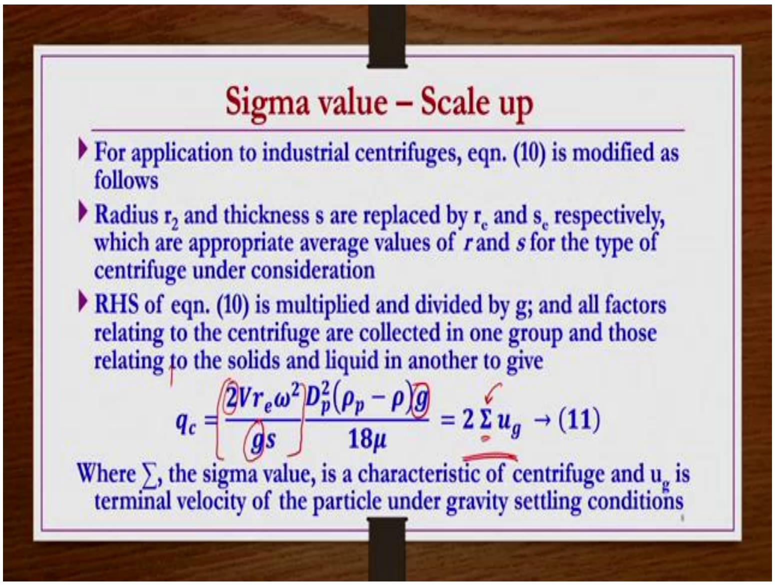

Anyway, we see the problem but let us go into the evaluation of the sigma value. For application to industrial centrifuges equation number 10 whatever we just derived for case when r_1 is closely equals to r_2 is modified as this. So, radius r_2 and thickness s are being replaced by r_e and r_s respectively. Which are appropriate average values of r and s for the type of centrifuge under consideration. So, that is one we are doing and then what we are doing, the equation that equation number 10 just derived for q_c.

That is $\frac{2u_tV}{s}$. In that equation we are dividing and multiplying that equation in the right hand side by the g. And, then we will have a kind of terms where all the terms related to the centrifugal field are kept as a kind of one group and then remaining terms related to the gravity sedimentation we kept as , we are going to keep as a kind of other group. So, RHS of equation 10 is multiplied and divided by g and all factors relating to the centrifuge are collected in one group and those relating to the solids and liquids in other group.

So, this is the equation actually, this is the equation number 10 that we have derived just now. This equation what we are doing, we are just simply dividing and multiplying by g in the RHS. And then whatever the particle solid liquid properties are there, viscosity, particle density and then liquid density particle size, these we are writing as a one group. Then we can see this, this is having a kind of $\frac{g\rho D_p^2}{18\mu}$ form. And then remaining terms related to the centrifuge that is $\omega^2 r_{eff}$, s_{eff} V etc, these things, V is nothing but the volume of the liquid. So, this remaining thing we are writing as other group. So, now here what we can see, this $\frac{g\rho D_{pc}^2}{18\mu}$ is what?

Is nothing but the terminal velocity of the particles settling in gravity field if the settling velocity is under Stokes' regime. If the particles settling in Stokes' regime due to the gravity field then what is the settling velocity u_t expression that we have derived previously? We have derived it as $\frac{g\rho D_p^2}{18\mu}$.

So, that let us indicate it as u_g and then here in this equation and the other terms that is related to the centrifuge terms. This 2 you keep it as it is and then remaining terms $\frac{V r_e \omega^2}{gs}$ you write it as Σ, that is nothing but sigma actually, that is nothing but the sigma. So, this q_c we can write it as $2\Sigma u_g$, it is not a kind of summation, this Σ is not a kind of summation, it is a kind of symbol that has been used for this scale of purpose.

So, the equation number 10 we can write it as $2\Sigma u_g$ simply dividing and multiplying the right hand side of equation number 10 by gravity, acceleration due to gravity g and then rearranging it, so $q_c = 2\Sigma u_g$. Whereas, the Σ value is a characteristic of centrifuge and u_g is the terminal velocity of the particle under gravity settling conditions.

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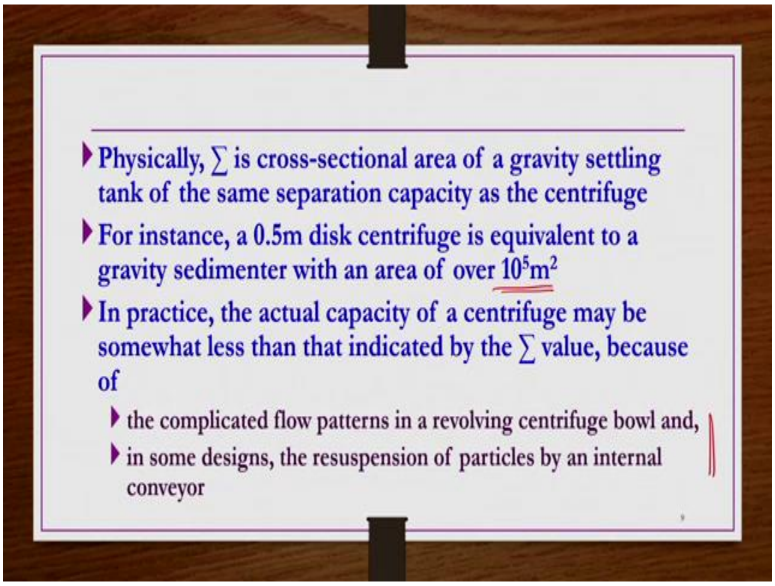

So, as I mentioned physically Σ is cross-sectional area of a gravity settling tank of the same separation capacity as the centrifuge. As I mentioned physically what does the sigma value indicate? The sigma value indicate the cross-sectional area of a gravity settling tank of the same separation capacity as the centrifuge. Let us say take the same example, you have a liquid sample in which we have the particles like 0.1 to 10 microns let us assume. And then you wanted separate all the particles having size greater than D_{pc} >= 1 micron.

Then if you do the separation in centrifugal bowl, you can take a disk centrifuge of radius something like 0.5 m diameter like that and then get it done with by calculating that volumetric flow rate whatever the volumetric flow rate you have to provide that you can calculate. But that separation if you wanted to do in gravity sedimentation tank, then how much cross-sectional area should you provide for that sedimentation tank in which the particles are settling by gravity?

That information, that cross-sectional area of the sedimentation tank is nothing but the sigma value which is going to be very large in general, order of 10^3 to 10^5. We are going to see a few problems as well. So, for instance a 0.5 m disk centrifuge is equivalent to a gravity sedimenter with an area over 10^5 m^2, you can see how much is the difference. Now, where is the bowl of 0.5 radius centrifugal bowl, even that is very small one.

And, then 10^5 m^2 gravity sedimentation tank how big it is? So, that is the other advantage of using this centrifugal separation processes. In practice, the actual capacity of centrifuge may be somewhat less than that indicated by the sigma value. Because, of the complicated flow patterns in revolving centrifugal bowl and in some designs the resuspension of particles by an internal conveyor may also take place. But these discrepancies are not going to be too large from the calculated values anyway.

