Mechanical Unit Operations

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Lecture 34
Centrifugal Separations

Welcome to the MOOCs Mechanical Unit Operations. The title of this lecture is Centrifugal Separations. Previously in one of the lectures, we have already seen the centrifugal force, particles settling under centrifugal field, those kind of things we have seen and then compared with the particles settling in a gravity field.

There we have found that the magnitude of a centrifugal force is several hundred or sometimes several thousand times higher than the gravitation force. So some particles if you wanted to separate from a solid fluid system, if some particles taking very long time to settle or being separated from under gravity field then that is not going to be practically possible. Or you may not wish to wait for so long for those particles to be settle under gravity and then you separate and then you go for the subsequent operations. So that is not possible always.

So under such conditions, if you apply kind of centrifugal field for separation of those particles then the separation is going to be taken place in very less time because the magnitude of centrifugal force is in general much higher than the gravitational force – several times like hundred times or thousand times depending on the rotational speed of the centrifugal ball that we are using. That is one advantage. Another advantage is like that in general gravitation sedimentation equipment or very very big sized tanks or containers or kind of things are used for gravity separations.

But centrifugal separation can be done in small bowls having diameter 700 to 1200 mm diameter only, so such is the advantage. Because of these two major advantages of centrifugal field in general, you know suppression based on centrifugal field is going to be advantageous as well as economical over a gravity separation especially if the separation or the settling velocity of the particle is very very small in general. So now we see why centrifugal separations are required as I mentioned.

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Wide range of industrial applications are existing where centrifugal force is used in place of gravitation force to accelerate separations. The acceleration of separation can be done by using these centrifugal forces. Acceleration of separation can be several thousand times compared to gravity.

Some benefits include far greater rates of separation i.e. possibility of achieving separations which are either not practically feasible or actually impossible in the gravitational field. Some particles let us say if you have very fine micron size or sub-micron size particles are suspended in the air then if you wanted to pure that air then gravity separation if you are doing, try to do, that is going to take long time, very very long time or sometimes it is not even possible. But if you apply centrifugal field for such cases it is easy that acceleration of separation would be taking place and then under centrifugal field the separation of those particles can be easily done as done sometimes in cyclone separators et cetera.

And then substantial reduction of size of the equipment is possible by using centrifugal field in place of gravity separation as I already mentioned.

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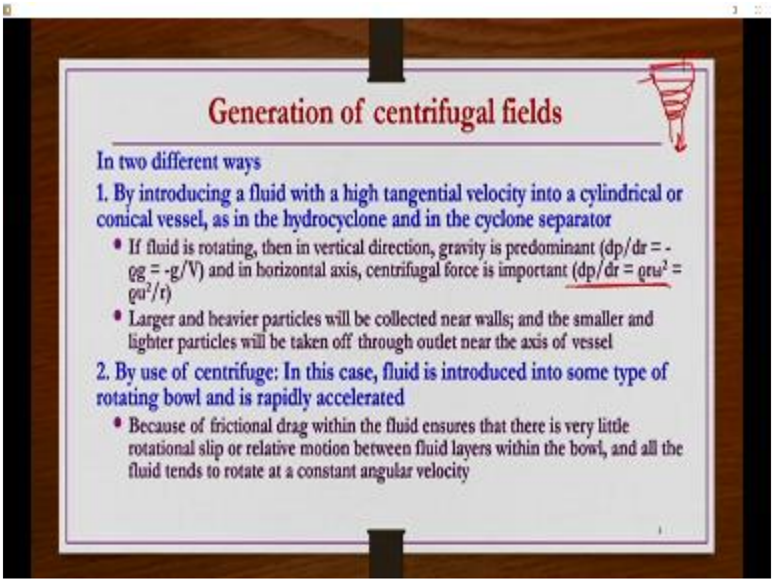

Then how to generate centrifugal field? Having seen that advantage of centrifugal force, now next point is that how to generate centrifugal field. There are two different ways are possible in general:

First way is that by introducing a fluid with a high tangential velocity into a cylindrical or conical vessel, as we do in general in hydrocyclones or cyclone separators. So let us say, what we have? We have in general cyclone separators or hydrocyclone separators or something like conical shape something like this. The fluid that comes in that are the fluid that is containing the particles, fine particles, they come at high velocity and then hit the wall. So then they are kind of spiral of this, rotation of this fluid element will take place and when they are hitting at high velocity to the surface of the cone and then cone radius is, size of the cone, I mean the cross-section of the cone decreases gradually downwards.

So then because of that one kind of rotation, increased rotation of the fluid element will take place and then that will generate a kind of centrifugation and then particles will be settled at the bottom and collected there. Whereas thick layer air can be collected from the top. This is what we do. This is one way of doing the, or generating the centrifugal field. So here at any point what you see, you have a kind of two forces. One is the gravitational force that is acting downward in the Y direction and then another one is the centrifugal force that is acting in the radial direction.

So if fluid is rotating then in vertical direction gravity is predominant, so $\frac{dp}{dr}$ should be nothing but $-\rho g$ or $-g/V$. We can write V is a kind of volume per unit mass kind of units and in horizantal axis what we have? We have centrifugal force predenominating with pressure drop $\frac{dp}{dr}$ is nothing but $\rho r\omega^2$ that can be written $\frac{\rho u^2}{r}$as well. So $\frac{dp}{dr} = \rho r\omega^2$, that again anyway we are going to derive in subsequent slides.

Then larger and heavier particles will be collected near walls and then smaller and lighter particles will be taken off through the outlet near the axis of vessel.

The second approach is by use of centrifuge – in this case what happens, fluid is introduced in some type of rotating bowl and is being rapidly accelerated. You take a bowl and in that bowl you take these fluid containing particles and then rotate that bowl at very high rotational speed. So then what happens, you know heavier phase will be thrown towards the wall of the container bowl and then will be taken away separated from the other phase, lighter phase. So that is what the other way of indcing the centrifuge.

So because of frictional drag within the fluid ensures that there is a very little rational slip or relative motion between fluid layers within the bowl and all the fluid tends to rotate at a constant angular velocity. These are the two ways that we can apply to generate centrifugal field in general. Now the areas of applications: there are large number of applications are available for this centrifugal separations. The separation by using centrifugal field.

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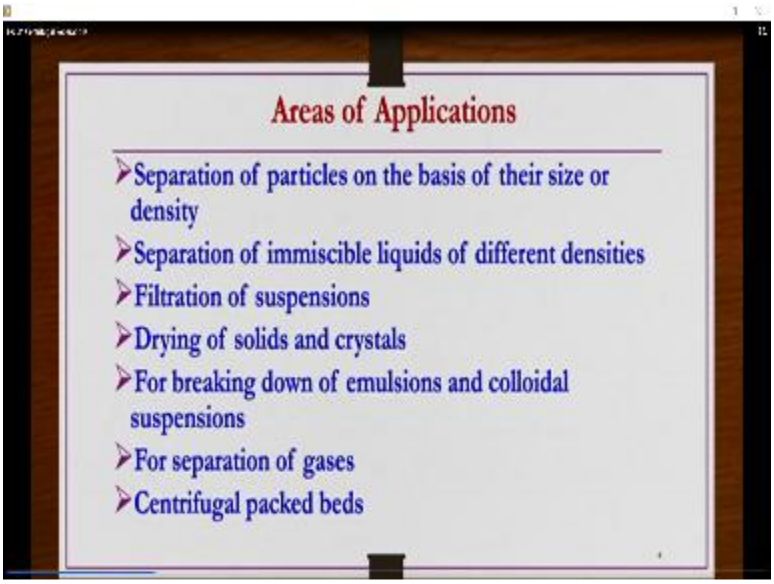

Separation of particles on the basis of their size and density and then separation of immiscible liquids of different densities. Sometimes there may be immiscible liquids, let us say from oil industry, from vestibule seeds, edible oils when you produce, there are kind of two phases aqueous phase and oil phase in general. So these two phases are immiscible and their densities are very close to each other. So separating those two phases is a kind of very difficult task by gravity or it will take a long long time.

So if you apply centrifugal field so then those immiscible liquids of different densities but close to each other, the densities are different but close to each other, so those separation, those immiscible liquids can be separated easily.

Then filtration of suspensions, already we have seen in one of the previous lecture you know centrifugal filtrations, that are quite famously used.

And then drying of soilds and crystals, in those centrifugal filtration we have also seen like you know sometimes if you want to partially dry the solids that have been separated from the slurry then you know, you rotate those solids in the same centrifugal separation unit for a very large, for some more time but very high rotational speed compared to the rotational speed of a filtration separation. Now the separation of the slurry will take whatever the rotaional speed you have given.

Compared to that one, you have to rotate it at a very high velocity. Then whatever the liquid that is there between the particles of the cake are trapped between the particles of cake, that is interstitial spaces of the particles in the cake are being occupied by the liquid. Those liquid also be drained off and then solids would be partially dried. So drying of solids and crystals is one application.

