Particle Characterization
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Module No. # 7
Lecture No. # 19
Particle Removal: Wet Cleaning

Welcome to the nineteenth lecture in our particle characterization course. In the last lecture, we started reviewing methods for removal of particles from surfaces, which is an important step in many processing industries, where high purity of surfaces is critical and also has a, has a way to measure particle adhesion forces on surfaces. If you can remove them by applying a certain force, and then, find the threshold removal force at which the particles first start to become dislodged from the surface, we can use it also as a measure of the adhesion forces, which are otherwise very difficult to measure directly.

So, we will continue the discussion today. In the last class, we primarily focused on dry methods of particle removal which did not involve the use of a liquid medium; but, there are, as we discussed, many inherent advantages to using a liquid intermediary in order to promote the release of particles from surfaces. And so, we will discuss a few methods involving liquid assisted removal of particles. Today, the most aggressive of such methods is where you actually use strong chemicals to etch particles from surfaces. For example, you can use an acid to etch inorganic as well as organic materials from surfaces; it is something that is done routinely. For example, in passivation processes where you use a strong acidic as well as alkaline chemistry to remove various contaminants from surfaces and particularly, iron because iron is the trace impurity that can lead to rusting corrosion and so on. So, passivation, for example, steel is done in order to remove iron particles from the surface.

In semiconductor manufacturing also, if you look at how silicon wafers are made, the processes that they go through are fairly chemically intensive and by the time the wafers are ready to be shifted, they would have accumulated many types of chemical contaminants on them; everything from organic photo resist to inorganic debris that accumulates from equipment and processes and so on.

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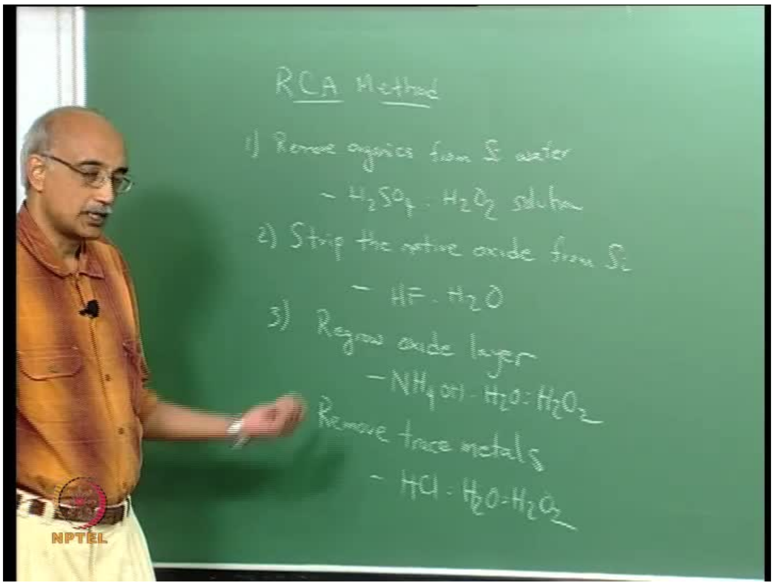

RCA Method

1) Remove organics from Si wafer
   – $H_2SO_4 : H_2O_2$ solution
2) Strip the native oxide from Si
   – $HF : H_2O$
3) Regrow oxide layer
   – $NH_4OH : H_2O : H_2O_2$
Remove trace metals
   – $HCl : H_2O : H_2O_2$

So, cleaning of silicon wafers is particularly challenging and there is a process that has been developed, called the R C A process which the industry has been using for the last 40 years and it continues to be used even today. The R C A method is basically a 4-step process.

In the first step, you remove organics from the silicon wafer and this is done using a H 2 S O 4 H 2 O 2 solution. The second step is actually, strip the native oxide that is S I O or S I O 2 from silicon and this is done using a mix of H F and H 2 O hydrofluoric acid, water mixture. The third step in the process is end to re-grow the oxide and this is done by using an alkaline treatment. Ammonium hydroxide H 2 O H 2 O 2 mixture is used for this purpose and the fourth step is then, remove trace metal impurities. This is done using H C L H 2 O and H 2 O 2. So, as you can see from a description of this process it is chemically intensive and fairly complex in terms of the various chemistries that are being used, which range from acidic to oxidizing to inorganic to alkaline and again back to acidic. So, the surface is getting fairly strong chemical treatment during this process and basically, this process is so aggressive it will pretty much strip everything that is on the surface down to the mono layers; which is a kind of cleanliness that you need on the semiconductor wafers that are used as your chips in your electronic devices. This process is virtually 100 percent effective. What is the downside? There is always at downside to every good story.

The down side is, it is very difficult to make all these chemicals in a pure form there are always trace impurities in all chemicals whether they are brought to you in bottles or whether they have piped into your process. It is better if they are piped in because, you can have point-of-use filters which you can use to clean up the solvent just before you use it in your process. But, particularly when you are buying it in containers and using them in your process you really do not have that point-of-use control. So, it is very hard to predict and control the contaminants that are going to transfer from the component. I mean from the from the chemical itself the other problem with this type of a process is the requirement of a drying step. Afterwards, there are going to be liquid residues on the surface which have to be completely removed from the surface and then the surface has to be dried. So that not even a mono layer of moisture remains on the surface; that adds complexity as well as cost to the process.

The third problem with this process flow sequence is again, if you look at silicon wafer manufacturing, it is predominantly a dry process. There are not too many chemicals - liquid chemicals being used through the process. So, all of a sudden now you have a wet process that is, like an intrusion into a process flow which is predominantly dry; so any time you try to do something like that again, it greatly increases the logistical complexities of running the process. So, this type of strong chemical cleaning is certainly available but should only be resorted to when milder methods of particle removal fail.