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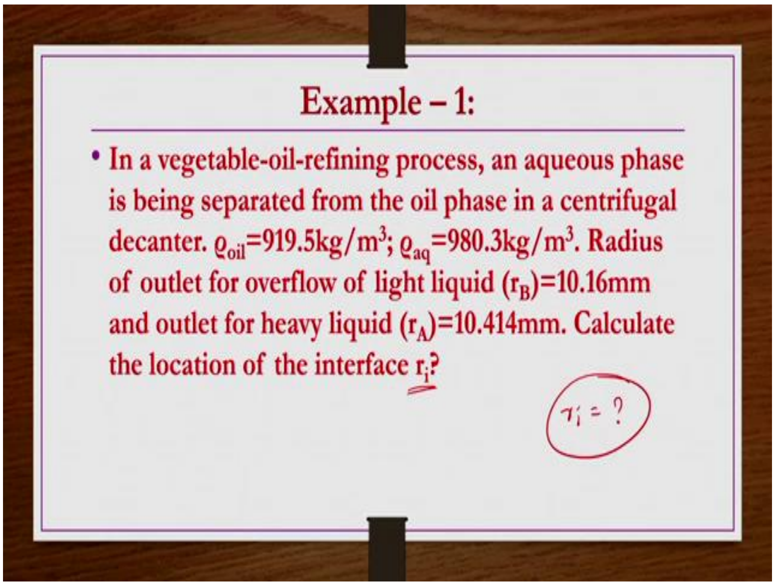

So, now we see some example. The first example is about finding out the neutral zone that we have derived in the previous lecture. So, in a vegetable oil refining process, an aqueous phase is being separated from the oil phase in a centrifugal decanter. Oil density, aqueous phase density are given, radius for outlet for overflow of liquid that is r_B is given. Similarly, radius of outlet for heavy liquid that is r_A is given. So, calculate location of the interface r_i or the size of the neutral zone, r_i that we have to find out. That is the question, this question the derivation for r_i what we have done, we have done in a previous lecture. There we have not taken any problem, so we are taking here.

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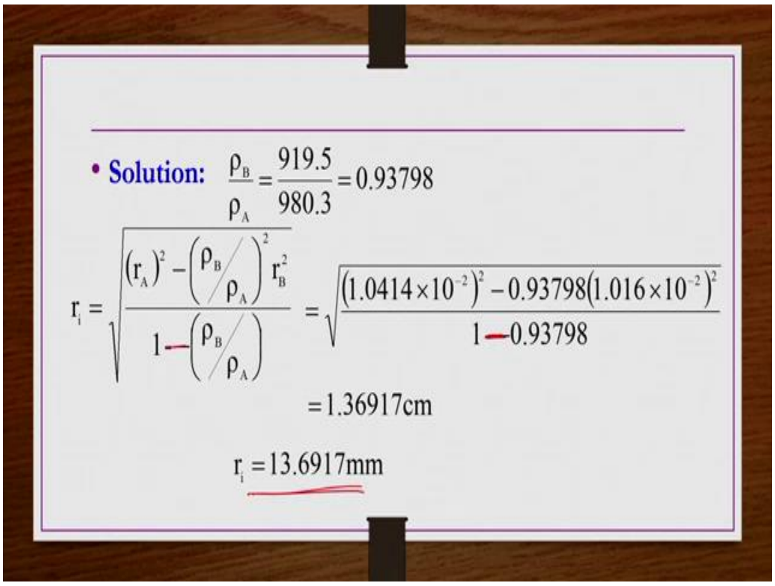

So, here we need r_i is a function of $\left(\frac{\rho_B}{\rho_A}\right)$, so we know that r_i is function of $\left(\frac{\rho_B}{\rho_A}\right)$. So, $\left(\frac{\rho_B}{\rho_A}\right)$ if we do it comes out 0.93798, then $r_i = \sqrt{\frac{(r_A)^2 - \left(\frac{\rho_B}{\rho_A}\right)^2 (r_B)^2}{1-\left(\frac{\rho_B}{\rho_A}\right)}}$. So, then we get this value, substitute all this value ρ_A ρ_B values are given, r_A r_B values are given, so everything is known, substitute here simply and then simplify. Then r_i location is going to be 1.36917 cm that is approximately 13.7 mm.

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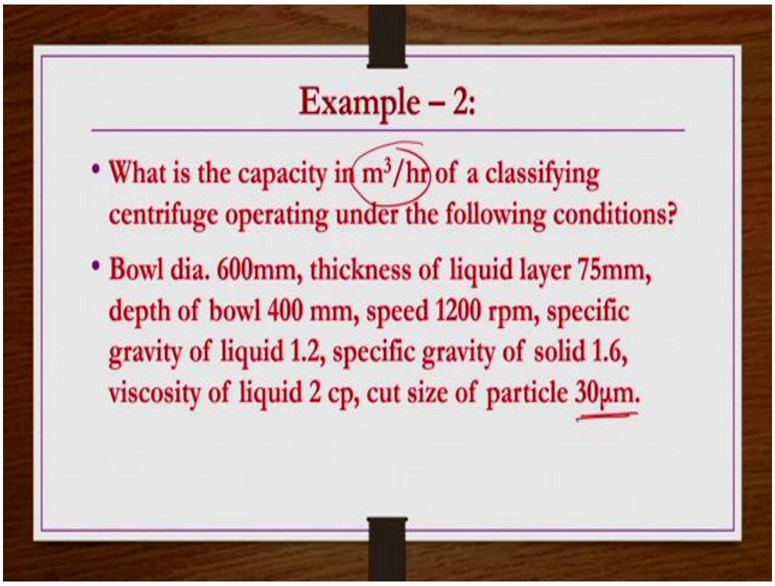

Now, we go to the example number 2. What is the capacity in m^3/h of a classifying centrifuge operating under the following conditions? Bowl diameter is given, thickness of liquid layer is given, depth is given, speed is given, specific gravity of liquid and solids are given, viscosity of liquid is given, cut size of the particle D_{pc} is given 30 microns. Then you have to calculate the volumetric flow rate in meter cube per hour. Volumetric flow rate has to be reported in meter cube hour. We get from solution m^3/s, in m^3/s we get the answer but that has to be converted in m^3/h.

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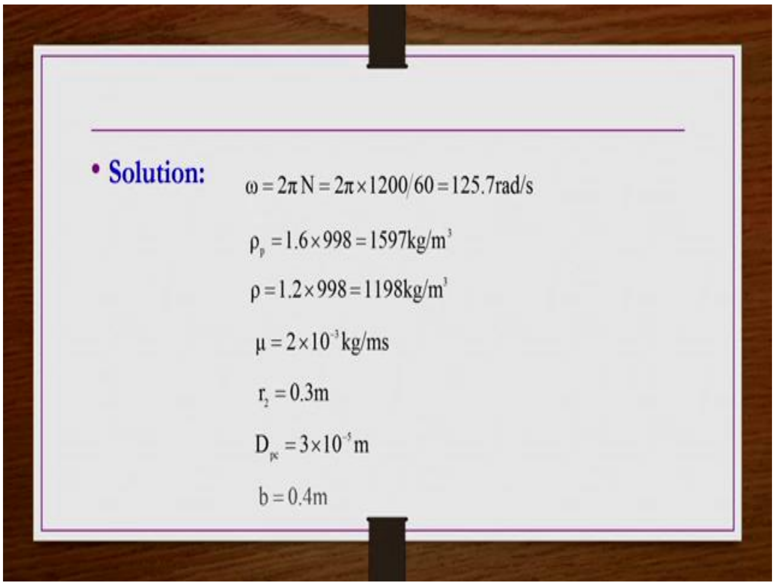

So, this rotational speed is given so ω you can find it out by using $2\pi N$, so that is 125.7 rps. So, ρ_P is given, ρ is given and specific gravities are given and then we are multiplying by 998. So, then we get the kg/m^3 units density for ρ_P and ρ. μ is given, r_2 is given, D_{pc} is given as 30 microns, we can write it as 30 x 10^{-6} m or 3 x 10^{-5} m, b is given as 0.4 m.