And then in one of the previous lecture also we have seen emulsions and colloidal suspensions, so they in general aglomerate. You wanted to make kind of uniform solution, then breaking down of emulsions and colloidal suspensions can be done by the centrifugal field. And then some time for separation of gases espeicially in nuclear industries where isotopes are of this closed density to each other. Then some of the other areas are centrifugal packed beds where you can find this application centrifugal separations.

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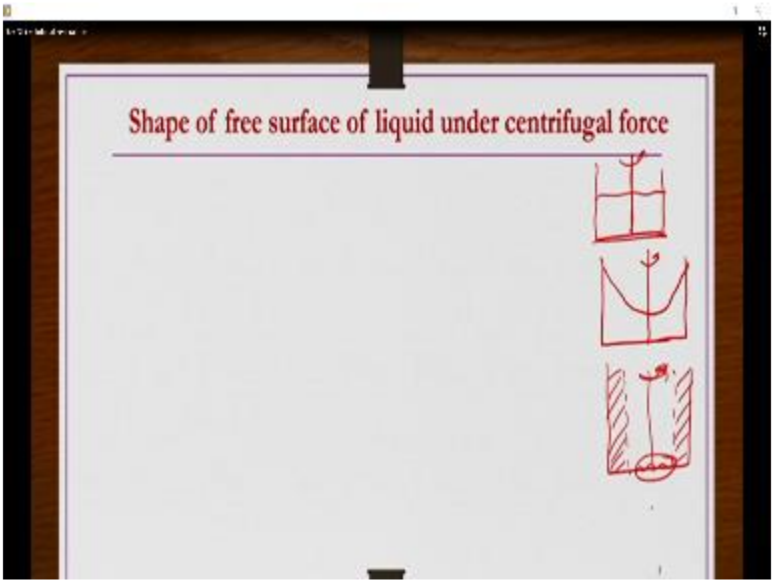

Now shape of free surface of liquid under centrifugal force: we all know that when in a bowl if you take a fluid and then rotate it, the interface will have a kind of paraboloid kind of shape. If you rotate at much higher speeds, then it will be the liquid would be kind of attached layer to the walls of the container and then almost bottom of the surface is bowl is kind of vacant kind of thing. That is let us say if you have a kind of centrifugal bowl here, initially you take a liquid and then you rotate. You rotate at certain velocity. So when you are rotating at moderate rotational speeds, then the interface will have kind of a paraboloid shape like this.

So when you rotate at very high speeds, then what happens you know, these liquids may form kind of almost two different layers. So there on the liquids the whichever liquid is being rotated is under centrifugal field and then centrifugal field if it is strong by large rotational speeds, these liquids are you know attached to the wall as a kind of cyclindrical layer like this where leaving this bottom without any liquid, almost kind of dry bottom, you can see here.

These kind of things in general we see, we know but can we generate or develop a kind of equation for this, that we are going to see now.

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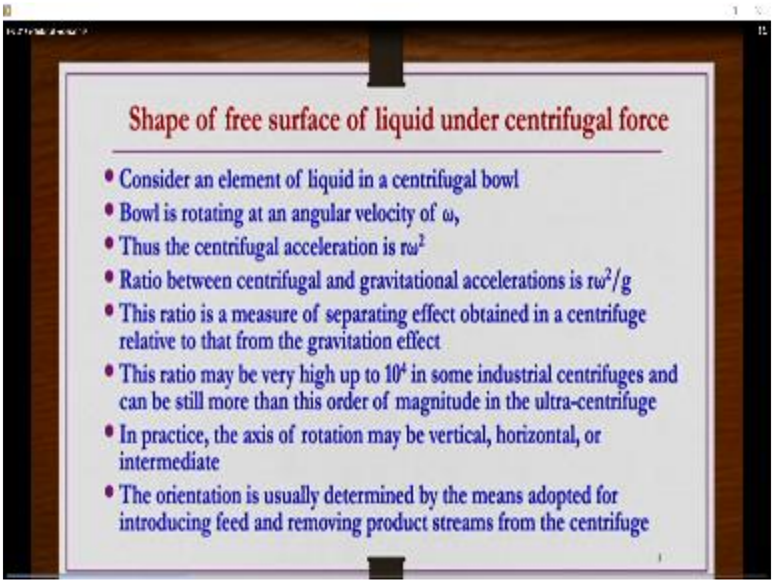

Consider an element of liquid in a centrifugal bowl. Bowl is rotating at an angular velocity ω, so the centrifugal acceleration is nothing but $r\omega^2$. Then ratio between centrigual and gravitational acceleration is simply $r\omega^2$. This is also we know. This ratio is a measure of separating effect obtained in a centrifuge relative to that from the gravitational effect.

This ratio may be very high up to 10^4 in some industrial centrifuges and can be still more than this order of magnitude in the ultra centrifuges as well. In practice this axis of rotation may be vertical, horizontal or intermediate but whether the axis of rotation should be vertical, horizontal or intermediate that depends on the applications.

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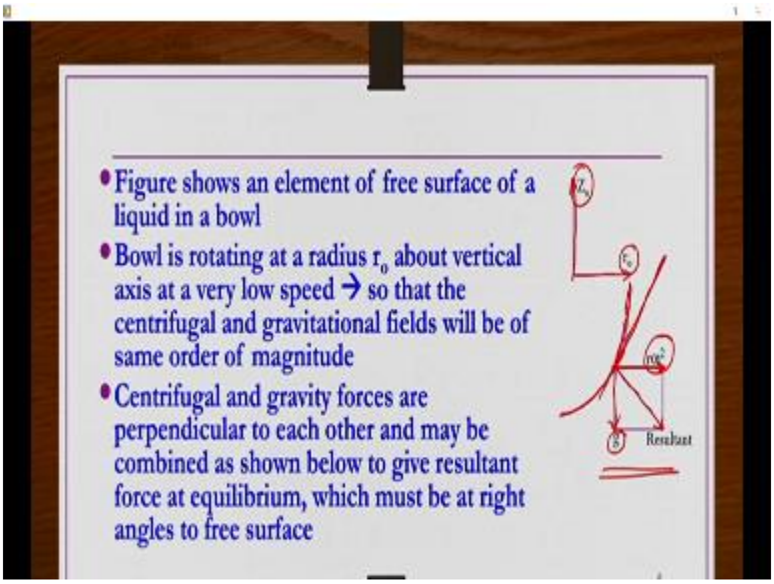

Now let us say you have taken a centrifugal bowl and then you rotate at kind of a moderate speed, not very high speed so that you know both gravitational and centrifugal forces are of comparable magnitudes. So this radius of this paraboloid is r_0 and then it is rotating along this axis, vertical axis z_0 at this location. Let us say, at any point on this paraboloid if you wanted to find the relative magnitude of these centrifugal and gravity forces, what you can do, you can draw a kind of tangent like this so that there what you do, for that tangent you try to get the normal components like this.

One is in the downward direction where the gravity is predominating, another one is kind of the horizontal direction where the centrifugal field is dominating. If you take the resultant of these two vectors, summation of these two, then the resultant whatever is there that is going to be the total force that is acting at that particular point where you have drawn the tangent.

Figure shows an element of free surface of a liquid in a bowl. Bowl is rotating at radius r naught about vertical axis at a very low speed so that the centrifugal and gravity fields will be of same order of magnitude. Centrifugal and gravity forces are perpendicular to each other and may be combined as shown below, here to give a resultant force at equilibrium, which must be at right angles to free surface. So this resultant whatever is there that is at the right angle. So if this is a kind of tangent, at this point of tangent if you have this right angle at right angle if you draw a line, so that is going to give you the resultant of these two, which is nothing but summation of these two; r and $r\omega^2$ and g.

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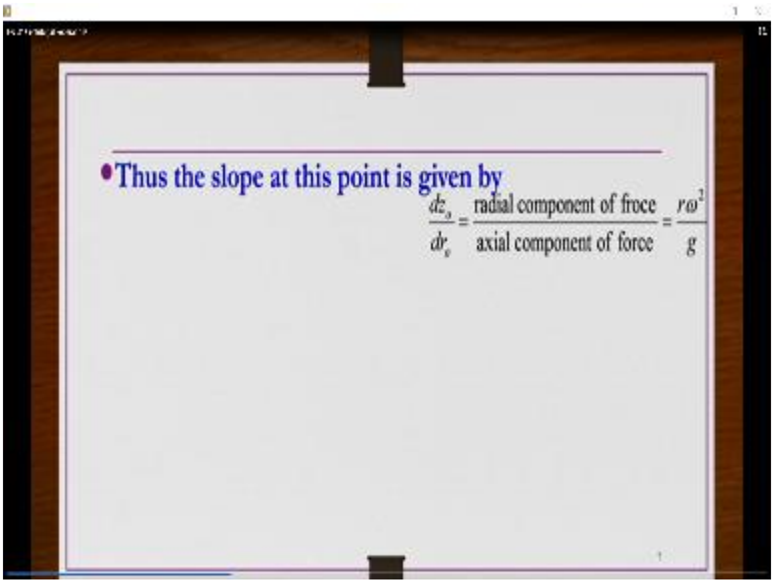

Thus the slope at this point is given by $\frac{dz_0}{dr_0}$, obviously the slope, the slope at that point whatever the tangent that you have drawn, that slope, this tangent.