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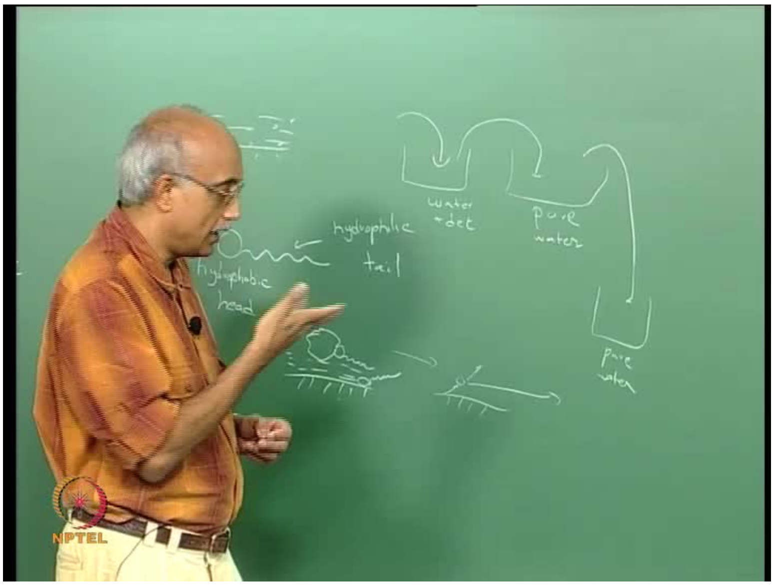

Now, what is the mildest method of particle removal in a liquid medium? Just soaking; so if you have a surface and you have dirt on it, again in a dry state, these particles are strongly adhered to the surface. Very difficult to get them apart; so what do you do? You basically dunk this whole thing in a liquid so that, now there is a liquid medium encompassing the particles as well as the surface of the acetone.

Again, imagine dirty plates. A lot of this discussion will be, will make more sense if you imagine a physical situation where you are trying to do something like that. You have a dirty plate on which food material is dried; very hard to clean it. So, the first thing you will do is to immerse it water and let it soak. So, it is basically what we are talking about; in principle, the liquid should get into the interface between the particle and the surface and help losing the particle but, it does not always happen because water has a high surface tension liquid. So, even though you have dunk this in a in a liquid there is actually no liquid that is between the particle and the surface; it does not wet the interface.

So, how do you address that? By adding detergents and surfactants help reduce the surface tension of the liquid; so that it is gets into the interface between the particle and the surface. So, that is good but, detergents and surfactants do something else which is even better now when you look at a detergent molecule or a surfactant molecule.

You can, kind of imagine them as looking like this. They have a hydrophobic head and this portion is called the hydrophilic tail. They are all constituted in such a way that there is a hydrophobic portion and a hydrophilic portion you can also look at, is as a hydro carbon portion and a portion that contains typically a polar solvent like alcohol. So, they have blends of solvents and alcohols or blends of hydrophobic materials and hydrophilic materials. So, they kind of look like this; so what happens when you put a detergent in water and then you soak a surface with particles on it? Inside that solution, what is going to happen is let us say, you have a particle that is, looks like this; and you have a surface. Because of the reduction in the surface tension, the water will get into this interface which is good but in addition, these detergent molecules that are mixed into the water will orient themselves such that the hydrophobic portion will attach itself to the particle and the hydrophilic portion will be sticking out.

Similarly on the surface also the hydrophobic portion will attach and the hydrophilic portion will stick out now the reason for this is as we discussed earlier there are entropic reasons for why this happens because water is extremely hydrophilic it repels the hydrophobic portion of the detergent molecule and forces it towards the particle and the surface where they attached to the to the respective surfaces so the other side of the molecule the hydrophilic side is now sticking out.

So, now what happens? This particle and this surface when they will now see each other, they see these 2 molecules sticking out. They are both hydrophilic so, will they attract each other no? Because, water again is more hydrophilic than either one; so even though they both have hydrophilic tail sticking out, they will ripple each other because, they preferably want to attach themselves to the water molecule. So, you setup a repulsion force between the particle and the surface and that is really why detergents are supremely effective. They induce a state where the particle and the surface instead of being naturally in adhesive contact, are now actively repelling each other; trying to push each other away. So, as you can imagine when this happens, the particles now are loosened from the surface.

They actually have a tendency to move away from the from the surface and become entrained in the liquid. Now, if you have some kind of a flow mechanism that is also setup. These particles had moved away from the surface and get into the bulk of the liquid can quickly be transported away from the surface so that they do not re-entrain or re-deposited on the surface.

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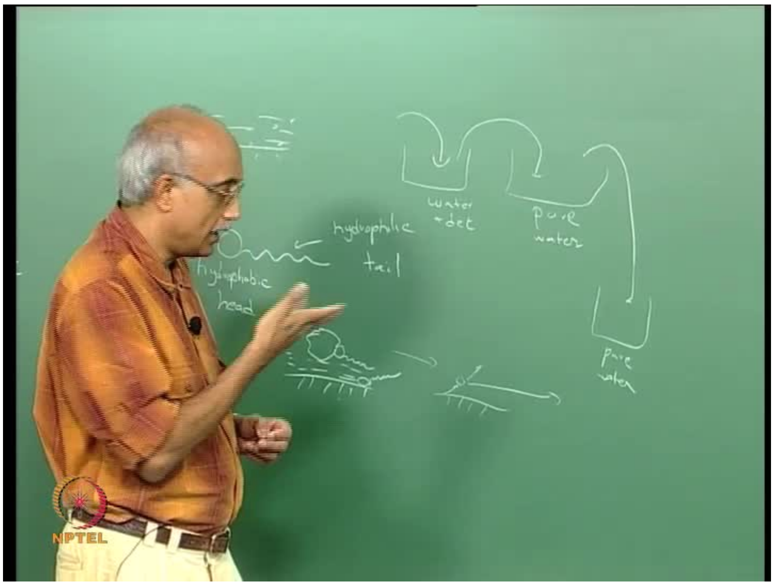

So, that is basically how surfactant based cleaning works; very simple. It is mostly a physical action. The surfactants do not react with the contaminants chemically. What they help is in promoting betting between in the, at the, interface between the particle and the surface and in inducing a force of repulsion between the particle and the surface. Again, looks good; what are the down sides?