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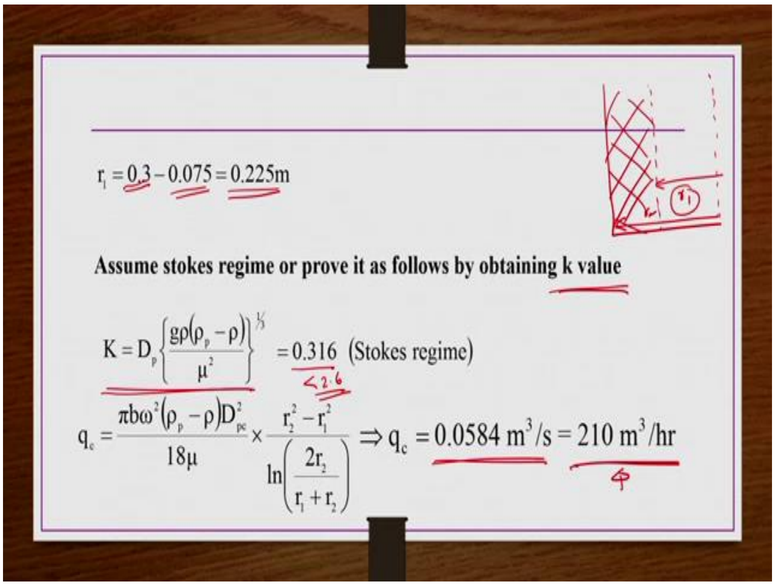

So, r_1 is required, r_1 is nothing but the liquid layer thickness is given as 75 mm kind of thing, so then r_2 is given. So, let us say this is the central axis of rotation. And then liquid interface is this one r_1, this is r_1 is given and this is r_2 is given. This is r_1, this r_2, r_2 is given but r_1 is not given but, this thickness of this liquid layer is given. So, from r_2 if you subtract this thickness of the liquid layer you will get r_1. Because, in q_c calculations we need r_1 so r_1 is equals to 0.3 minus the liquid layer thickness 0.75 is equals to 0.225 m, in m I have written here.

So, r_2 is given, liquid layer thickness is given. So, from r_2 if you subtract the liquid layer thickness then we get r_1, then we get r_1 as 0.225 m. Assume Stokes regime or prove it as following as follows by obtaining k value. Actually, whatever the derivation that we have done till now, the working principles we developed they are valid only for Stokes' flow regime. We have taken u_t as $\frac{r\omega^2\rho D_p^2}{18\mu}$ that is valued if the particles are settling under the Stoke' regime.

So, but the present flow conditions or within the Stokes' regime or not that we have to make sure, then only corresponding q_c equation whatever we derived we can use it. How to find out whether the particle is settling in Stokes' regime or not? We have already seen in one of the previous lecture finding out the k value. If k value is less than 2.6 then the particle is settling in the Stokes' flow regime. So, let us say this k value calculation this k is nothing but $D_p\left\{\frac{g\rho\Delta\rho}{\mu^2}\right\}^{1/3}$, this we have already seen.

So, D_p is given 30 microns, ρ, ρ_P are known, μ are known, μ is also known, so then when you substitute you will get 0.316 so which is less than 2.6, so then it is under Stokes' flow regime. So, we can happily use this qc expression without any problem. So, then q_c we have developed it as a $\frac{\pi b\omega^2(\rho_p-\rho)D_{pc}^2}{18\mu}\times\frac{r_2^2-r_1^2}{\ln\left(\frac{2r_2}{r_2+r_1}\right)}$ So, in this equation now everything is known, so simply substitute and then calculate the simplifications. If you do, you will get 0.0584 m^3 /s.

If you convert it into the meter cube per hour it is approximately 210 m^3 /h of flow rate you have to provide so that the particles of size 30 microns or larger can be separated from the feed liquid which is having wide particle size distribution. So, whatever the particles having the size less than 30 microns would be retaining in the liquid only and going out along with the overflow liquid if you provide this flow rate. Whereas the all particles having size greater than 30 microns will be reaching the bowl wall within the resistance time of liquid and then being separated.

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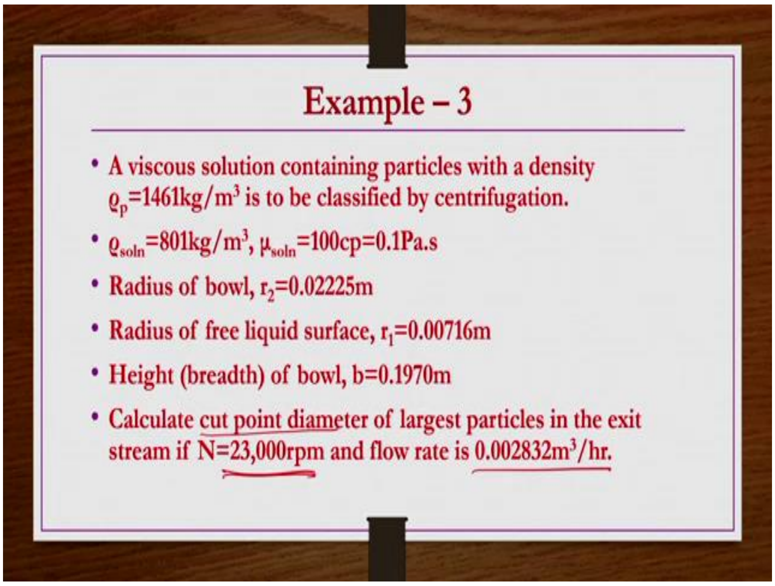

Now, we take another example. A viscous solution containing particles with a densityρ_p is equals to 1461 kg/m^3 is to be classified by a centrifugal bowl. So, then solution viscosity density are given, radius of bowl is given, radius of free liquid surface r_1 is directly given in this problem, bowl height b is also given. So, calculate the cut diameter if the flow rate is 0.002832 m^3/h. And, then rotational speed is 23000 rpm. So, it is the other side of the previous problem, previous problem D_{pc} is given, flow rate we have to calculate. Now D_{pc} we have to calculate and then flow rate is given.