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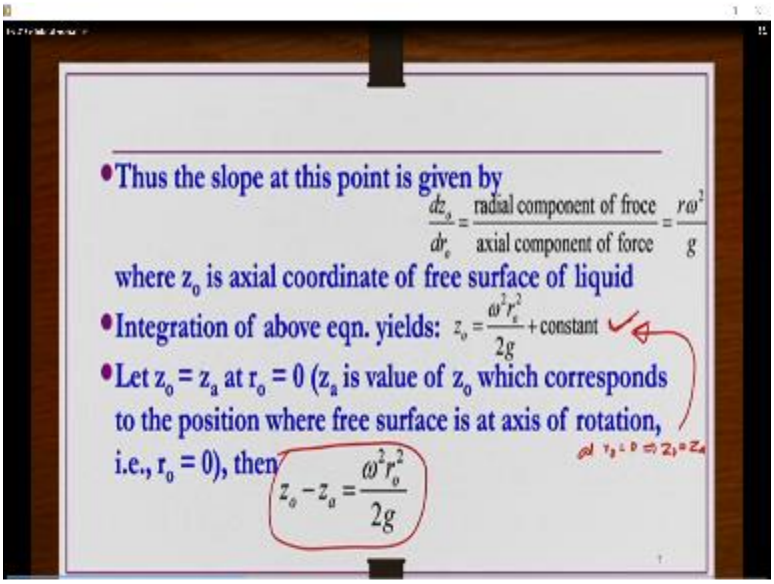

At this point if you draw the slope then what you have? $\frac{dz_0}{dr_0}$. So that is $\frac{dz_0}{dr_0}$ is equals to radial component of force divied by the axial component of force, that is nothing but $\frac{r\omega^2}{g}$ where z_0 is the axial coordinate of free surface of the liquid.

Integration of the above equation will give us $z_0 = \frac{\omega^2 r_0^2}{2g} + constant$. Then let z_0 is equals to z_a at r_0 is equals to 0, that is z_a is value of z_0 which corresponds to the postion where the free surface is at axis of rotation i.e. at r_0 is equals to 0. Then in this equation, if you substitute r_0 is equals to 0 then constant is going to be z_0 is equal to z_a.

At r_0, the boundary condition is what? At r_0 is equals to 0, we have z_0 is equals to z_a. So this when you substitute here in this equation, you will get constant is equals to z a and then we substitute here and then simplify and you can write this equation as $z_0 - z_a = \frac{\omega^2 r_0^2}{2g}$. This is the equation that represent the free surface of fluid layer which is under a centrifugal action.

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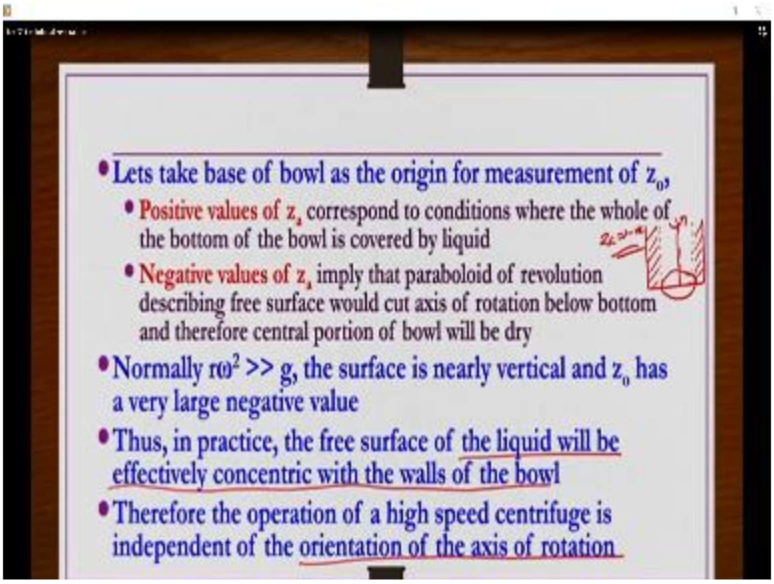

So let us take base of bowl as the origin for the measurement of z_0 and if positive values of z_a corresponds to conditions where the whole of the bottom of the bowl is covered by liquid, so as I mentioned like different speeds if you do this rotations kind of thing, if you do kind of a rotation at smaller flow rates, if you rotate this bowl at lower angular velocity so then you can have a kind of interface something like this. So this is all kind of liquid. So the whole of the bottom of this bowl is covered by the liquid. Under such conditions, in general, whatever the z_a that you get is going to be kind of a positive one.

If you have kind of negative values of z_a, then what will happen? This bowl again you know, that is corresponds to – this is the rotational axis along which it is rotating. If z_a is negative, then we will have kind of a fluid attached to the bowl as a kind of layer and then rotating without any relative slip. And then this bottom of the bowl is completely dry and exposed. So under such conditions, z_a is nothing but negative one.

So negative z_a you can have if the rotational speed is very high, positive z_a you can have if the rotational speed is low to moderate. But in general, we know that r omega square is much larger than the g, i.e. centrifugal force is much larger than the gravity force. The surface is nearly vertical and z_0 has a very large negative value.

Thus in practice, the free surface of the liquid will be effectively concentric with the walls of the bowl and therefore the operation of high-speed centrifuge is independent of the orientation of the axis of rotation, whether are you rotating along the vertical axis or along horizontal axis or at some intermediate angle that is not going to show any kind of effect because this interface, whatever the liquid interface is there that is independent of orientation of, because now this layer at high speeds is attached kind of layer of liquid attached to the walls without any kind of relative slip kind of thing.

So this is about the shape of the interface in centrifugal field, shape of the interface of a liquid in a centrifugal field, that derivation we have seen. Now we see the pressure, pressure drop. What is that pressure in the centrifugal force that is causing the separation to occur. So that we are going to calculate, i.e. $\frac{dp}{dr} = r\omega^2$ is there, that we are going to derive now.

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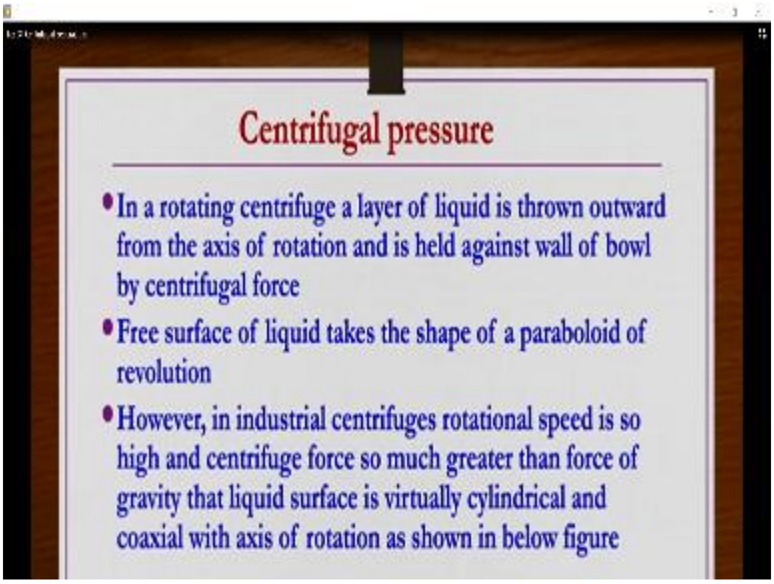

In a rotating centrifuge, a layer of liquid is thrown outward from the axis of rotation and is held against the wall of bowl by centrifugal force. Free surface of liquid takes the shape of a paraboloid of revolution. However in industrial centrifuges, rotational speed is so high and centrifuge force is so much greater than the force of gravity that liquid surface is virtually cylindrical and coaxial with the axis of rotation as shown here in this figure:

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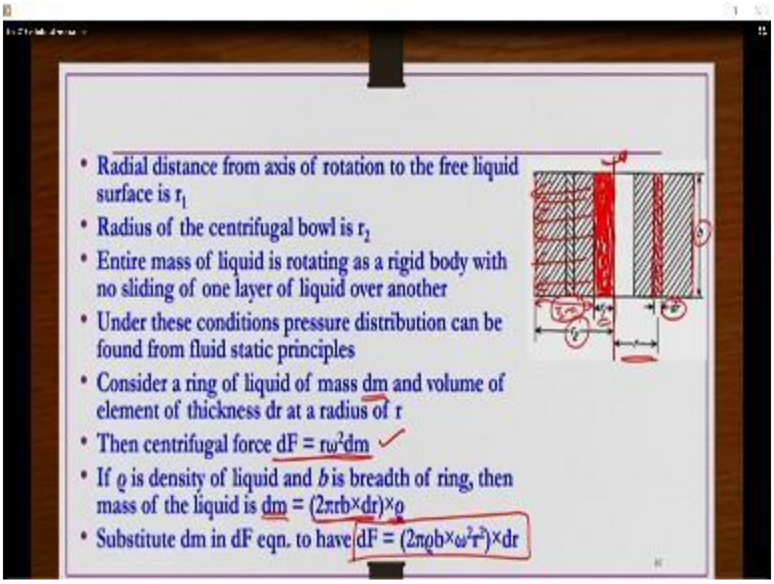

If you have kind of a very high rotational speed, this is the wall, actually this is the wall of the bowl, so which is having a kind height b and then radius r_2, this is the central axis of the bowl. The radius of this bowl is r_2. If you rotate this one at very high speed having the liquid already present in the bowl when you rotate at very high speeds, the liquid is usually thrown outward toward the wall and almost concentric cylindrical interface you can see here as shown in the picture. And then this is going to be very true, very often occurs in many of the industrial centrifuges that often applied for a given separation, solid separations.

