Downstream Processing
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Lecture - 8
Solid Liquid Separation

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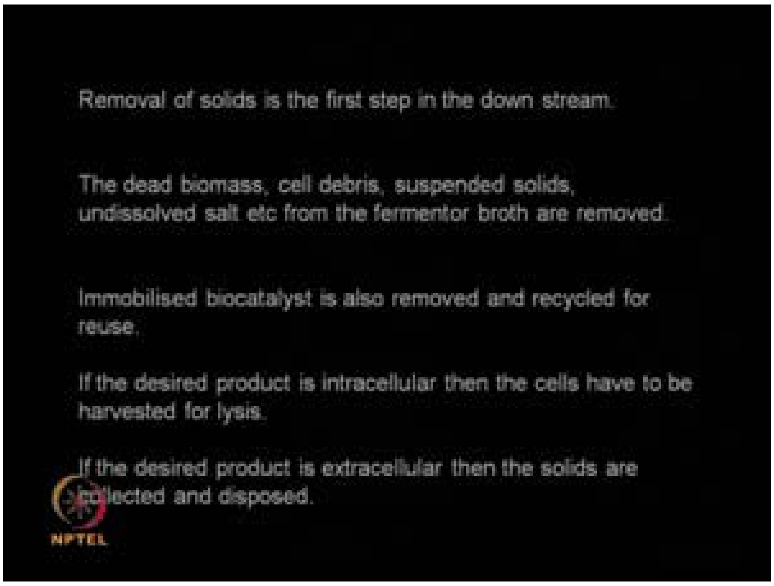

Today, we are going to start a new topic, it is solid liquid separation. This is the generally the first step in downstream process. It can happen immediately after the fermentation or just after a bio transformation. If you look at fermentation you are going to have dead bio mass, cell debris, salts; especially salts which are precipitated out, there could be suspended solids. So, all needs to be removed; we do want to go into any other downstream without removing all these.

Hence, solid liquid separation takes place at this particular stage. If you have immobilised bio catalyst; for example, you have immobilised an enzyme. Then you want to resort to filtration, remove the enzyme and then may be recycle it again. Because especially in the enzyme catalysed processes, the cost of the enzyme is very, very high; you do not want to throw it out. So, you may like to take it back into the bioreactor. So, in such situations also, you would like to resort to solid liquid separation.

If your product is inside the cells; that means, if it is intracellular, then your medium or the broth is of interest for you, it is cells which are interest for you. So, in such a situation, you need to harvest the cells; that means collect all the cells and then resort to cell breakage which we talked about in the past two lectures and so on actually. So, in such a situation, you are interested in the cells and not in the liquid. So, if your products are in the extracellular, you are not interested in the cells; but you are interested in the extracellular medium.

So, all these conditions you need to resort to a solid liquid separation. There are different types of solid liquid separations, we are going to talk about. You must have heard about things like sedimentation, settling, flocculation, filtration, centrifugation. And in filtration you have different types of filtration techniques; similarly, with centrifugation you are going to have different types of centrifugation techniques. So, we will look at each one of them directly in more detail in the next course of lectures.

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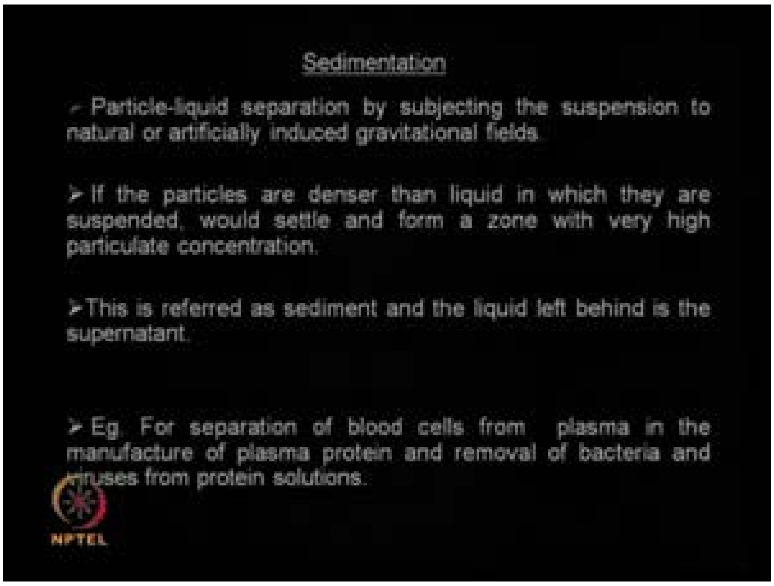

Let us look at something called as sedimentation. So, what are you doing in sedimentation is you are allowing the particles to settle down due to gravitational forces. So, initially particles may be in suspended form, but you are allowing enough time, so that the particles can settle down due to gravitational forces; that is what sedimentation is actually.

So, if the particles are denser than liquid, what will happen? You are going to have all the particles settle down. So, at the bottom you are going to have a very concentrated slurry, mostly of solids and at the top you are going to have mostly clear liquid. So, that is called supernatant and you may just take the bottom which is going to be very strong than the solids.

Especially, if you are interested in separation of blood cells from plasma, if you are going to manufacture plasma protein, removal of bacteria from viruses and viruses from protein solutions. In such situations you are going to resort to this type of sedimentation. In fact, sedimentation is cheapest process; all you need is large vessel which can do this job and enough settling time, so that the solids can settle down comfortably and you get a good separation time solids and a super clear natant at the top.

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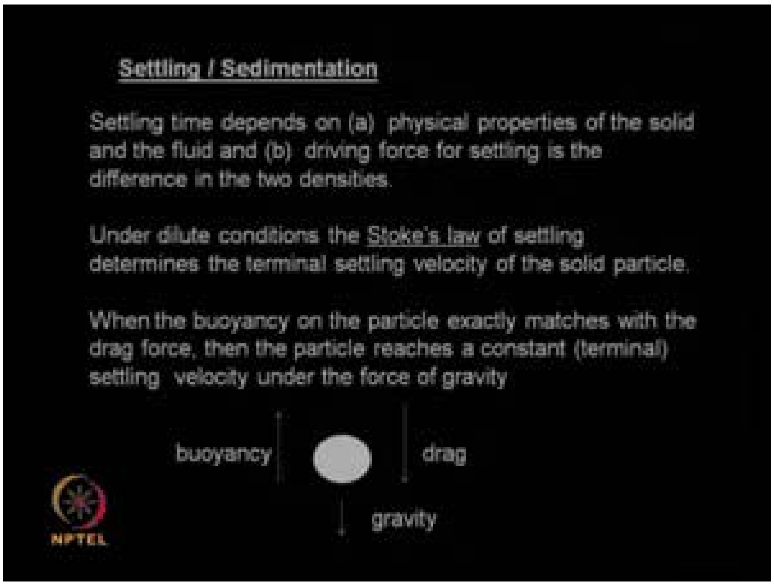

So, the settling time of the solids depend on couple of important parameters; physical properties of the solid. That means things like density, the size of the solid, porosity of the solid and the driving force for the settling. That means, the difference in the density is between the solid and the liquid. If the difference in the density of solid and liquid is very large then you are going to have a good settling. If the difference between the density of solid and liquid is very small then settling is going to be very slow.

So, you need to give enough time. So, under dilute condition the law which governs the settling solid is called the stokes law; you must have all studied stokes law long time back may be in your first year or even before in your schooling as well actually.

So, stokes law gives you an idea of terminal settling velocity of solid particle suspended under medium, under dilute condition. Why do you say dilute condition? If the slurry is very high that means if the slurry concentration is very high there could be interaction between one settling solid and another settling solid. So, it is not going to be completely free from the interaction that is why we call it dilute conditions.

So, what are the various forces that are acting on a solid which is freely suspended in a liquid; many things are happing one is the buoyancy you must all have heard about buoyancy of the solid. So, buoyancy depends upon the density of the liquid as well as the volume displaced by the solid correct. So, we have studied I think in our school.