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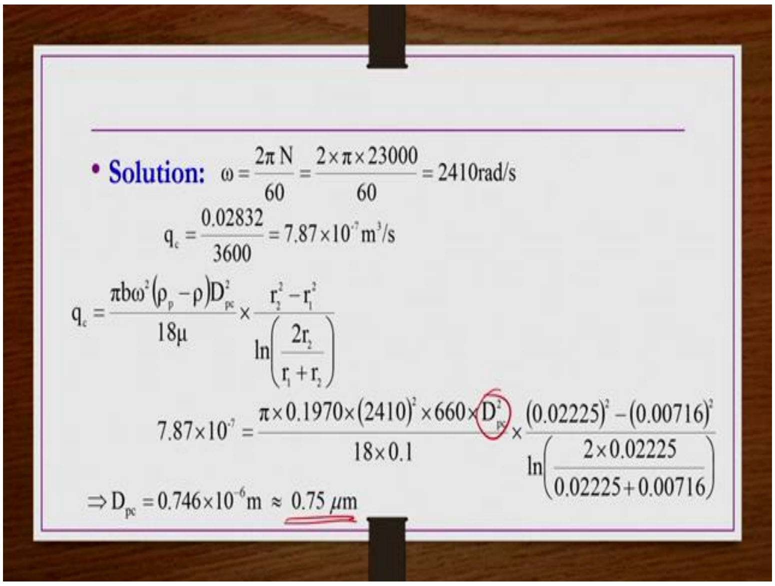

So, omega $\frac{2\pi N}{60}$ comes out to be 2410 rps, $q_c$is given in m^3/h so that we have to convert into the m^3/s. Then it comes out to be 7.87 x 10^{-7} m^3/s. So, then q_c is nothing but $\frac{\pi b\omega^2(\rho_p-\rho)D_p^2(r_2^2-r_1^2)}{18\mu\ln\left(\frac{2r_2}{r_1+r_2}\right)}$ This equation we have derived, so in this equation everything is known except the D_{pc}.

Except the pc everything is known in this equation. So, substitute all these values and then find out this D_{pc} so then D_{pc} you are going to find it out as a 0.75 microns. So, that means if you provide 0.2832 m^3/h of a feed flow rate then particles of size greater than or equals to 0.75 microns will be separated. Will be separated for this flow conditions and then for these fluid properties whatever given this problem.

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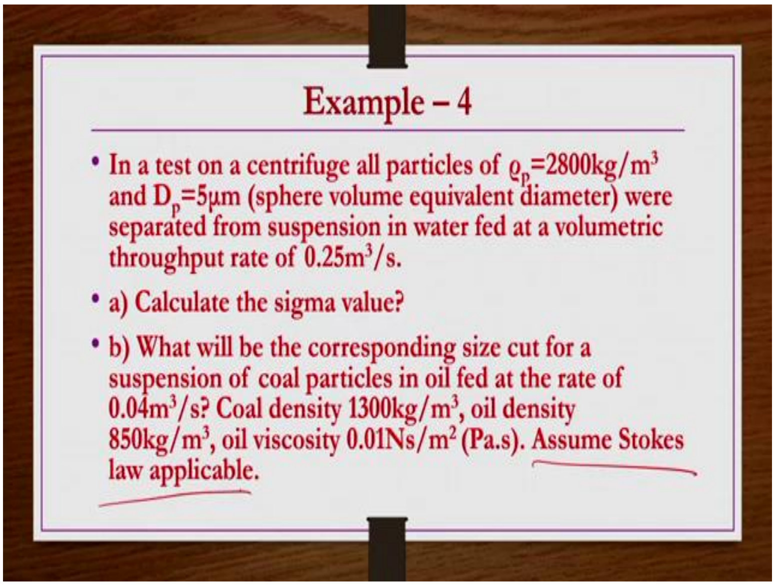

Another example problem: In a test on centrifuge all particles of ρ_p 2800 kg/m^3 and D_p 5 microns sphere volume equivalent diameter is given. Were separated from suspension in water feed at volumetric throughput of 0.25 m^3/s, q is given, D_p is given, ρ_p is given here. Calculate the Σ value. Σ value we have to find out, what will be the corresponding size cut for a suspension of coal particles in oil fed at the rate of 0.04 m^3/s when this sigma value is there?

Correspondingly, the same thing is used like for this suspension of coal particles are there, so then what should be the corresponding size cut? That we have to find and then it is given that assume Stokes' law applicable, so we do not need to find out k value.

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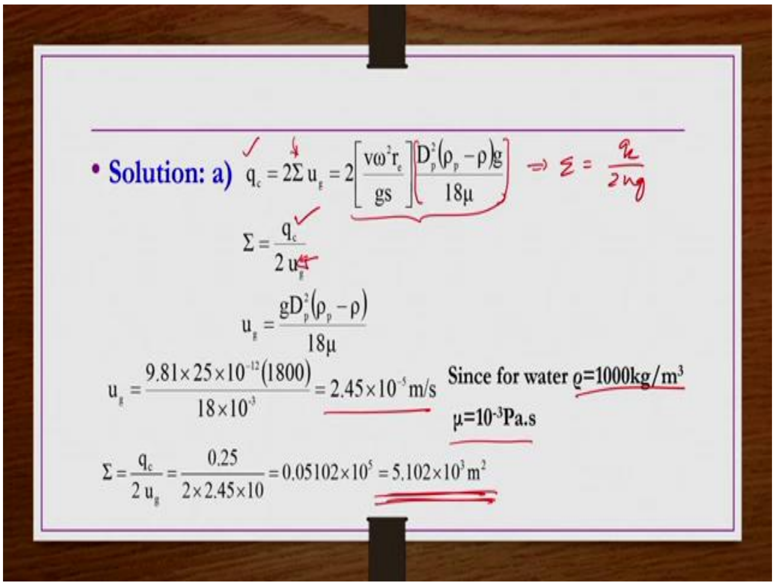

So, first part of the solution is finding out the sigma value that is q_c is equals $2\Sigma u_g$ that we already know. And then if you expand this equation $q_c = 2\Sigma u_g = 2\left[\frac{v\omega^2 r_e}{gs}\right]\left[\frac{D_p^2(\rho_p - \rho)g}{18\mu}\right]$. So, here we have to find out the Σ value, q is given. If you wanted to use this part of the equation you need to know ω, s, v and all these things which are not given. So, then what you can do? You can use this equation that sigma is equals to $\Sigma = \frac{q_c}{2u_g}$.

Because, u_g is nothing but this part that you can calculate because D_p is given, ρ_p ρ μ are given. So, $\Sigma = \frac{q_c}{2u_g}$ and then solution is like it mention like the viscosity and then the density of the solution are same as of that of water. So, u_g is nothing but $\frac{g\rho D_p^2}{18\mu}$ And for water ρ is 1000 kg/m^3, μ is 10^{-3} Pa-s at a given conditions. So, u_g you can find it out as a 2.45 x 10^{-5} m/s.

So, now q_c is known, u_g also you calculated, you submit here, so then sigma value you can get it as 5.102 x 10^{-3} m^2. So, what does it mean? Whatever the separation that you are doing by using this centrifugal bowl if you wanted to do the same separation by gravity sedimentation tank, then you have to have such big gravitational sedimentation tank whose cross-sectional area is 5.102 x 10^{-3} m^2, such big sedimentation tank one should provide.

