Particle Characterization

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Module No. # 03
Lecture No. # 08
Morphological Characterization:
Light scattering from spherical particles

Welcome to this eighth lecture in the particle characterization course. In the last lecture, we started discussing some static methods for characterizing particle size. We initially discussed various microscopic techniques for doing size analysis, and later we started discussing methods based on light scattering.

Initially, we discussed how light is attenuated during its passage through a suspension of particles, and how by looking at the extent of attenuation, we can estimate both the concentration of particles in suspension as well as the surface area or the scattering area of particles that are in suspension, and from that, estimate the size of particles that are suspended in the fluid.

Then towards the end of the lecture, we started discussing scattering called characteristics of single particles, particularly spherical shaped particles, and I mentioned that essentially the scattered light intensity from a particle is proportional to the incident light intensity, but scattering also depends on parameters such as the wavelength of the light, the refractive index of the medium that the particle suspended in, the size of the particle as well as the scattering angle, and we also discuss the fact that light, when the incident light is polarized, the scattered light also tends to carry forward the same polarization.

So, if light is polarized in two directions, - one parallel to the scattering plane and one perpendicular to the scattering plane - then the scattered light will also be polarized in a similar fashion. So, essentially, the intensity of the scattered light is the algebraic sum of the intensities in a plane, that is, parallel to the scattering to the scattering plane, and in a plane, that is perpendicular to the scattering plane.

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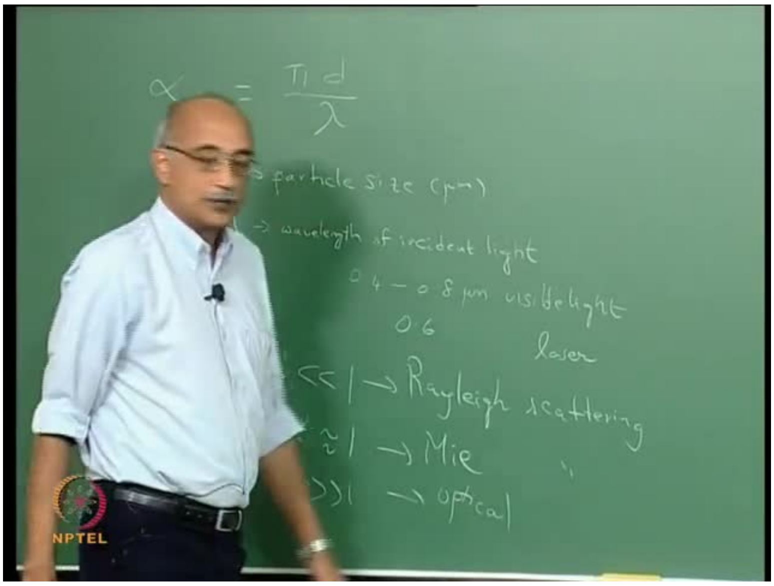

Now, when we look at light scattering characteristics of a particle that is suspended in a medium, there are really two dimensionless parameters that are very crucial to consider: the first one is alpha which is defined as pi times d over the lambda, where d is the particle size in micro meters, and lambda is the wave length of incident light. Again, for visible light, the range of wavelength is roughly from 0.4 to 0.8 micro meters, and laser is somewhere in the middle of this wavelength range.

So, if you look at this ratio, why is it is so critical? When this parameter alpha is much smaller than 1, this is called the Rayleigh scattering regime. When alpha is of the order of 1, this is called the Mie scattering regime and it turns out that loss that governed scattering of incident light vary greatly depending on whether you are in the Rayleigh regime of scattering or in the Mie scattering regime, because when alpha is much greater than 1, you can essentially go back to microscopes, because now, you are in a size range where the particles are actually visible to the naked eye, and certainly with microscopy of reasonable magnification, you can study the size as well as shape characteristics of this particles very well. So, alpha much greater than 1 corresponds to so called optical regime.