Then, there is the drag force; the force which is trying to slow down the movement of the solid; and this depends upon the surface area of the solid correct. And then the solid is settling why it is setting it is settling because of the gravitational forces. So, if all these match then we are saying that the solid is reaching a terminal settling velocity. So, as soon as a solid enters a large liquid medium which not going to reach a terminal setting velocity. But once all these forces balance it is going to reach a terminal setting velocity.

And, that velocity is going to be constant that determines how long the solid will take to reach the bottom of the vessel. So, why is it important once I know what is the terminal settling velocity? And if I know size of my vessel that means if know height of my vessel; I will know how long it will take to reach the bottom. So, I can decide that I carry out the sedimentation or setting for so many minutes hours depending upon the terminal settling velocity and the dimensions of my vessel.

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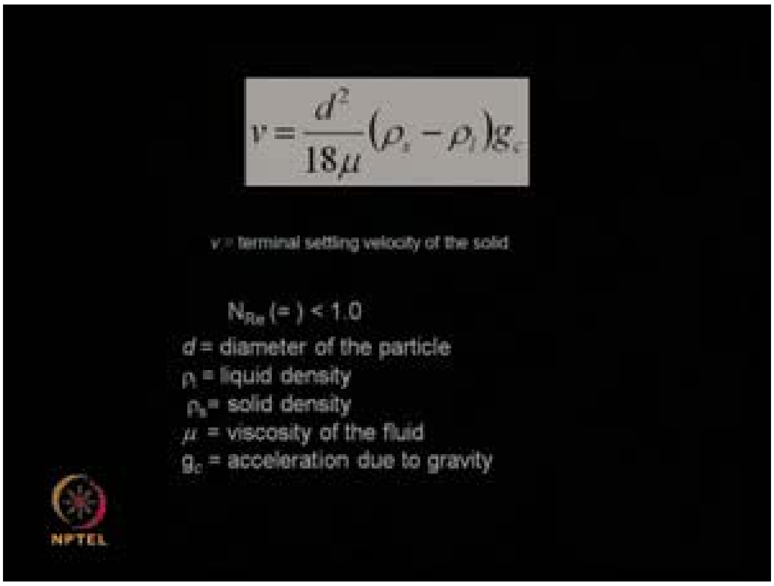

So, if you balance all these you get a relationship which is shown above and this is based on your stokes law. This is the terminal setting velocity v on the left hand side and then we have many terms on the right hand side with which determines the terminal settling velocity; d the d is the diameter of the particle. And you have some term in the bracket that this is the driving force difference in the density between the solid and the liquid. So, this is the driving force if this number is very large the terminal settling velocity is going to be very large.

And, if this number is small is very small and at the bottom we have a term mu which is the viscosity of the fluid. So, if the viscosity of the fluid is very large that means its preventing its dragging the solid from settling. So, if the viscosity of the fluid is very low then it will settle down nicely. So, if I am doing settling in aqueous medium plane water it may be very large. But then when I have cell debris, dead bio mass, DNA and so on my viscosity of the fluid goes up because of these bio molecules. So, the settling will become much slower.

So, if you are carrying out experiments in your lab and you test the settling of a solid in water. And when you test it out in a fermentation broth both are going to be very different yet we have to be very careful on that. Because a fermentation broth will contain all the cell, debris, intracellular medium, intracellular material and so the viscosity goes up.

And hence the settling velocity will be less unlike doing a settling study in a pure water medium. So, this equation table tells you that the velocity is directly proportional to the diameter square of the particle, inversely proportional to the viscosity, directly proportional to the difference in the density; and g is of course acceleration due to gravity you all know that right.

So, this is valid only for dilute conditions and for very low Reynolds number. You all know what is the Reynolds number? Reynolds number is a function of the physical properties of the particle. So, Reynolds number is given by d e row by mu; d is the diameter of the particle, v is the velocity, row is the density of the fluid and mu is the viscosity of the fluid and it is valid only Reynolds number is less than 1. That means that at very low velocities not at very high velocities. If the velocity is very high you create a turbulence then you cannot use this particular relationship. If the velocity has to be low then this particular stokes law is valid.

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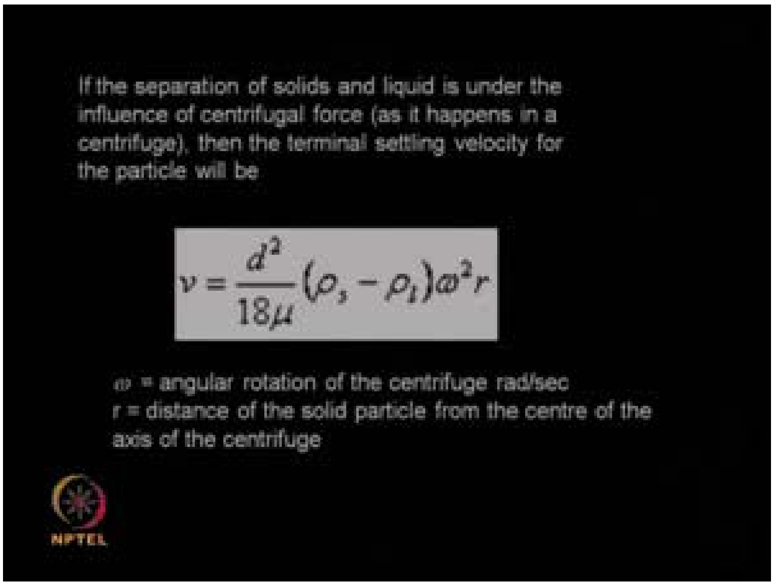

This is with respect to settling taking place under the influence of gravity, but supposes I have a centrifugal force as is the case in a centrifuge. Then how will that settling vary? If you look at the previous equation if you remember and this particular equation you see that there is one small difference the omega star r term here; the omega r square term whereas in the settling in the influence of just gravity you have g c. So, that is the only difference between settling taking place under the influence of gravity, settling taking place under the influence of centrifugal force that is the only difference. Because the centrifugal force is almost equal to the gravity.

Now, here if you look at the centrifugal force it is made up of 2 terms the omega that is the angular rotation of the centrifuge radians per second. And r is the distance of the solid from the centre of the axis of the centrifuge. So, if r is large that means particle is far away from the centre of the axis of the rotation then your settling velocity will also be high; it is like a centrifugal force.

So, if you are very far away from the centre you can feel the force much higher. So, if I have very large rotation speeds; then I can have very large terminal settling velocity. So, that is the advantage of the centrifugal settling when compared to a gravitational settling. In gravitational settling we cannot go beyond g right g c is number fixed whereas here in centrifugal settling I can keep on increasing rpm of centrifuge.

So, by increasing rpm of my centrifuge my omegas goes up. So, I can achieve very high terminal velocity that is in my laboratory generally I do not do gravitational, separation of cells and broth. I use a centrifuge by doing that I am creating very large force. So, that these separation velocities is very high understand.

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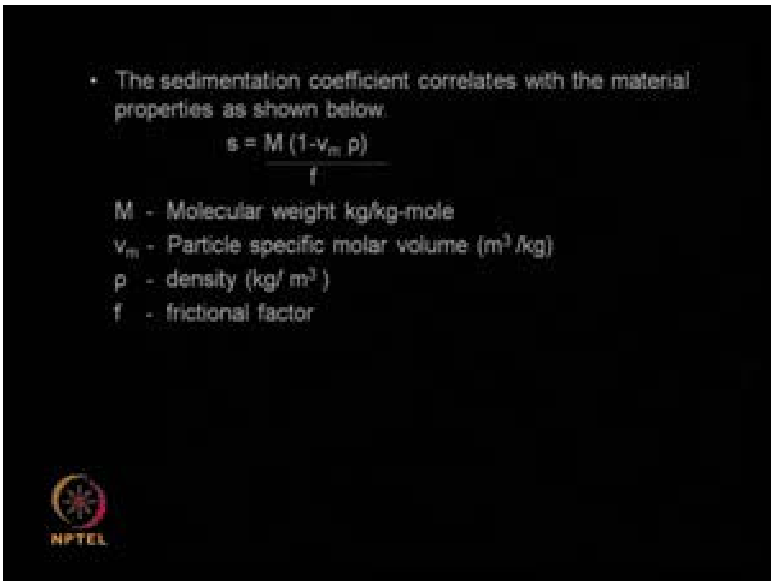

So, there is something called a sedimentation coefficient; which is function of all material properties which we talked about actually. So, the sedimentation coefficient is nothing but the molecular weight of the material or the solid which we are talking about; and then particle specific molar volume. Particle specific molar volume is nothing but inverse of the particle density. And then we have something called frictional factor; frictional factor is function of the physical surface properties of the solid.