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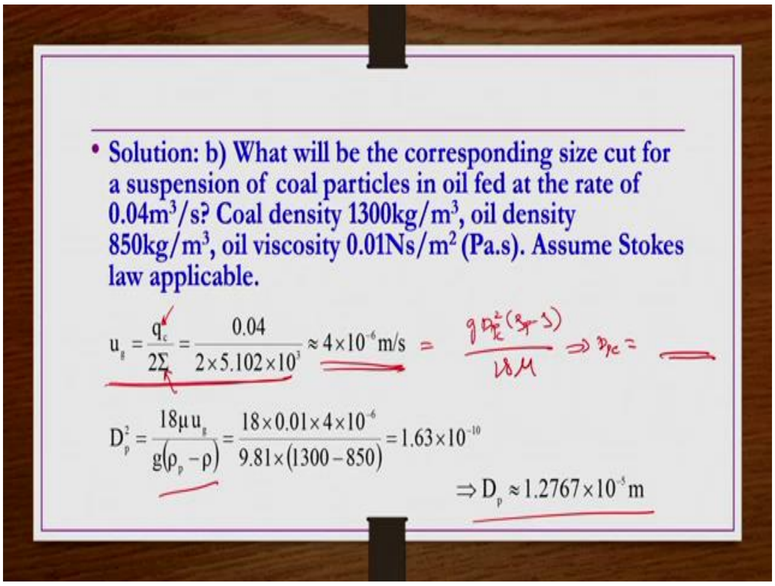

Second part of the question, if the sigma value is this one and then bowl is used for some other separations like coal suspension then what would be the cut size? What will be the corresponding size cut for the suspension of coal particles in oil fed at the rate of 0.4 m^3/s

? The q is also different now, so then here we have to find out D_p. So, the same expression we are going to use here also, $\Sigma = \frac{q_c}{2u_g}$. So, because the other equation that equation number 10 for q_c in terms of r_1 and r_2 and all that v etc, ω etc., are not possible because is not given here in this equation, so what we do?

We calculate D_{pc} by different approach. What we do? From using this $q_c = 2\Sigma u_g$, so new flow rate 0.04 m^3/s is given. Σ we just calculated it as 5.10 x 10^3, from here for this case we calculate u_g. Previous case was for different condition. For these conditions now you can calculate $u_g = \frac{q_c}{2\Sigma}$. And then now this you equate by $\frac{gD_p^2(\rho_p-\rho)}{18\mu}$.

So, then if you put it here c cut diameter, so whatever the particles of this D_{pc} you will get, all those particles are size greater than this D_{pc} will be separated. So, this approach we are going to follow. So, D_p^2 this u_g is nothing but $\frac{gD_p^2(\rho_p-\rho)}{18\mu}$. From here we can write it as D_p^2 is equals to $\frac{18\mu u_g}{g(\rho_p-\rho)}$. So, then from here you get D_p^2 is equals to 1.63 x 10^{-10}. And then D_p you are going to get it as approximately 1.2767 x 10^{-5} m or approximately 12.7 microns, this will also we can do it. We are doing this way because ω et cetera, those information are not available.

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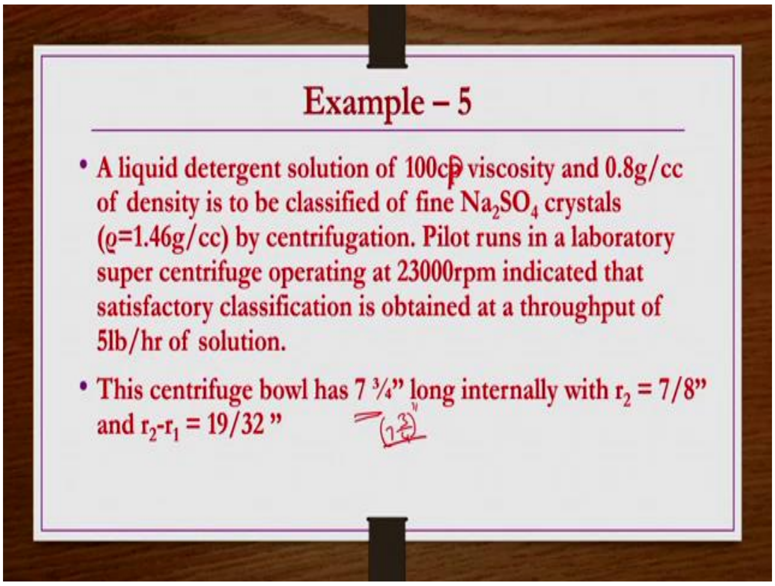

Another example problem: a liquid detergent solution of 100 cp viscosity and 0.8 g/cc density centipoise, viscosity is given in centipoise. Is to be classified of fine Na_2So_4 crystals of density 1.46 g/cc. Pilot runs in a laboratory super centrifuge operating in 23000 rpm indicated that satisfactory classification is obtained at a throughput of 5 lb/h of solution. This centrifugal bowl has $7\frac{3}{4}$ inch long internally with r_2 is equals to $\frac{7}{8}$ inch and $(r_2 - r_1)$ $\frac{19}{32}$ inch, this is $7\frac{3}{4}$ inch that is $\frac{31}{4}$. Determine D_{pc} for this separation.

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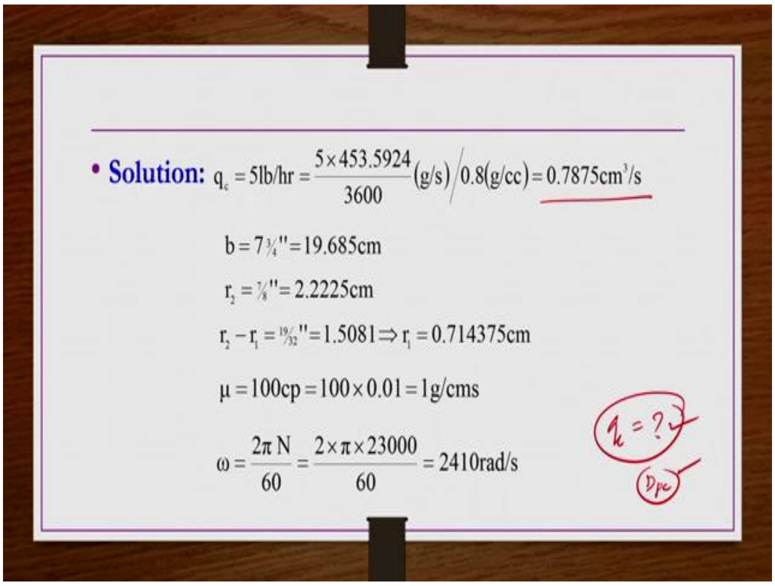

So, q_c is given in lb/h, let us convert it in cm^3/s, we will do this problem in CGS units. So, when you will convert you will get this value, b is given, so b $7\frac{3}{4}$ inches. So in centimetre it is

19.685 centimetres, r_2 is 2.2225 cm, $r_2 - r_1$ is 1.5081 cm. So, r_2-1.5081 would nothing but r_1 that is 0.714375 cm. μ is 100 centipoise so that is 1 g/cc-s. So, then ω is the other requirement that is N is to 23000 rpm is given. So, omega comes out to be 2410 rps. So, now everything is known in this q_c expression except the D_{pc}, so this we can find it out.