Radial distance from axis of rotation to the free liquid surface is r_1. So let us say initially liquid is there, so that liquid is kind of having this thrown towards the kind of wall, so like this. So towards the center of this bowl, we have a kind of empty column kind of thing without any liquid and then liquid is thrown towards the wall which is forming a kind of concentric interface like this. So this part whatever this filled part that I am showing is empty. There is no liquid kind of thing. So that is the radius of the interface. Free liquid surface, whatever this is the liquid that is thrown here and then liquid is now occupied from r_1 to r_2.

That is this is $(r_2 - r_1)$, $-r_1$ is nothing but the thickness of the liquid that is forming as a kind of layer along the surface and then this interface, whatever is the liquid interface is there, that radial distance from the axis of rotation to the free liquid surface is nothing but r_1. Radius of the centrifugal bowl is r_2. Entire mass of liquid is rotating as a rigid body with no sliding of one layer of liquid over another. Under these conditions, pressure distribution can be found from static principles.

Now consider a ring of liquid, now within this liquid layer it is actually both side is there. So within this liquid layer what you do, you take a layer of liquid or a ring of liquid. We cannot say layer because now it is now the centrifugal bowl. Entire bowl surface is attached with the liquid layer forming a kind of a static liquid without any sliding of liquid layer, one liquid layer over another liquid. Those kind of things are not there. So it is a centrifugal bowl rotating very high speed. So within that liquid which is being attached to the bowl surface on that bowl surface, that liquid layer, what you do, you take a ring of having thickness dr at distance r from the axis of rotation.

From the axis of rotation at distance r, you take a ring of liquid of thickness dr and then consider mass of that liquid in that ring of liquid is dm. So then volume of element at thickness dr at radius of r, you can calculate. So the centrifugal force for that ring of liquid would be nothing but $dF = r\omega^2 dm$. So $r\omega^2$ is nothing but the centrifugal acceleration like gravitational acceleration or acceleration due to gravity g is there. Acceleration due to centrifugal force, whatever is there that is r omega square. If that is multiplied by the mass then you will get the centrifugal force. You get centrifugal force but that we are doing now for a layer of the liquid or the ring of a liquid having the thickness dr.

So within this layer of ring of liquid having thickness dr, so the centrifugal force dF. That should be $r\omega^2 dm$ where dm is nothing but the mass of the liquid present in that ring of thickness dr. So centrifugal force $dF = r\omega^2 dm$. but if the density of the liquid is constant and then breadth or height of the ring is given as same as the height of the bowl b, then mass of the liquid dm is nothing but volume of that particular ring of liquid multiplied by the density of the liquid.

Then volume of that particular ring of thickness dr is nothing but $(2\pi rb \times dr) \times \rho$ then you will get the mass of the liquid in that ring of the liquid. So that is $dm = (2\pi rb \times dr) \times \rho$. So now this dm you can substitute here in this equation. When you substitute, you will get $dF = (2\pi\rho b\omega^2 r^2) \times dr$. Now the force is there, if you divide by the area, then you will get the pressure. So the pressure due to the centrifugal force, that you can obtain now.

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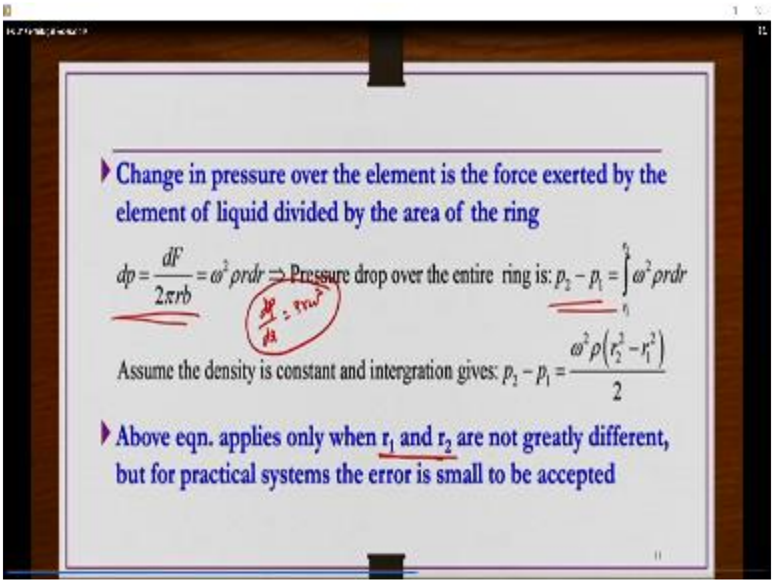

So change in pressure over the element in the force exerted by the element of liquid divided by the area of the ring, then we will get dp. So, dp is equal to dF by area of the ring. Area of the ring is what? $2\pi rb$. $2\pi rb$, so that is nothing but now, dF we already got it. If you divide $\frac{dF}{2\pi rb}$, then you will get $dp = \omega^2 \rho r dr$ or from here we can write $\frac{dp}{dr} = \rho r \omega^2$. So let us say pressure drop over the entire ring is $(p_2 - p_1)$. Then you integrate this right hand side and then substitute ring size r_1 to r_2. Then we will get $(p_2 - p_1) = \frac{\omega^2 \rho (r_2^2 - r_1^2)}{2}$. r_2 is nothing but bowl radius and r_1 is nothing but the radius of the interface.

So $(p_2 - p_1)$, p_2 is nothing but pressure at the bowl wall and then p_1 is nothing but pressure at the liquid free surface which is at r_1 distance from the axis of rotation. Ok. So that is $(p_2 - p_1) = \frac{\omega^2 \rho (r_2^2 - r_1^2)}{2}$. Remember, this equation applies only when r_1 and r_2 are not greatly different from each other, that is liquid layer thickness whatever that is attaching to the centrifugal bowl because of the centrifugal field is not very thick, it is thin so that r_2 and r_1 are now different from each other because $(r_2 - r_1)$ is nothing but the thickness of that liquid.

But for practical system, the error is so small that you do not need to worry about this r_2 and r_1 differences, how much they are different from each other because practically when you apply high centrifugal field, this difference in r_2 and r_1 is going to play a kind of very less influence. So, now using this centrifugal field how to do separation of immiscible liquids of different densities?

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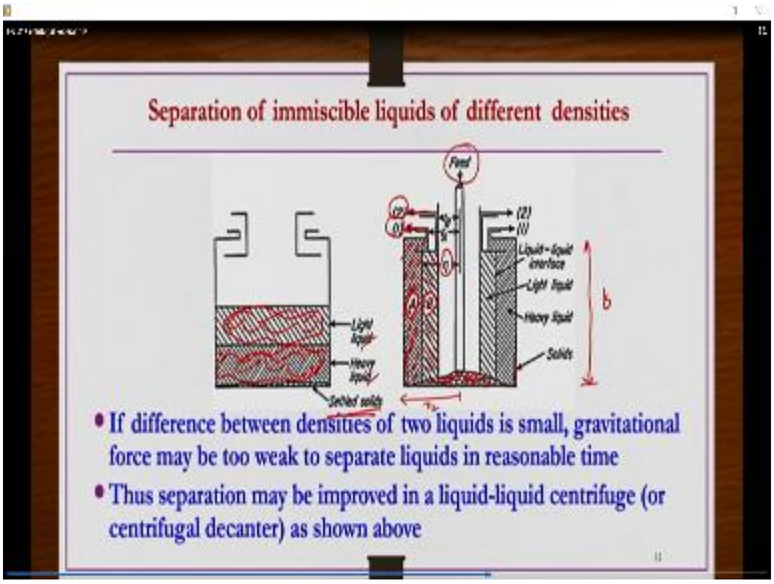

Let us say, you have a immiscible liquids – light liquid and then heavy liquid. And then there may be let us say some small solids also. Forget about the solids, we do not need to worry as of now. So when you do separation of these immiscible liquids by the gravity, it will take very very long time and then after very very long time, this heavier liquid will be forming as a kind of bottom layer and then on the top one, light liquid will be forming as a kind of light liquid layer so that they can be separated out. But here it is going to take long time because in general immiscible liquids, though the densities are different but the difference in densities of heavier and then lighter liquids is not very high. In general that is the case.