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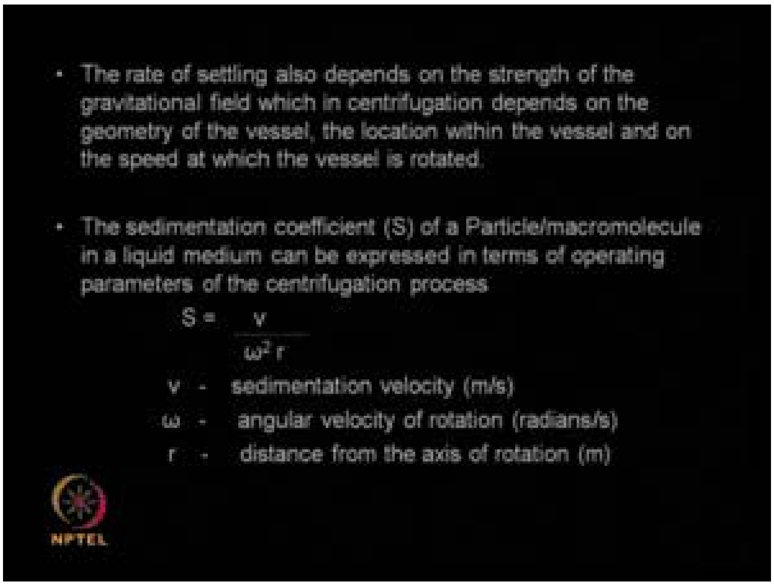

Now, so the sedimentation coefficient of a particle liquid medium can be expected in terms of many operating parameters in a centrifuge. For example, if I do it in a centrifuge separation and it is depend upon the omega the r; r is nothing but the distance of the particle from the centre and V is the sedimentation velocity. So, the sedimentation coefficient of differs when I am performing the settling and influence of gravity or when you have a centrifugal force in place actually.

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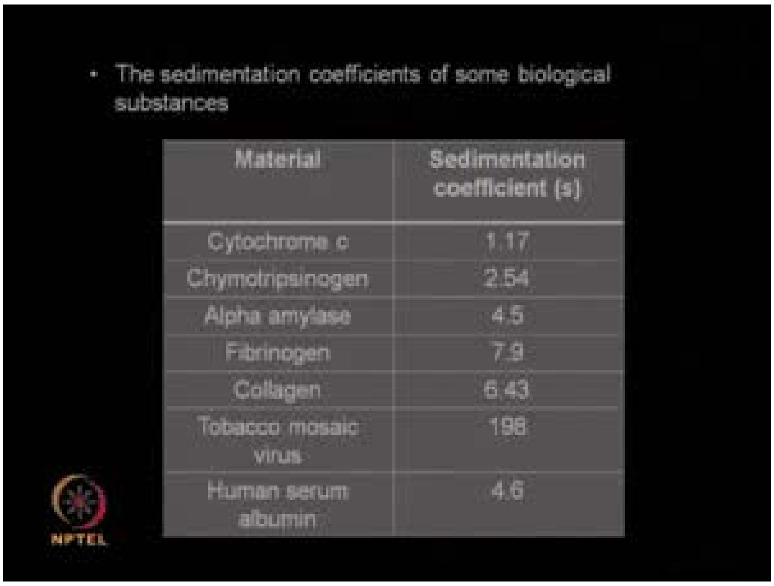

There are several sedimentation coefficient values that are given for a wide range of material. For example, if you see cytochrome c; sedimentation coefficient is about 1.1 second, collagen we are talking in terms of 6 second. If you are talking about tobacco mosaic virus another 98 seconds, human serum albumin talking in terms of 4.6 seconds.

So, you can see large variation sedimentation coefficient almost starting from 1 second going up to around 200 second. So, there is 200 times the difference in this sedimentation coefficient. So, the sedimentation coefficient also determines the terminal settling velocity; as I had mentioned before actually its sedimentation coefficient depends determines the terminal settling velocity.

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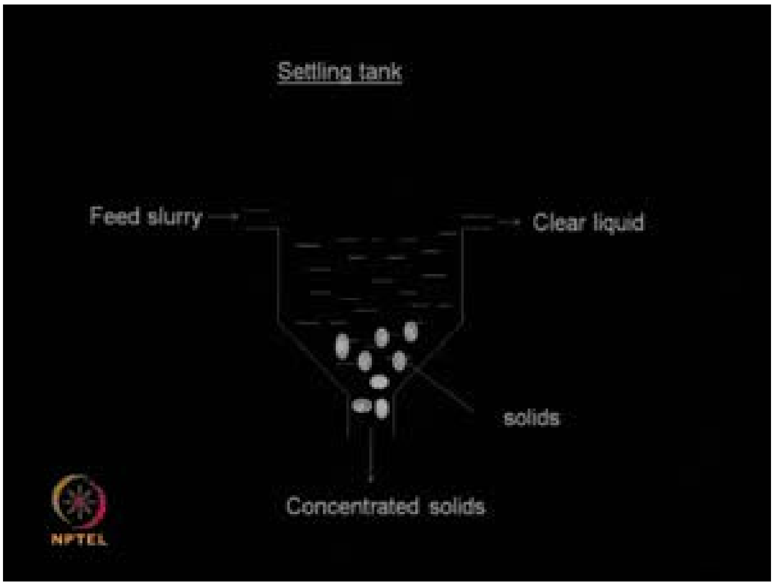

So, in a settling tank what do you do? You introduce a feed slurry which contains solid as well as the liquid; and there is a large tank. And you allow solids to settle down based on the terminal settling velocity the solids will take so much time from the top and reach the bottom. So, in the bottom you are going to have concentrated solids which can be slowly discharged. And on the top we have the supernatant which will be mostly clearly liquid which can be taken up; and then you can do other downstream operations. So, this is a simple set up for performing a settling operation or a sedimentation operation.

So, you do not need extra energy to carry out this particular unit operation; and you do not need any fancy equipments also to carry out all these unit operations. So, that is why it is advantages. But then you need to put in lot of time because the settling take space because of the gravitational forces. So, the terminal settling velocity are also much less. And hence time also is much higher unlike a centrifuge where you can achieve very high settling velocities. Because of the omega square r term coming instead of g term coming in settling in a gravitational situation.

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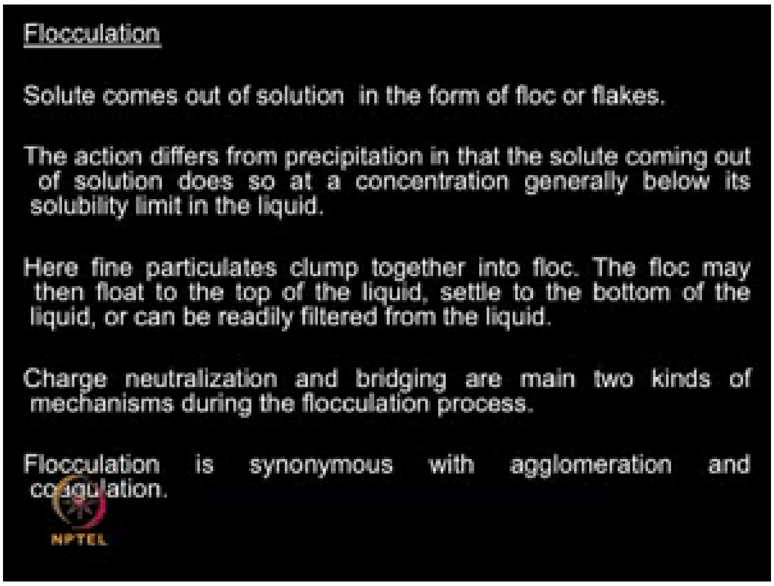

Now, another technique for separating solid and liquid is called flocculation. So, when you have particles very small particles 0.1 micron size particles; they do not seem to come closer and agglomerate. But this seems to be moving around inside the liquid medium because of the electrostatic forces electrostatic repulsions. So, the because the particles are so small they do not get enough terminal settling velocity them to settle down. So, that is a big problem.