Surfactants can also have impurities; so those impurities can now deposit on the surface any time you introduce a foreign material - a chemical into a process. It is the potential contaminant to the product that you are trying to clean. So, what do you have to do? You have to have a rinsing step. You have to make sure that any residual surfactant that is left on the surface or any impurities that were in the surfactant to begin with, are completely rinsed away from the surface. So, in addition to this soaking step you really need a multiple step process. You have one tank where you have water plus detergent and you do the detergent cleaning. It has to be followed by a pure water tank where you remove any residual detergent from the surface and you remove any impurities that may have transferred to the surface from the detergent and by the way, a thumb rule is - for every stage you have where you are using a detergent, you need at least 2 stages of rinsing in order to completely remove the detergent.

So, you have to now add another tank to this; to the sequence again with pure water. Instead of doing the cleaning in one step now, you are doing it in 3 steps and then manufacturing capacities is at a premium when space is that; a premium, it is not something you want to deal with.

This is again a kind of a disadvantage with any wet cleaning method unless you are doing the cleaning with a high vapor pressure solvent. High volatility solvent which will naturally evaporate but, even in that case you need at least some kind of a vacuum to be, to suck out the last mono layers of this high volatility solvent because many of these processes you cannot even tolerate atomic layer of impurities left over solvent. For example, so as long as you are talking about wet cleaning, the plus point is adhesion forces are significantly reduced; cleaning processes are very aggressive. The down side, the biggest down side is, you need a subsequent drying step to remove the liquid from the surface otherwise, a liquid itself becomes an impurity.

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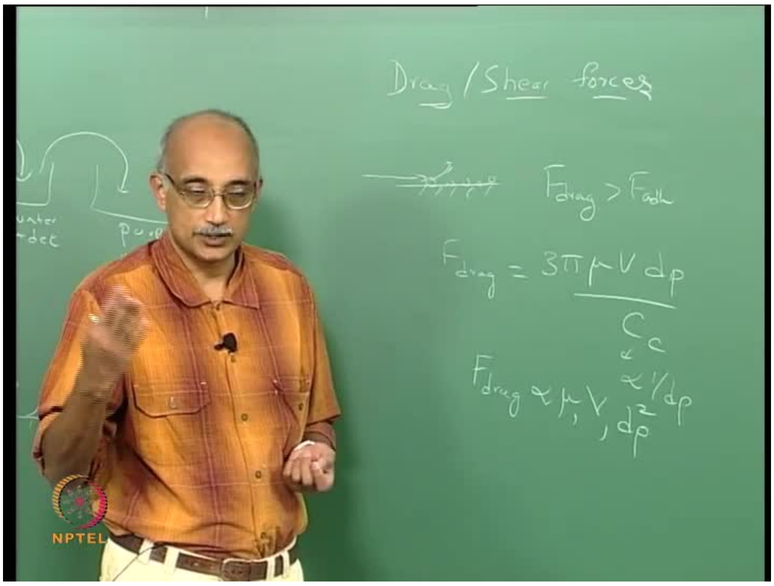

Another type of wet cleaning that we touched upon in the last class is using drag forces and shear forces to do the cleaning for you. So, here the principle is that you are a,… you have particles again sitting on a surface and you exert a force in the shearing direction in the tangential direction and as soon as this tangential force exceeds the adhesion force, the particles become this large from the surface and they can be removed from the surface.

Now, the drag force exceeding the adhesion force is a required condition for particle removal but it is a necessary condition but, not sufficient because as you can imagine when this force exceeds the adhesion force, the particle is not necessarily, immediately, lifted up the surface; it can actually roll on the surface. This rolling mechanism is something that is particularly predominant. When you get finer sizes they do not want to leave the surface but, they are being forced to so. They kind of reach a compromise and they cannot stay in the same place. So, they just start rolling along the surface; this rolling motion is something that is particularly pronounced when you have very smooth surfaces. When you have a rough surface it is difficult for the particle to roll on along the surface, as a greater tendency for the particle to lift off and be removed from the surface. But, on highly polished surfaces you also have to look at the rolling mechanism has something that you need to prevent from happening.

Now, the formulae for drag is 3 pi mu V d p by C c; we will get into this in more detail when we talk about transport characteristics of particles but, I am sure you are familiar with the basic equation mu is the viscosity, v is the relative velocity, d p is the particle diameter and C c is called the Stokes-Cunningham correction factor for a for a no slip condition and by the way, this parameter is proportional to 1 over d p. So, what that effectively means is the drag force is proportional to mu proportional to velocity and proportional to square of the diameter.

What are the implications of this? Well, this would the first implication is higher viscosity fluid exerts greater force and in fact, that is why water is a much better cleaning medium than air because the viscosity of air or viscosity of water is about 55 times the viscosity of air. All other things being equal, if you do the shear cleaning with water it is going to be 55 times more aggressive.

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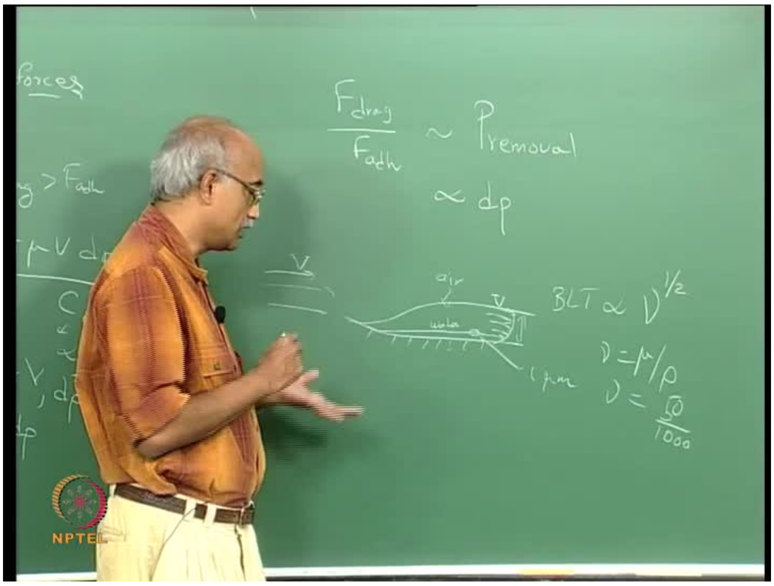

Velocity is a major player; the greater the velocity of flow, the greater the particle removal potential and this says that as particle size increases, the particle removal force goes as particle size squared. Because, a negative implication of this is that as a particle size decreases, the removal force drops very rapidly. Again, remember that F adhesion goes as d p; so if you take the ratio of F drag to F adhesion which you can look at as a metric, that gives you the probability of removal then this would go as d p. Because you are basically dividing this by this; so the ratio of the drag force to the adhesion force will scale as particle size and that is the reason why, remember the question I asked couple of lectures ago. That is a reason why larger particles are easier to remove particularly using shearing forces compared to finer particles.