Let us say, the example of obtaining edible oil from vegetable seeds then whatever aqeous oil phases that we get, the densities are in general, oil phase may be having 0.95 gram per cc and then aqeous phase may be having 0.98 or 1.00 gram per cc, something like that. They are very close to each other. Under such conditions, if the densities are close and then forming immiscible phases, settling of those immiscible liquids into two separate layers by gravity is going to take very long, is going to take very long time.

But if you take kind of a centrifugal bowl and then in that one you take this immiscible liquids and then rotate that centrifugal bowl at high speeds, then what happens is like whatever the heavier phase is there, heavier liquid is there, that will be attached, that will be thrown towards the wall and then form a kind of layer A like shown here and then next to that one, the lighter liquid shown as zone B that will be attached very next to this heavier liquid and then from the top, heavier liquid can be taken from this outlet 1 and then lighter liquid can be taken from this outlet 2.

So, here the notations are again same: r_2 is kind of radius of the wall, then height of the wall is B let us say. Now this r_A and r_B are the corresponding radius of this outlet for heavy liquid collection and then light liquid collection respectively. Because the feed is continously coming in and continously you can take out these things, so that you do this process continuously. The interface between this heavy liquid and then light liquid whatever is there, that is r_i, that is r_i and this r_i is kind of very important calculation, this r_i calculation based on that one this r_A and r_B locations are set so that the collection of this heavy and light liquids can be taken continuously.

So what is the r_i? r_i is known as the neutral zone. A is a kind of heavy liquid zone, B is kind of light liquid zone and then in between that interface whatever is there, that is r_i having the radius r_i which is known as the neutral zone. So that r_i, we are going to calculate now.

So in this process if at all some solids are there, they will be kind of settled at the bottom and then few solids may be climbing towards the corner of the wall like this, that is also possible. So if at all solids are there, you know, one has to be careful while rotating this bowl, so that is at what speed one has to rotate this bowl, that one has to be careful because if it is rotating too high, very very high speeds, then these particles will also be coming towards the wall. We do not want that high velocity, we want those particles to be at the bottom only.

So because this particle's density is going to be much higher than the density of heavier liquid, so that one we have to be careful. Anyway this particular thing, when there are particles are also there, that we are going to take in the kind of next lecture. So as of now, forget about particle, solid particles in this case. If difference between densities of two liquids is small, gravitational force may be too weak to separate liquids in reasonable time.

Thus separation may be improved in a liquid liquid centrifuge or centrifugal decanter as shown above in this picture.

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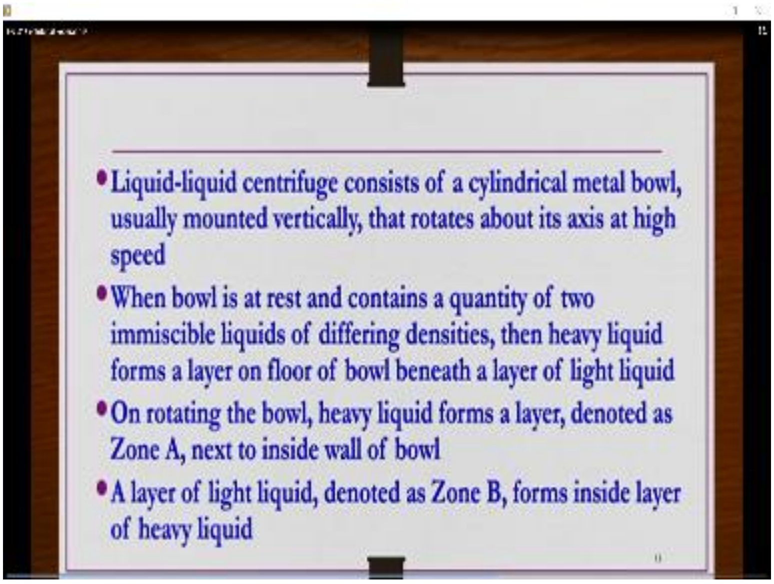

So liquid-liquid centrifuge consists of a cylindrical metal bowl, ususally mounted vertically, that rotates about its axis at high speed. When bowl is at rest and contains a quantity of two immiscible liquids of differing densities, then heavy liquid forms a layer on the floor of the bowl beneath a layer of light liquid. On rotating the bowl, heavy liquid forms a layer, denoted as zone A, next to the inside wall of the bowl. And then layer of light liquid denoted as zone B forms inside layer of the heavy liquid.

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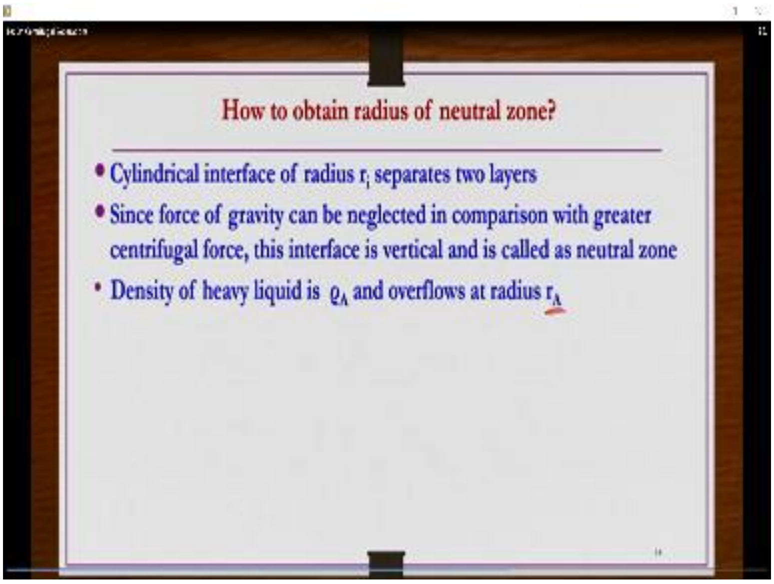

How to obtain the radius of neutral zone? The cylindrical interface of radius r_i which separates these two layers which are forming zone A and zone B, that known as a kind of neutral zone. So that r_i we have to calculate. Since force of gravity can be neglected in comparison with greater centrifugal force, this interface is vertical and is called as neutral zone. So if the density of a heavy liquid is ρ_A and then overflows at radius r_A, so there is an overflow opening at the top for this heavy liquid to go out and then radius of the overflow distance, that r_A distance is there from the central axis.

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That is this r_A is location of overflow ducts from where, you know from the top heavy liquid is taken. r_B is the location of the distance from central axis to the location of overflow for a lighter liquid. Ok.

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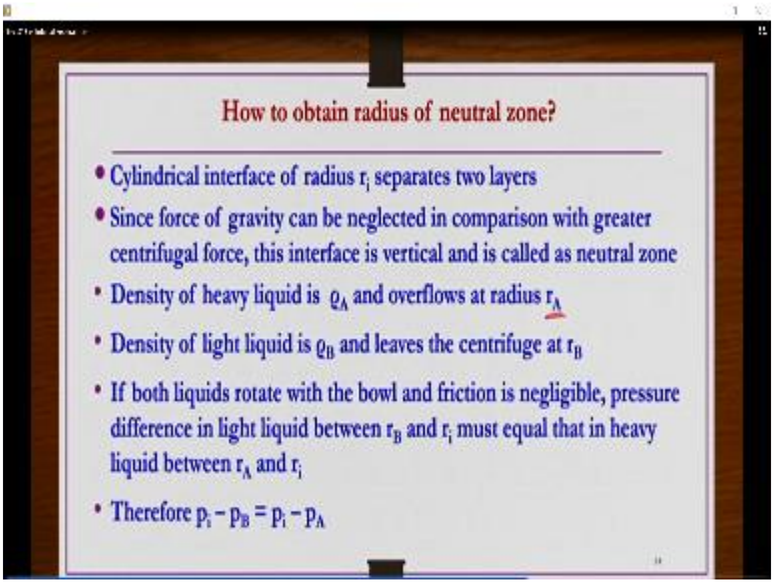

Simialrly, density of light liquid is ρ_B and leaves the centrifuge at r_B. If both liquids rotate with the bowl and friction is negligible, pressure difference in light liquid between r_B and r_A must be equal that in heavy liquid between r_A and then r_i. This is the reason because we need to know the pressure distribution in centrifugal field in order to get these calculations. What we have done, we have previosuly derived $\frac{dp}{dr} = \rho r \omega^2$. So therefore, in order to have this neutral zone to be stable this $p_i - p_B = p_i - p_A$ where p_A is nothing but pressure at the interface there at neutral zone. p_A and p_B are nothing but pressure in the zone A and zone B respectively.