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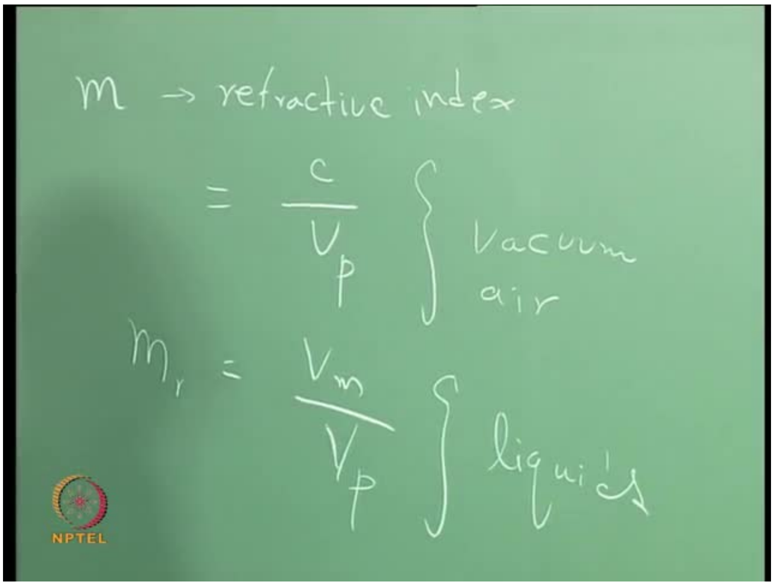

m → refractive index

$$= \frac{c}{V_p} \Big\} \text{vacuum, air}$$

$$m_r = \frac{V_m}{V_p} \Big\} \text{liquids}$$

So the reminder of this lecture, you are going to focus more on the Rayleigh regime and the Mie scattering regime. The other dimensionless parameter that is important to consider is, of course, the refractive index. So, m - the refractive index can be defined as c over V p where c is the velocity of light in vacuum and V p is the velocity of light through the material of concern. So, if a particle is alumina, then the V p value that we consider would be the velocity at which light is transmitted through alumina as a material.

However, it is very rare that we consider particles that are suspended in vacuum. Most commonly the particles that we are looking at will be suspended in a fluid, whether it is air or water or some other gaseous or liquid. Material - it is most likely that there will be a medium in which the particle is suspended. In that case, we talk about a relative refractive index m r which can be defined as V m over V p, where V m is the velocity of light transmission through the medium in which the particle is suspended, and V p still remains the velocity of light transmission through the material that the particle is made of.

Now, when we consider these two cases, when should you use this and when should you use that. Obviously, when you have particles that are suspended in vacuum, you can go back to your definition of the absolute refractive index.

But even in cases of aero salts, that is, where particles are suspended in air, most of the time it is a reasonable assumption to say that V m is approximately equal to c. So, in the case of air bound particles, you are most of the time using m as your refractive index.

However, when you talk about particles that are suspended in liquids, there is a huge degradation in the velocity of light transmission through a liquid compare to through vacuum or through gaseous medium.

So, this definition is applicable predominantly for particle suspended in vacuum and air, whereas, this definition is something you use for particles that are suspended in liquids, and when we discuss use of light scattering as a technique to measure particle size and you look at practical applications, in which, this method is used. They are roughly equally divided into particle suspensions in air and other gases, and particle suspensions in water and other liquids. So, both cases are equally important in terms of manufacturing industries and the prevalence of use of light scattering techniques for particle size characterization.

So, it is important to keep in mind these two definitions. In the discussion that follows just for simplicity sake, we will use m as the refractive index.

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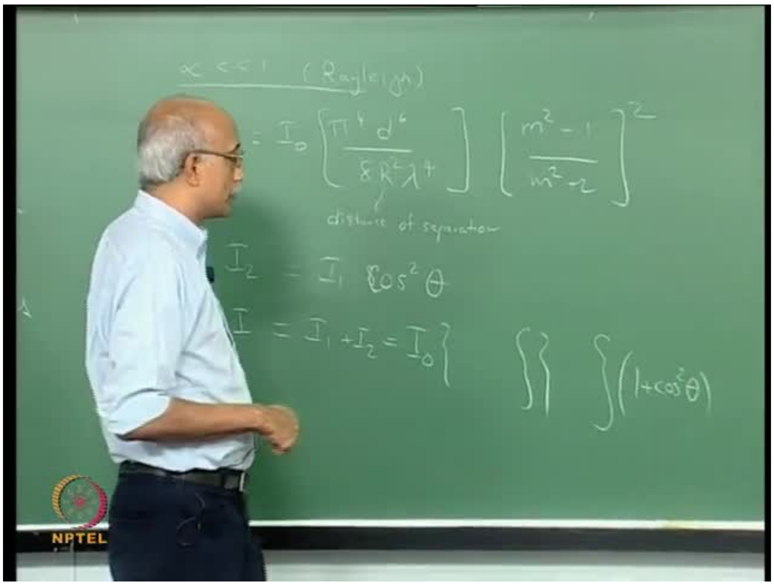

But keep in mind that we talk about m in the case of particles liquids but we are really talking about is the relative refractive index. So, let us first talk about the alpha much less than 1 or the Rayleigh scattering regime.