Now, the other factor here is in order for this to work, what is what is the requirement? Is this always true? Does this always work? For example, suppose you have a surface and you have a 1 micron size particle sitting here and you are doing this shear cleaning, so you have some fluid. Let us say, it is a liquid that is being flown across the surface; is this always going to able to able to remove that particle or what will prevent it from happening?

What effect boundary layer effect because, as soon as this happens you are going start forming a boundary layer here right? If the boundary layer thickness is greater than that the size of the particle, the particle is never even going to experience velocity; this V if you look at the velocity profile, what is that going to look like? V now is the main stream velocity where the particle is going to experience a velocity that is much smaller; may be only 10 percent of the velocity that is achieved at the edge of the boundary layer. So, what happens is very fine particles like in the 1 micron size range 10 to hide in the boundary layer so drag cleaning is virtually ineffective for such particles so what is the strategy to address that you have to try and make the boundary layer as thin as possible.

How do you do that? Again, going from gaseous media to liquid media makes a difference; which one has a thinner boundary layer, gas or a liquid? Liquid; the reason is the boundary layer thickness is proportional to the kinematic viscosity mu to the power half. Roughly, now what is the definition of this kinematic viscosity mu by rho? Now, mu or the viscosity of a liquid like a series 55 times that of air; but how about density? Density is 1000 times greater for a liquid compared to air. So, this ratio mu is greater for Nu is equal to mu divided by rho. So, for example, for a liquid the viscosity let us say, it is 50 times higher but, the density is a 1000 times higher. So, the ratio is actually 1 over 20; you take the ratio of that the boundary layer of thickness for a liquid is an order of magnitude smaller for a liquid compared to a gas. So, again that is a reason why liquid based spray cleaning or shear cleaning is preferred over gaseous cleaning.

It has greater viscosity but it at the same time, it has lower kinematic viscosity which results in a smaller boundary layer thickness. So, if this is the boundary layer thickness, corresponding to air for the same velocity, the boundary layer thickness for water may be much smaller and now a particle which was able to hide in the boundary layer when you have a gas flowing, is now exposed when you have water flowing. So, in a spray cleaner liquid media are much more effective compared to gaseous media like air and so on. Now, when we talk about this type of cleaning mechanism, the drag force changes as you change the velocities. That expression that we have written earlier is applicable in conditions where the velocity is very low.

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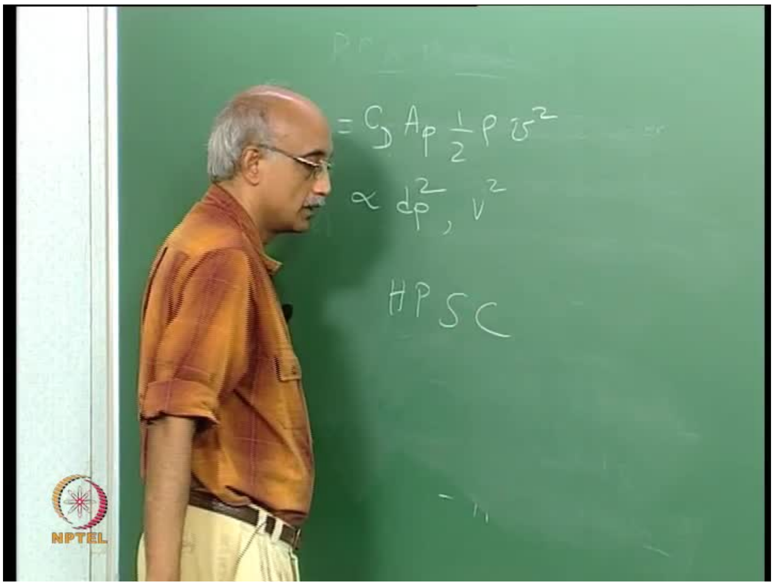

Relatively, as the velocities increase the expression for shear force becomes a drag coefficient times area of the particle times half of rho u square. Now, in this case again you have a proportionality d 2 d p square assuming that it is a spherical particle the area of the particle is still proportional to the square of the size. So, that does not change but now the velocity has a greater effect whereas previously, we had a linear dependence on V. Now, we have a V squared dependence and at this stage the drag coefficient which itself is a function of Reynolds number, also starts to play a role. But, the interesting thing here is that this gives us a clue that if you want to do more effective particle removal increasing the velocity makes a lot of sense because, it is a square dependence rather than a linear dependence.

And in fact there is a process called high pressure spray cleaning which is very widely employed again in precision manufacturing industries to overcome this boundary layer problem see the boundary layer itself if you look at the thickness it is also a function of the velocity as you increase the flow velocity particularly as you start inducing turbulence the boundary layer becomes thinner and thinner

In fact, if you can induce sufficient turbulence and you can start turbulent eddy transport across a boundary layer, you can effectively make the boundary layer vanish. So, in high pressure spray cleaning, what we do is we use very high pressures to inject the liquid at very high velocities from a very focused nozzle. Remember, we were discussing fan nozzles and focus checks the other day. So, here in high pressure spray cleaning, you specifically employ pressures that can get you hundreds of meters per second velocity of the liquid flowing across the surface. When you do that the boundary layer is virtually absent and you can even remove submicron particles from surfaces.