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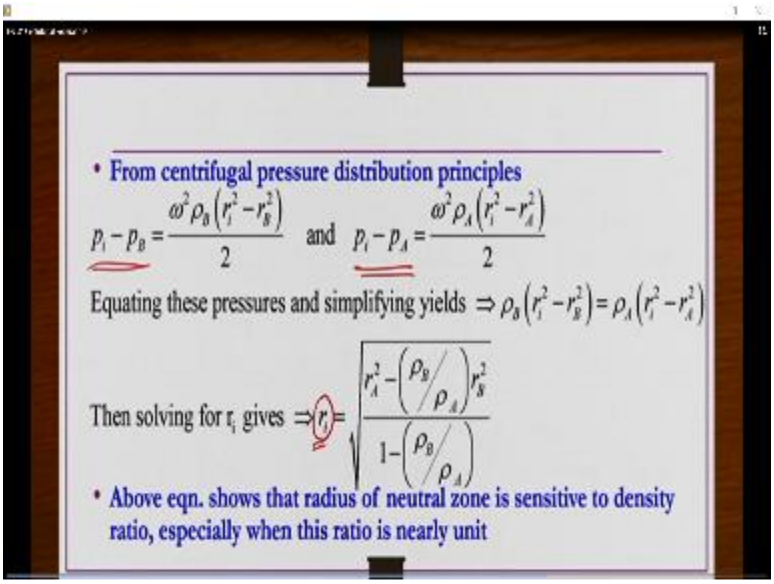

So from centrifugal pressure distribution principles, we have already seen that $\frac{dp}{dr} = \rho r \omega^2$. When you integrate them, then we have $(p_2 - p_1) = \frac{\omega^2 \rho (r_2^2 - r_1^2)}{2}$. That is what we have. So that principle if you apply here, $(p_i - p_B) = \frac{\omega^2 \rho_B (r_i^2 - r_B^2)}{2}$ and then $(p_i - p_A) = \frac{\omega^2 \rho_A (r_i^2 - r_A^2)}{2}$. But these two things are equal at the neutral zone, these two quantities. So then when we equate these equations, you will get $\rho_B (r_i^2 - r_B^2) = \rho_A (r_i^2 - r_A^2)$.

So when you solve this equation for r_i, we will get $r_i = \sqrt{\frac{r_A^2 - (\rho_B/\rho_A) r_B^2}{1 - (\rho_B/\rho_A)}}$. So now we can see (ρ_B/ρ_A). The density ratio of light to heavy liquid is going to play a kind of very vital role in positioning this r_i. So above equation shows th`at the radius of neutral zone is sensitive to density ratio, especially when this ratio is nearly unit. If it is like almost close to 1, so then this value is going to be, denominator one is going to be close to 0. Then it is going to be a kind of very large value and then under such conditions this r_i is going to be unstable.

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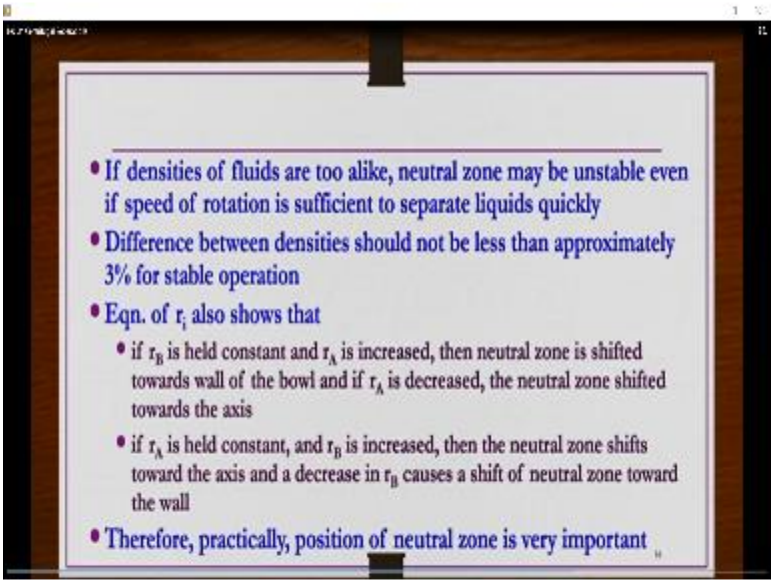

If densities of fluids are too alike then neutral zone may be unstable even if speed of rotation is sufficient to separate liquids quickly. Difference between densities should not be less than approximately 3 percent of, so that to have a kind of stable operation. So equation of r_i from there, what we can understand: if r_B is held constant and r_A is increased, then neutral zone is shifted towards wall of the bowl and if r_A is decreased by keeping r_B as constant then neutral zone has to be shifted towards the axis. So this is the importance of calculation of r_A based on the r_i value.

One can change the locations of r_A and r_B locations so that we can have the effective and then clear separations of these two phases. Simialarly, if r_A is held constant then r_B is increased so that neutral zone shifts towards the axis, and then decrease in rB by keeping r_A constant causes a shift of neutral zone towards the wall. So according to this value of r_i, one can place this r_B and then r_A locations so that the separation of these two phases can be taken effectively and continuously.

Therefore, practically position of neutral zone is very very important. That is the reason we have calculated what is this r_i.

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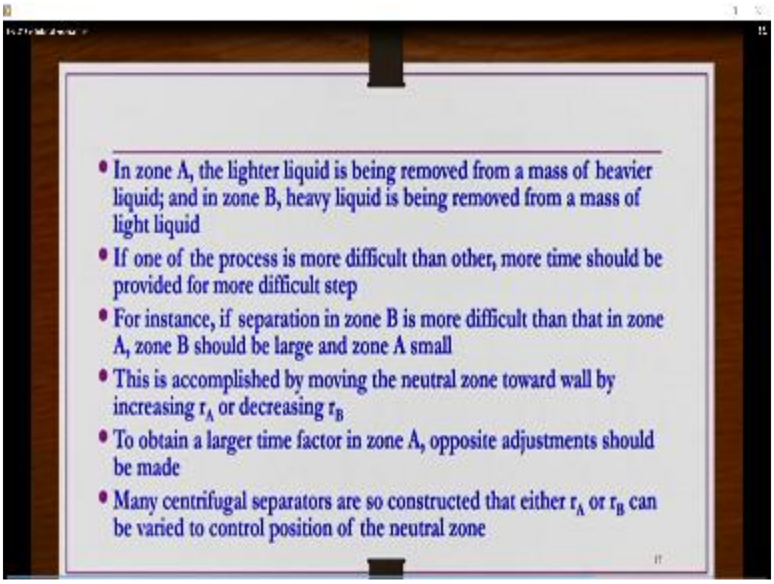

In zone A, the lighter liquid is being removed from a mass of heavier liquid and in zone B, heavy liquid is being removed from a mass of light liquid. If one of the process is more difficult than the other, more time should be provided for more difficult step. Let us say, if separation in zone B is more difficult than that in zone A, then zone B should be large so that more time is there for the liquid to separate and then zone A has to be small. That is the advantage of knowing this r_i information.

This is accomplished by moving the neutral zone toward wall by increasing r_A or decreasing r_B accordingly as per the requirement. To obtain a large time factor in zone A, opposite adjustments should be made that is moving the neutral zone towards the axis of rotation and then decreasing r_A and then increasing r_B. So the opposite one has to be followed. Many centrifugal separators are so constructed that either r_A or r_B can be varied to control position of the neutral zone as well.

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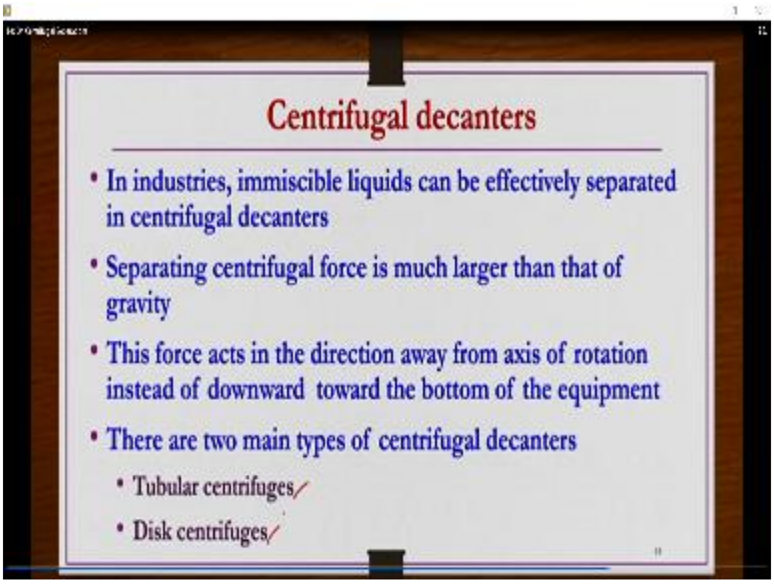

So now we see a few centrifugal decanters – equipments that are used for the separation of immiscible liquids or separation of immiscible liquids and solids from a mixture of solids and immiscible liquids. There are several types of decanters or centrifugal decanters are available. What are they? Some of the industrially famous one we are going to discuss now.