In this regime, obviously, the particles are much smaller than the wavelength of the incident radiation, and the relationship between particle size and the various other parameters to the scattering characteristics of the particle can be established fairly, conclusively. As we will see later on the Mie scattering regime is actually much harder to deal with; there is a lot of variability in the scattering signal and prediction of scattering intensity as a function of theta becomes very complex.

But in the Rayleigh scattering regime, there are well established formulae for calculating scattered light intensity as a function of the various parameters that are involved, and again, we have to split the contribution in to I 1 and I two; I 1 is equal to I 0 times pi to the power 4 d to the power 6 over 8 R square lambda to the power 4 times m square minus 1 over m square plus 2 the whole square.

I do not expect you to remember the formula but make sure you understand the functional dependency that you see here. The first thing is I 1 which is scattering in a perpendicular plane to the scattering plane is not theta dependent, it is a constant value for all theta. So, the scattering angle does not enter as a parameter.

The second thing is you see the d to the power 6 dependent. As I mentioned in the last lecture, scattering intensity goes as d p to the power 6. So, there is a very steep drop in scattered light intensity as the particle size decreases, or by the way is the distance of separation between the observer and object.

And like most forces that are distance dependent, there is an inverse relationship between distance and the force, you know, just like magnetic force or electrical force. That is always sensitive dependence on the distance of separation from the field and where the measurements are taken, and finally, lambda - in this case also appears in the denominator, and the dependence on m is given there.

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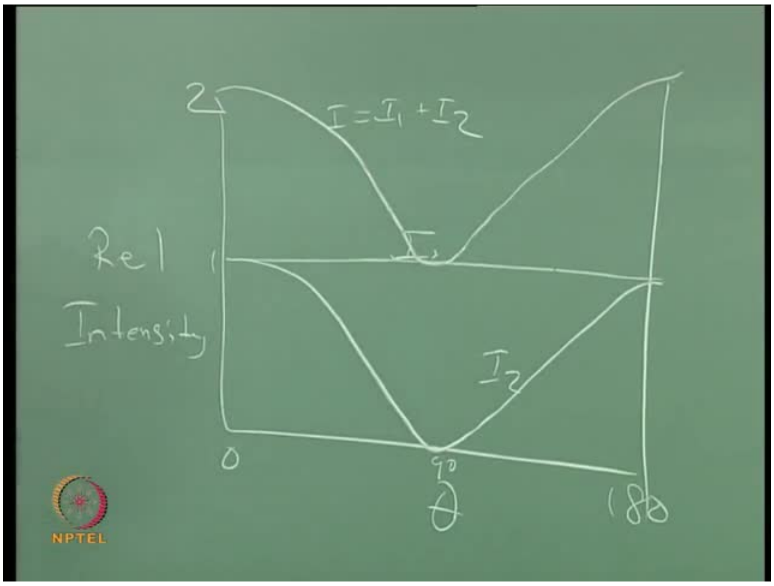

Now, I 2 is simply the same multiplied by a cos square theta parameter. So, the theta dependence really comes in I 2, and the total scattering intensity I which is equal to I 1 plus I 2 is then given by I 0 times these two terms times 1 plus cos square theta. So, this is the overall expression for scattered light intensity from a spherical particle. Now, if you plot this as a function of theta, so, theta goes from 0 to 180, and let say that you are plotting a relative intensity here.

I 1 will essentially have a constant profile with respect to t theta. Let us say that this is 1, I 2 has a theta dependence and so, it will actually have a minimum at a theta of 90 and have a characteristic shape that looks like this. So, the total intensity I will then have a shape that looks like this, so, this is I equals I 1 plus I 2, of course, this will be in relative terms, it will be 2.

So, if you are trying to measure scattered light intensity from spherical particle that is in the Rayleigh scattering regime, you can see that the dependences are very well established. The expected relationship between scattering angle theta and the scattering intensity is also well established predicted and it can be measured and validated as well.

So, particle size measurement in the Rayleigh regime is actually the easiest accomplish. Now, what do we, when we say alpha much less than 1, what are the actual sizes we are talking about? It has to be roughly in the 1 micron size range.