So, what do you do? You need to neutralize these electrostatic forces. So, if you can neutralise these electrostatic forces they can come together they can collaborate. And they will start agglomerating; once they agglomerate they can settle down nicely. If they are very heavy or they can form big lumps and stay on the top of the liquid medium itself. So, they form floc or sometimes they are also called flakes.

So, the flocculation is not exactly like precipitation there is different between flocculation and precipitation. Precipitation happens when the concentration of the solid matches with the solubility. So, beyond that value whatever is present will come out as the solid liquid medium. So, that is called as precipitation whereas here in concentration in flocculation is much less than the solubility limit in the liquid. That means, they have still not you can still dissolve that solid; if you use some other means; the liquid medium which has not reached is saturation limit for the solid.

So, ones you remove the electrostatic repulsion and forces the solids get aggregated they form flock. So, that they can either float on the top forming big lumps of floccus or they are called flakes. They are very heavy when compared to liquid they can settle down at the bottom. Then it is almost like sedimentation the bottom will contain concentrated solid, top will be containing the clear liquid.

So, how do you do this? You can add large number of different types of chemicals which can neutralise the present on the surface of these fine solids. So, during the flocculation process 2 things happen; neutralisation and bridging. So, these are 2 mechanisms that take place during this process actually. So, you can call it agglomeration, you can also call it coagulation. So, all these names are synonymous to each other actually.

So, many flocculants has been tested. And depending upon the types of solids you are processing, you can use different types of flocculants. So, when you say different types of solids the type of charges that are generated by the solid surface; you use different types of flocculants.

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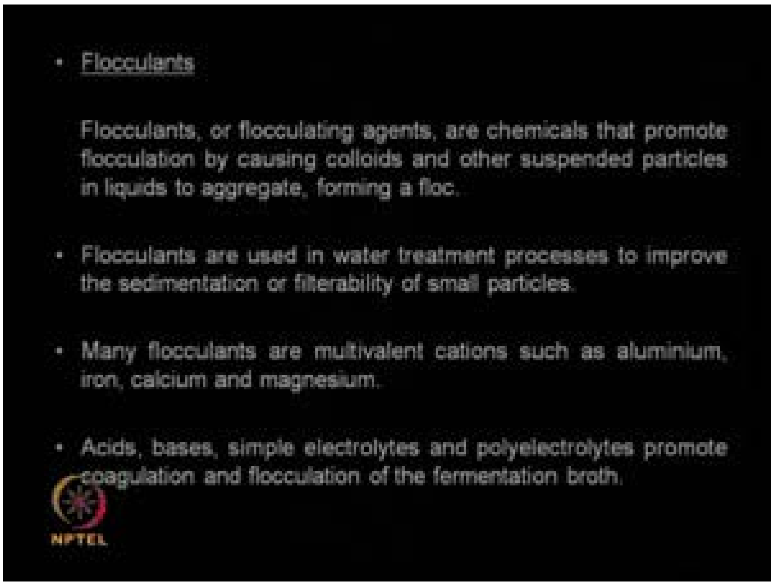

So, they are generally chemicals flocculants are used in water treatment chemical quite a load. So, water before it is sent to domestic use; generally they use flocculation type of downstream to remove whatever suspended solids that are present. And then the water for domestic purpose is chlorinated to kill all the viruses. Because the water will contain lot of fine solids which will not settle down actually. And you cannot filter solid which is so small; it is not possible to use any type of filtration. So, that way flocculation is adopted.

So, generally these flocculants are multivalent cations of aluminium, iron, calcium magnesium; so lot of multivalent. So, it can be even acid, bases simple, electrolytes, photo electrolytes all these; they all promote coagulation. And also they help the flocculation of the broth; if you are performing downstream after a fermentation operation.

For example, in the manufacture of a ethanol; after the fermentation you will find suspended solid and which will be just floating and it will not settle down. Because of the size as well as because they are lighter. So, there you need to resolve some type of flocculation downstream processing. Sometime even long chain polymer flocculants are also added.

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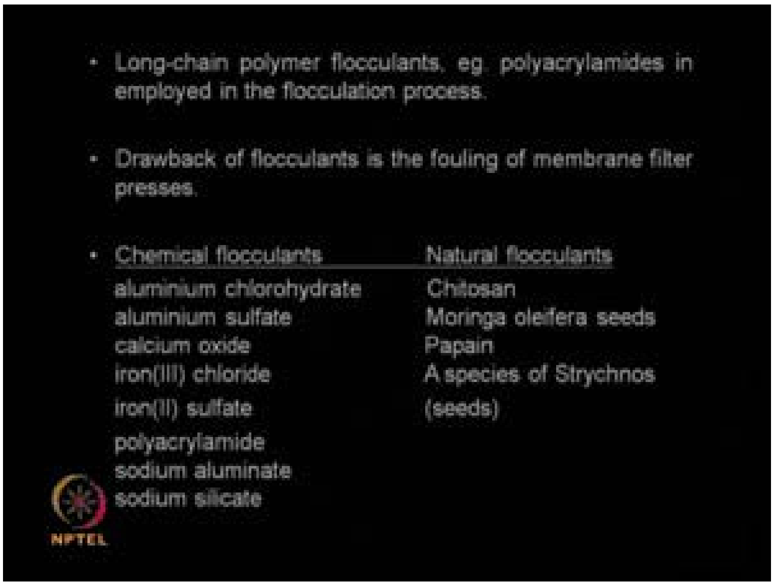

For example, poly acrylamides they have also been tested as flocculants, flocculent or a flocculating agent and they have found to be very good. Of course, there are some draw back. If you are resorting to membrane filtration after flocculation these flocculants may go and foul your membrane surfaces. So, that one problem actually. And other thing is flocculants itself could be material which may be destroying your proteins or any other product of interest. So, that is a big problem you need to consider.

So, there are types of flocculants; chemical flocculants, natural flocculants as the name implies chemical flocculants are synthetic chemical which are synthesised in your or manufactured whereas natural flocculants are naturally available material. Aluminium chlorohydrate, aluminium sulphate, calcium oxide, ferric chloride; all these are possible chemical flocculants even iron sulphate that is ferrous sulphate whereas if you look at the natural ones chitosan, oleifera seeds, papain and large number of seeds have been tested.

And some more chemicals these all are acrylamide as I mentioned these are polymerade, sodium aluminate, sodium silicate they are some more chemical flocculants. So, large number of chemical flocculants are available in the market; and one could test out depending upon the type of application.

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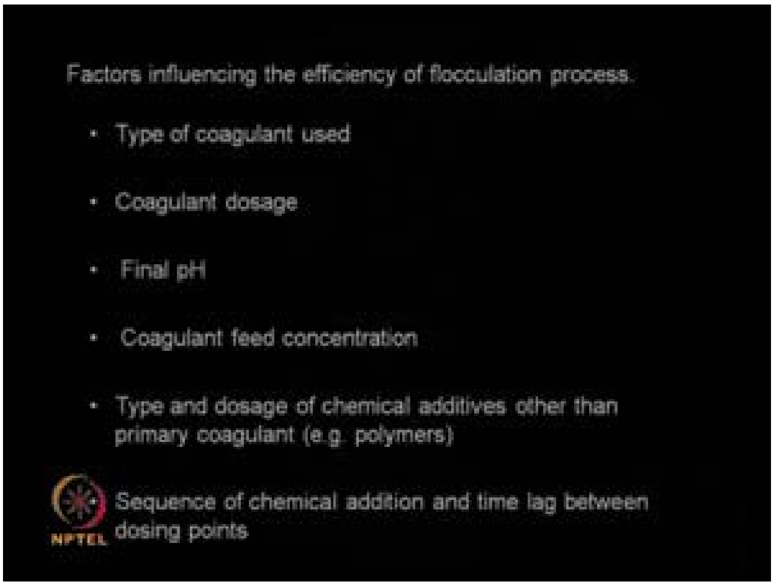

So, what are the factors which influence this flocculation process large number of flocculation process; the type of the coagulant or the flocculant used to perform these operation; the amount of coagulation you are using the PH. Because I mentioned flocculation happens because charges and because of electrolyte forces. So, the pH has very strong effect on the charge. So, the pH can either enhance or speed up the floc formation or they can retard or slow down.