The down side of it is at that kind of pressure, at that kind of flow velocity, you can actually start cutting the surface. In fact, high pressure water jets are used to cut metals. So, you have to be very careful when you use these high pressures sprays. You want to control the pressure in such a way that you get the cleaning that you want but, at same time, you do not start damaging the surface. This is especially important when you have coated surfaces that have polymers on them or painted surfaces because, paint varnish coatings, platings can all become damaged very easily when you entrain high pressure jets on top of them. But, if you have to resort to spray cleaning and you have to remove sub-micron particles then, the only option you have is really to use very high pressure jets which can damage substrate.

And, that brings us to the last cleaning method that is probably the most widely used in industry for removing sub-micron particles and that is method based on acoustic fields particularly, ultrasonic cleaning and megasonic cleaning.

Now, these techniques are particularly suited to removing even the finest particles from surfaces without causing excessive surface damage provided, they are properly controlled and optimized and so on. So, we will talk about these techniques in a little more detail.

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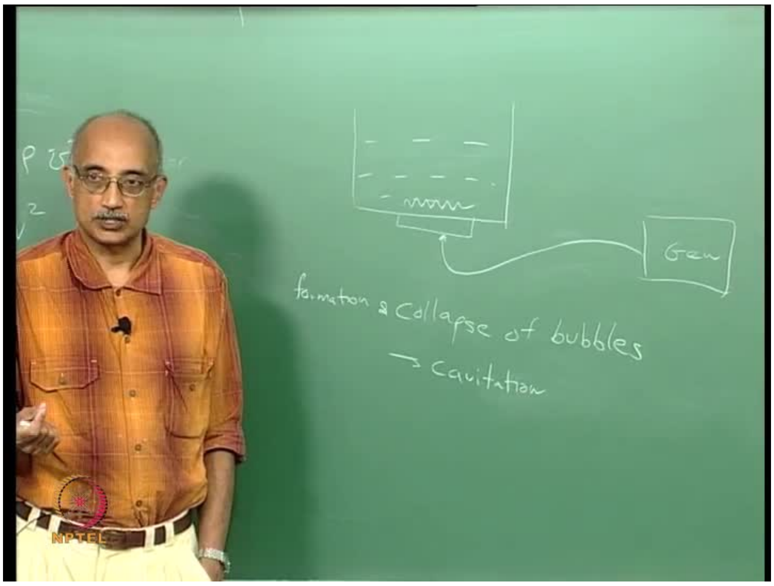

So, in the case of both ultrasonic cleaning and megasonic cleaning, what you do is you take a liquid medium and you have a generator that generates an acoustic field and you have a transducer that is attached to the tank in which the liquid is contained and this electrical energy is transferred to this transducer which converts it into a mechanical energy (Refer Slide Time: 28:00).

Essentially, this transducer takes this energy input and converts it into an oscillating pressure field that is setup within the liquid. Now, as the liquid oscillates, essentially you have a pressure excursion; the liquid keeps going through alternating phases of compression and expansion or rarefaction. Now, what happens when you take a liquid and you expand? It breaks into bubbles. So, during the expansion phase you start forming these bubbles in the liquid; the next phase is compression. During the compression phase, you are squeezing the bubble and ultimately it implodes. It collapses on itself and as it does it releases energy as a wave. So, the energy that was present in the bubble volume before it collapsed must be conserved and the way it is conserved is by transmitting that energy as soon as the collapse happens in the form of a shock wave which essentially travels through the liquid.

So, this phenomenon of collapse of bubbles associated with an oscillating pressure field; so it is basically the formation and collapse of bubbles is known as cavitation. The bigger the size of the bubble before it collapses, the greater will be the cavitation energy. So, if you use low frequency Ultrasonic's the bubbles have more time to grow before they collapse.

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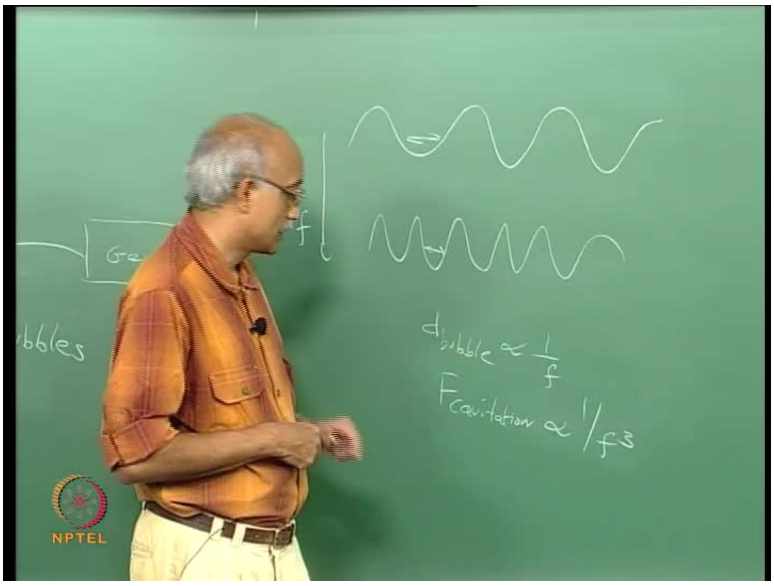

So, the cavitation forces are much higher in low frequency Ultrasonics compared to high frequency Ultrasonics. So, basically if you have, feel like this versus one that looks like this, the time that is available for a bubble to grow is much greater here compared to here.

So, the frequency is increasing in this direction as you keep increasing the frequency of the acoustic field. The bubble volume before it collapses is smaller and smaller; so the energy release which is essentially a volumetric phenomenon is also decreasing by the same amount. In fact, the d p or d bubble the bubble diameter just before collapse is roughly proportional to 1 over f; the lower the frequency, the higher the bubble diameter. So, that means that the cavitation force f cavitation is proportional to 1 over what? If the bubble diameter is proportional to 1 over f, what is the associated cavitation force when the bubble collapses? Remember, I told you it is a volumetric effect. So, this is actually proportional to 1 over f cubed because, as the frequency increases the bubble diameter goes down proportionally but the volume of the bubble goes as 1 over f cube.