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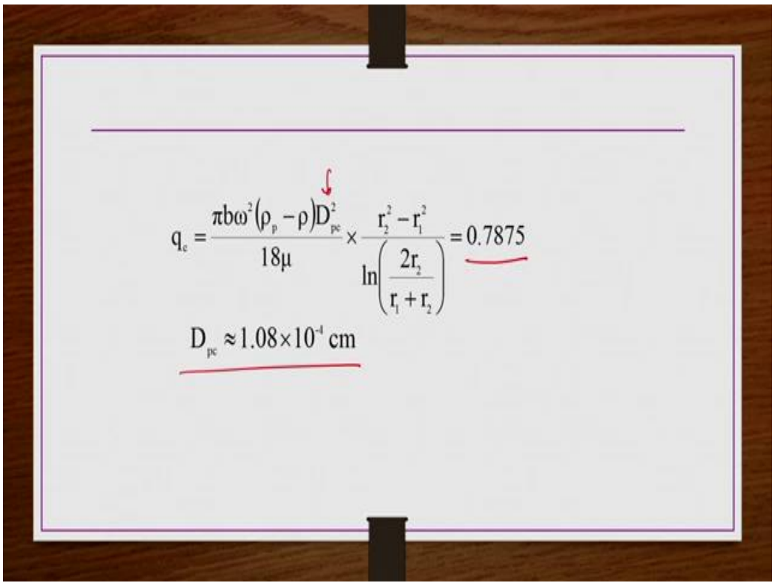

So, q_c we have this expression and then q_c is given as 0.7875 cm^3/s. So, 5 lb/h that is 0.7875 cm^3/s. So, now here you substitute all these values except this D_{pc} which is not known. And then simplify this equation, you will get D_{pc} is approximately 1.08 x 10^{-4} cm. This is how you have to solve the problems using the centrifugal separation principles. Now, we see a few basics about the cyclone separators.

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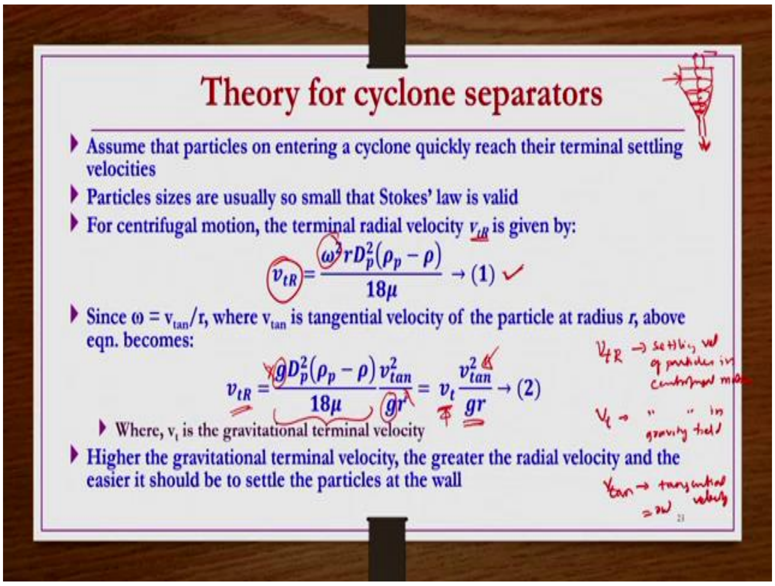

Cyclone separators are conical shape bowl vessels like this. So, here what happens, the fluid which is containing particles is being introduced into this vessel at high tangential velocity. And then when this hits the surface and then because of the conical shape this fluid rotates in this direction. Vertex downward that will be formed. When the fluid reaches down then upward liquid vertex will be found like this and then clear liquid will be taken from the top.

Whereas the particles when this fluid rotates down like this, these particles will hit on the conical vessel surface here and then being separated and collected from the bottom, that is the principle. Simply, that is the principle of the cyclone separator. For this (equation) for this case we are going to develop the required equations. Assume that particles on entering a cyclone quickly reach the terminal settling velocity that is important. Particle sizes are usually so small that Stokes' law is valid.

Because this kind of separation cyclone separators we use in general to separate microns sized particles from the dust laden air or gasses something like that. So, those particles in the air or the gaseous effluent from industries how the particles of very small size of micron size. So, such micron size particles will obviously settle in Stokes' regime because their settling velocity would be low. Why? Because the particle size is order of 10^{-6} or even small in m.

For centrifugal motion the terminal radial velocity V_{tR}. So, let us say the now here what happens? When the fluid comes in here and then rotates going down like this here as a kind of vertex, because of the vertex forming here. There are two forces are there, one is centrifugal force because this fluid is rotating, another one is the gravity field force is also there. So, whatever the terminal velocity for the particles due to the centrifugal force that we call designated as V_{tR}.

So, at some location R V_{tR} is nothing but $\frac{r\omega^2 D_p^2(\rho_p-\rho)}{18\mu}$, this we already derived in one of the previous lecture. So, the settling velocity of particle in centrifugal field under the Stokes' regime is V_{tR}, now we designating as V_{tR}, previously we have written as ut c kind of thing. So, now we are writing V_{tR}, it is nothing but $\frac{r\omega^2 D_p^2(\rho_p-\rho)}{18\mu}$. And then we know that tangential velocity V tangential is nothing but $r\omega$.

So, in place of this omega if you substitute $\frac{v_{tan}}{r}$ then we have this equation like this, here what we are doing? This equation in this equation in place of omega we are writing $\frac{v_{tan}}{r}$, so $\frac{v_{tan}^2}{r^2}$ should be there and then remaining 1 r term was already there here, so this r^2 of the r term is cancelled out. Then further we are multiplying and then dividing by g. So, that this part $\frac{gD_p^2(\rho_p-\rho)}{18\mu}$ is nothing but terminal velocity of the particle settling under the gravity field and then Stokes' regime is valid.

Under the Stokes' regime if the particle is settling in a gravity field then the settling velocity is nothing but $\frac{gD_p^2(\rho_p-\rho)}{18\mu}$. That is ut, we have written previously, now we are writing V_t just change of symbols only. And then what are the remaining terms? $\frac{{v_{tan}}^2}{gr}$. Now, form this equation what we understand, if V_t is higher so that is the settling velocity of the particle. Though it is in the Stokes' regime but upper end of the (stoke) if it is goes towards the upper end of the Stokes' regime.

So, then this V_{tR} is going to be further greater. V_{tR} that is tangential velocity, tangential radial velocity for that particle due the centrifugation. That is going to be much higher because V_t is increased. So, because tangential velocity is anyway that larger and then g and r all are positive values, then it will further V_{tR} is going to be further larger for a higher V_t value that is what we see now. Higher the gravitational terminal velocity V_t the greater the radial velocity V_{tR} and the easier it should be to the particles to settle at the wall.

So, that means if you want particles to be settling at the wall you should provide the upper end of a gravitational terminal velocity for those particle size. Now, so I just rewrite once again so that to avoid confusion, V_{tR} is nothing but settling velocity of particles in centrifugal motion. V_{tR} is nothing but settling velocity of particles in gravity field. And then v_{tan} is nothing but tangential velocity which is nothing but r omega. But, in general getting this V_{tR} information directly is difficult because you need to know tangential velocity. You need to know the gravity settling velocity and then r position what r position and all those things.