So, the coagulant feed concentration. How much of coagulant feed I need to add? So, what other additives I am going to add apart from the coagulation. Example am I going to add any polymeric material, am I going to add some adsorbent. So, all these needs to be also considered because they all will have an effect on the your efficiency of flocculation process.

Then sequence of addition. So, am I going to add one flocculating agent followed by after certain time period, am I going to add again and the same? And what will be the gap between each addition or dosing? So, all these will have an effect on the efficiency on the process. And then once I have added these flocculent; how hard am I mixing the flocculent with the broth.

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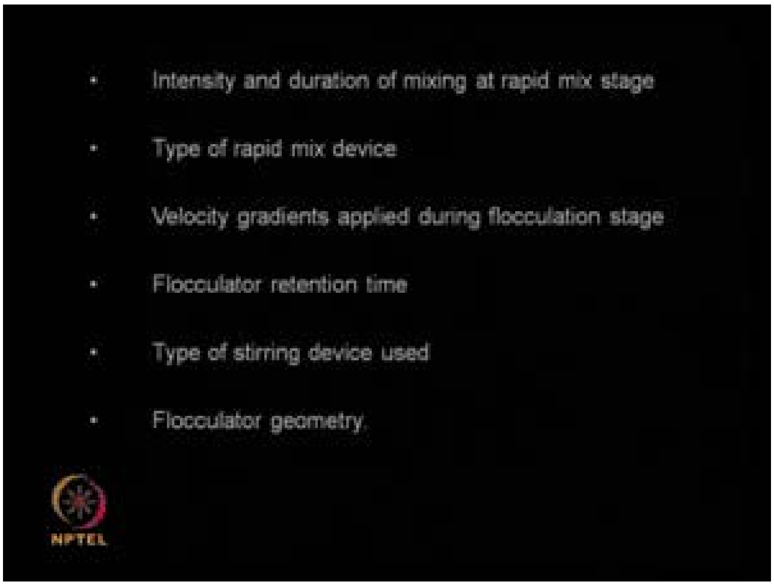

And, what is the duration of mixing that will also have an effect on that. What type of devices we use for performing these mixing operation are we creating any velocity gradients during this flocculation stage. How long the flocculator material will remains in the flocculation or a flocculator? Type of stirring; I used am I using a agitator. What type of agitator I use? And then the flocculator geometry am I using a cylindrical vessel for performing the flocculation or am I having a conical vessel and so on actually.

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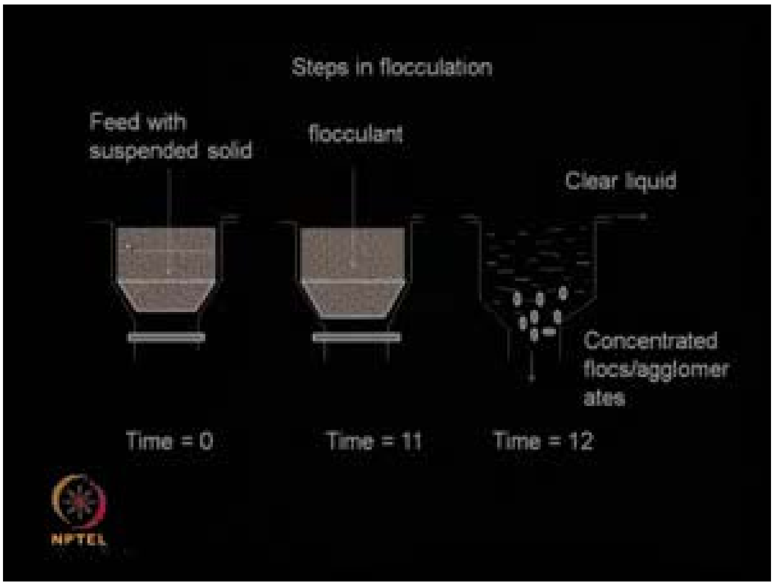

So, what are the different steps in flocculation? So, initially say at time 0 you are adding your slurry which contains suspended solids. Then after some time you are adding your flocculent; then that dozing your flocculent. Then you may be agitating then stopping the agitation allowing the floccus to form. Then once the floccus are formed and if the floccus are heavier than the liquid what will happen they will start settling down.

And the bottom will have the floccus and the top will be clear liquid. But whereas, if the floccus are lighter than the liquid; then they will be floating as 2 layers will have a clear liquid at the bottom and the floccus at the top. So, we need to just remove the floccus at the top and we can collect all the clear liquid from the bottom.

So, depending upon whether the floccus that is forming is denser than the liquid medium or it is lighter than the liquid medium the floccus will be either settling at the bottom or will remain at the top. So, you have to add the flocculating agent; you need to perform certain agitation, you need to allow the floccus to coagulate or come together. If it is going to be settling then you need to give some more time for them to settle down and reach the bottom of your flocculator. So, there are many small time steps which are involved overall cycle time is a combination of all these or a summation of all these various times.

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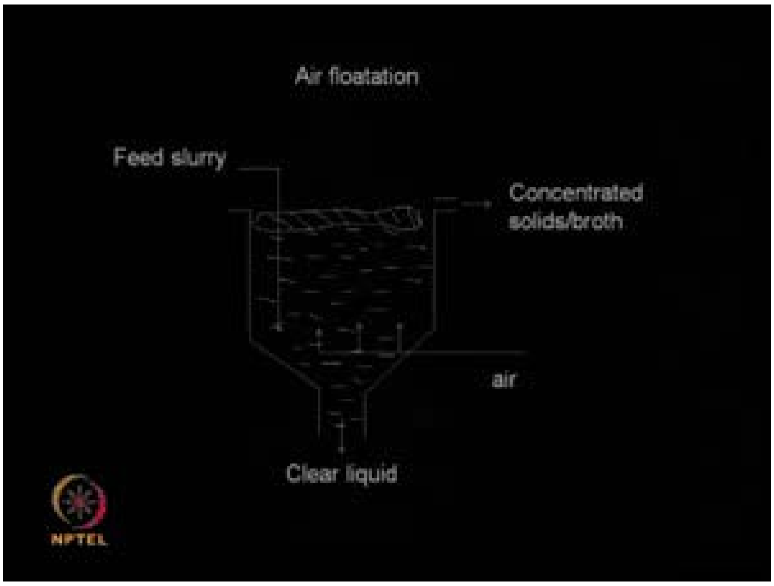

There is another technique which also can help the flocculation process that is called the air flotation. Here again you have very fine solids which are not coming as floccus. And settling down you do want to add any chemical to do that. And the solids may be lighter than the liquid that means the density of the solid may be less than the liquid density. So, in such a situation you may be passing air and the air may help to form floccus or froth which may float at top of the liquid layer.

The broth of the concentrated solids of the froth can be skimmed out from the top it is almost like the froth that is forming on top of milk; it can be skimmed out and bottom will be clear liquid. So, advantage in this technique is you are not adding any flocculant; all you need is air which needs to be come from bottom. This type of technique is quite used in environmental applications if you want to remove solids which are not at high concentrations and which are very light.