So, the energy release which is volume dependent also goes as 1 over f cube. Now, so this would argue that if you want to do ultrasonic cleaning you have to keep the frequency as low as possible. But, that is not always true for 2 reasons: one is again, if you use a very low frequency and you get a very high cavitation force, you can actually start damaging materials and that is called cavitation erosion which is good and bad. It is bad when you are trying to clean surfaces and materials because it can actually cause damage to the surface. It is good when you are trying to, for example, fragmental material deliberately; for example, if I have an agglomerates, a solution and you want to break them down into individual particles, cavitation erosion is the way to do that. Or, if you want take larger particles and break them down into smaller sizes for example, micron to Nano then, this cavitation erosion actually helps you do that. It is a process called,… so no fragmentation which we actually do a lot of work in our lab using,… so one reason not to use too lower frequency in surface particle removal, is to avoid damage in the substrate.

The other reason is that, if you look at that boundary layer thickness that I had sketched earlier that also has a dependence on the frequency; the thickness of a boundary layer around an object in the presence of a acoustic field has this type of a dependence.

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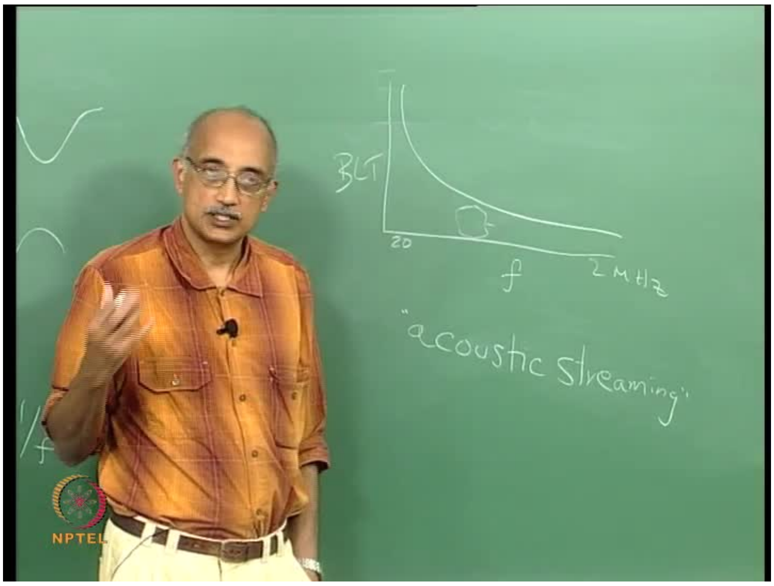

So, as you increase the frequency let us say, that the minimum frequency you look at is 20 kilo hertz and the maximum is 2 megahertz, the bound layer thickness can change by more than one order of magnitude. As you change the frequency so again, if you talk about a particle that is about this size if you are trying to clean it using 20 kilo hertz, the boundary layer is too thick.

The particle would not even see the acoustic field as you keep increasing the frequency eventually you will reach a level where the particle will be exposed and can be removed from the surface so that again argues in favor of looking at higher frequencies.

The third reason for doing high frequency particle removal is that as you keep increasing the frequency. What happens, the cycle is very fast so bubbles form to very fine sizes and then they collapse immediately and that is why cavitation forces are very low. But, the other implication of that is the density of bubbles is much greater when you use higher frequencies. Virtually, every millimeter of the liquid surface gets broken up into bubbles and so you have a huge number density of bubbles as the frequency increases and as they form and implore they essentially combine with each other so they form like a microscopic phenomenon.

Cavitation is a localized phenomenon because these bubbles are forming and exploring or imploring in one location. So, it tends to be very non-uniform and very aggressive as you go to higher frequencies because, the bubbles are smaller and they are much closer together because of the increase in number concentration; it becomes a continuous phenomenon.

So, what you see is something called acoustic streaming. Acoustic streaming essentially refers to an unidirectional flow that is induced in the liquid when you couple a very high frequency ultrasonic field to it; typically in the megasonic range. So, if you look at the difference between the megasonic field and an ultra-sonic field, megasonic field has a strong streaming characteristic whereas, the ultrasonic field has a strong cavitational characteristic. Now, in terms of particle removal forces, it turns out that acoustic streaming is essentially a sharing mechanism. Because, all you have done in this mechanism is generated if you have particles sitting on a surface. Acoustic streaming results in extremely high velocity flow of liquid over the surface. So, compared to a general spray cleaner you can achieve velocities in a megasonic cleaner that are 100 times higher; 1000 meters per second flows are possible in a megasonic tank but it is basically a shear based cleaning mechanism which means it has it is own limitations.

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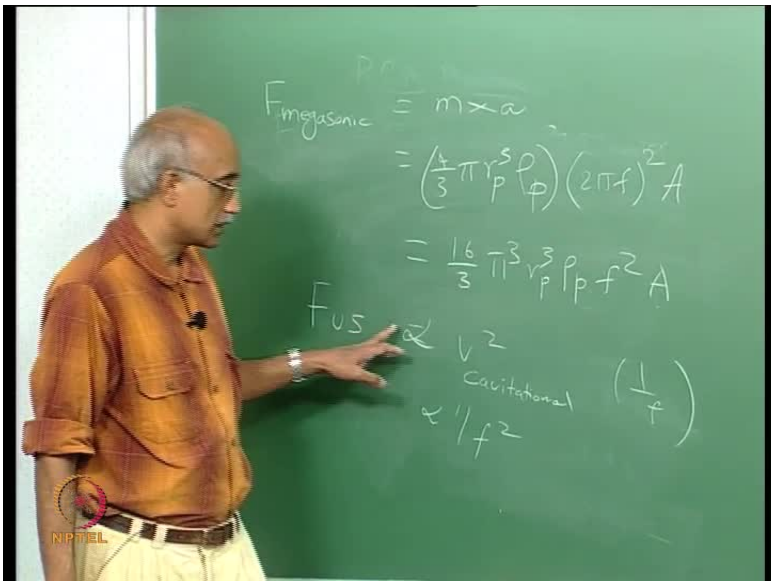

So, the force in a megasonic field is basically mass times acceleration. you are You are taking a shock wave or a force that is generated in the fluid because of fluid motion and you are transferring it to the particle. So, the mass of the particle multiplied by the acceleration that it experiences will be the total force that is supplied to the particle by the megasonic field. So, this becomes, the mass of the particle is let us say 4 by 3 pi r p cubed times rho p which is a mass of the particle that you are trying to remove times acceleration in a megasonic field. Now, the expression for this is 2 pi f squared times the amplitude a; so f is the frequency of the acoustic field and A is the amplitude of the acoustic field. When you combine these 2, this is 16 by 3 pi cubed r p cubed rho p f squared a; so, this is the overall force that a particle will experience in the megasonic field; where the primary mechanism is a shearing mechanism. So, the dependences is here again are interesting; it says that there is a dependence on f square; so as the frequency increases the particle removal force increases as square of the frequency direct proportionality to amplitude.