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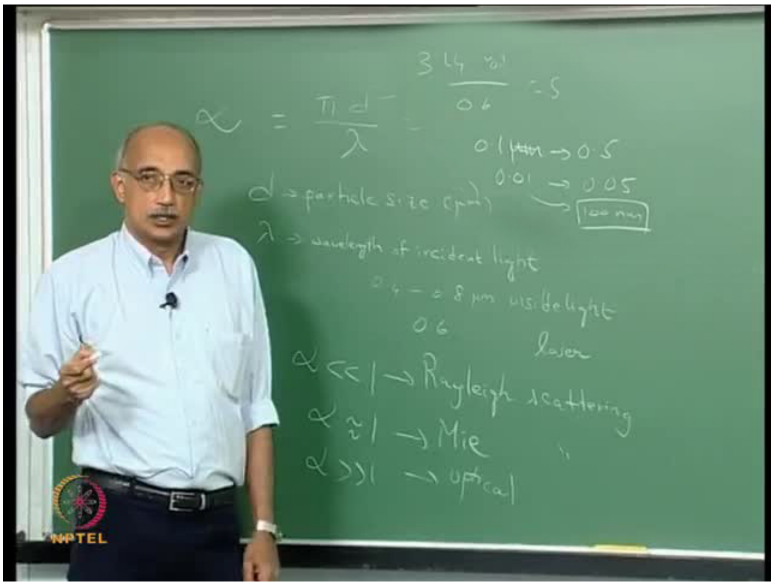

Now, when d is equal 1 micron, then this is, let us say 3.14, so, this works out to about 3.14 times 1 divided by, let us say 0.6, it is works out to roughly 5 which is clearly not much less than 1.

So, when we talk about alpha values being much smaller than 1, you are talk about sub-micron particles. A 0.1 micron size particle will then correspond to an alpha value of roughly 0.5.

A 0.01 micron sized particle will correspond to 0.05 here which is much smaller than 1. So, now, what is this correspond to? 100 nanometers. So, the Rayleigh scattering regime in terms of actual numbers essentially starts where nano ends. I mentioned earlier that nano is a size range that is conventionally defined as 1 to a 100 nanometers.

100 nanometers to roughly 500 nanometers or so is what you call the sub-micron regime and that is where the Rayleigh scattering effectively happens. So, when you use particle counters, that are using light scattering as a basic principle. They are most accurate in the size range of roughly less than a micron to more than 100 nanometers.

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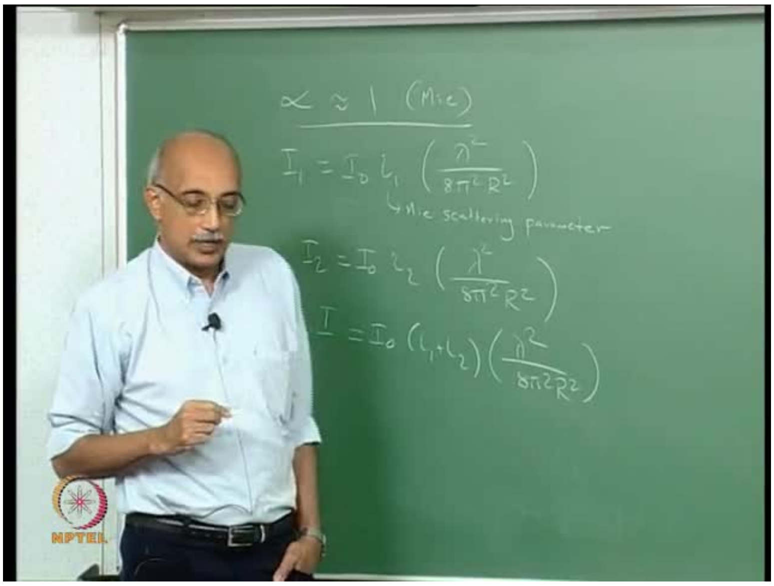

Let us consider the Mie scattering regime next. So, when alpha is roughly equal to 1, we call this is the Mie scattering regime. In this size range, again there is a linear relationship between I 1 I 2 and I 0, but then, you introduce something called lower case I 1 which is called the Mie scattering parameter.

And the actual expression then becomes I 0 times I 1 divided by lambda squared over 8 pi squared R squared, and similarly, I 2 equals I 0 times I two times lambda squared over 8 pi squared R squared, and so, I equals I 0 times I 1 plus I 2 times lambda squared by 80 pi squared R squared.