In industries, immiscible liquids can be effectively separated in centrifugal decanters. Separating centrifugal force is much larger than that of gravity, that is the reason centrifugal force are in general applied so that they do separation of immiscible liquids. This force acts in direction away from axis of rotation instead of downward toward the bottom of the equipment as the gravity does. There are two main types of centrifugal decanters: tubular centrifuges and then disk centrifuges. So let us start with the tubular centrifuge.

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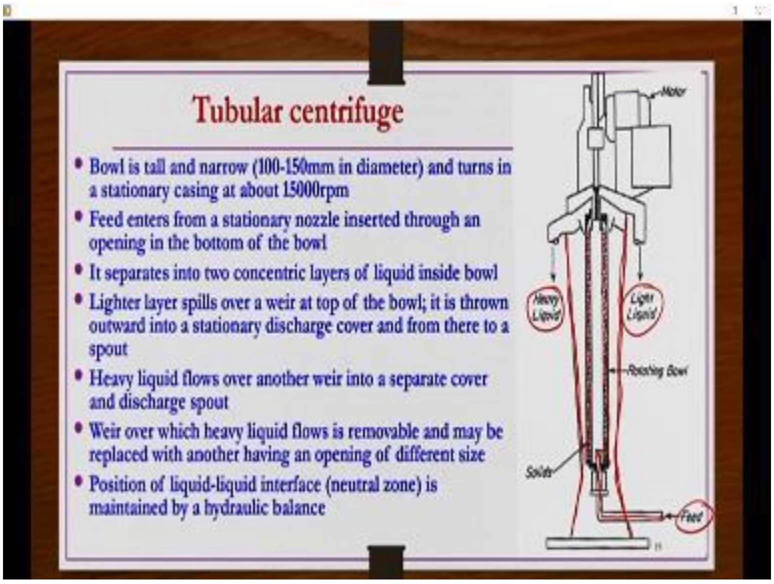

In the tubular centrifuge, actually a kind of a tall and narrow bowl we have. The bowl is having diameter 100 to 150 mm. This bowl is rotating by vertical axis like this. The feed is coming here, continuously like this and then given in this one. So then when this feed is having immiscible liquids, then whatever the heavier liquid is there, that will be thrown towards the wall and then collected from this heavier liquid duct or weir. So lighter liquid is towards this interface of heavier liquid, not towards the wall of the liquid. So from there you know, there is a weir that is connecting to collect the lighter liquid. That is the basic principle and this bowl whatever that we are having, that is rotating at high speed.

Actually, this is the bowl and this is present in a kind of casing like this. So this heavy liquid side wear whatever is there, that can be removable and that can be adjusted as per the requirement. So whether it is tubular centrifuge or disk centrifuge, whatever it is there, the working principle is same. Design, how the centrifugation is done, how the collection of this heavier and then lighter phases has been done, that is the only difference from one design to the other design.

So, here in tubular centrifuge, bowl is tall and narrow having the diameter in general 100 to 150 mm only and turns in a stationery casing at about 15,000 rpm. It rotates at very high speeds. Feed enters from a stationery nozzle inserted through an opening in the bottom of the bowl. It separates into two concentric layers of liquid inside the bowl. Lighter layer spills over a weir at top of the bowl, it is thrown outward into a stationery discharge cover and from there to a spout.

Heavy liquid flows over another weir into a separate cover and discharge spout. Weir over which heavy liquid flows is removable and may be replaced with another having an opening of different size. Position of liquid liquid interface that is neutral zone is maintained by the hydraulic balance. This is about the tubular centrifuge.

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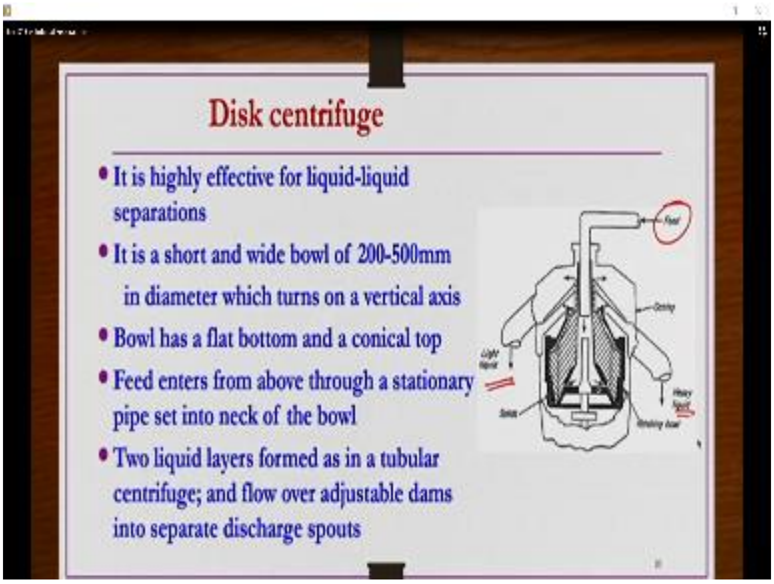

Now disk centrifuges. Here the working principle is the same. Again we have a bowl in which we take the feed and then rotate it so that the feed separates into the two phases – heavy and then lighter liquid phases, like that. But within the bowl what we are having, we are having some kind of conical sheets kind of disks are there. So towards the centre or towards the wall of this or towards the edge as well as towards the centre of these sheets there are kind of holes through which you know, these holes forms a kind of channel so that liquid pass from one sheet to the other sheet kind of thing.

So, it is highly effective for liquid-liquid separations. It is a short and wide bowl of 200 to 500mm in diameter which turns on a vertical axis. The bowl has a flat bottom and conical top as shown here in the picture. Feed enters from above through a stationery pipe set into neck of the bowl. Two liquid layers formed as in tubular centrifuge and flow over adjustable dams into separate discharge spouts. So there is a light liquid discharge spout and then heavy liquid discharge spout is there.

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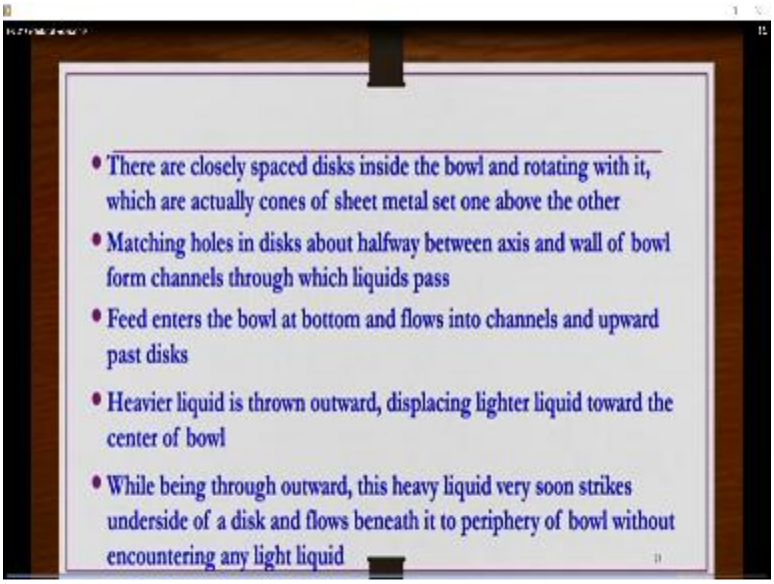

There are closely spaced disks inside the bowl and rotating with it which are actually cones of sheet metal set one above the other. There are n number of conical metal sheets kind of thing are there which are used as a kind of a disk and they are spaced very close to each other. And this set is there inside the bowl.

Matching holes in disks about halfway between the axis and wall of the bowl form channels through which the liquids passes from one disk to the other disk or from the space between two disks to the next space between another subsequent two disks, like that. Feed enters the bowl at bottom and flows into channels and upward past the disk. Heavier liquid is thrown outward displacing lighter liquid toward the centre of the bowl. While being through outward, this heavy liquid very soon strikes the underside of a disk and flows beneath it to periphery of a bowl without encountering any light liquid.