Amplitude is basically the power input so if you are running, you are running your Ultrasonics at 500 watts verses 1 kilo watt; you will get twice the force at 1 kilo watt that you do at 500 watts. The size dependence now is a cube of this, of the particle size which means, again that as particle size drops the cleaning effectiveness is going to be significantly reduced and then particles density is there.

How does this differ from f ultrasonic when you have an ultrasonic field? It is a cavitational mechanism; so can you describe it in terms of a mass and an acceleration. Well, you can accept that now what you have to do is really go back to modeling; it as a shearing force with the particular velocity; this is proportional to V square where this V is now the cavitational velocity. And the cavitational velocity goes as 1 over f. So, as the frequency drops the cavitational velocity will increase correspondingly. So, what this means is the ultrasonic force goes roughly as 1 over f squared. Now, this is that energy that is transferred to the surface; now, as we saw earlier if you just look at the energy released from the surface it goes as 1 over f cube.

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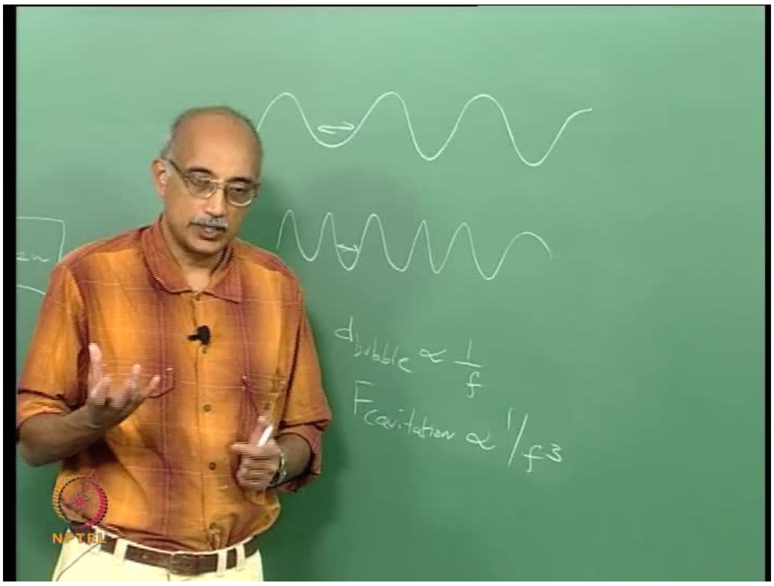

Actually, this is the energy that is released as a bubble implodes; this is the energy that is transferred to the surface. What happens to the rest of the energy? It gets dissipated as heat. So, when you do an energy balance in an ultrasonic cleaner, the fraction that is lost as heat is your inefficiency in the process. So, you should design the system to minimize loss of input energy to simply heating up of the water and try to direct as much of it to removing particles from the surface as possible.

So, the net effect if you have an ultrasonic field, if you operate at a very high frequency it is basically a megasonic mechanism. If you operate at a very low frequency it is a cavitation mechanism. But, if you operate at an intermediate frequency you can in principle capture both effects; the cavitation effect as well as the megasonic or the streaming effect.

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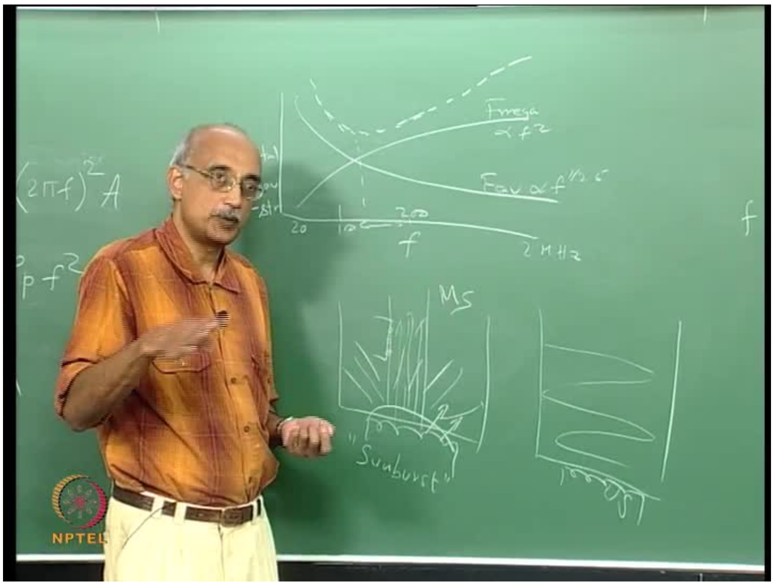

So, if I plot f total which is F cavitational plus F streaming as a function of frequency what will you get? Well, let us look at them - individual pieces we saw earlier that F megasonic or f streaming goes roughly as F square and F cavitaional goes roughly as f to the power somewhere between 2 to 3. So, but it is in the other direction so this goes as roughly F to the power 1 by let us say 2 point 5 this is the F cavitational.

So, F total essentially, is a is a sum of these 2; so when you sum these 2 what type of behavior do you think we will see? By the way, the frequencies here we are, here at about 20 kilo hertz and over here, we are here at 2 megahertz let us say, somewhere in between is 200 kilo hertz it turns out that if you look at total acoustic force as a function of frequency (Refer Slide Time: 41:40). It has a shape like this; it has a minimum somewhere in the 100 to 200 range; because at that, in that frequency range the cavitational effect has dropped quite a bit but the streaming effect has still not picked up. So, the net of that is that, from a particle removal view point a minimum force is obtained when you are in this intermediate range of 100 to 200 kilo hertz.