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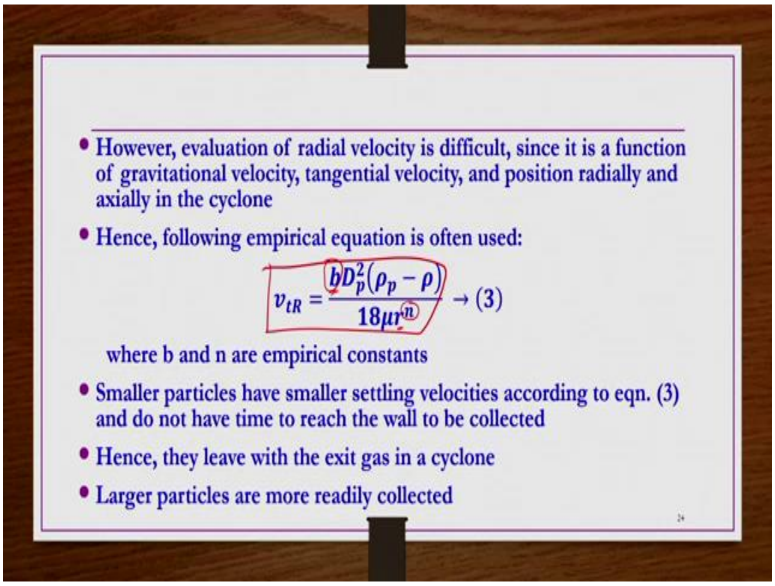

Evaluation of radial velocity that is V_{tR} is difficult because it is function of gravitational velocity. Gravitational terminal velocity, tangential velocity v_{tan} and position radial position r. So, that is the reason we have a kind of empirical equation often used of this form. This empirical equation, not the derivation it is empirical equation $V_{tR} = \frac{bD_p^2(\rho_p - \rho)}{18\mu r^n}$. Whatever this $r\omega^2$ is there that one and then this here r are there, they are modified such a way they are some kind of empirical constants in terms of empirical constants are written. So, this n and b are nothing but empirical constants.

So, smaller particles have smaller settling velocities according to this equation obviously. And do not have time to reach the wall to be collected. So, obviously they live with the exit gas in cyclone separator without being separated. Whereas the larger particles are more readily collected at the wall and being separated from the bottom of the cyclone separator. So, these are the few details about the cyclone separators.

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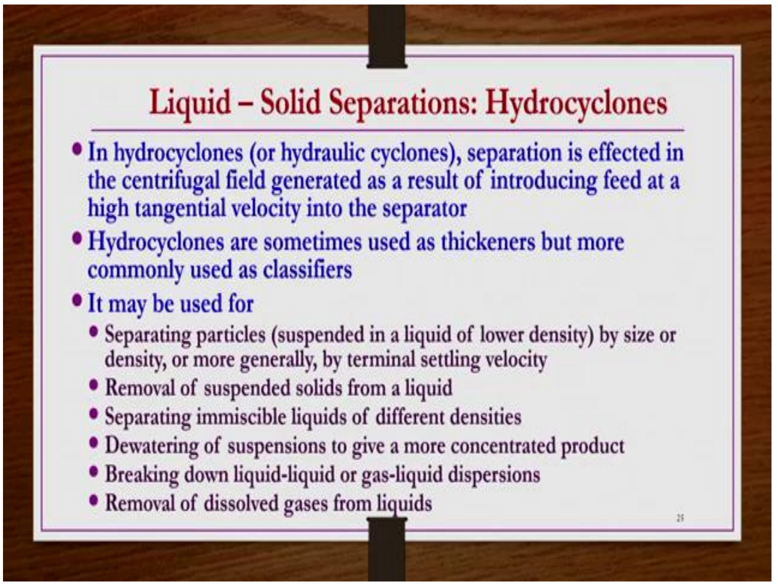

Now, we go to the hydrocyclones. Cyclones are also used for the liquid-solid separations also, they are known as the hydro cyclones in general. So, in hydrocyclones or hydraulic cyclones separation is affected in the centrifugal field generated as a result of introducing the field at high tangential velocity into the separator. The same way exactly the same way the process happens whatever for the cyclone separator. Pictorially also we will see now in the next slide.

Hydrocyclones are sometimes used as thickeners but more commonly used as classifiers as well. It may be used for separating particles suspending in a liquid of lower density by size or density or more generally by terminal settling velocity differences. Removal of suspended solids from a liquid further purpose also they are used. Separating immiscible liquids of different densities for that also used and then also used for dewatering of suspensions to give a more concentrated product.

And then sometimes breaking down liquid-liquid or gas-liquid dispersions. For that purpose also these hydrocyclones are used. Removal of dissolved gases form liquids are also being separated by these hydrocyclones.

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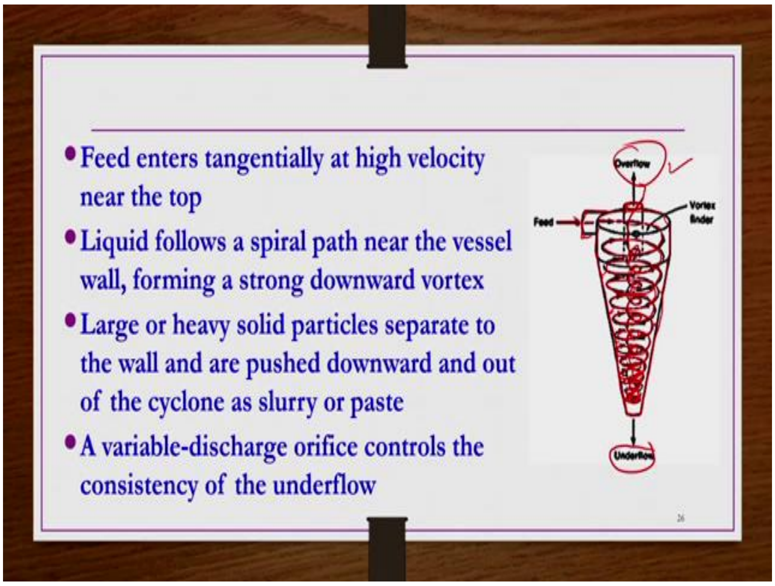

So, pictorially if you see, so these are also kind of same like cyclone separator like this. They have a kind of conical column like this. So, now the feed comes in here at velocity like this and then this hits the wall and then because of that one it undergoes a kind of rotational motion like this. And because of this rotational motion what happens, centrifugal field will be developed. So, this feed containing the particles they will be going through under kind of rotational motion like this.

And then in this process what happens, this feed whatever having the particles it is having the particles also, those particles being hit on the walls of this container cyclone separator. And then settling at the bottom will be taken as a kind of underflow. So, once this feed reaches the bottom like this here what happens, almost clear liquid generate a kind of secondary vertex which moves upward through the centre of this larger vertex like this and then moves like overflow from here.

Also, there are two vertex; one is the bigger vertex that is moving down because of the high tangential velocity feed coming in. And then once the particles most of the particles are being separated while this fluid is going down in a vertex motion like this, so these particles are being hit on the cyclone wall and then being separated. So, by the time that the feed reaches the bottom most of the particles are being separated so that will be having the lower density kind of thing.