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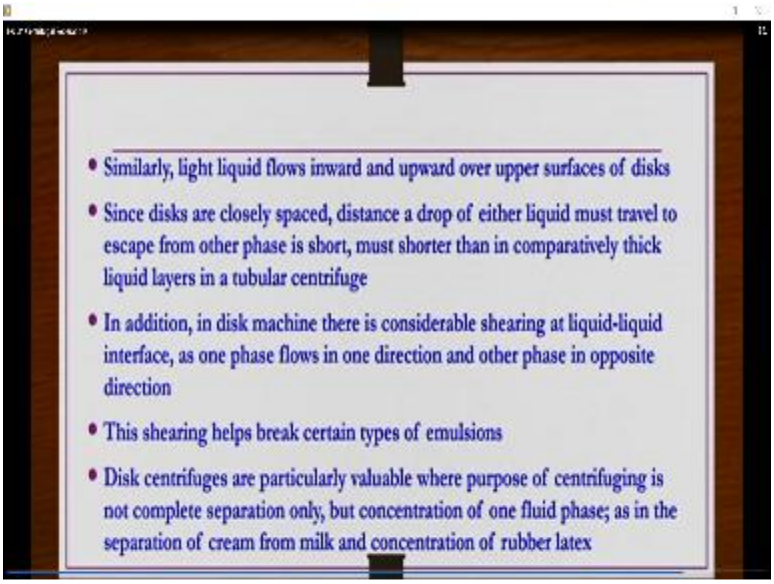

Similarly, light liquid flows inward and then upward over upper surface of the disk. Because of the having this disk what happens, these liquids they are moving into different directions. The heavier liquid is moving towards the wall and then lighter liquid is moving towards the axis of the bowl. So then because of that movement, there is a kind of friction also. Since disks are closely spaced, distance a drop of either liquid must travel to escape from other phase is short, must shorter than in comparatively thick liquid layers in a tubular centrifuge.

In addition, in disk machine, there is considerable shearing at liquid-liquid interface as one phase flows in one direction and other phase in opposite direction. Because of this one, you know it helps shearing, whatever the shearing is there, it helps break certain type of emulsions if at all they are existing in the feed system.

Disk centrifuges are particularly valuable where purpose of centrifuge is not complete separation only but concentration of one fluid phase as in the separation of cream from milk and concentration of rubber latex et cetera.

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Let us say, sometimes if you have solid impurities in the feed, whatever the feed that immiscible liquids that you are separating, in the feed if you have solid impurities then how to clean up in centrifuges. So whatever the disk centrifuges that can be modified so that the solids can also be removed. However before that what we need to know? If liquid fed to disk or tubular centrifuge contains dirt or other heavy solid particle, solids accumulate inside the bowl and periodically must be discharged. This is accomplished by stopping the machine, removing and opening bowl and scraping out its load of solids. That is one way.

But this becomes uneconomical if the solids are more than a few percent of the solids. You cannot afford to have kind of interrupting the process especially in the industry level and then if the solids percent is very high then you are forced to stop the process and then do the separation, so that is not going to be economical. Tubular and disk centrifuges are used to advantage for removing traces of solids from lubricating oil, process liquids, ink and beverages that must be perfectly clean. They can take out gelatinous slimy solids that would quickly plug a filter.

Usually they clarify a single liquid in a bowl provided with but a single liquid overflow. However they also may throw down solids while simultaneously separating two liquid phases. How it is being done, that we see now.

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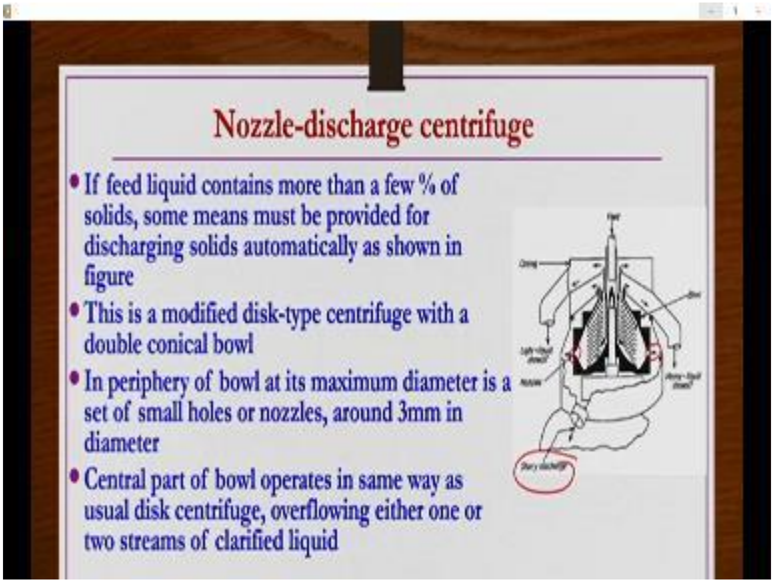

Nozzle discharge centrifuge – it is nothing but modification of a disk centrifuge. That we are going to see, how it looks like. It is like you know, pictorially if you see, it is almost like similar kind of a disk centrifuge but at the bottom there is a kind of provision to collect the solids. If feed liquid contains more than a few percent of solids, some means must be provided for discharging solids automatically as shown in picture. This is a modified disk type centrifuge with a double conical bowl.

In periphery of bowl at its maximum diameter is a set of small holes or nozzles around 3mm in diameter. So at this periphery, what we have is nozzles. We have a kind of nozzles of a very small size like 3mm in diameter, something like that. Central part of bowl operates in same way as usual disk centrifuge, overflowing either one or two streams of clarified liquid.

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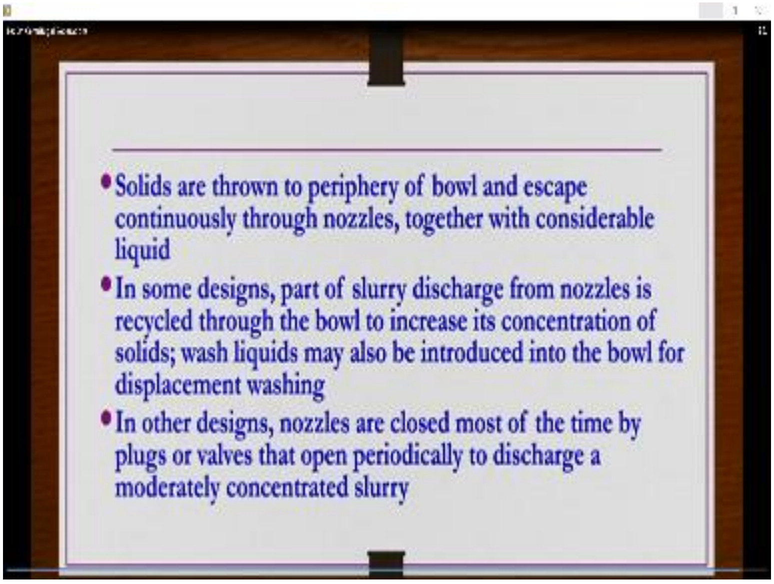

Solids are thrown to the periphery of bowl and escape continuously through the nozzles together with considerable liquid also. In some deisgns, part of the slurry discharge from the nozzles is recycled through the bowl to increase its concentration of solids. Wash liquids may also be introduced into the bowl for displacement of washing as well. So through the nozzle, not only the solids are being discharged but some amount of liquid is also being collected or being taken out. So what happens, this liquid if you want like a dry solids kind of thing, this liquid has to be drained off.

So further what you can do? You can take this concentrated solid sludge again and throw inside the the disk vessel, further separation of the liquid can be taken place. A kind of recycling can be done. In other designs, nozzles are closed most of the time by plugs or valves that open periodically to discharge a moderately concentrated slurry. So this is about the several types of centrifugal decanters.

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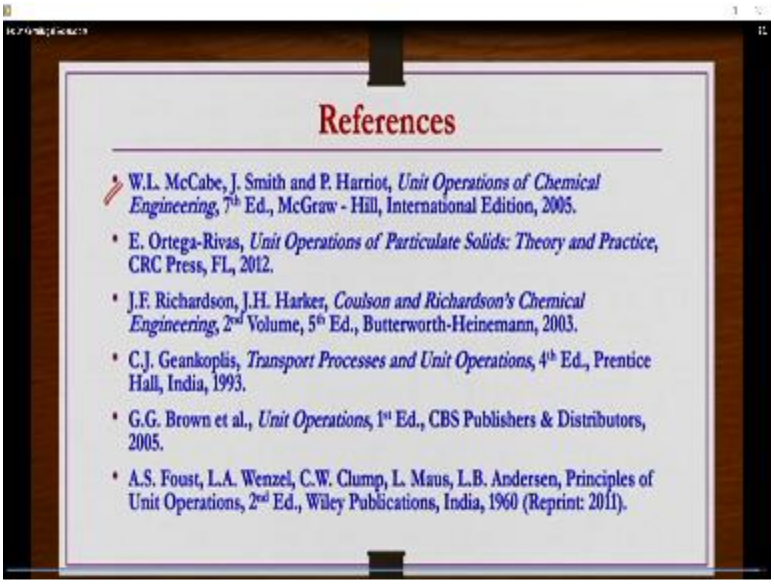

The references, we have several refernces for this lecture. But primarily the lecture, the notes that has been prepared for this lecture can be taken, can be found in this first book, Unit Operations of Chemical Engineering by McCabe, Smith and Harriot. So this reference is a kind of very important reference. Thank you.