The complexity is actually in this I parameter; I 1 and I 2 have very complex dependences on theta and the refractive index parameter m, and unlike the Rayleigh scattering regime where these predictions are valid irrespective of the medium and the particle - the materials that they are made of - as well as the scattering angle ranging from 0 to 180. In the Mie scattering regime, each of these becomes also system dependent.

So, they become more what we call constitute law. They are not universally applicable to all fluids and all particles but must be essentially recalibrated for every combination of fluid and particle, and so, if we look at, if you try to plot, for example, theta verses I in the Mie scattering regime.

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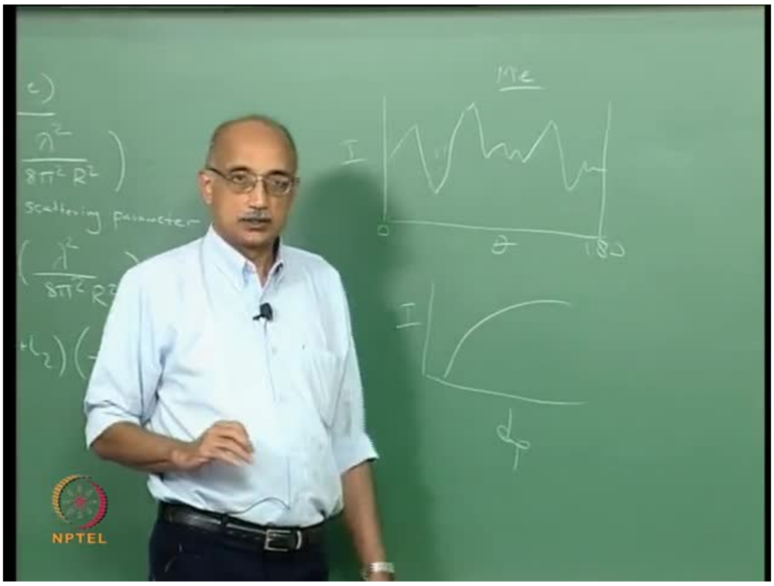

The relationship that you see will not be as clear cut as what we saw in the Rayleigh scattering regime but it will actually show a lot of scatter and also non-monotonic behavior which is roughly sickly curve in character. When you go from 0 to 1 eighty and it will have a significant dependence as I said on the actual materials that are under consideration.

So, when you think about it, then how do you even use this signal to predict size, because what this would tell me is - for the same particle size, you can have multiple intensity values, and for the same intensity value, there could be multiple particle sizes that contribute to that intensity value.

So, interpretation of the scattering spectrum in the Mie regime to calculate particle size becomes somewhat questionable. So, for particles that are roughly in the 1 2 half a micron range, the uncertainty in the measurement is very high. For particles that are larger, again you can go back to optical methods of analysis.

For particles that are smaller, you can use the Rayleigh scattering calculations. It is the particles that are in the range where they are too fine to be characterized using conventional optics. They are two course to fit in to the Rayleigh regime that the error in the measurement or the uncertainty in the measurement is highest.

So, when we when we look at particle counters in general and particle size analyzers, most of them tend to say that incitive calibration is necessary. In other words, you cannot rely upon a calibration that is done in a standards lab for example and use that evaluate your` particle samples. You have to the calibration in your lab using materials that are very similar to your system that is under consideration and you have to fix all the geometrical factors in your system as well as the wave length of a radiation, and essentially, you have to recalibrate every time any of these parameters changes, and so, that is one of the difficulties in using this technique to handle particles in that size range.

So, in the next lecture, we will we will talk about some alternative methods of measuring particles that are in that intermediate size range, that is very difficult to measure, but as you will realize, the size range that is smaller than 100 nanometers. Obviously, it is also difficult to measure because after other effect that we talked about that, as particle size decreases, there is a very steep drop of in the intensity of the scattered light.

So, up to let us say a 100 nanometers. You are in the Rayleigh scattering regime and it is possible to measure size fairly well, but what do you do when size drops below that value? Let us say that you still want to use light scattering as your technique. One reason is - in this size range, in, in the 100 nanometer size range, there are very very few techniques that are better than light scattering even with the limitations that it has, and so, you want to try a make light scattering work even for particles that are smaller but how do you do it? Same question I think I posted in the last lecture.

When you think about it, the only way you can do it is essentially by taking particles that are in this size range and making them grow larger so that the size increases in a controlled manner to a size where you can use Rayleigh scattering technique to detect the size. So, how do you do that? How do you grow the size of a particle? By making something condense on it. So, there are these particle sizing instruments which are known as condensation nuclear counters or condensation particle counters which essentially do exactly this. So, we will talk about those in some detail now.