And then those liquid will move up with a kind of as a kind of inner vertex and then taken away as a kind of overflow like this. This is the hydrocyclone process how it works. Feed enters tangentially at high velocity near the top. Liquid follows a spiral path near the vessel wall, forming a strong downward vertex. Large or heavy solid particles separate to the wall and are pushed downwards and out of the cyclone as a slurry or paste. A variable discharge orifice controls the consistency of the underflow at the bottom.

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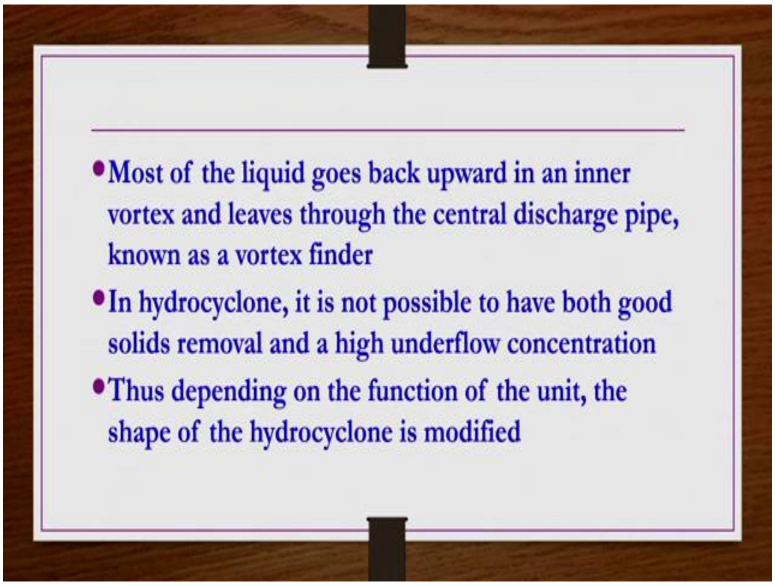

Most of the liquid goes back upward in an inner vertex and leaves through the central discharge pipe known as vertex finder. In hydrocyclone it is not possible to have both good solids removal and a high underflow concentration. Thus, depending on the function of the unit, the shape of the hydrocyclone is in general modified.

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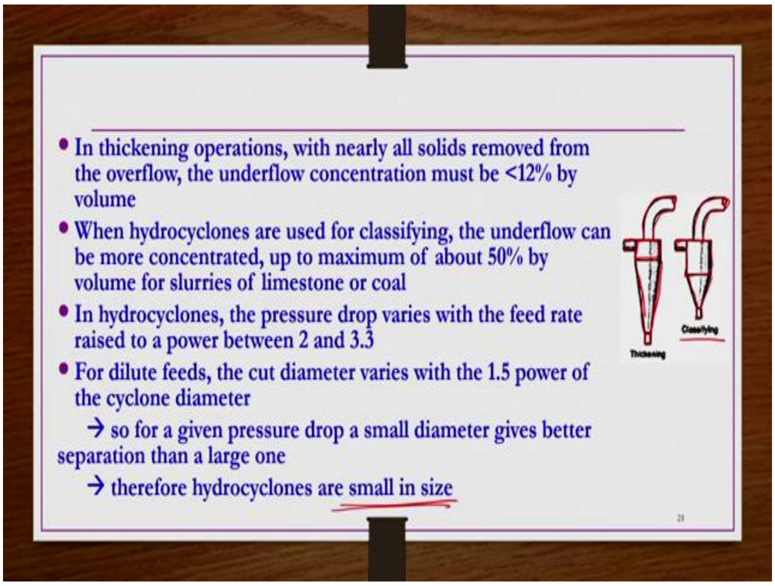

So, for classifying purpose you may have a kind of this kind of hydrocyclone where this top section is like this and then the conical section is a kind of smaller one like this. Conical section is the smaller one the other section is a kind of bigger one. That is what we have in general if you want to have a kind of classifying separation. If you want this hydrocyclone to act as a kind of thickening so that virtually all particles being separated for the liquid then you should design this hydrocyclone such a way that their conical section is bigger compared to other this section, fluid entering section.

So, that is the difference. As per the requirement this hydrocyclone designs are modified in general. In thickening operations with nearly all solids removed from the overflow the underflow concentration must be less than 12 % by volume. When hydrocyclones are used for classifying the underflow can be more concentrated up to maximum of about 50% by volume for slurries of limestone or coal. In hydrocyclones the pressure drop varies with the feed rate raised to a power of between 2 and 3.3.

For dilute feeds the cut diameter varies with the 1.5 power of the cyclone diameter, these are the some kind of experimental observation, from the experimental observation after doing some kind of curve fitting, empirical correlations, these numbers are achieved. So, for a given pressure drop a small diameter gives better separation than a larger one. Therefore hydrocyclones are in general small in size. Cyclone separators in general we have seen very big sizes in general in industry. But, these hydrocyclones are in general small in size, how small in general?

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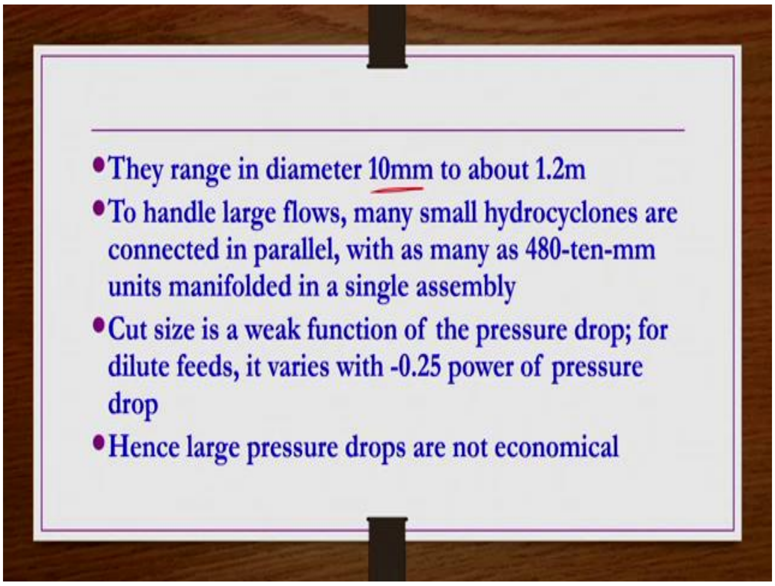

They range in diameter 10 mm to 1.2 m in general, so they can be as small as 10 mm hydrocyclones. To handle large flows, many small hydrocyclones are connected in parallel with as many as 480-ten-mm units manifolded in a single assembly. Such small ten mm hydrocyclones are taken and then such small ten mm hydrocyclones you take and then around 480 number, those many number of ten mm hydrocyclones are in general manifolded in a single assembly for or in order to handle large flows.

Cut size is a weak function of the pressure drop; for dilute feeds it varies with -0.25 power of the pressure drop. Hence large pressure drops are not economical in general for hydrocylones. This is about a few basic details about hydrocyclones.

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Then coming to the references we have several references for this course; all are listed here but primarily this lecture is prepared from this reference book: Unit Operations of Chemical Engineering by McCabe, Smith and Harriot. However, some problems are taken from this book, Richardson and Harker as well as Ortega and Rivas and then Geankoplis. A few problems are also taken form this book, Foust et al. Thank you.