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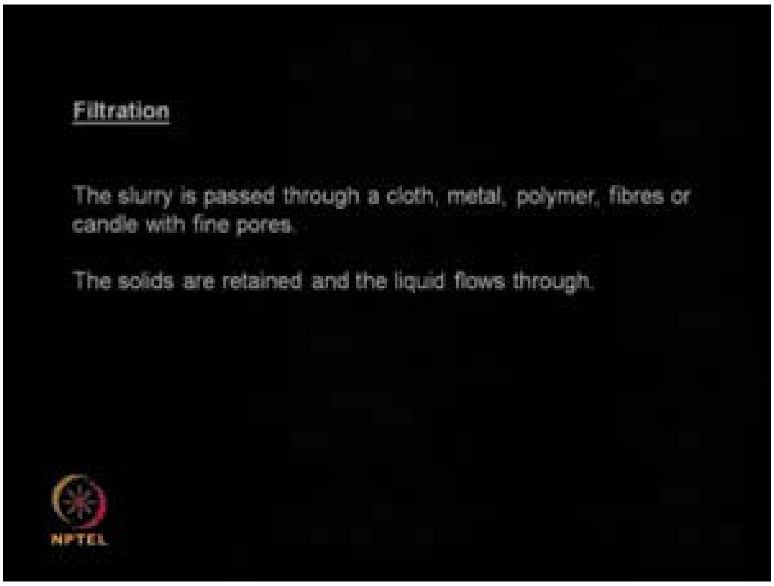

The next solid liquid separation process is the filtration. So, there are different types of filtration and we can use different type of material for performing for filtration process. You can use a cloth, you can use metal discs, we can use polymeric membrane, we can use fibres, candles with fine pores like at home where water purification system they have candles, ceramic candles which will have pores, which will hold solids. And liquid passes through it and get clear liquid. Sometimes stainless steel candles are used if the solids is very abrasive. So, the solids will be retained and liquid flows through. So, we all have seen a filter for a very long time at various locations for various purposes.

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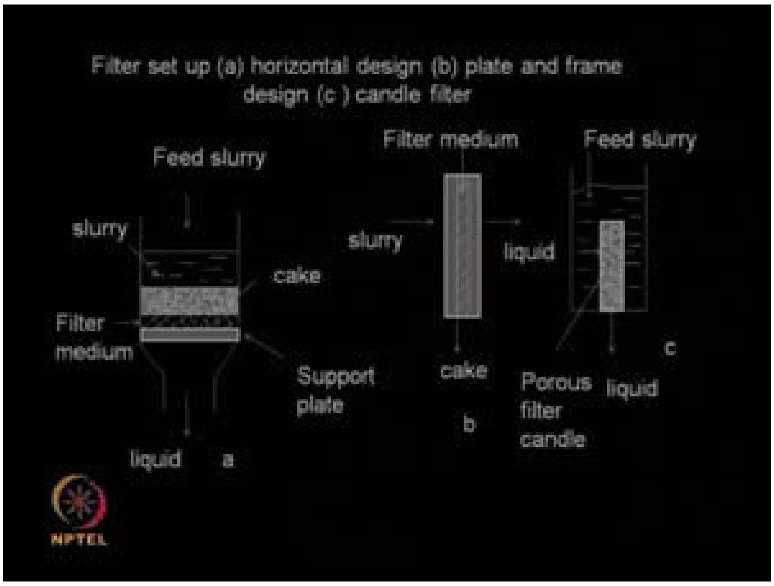

So, it is nothing new for us. There are different types of designs for filtration. So, you can have a filter medium this could be your cloth or this could be your metal centred disc or even membrane. So, the feed slurry is fed here, the cake is forming here and the liquid flows through the slurry. And the clear liquid comes here on this side this is typical design of a filtration assembly.

So, this a batch operation that means after some time there will be so much of cake that forms here the liquid flow will get slower and slower. And after some time there will not be any liquid flow. So, what we have to do? We need to stop the filtration process and we need to clear the surface of your cloth. And then restart the whole process once again actually.

Another design this is called plate and frame design; that means you have plates here and we have the cloths which is supported between 2 plates. So, the slurry flows through it and the solids are retained and the clear liquid flows. So, it is called plate and frame. So, I can many plates and frames in parallel. So, that I can perform these particular task on a higher scale.

The third design is your candle filter this is almost like the setup which you may have in your house hold. So, you have a candle a porous candle; it could be a ceramic, it could be even stainless steel. So, the speed slurry comes in and then the liquid flows through solids are retained; because of the size of the pores and the clear liquid goes down.

So, we seen different design of filtration where you can separate solids and liquid. In all these design if you see once the amount of solid build up is very high; liquid flow will stop then you need to clean the surface of the filter. So, that you can again start the process once more. So, it is almost like a batch operation it may run for 1 day, 2 days, 3days even 10 days and after that you need to clean your filter surface. So, this depends upon the concentration of the solids present in your slurry.

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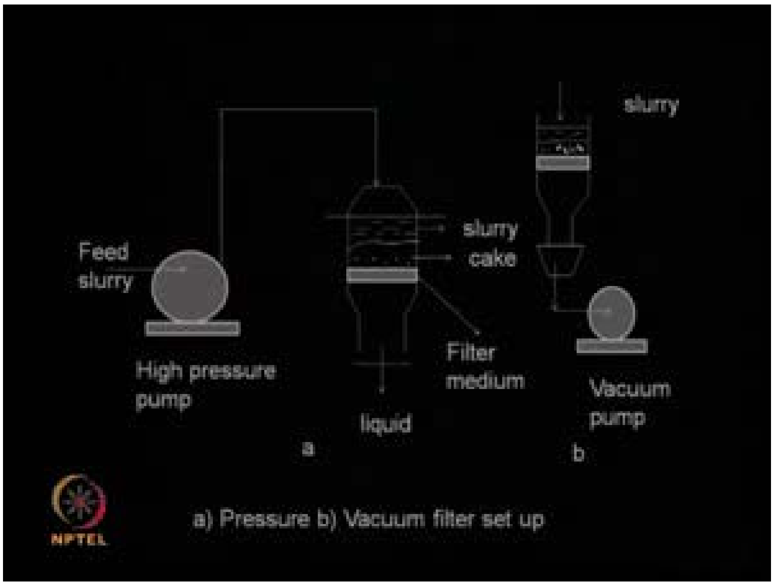

There are 2 ways by which I can do this job; I can do it through pressure or I can do it through vacuum. So, for example this is your filtration assembly; I have the filter medium here and I feeding the slurry at high pressure. So, the cake is formed on top of by filter medium and the clear liquid is flowing down. So, I can increase the pressure of the pump there by I can force more liquid to flow through. In this design I am applying a vacuum in the downstream or the filtration setup. So, I have that filter medium here, the slurry comes here, the liquid is sucked by the vacuum pump present here and the cake settles down at the top.

So, I can increase the vacuum; so that I can force more liquid to flow through the filter. So, this is the pressure system and this is the vacuum system. So, the amount of pressure I can apply depends upon the filter medium. If I am using a cloth; cloth may not be able to take very high pressure whereas if I am using a stainless steel filter then it may take up very high pressure. So, I can apply very high pressures if I have a stainless steel type of filter.

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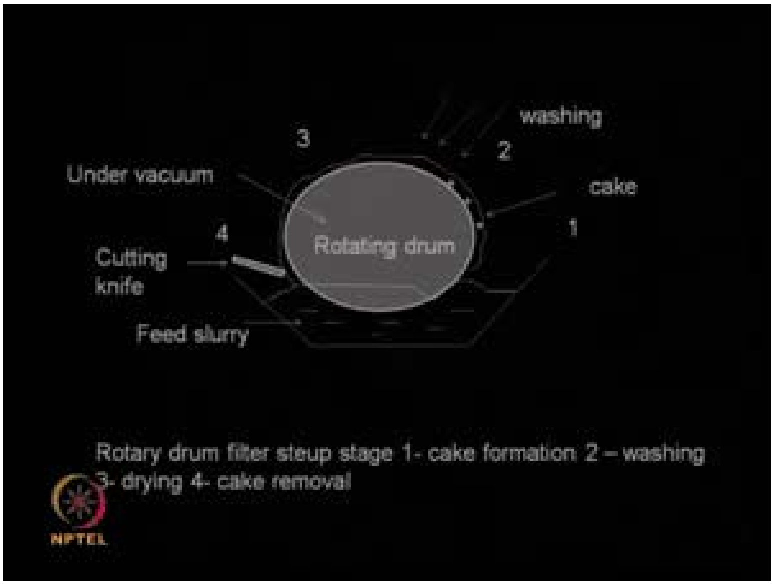

Another design is called the rotary drum filter where I have a rotating drum. And this rotating drum is immersed inside a bath containing a slurry. Slurry means I have the solid and the liquid; so the drum is slowly rotating and there vacuum inside the drum. So, the liquid gets sucked inside and the solids are retained at the top. And generally the solids attached to the surface when the drum is immersed inside the slurry tank. So, here you have a wet cake.