It is like the worst of both worlds; you are not getting good cavitation and you are not getting good streaming. If you are on this end, you get high force because of high cavitation. If you are on that end, you get high force because of high megasonic streaming. So, what is the message from this? If you are trying to remove particles from surfaces using acoustic fields, you can actually pick the frequency that you want; by the way, amplitude will simply move these numbers linearly because, amplitude has a linear effect on these forces. So, frequencies where you have the ability to tune your process; so the way. I would use this is, I mean this would tell you that you should always use high frequencies right because, if you are using a megasonic frequency there is no surface damage and your cleaning force is just as good as cavitation; so why not use it all the time?

Two reasons – cost: megasonic systems are much more expensive than ultrasonic systems. The second and which is the huge constraint as far as particle removal is a,… megasonic fields are unidirectional; they are not omni directional. Ultrasonics is omni directional. In other words, the force propagation is same in all directions. In megasonics this force that we are talking about f megasonic, only applies in a normal direction. For example, we have megasonic tank and when you have your transducer mounted at the bottom, the megasonic field that you get is essentially a plane that is centered around the transducer. So, all the forces are only on top of the transducer and in one direction only. So, it becomes very difficult to configure the orientation of the surfaces that you are cleaning in order to get good cleaning action because the surfaces have to be parallel.

In order to get a shearing force, so whatever the direction of the field you have to be able to mount the surface in such a way that the flow is parallel to the surface, so that you can get maximum shearing action. On the other hand, this is megasonics. If you look at an ultrasonic tank the field is absolutely uniform even if the transducer is mounted at the bottom.

The way that cavitation happens is inherently chaotic; it is unpredictable it is not repeatable or reproducible but, it is uniform and so you can essentially place your component or surface anywhere in this tank and you will get virtually the same energy of particle removal. That is a huge benefit particularly, in manufacturing lines where you typically do not clean one surface at a time. You will have a tray or a basket with hundreds of parts in it and you have to clean all of them simultaneously.

So, you really cannot do that very effectively with megasonic fields even though megasonics are wonderful, they are really restricted in their use to cleaning fairly simple and planar substrates; for example, a surface like this (Refer Slide Time: 40:45) would be nice, cleaned using Ultrasonics. But, if I am trying to clean something like that keyboard - very hard to do it with megasonics because, it is not a line of size cleanable object. There are lot of hidden areas, features, recesses that a megasonic field just cannot reach and so the industry now is trying to address that problem.

It turns out that if you instead of fixing the frequency at one value, if you sweep it slightly about that value for example, at 1 megahertz if you sweep it plus or minus 100 kilo hertz, that is enough to disturb the field sufficiently.

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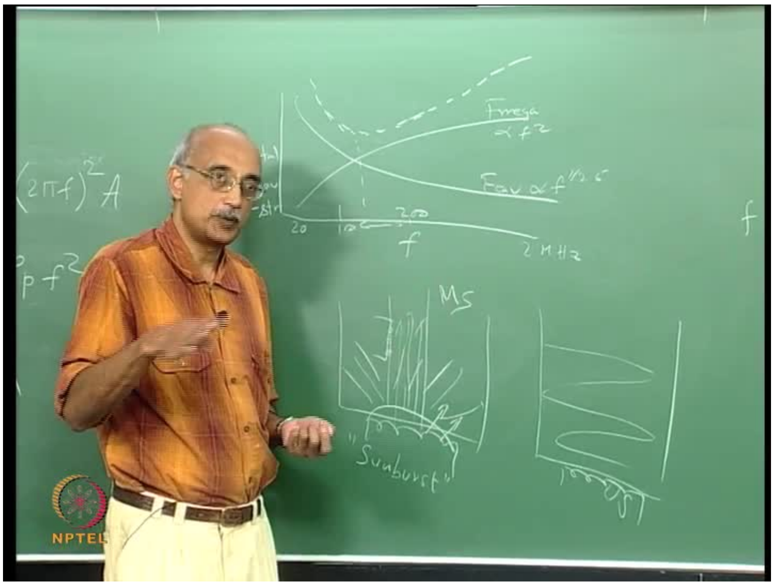

To make it behave more like a chaotic ultrasonic field, megasonics with sweep frequency is now being increasingly resorted to in order to keep all the advantages of megasonic cleaning. But, eliminating it is biggest disadvantage which is that it is a unidirectional line of cycleaner and make it into something that more closely resembles an ultrasonic particle removal technique where the positioning of the object is not that important.

There are still some biases if you get very close to the transducer. Even in an ultrasonic tank you will measure slightly higher intensities compared to when you are farther away and similarly, there are wall effects but those are fairly subtle effects. They are not part of magnitude effects and that is really, whereas, in the case of a megasonic tank you virtually fall of the cliff. If you are in the plane, you get high energy as soon as you move even slightly away; in conventional megasonics the energy level drops almost to 0.

So, by sweeping we are now trying to broaden this plane and make it more uniform. the other way that actually people have tried to do this in the past is having a hemispherical transducer which essentially, has the same effect because, the flow, the field, is normal to the surface so if you have a hemispherical transducer and you have the force propagating normally at every location you should get good coverage of the entire surface.

This type of megasonic cleaning is called sunburst megasonic cleaning because you can see that this design makes look like rays of the sun propagating out of this hemisphere. So, this technique was really the fall back for the megasonic cleaning industry till very recently when we found that sweeping the frequency is even more effective than the hemispherical design which comes with it is own efficiency disadvantages. A flat transducer is always more efficient to manufacture and to use compared to something that is rounded.

So, we have made some significant advances in that sense. That brings us to the conclusion of our discussion of particle removal methods that use liquids as the media. In the next lecture we will start looking at particle to particle adhesion forces. So far, we have been focusing mostly on particle to removal the surface adhesion and removal of particles from surfaces but in flows very frequently we deal with inter particle forces of adhesion which is also known as cohesive behavior. In the next few lectures, we will look at cohesive forces and their effects on flow of suspensions.