Now, if the solids contain some impurities which you would like to remove we perform something called washing; I can wash it with water or I can wash it with solvent which will remove the impurities. So, here I am washing and this is again sucked inside the drum and here we allow the solids to dry. And finally here we are cutting the solids out using a cutting knife. So, the solid sort of gets scraped of the rotating drum and once more the drum gets immersed inside these slurry tank.

And, once more the slurry gets sucked in that means liquid gets sucked in solids form a cake; and the cake once more goes up which gets washed which gets dried, which gets cut. So, this happens continuously. So, I can do this type of rotary drum filter operation in a continuous mode. So, I can continuously keep on adding slurry in side this slurry holder and I can continuously get wet solid out. So, the advantage of this is continuous operation number 1 and number two I can wash the solids using the medium like water or solvent which will remove some impurities that are present in my solid. So, that is advantage number2 with this setup. We are going to talk about each one of these unit operation in more detail. And we will also look at the design equations for designing this type of setup.

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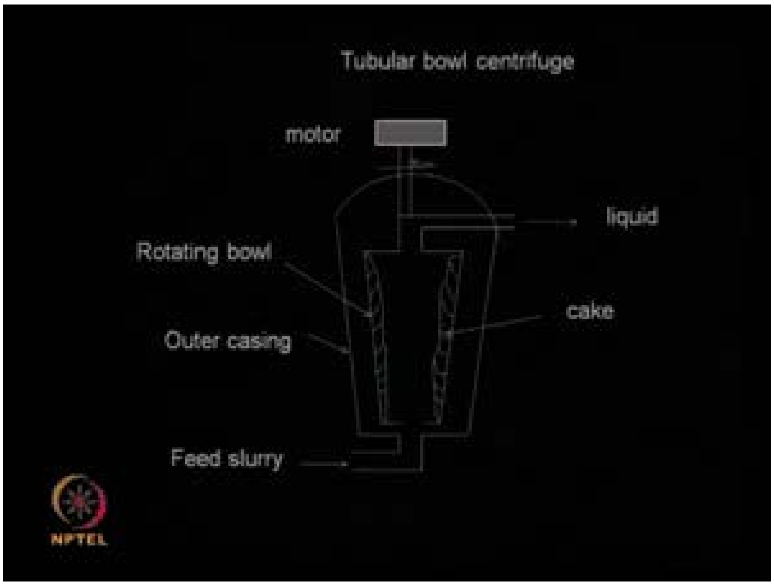

Lets us also look at some more solid liquid separating units. The next one is tubular bowl centrifuge this operates based on centrifugal force. So, you have bowl inside which rotates at very high rpm. So, you are sending in a feed slurry which contains both your solid and liquid; and because this is rotating and the solids face a centrifugal force. So, they are thrown out and they form a cake at the surface of this cylindrical vessel. And you get the clear liquid out here. So, the rotating bowl starts slowly collecting the cake. So, once the cake is built up we need to stop this particular unit operation and you need to remove all the solids.

So, this is called bowl centrifuge; this is good for very dilute slurry solution not for very concentrated slurry solutions. Because the cake built up will be so fast that you need to stop, start, stop, start, stop and so on actually. So, this very good for a dilute solutions this is called a tubular bowl centrifuge. So, you have a long tube which rotates at a very high rpm; the solids attach to the walls of this rotating cylindrical tube and the liquid flows out.

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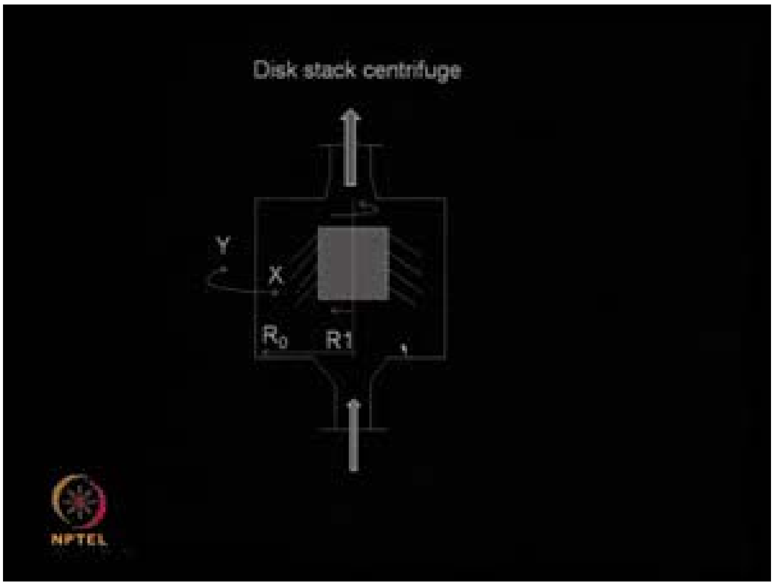

Next design is called disk stack centrifuge you have disks which are rotating. So, a slurry comes in and then slurry starts flowing through the disk. Because of the way disks are positioned the slurry flows through the disk and they are thrown out the solids. Because of the centrifugal force reach the outer layer surface of the centrifuge and they are collected. And the liquid flows from the central shaft or the central portion. So, the solids are thrown out and they reach the surface outer surface of the centrifuge. And they are collected at this portion whereas, the clear liquid flows out from the central portion this is called disk stack centrifuge.

So, here the this disk help slurry to flow in a centrifugal direction. So, there are 2 types possibly on centrifuges; one is the bowls centrifuge which is a cylindrical bowl. And the other one is the disk centrifuge which has got disk located oppositioned in certain angle. So, that the liquid flows and then the solids settle down or remain at the outer portion of the centrifuge, liquid flows out from the central portion. You can also use centrifuge for filtration also.

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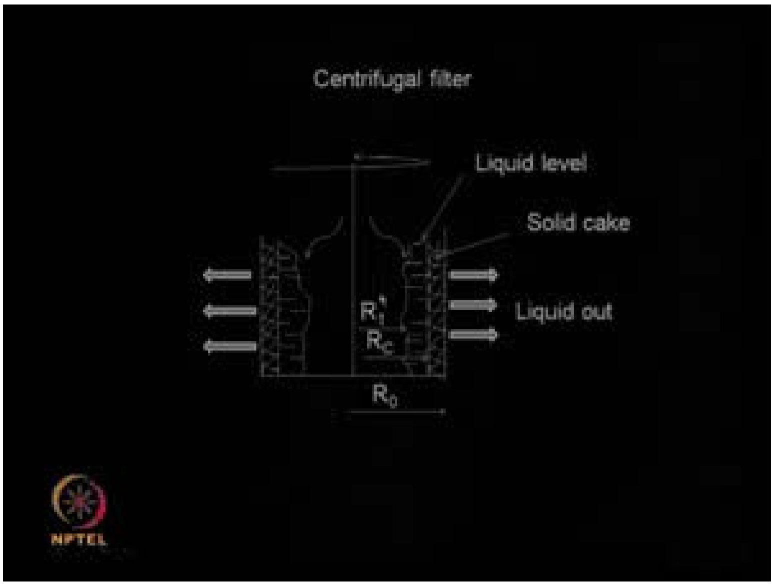

That is called the centrifugal filter. So, what you do is if the cylindrical surface of the centrifuge has fine pores; so as soon as the liquid and the solid reach the cylindrical portion the solid will get retained whereas the liquid will flow through the pores and come out. So, it is almost like a normal filtration only difference is here the forces are very high. So, because of the centrifugal force the liquid is pushed out towards the periphery solid settle down on the inner surface of the centrifuge. And the liquids flows through the solid bed and then they are collected outside the centrifuge this is called a centrifugal filter.

So, the advantage of centrifugal filter we can process more slurries. Because unlike a normal filter here the amount of driving force achieve is much more higher when compared to a normal filter. Because in normal filter if its pressure filter you are applying certain pressure whereas here we are talking very high gravity, very high centrifugal forces that can be achieved. And also if you have very large diameter centrifugal filter; the diameters are large again the centrifugal forces will also be large. So, you can achieve very high driving forces in centrifugal filter.

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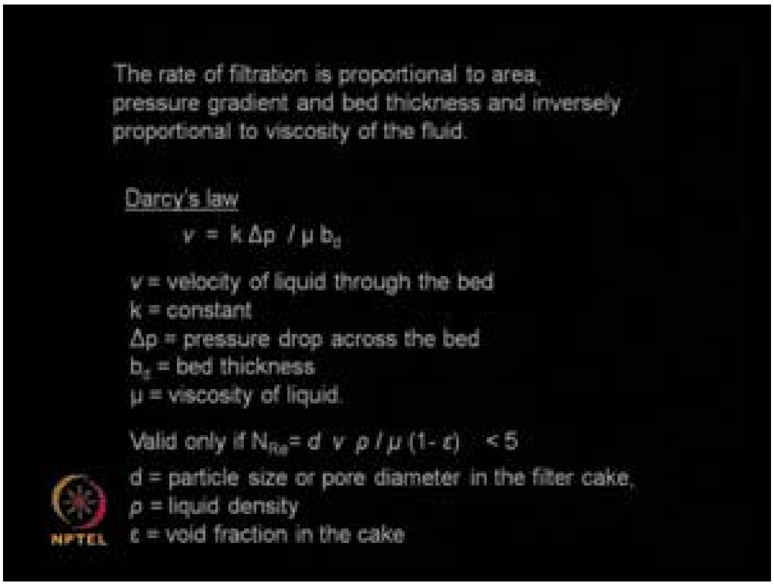

So, the rate of filtration of a slurry through a bed depends upon several parameters and we will look at these in more detail. Now, it is proportional to the area of your filtration setup, it will be proportional to pressure gradient, it will be proportional or inversely proportional to the bed thickness and also inversely proportional to the viscosity. So, the rate of filtration or the velocity of the liquid flowing through the bed will be proportional to your delta p; and it will be inversely proportional to your viscosity and bed thickness. This is called Darcy's law, this is a very simple law and it does not consider any parameters it just considers it as an ideal situation.

And it comes out with an relationship called V equals to delta p divided by mu b d. So, there is K is a constant delta p is the pressure drop across the bed and b d is your bed thickness. So, if I know the k; I will be able to calculate velocity through the bed. So, that is the main advantage of having a Darcy's law and if I know the velocity through the bed. That means, I can calculate the through put through the bed as you can see it is inversely proportional to viscosity.

That means, viscosity of the medium is very large my velocity is going to be very slow that means input will be very slow. And again if the bed thickness is very large my velocity is going to be very low. Of course, this is valid only for number less than 5; I talked about Reynolds number.

Reynolds number is a number which is the term describing the physical properties of the medium as well as the solid. So, it is generally it is defined as the diameter of the solid, the velocity, the density of the fluid divided by viscosity of the fluid. Here, you have one extra term coming here 1 minus epsilon. Epsilon is the porosity of the bed which comes into this but normally Reynolds number will be diameter of the solid multiplied of the velocity, multiplied by the density of the fluid divided by the viscosity of the fluid.

But here we are also considering the porosity of the bed; because the liquid flowing through a porous bed. So, the porosity term also comes here. Now this Darcy's law is valid only when you have Reynolds number less than 5 otherwise it is not valid. Now, we have the velocity of the liquid through the bed. Now, we want to calculate throughput through the bed. How do you go about doing that?

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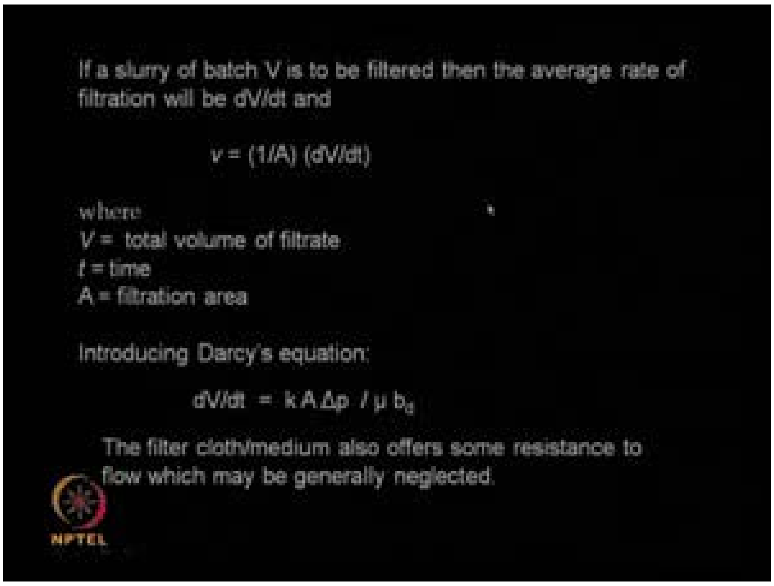

So, let us go do some mathematics in to that. So, imagine that I have a slurry of batch V that means the total volume of filtrate I want to filter. Then the average rate of filtration will be d v by d t correct. So, I want to filter some so many litres of liquid in so many hours. So, many litres divided by so many hours gives me the average rate of filtration; in reality it will not be constant.

Because initially filtration will be small as you keep accumulating solid the filtration will be slow; but we will take it as an average filtration rate; so it is d v by d t. So, the velocity will be equal to rate divided by area where area is the filtration area. Now, we can introduce this into the Darcy's law because I showed Darcy's law where velocity is the function of delta p; that is the pressure drop or pressure gradient divided by the bed thickness and mu as the viscosity of the fluid.

So, I can combine this equation as the Darcy's equation. So, by doing like that I get a equation like this d v by d t; V as I said v is the quantity of the slurry. Quantity means volume of slurry that needs to be filtered, k is some constant, a is the area of surface, delta p is my driving force divided by mu viscosity of the medium, b d is the thickness of the bed. Generally the filter cloth or filter medium also offer some resistance to flow and generally we can neglect that; it is not very high. So, we can neglect that. So, if you neglect that term.

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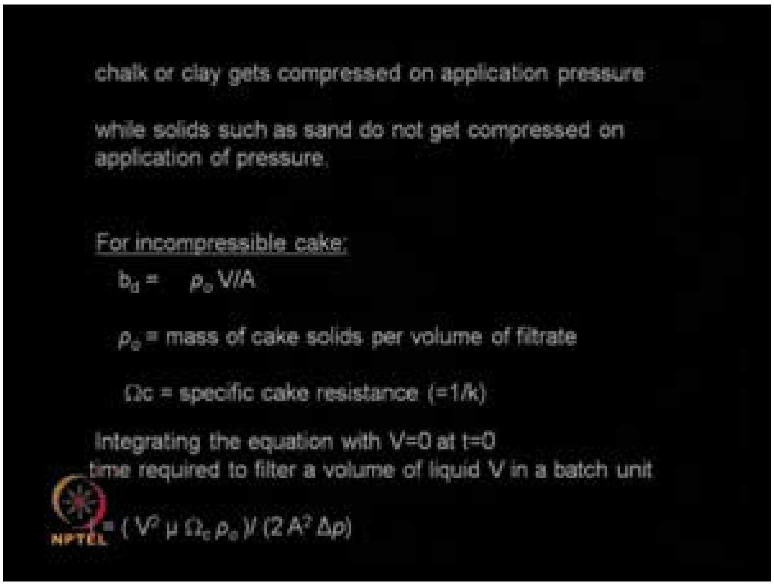

Then, we can get very simple relationship; if we do not neglect that term the relationship; becomes slightly complicated you will look at both these type of approaches. Now, there is another aspect which needs to be considered which is called the compressibility of the bed; some solid material under pressure will get compressed. And some solid material under pressure will not get compressed.

For example, if you take chalk if I put pressure it will get compressed. For example if you take clay when I put pressure it gets compressed whereas, if we take sand whether I put high pressure or medium or whether I put medium or low pressure it does not get compressed. So, there is factor known as compressibility and the equations filtration equations will change depending upon whether it compressible bed or it is a non-compressible bed; the equations will look very different.

Thanks.