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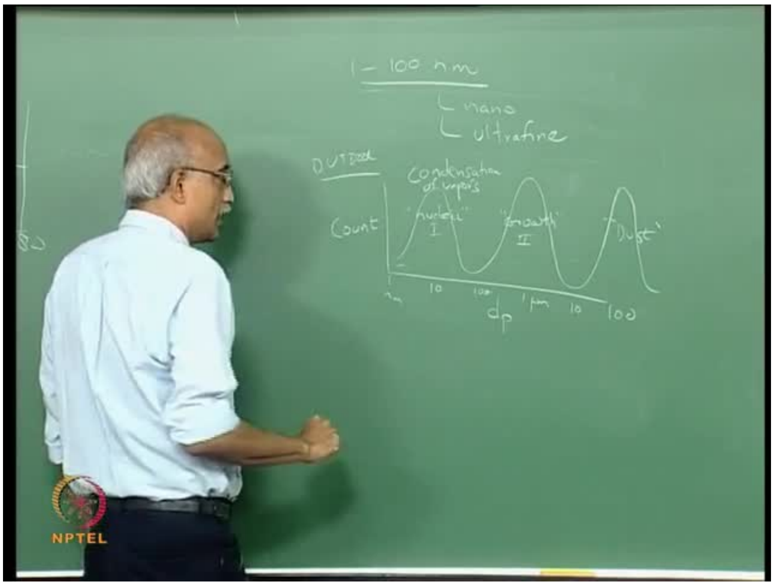

So, particles in the 1 to 100 nanometer size range, they are called nano particles. Before nano, became catch phase, they use to be known as ultra-fine particles.

Again the challenge with these particles is a fact that the scattered light intensity drops of very rapidly, so, you do not get a very strong enough signal and the noise in the measurement sometimes dominates over the signal. So, how do we deal with these particles? Well, the first thing to think about is how do this particles happen, you know, what causes the generation of particles in this very fine size range. If you look at particle size distribution in nature, suppose you go outside and take a sampling of the air and look at particle counts as a function of particle size.

It is very interesting that no matter what region of the world you are in, or what the topography of the land is. You get essentially the same signal or characteristic shape of this curve. So, if you plot size on this axis verse, let us say count on the vertical axis and you plot this all the way from 1 nanometer, let us say to 10, 100, 1 micro meter, 10 micro meters, 100 micro meters and so on.

What type of shape do you expect? Do you have any idea? Will it look like this or like this, like this, yes, actually the prevailing shape is try model; it will have three distinct peaks. That the height of this peaks may be different depending on where you do the sampling, I mean if you are in a highly polluted city, all these peaks may be very high;

whereas, if you are in a clean area, all these peaks may be very low but they all retained this try model characteristic.

And what is the reason for that? The very fine particles in this distribution are essentially caused by condensation of vapors. So, for example, in the atmosphere, you have all these chemical vapours that have been emitted in to the environment which will condense, and when they condense, they will form what are known as nuclei or nuclei’s.

So, that is basically what they speak represents. It is the first condensed phase nuclei that are formed when a phase change occurs from vapour phase to either solid or liquid phase. So, these nuclei that form could be in solid form or it could be in liquid form.

In class, the simplest example of this is of course formation of the initial nuclei of rain. Rain happens because water vapour condenses to form this verify nuclei. So, how does this happen? Where is the next stage in the formation of a rain drop? Agglomeration, so, this is the, what is known as a growth phase?

These nuclei find each other and start agglomerating, and eventually, they reach a size that brings them from here to here. So, this is region one, this is region two. (Refer Slide Time: 27:08) So, a particle, for example, a water droplet that was nucleated here, eventually becomes a large enough rain drop here, and then, it is starts to rain.

So, it is actually an interesting fact that you would think that in areas where the temperature is suddenly lower. That is a tendency for rain to happen, but actually turns out, that is not enough. The reason for example that cities like Chennai have very low rain fall, is because we have a kind of a, kind of a worst case scenario. We have high emissions from for example traffic on the roads and other reasons, but at the same time, Chennai is not a industrialized city.

Now, why does industry help? Usually you think of industries are also as polluting, but from the view point of rain, we actually require industries, because they emit particles, they very fine particles in to the atmosphere and these particles are actually served as the initial sizes where this nuclei can form, because now you are introducing a heterogeneous feature.

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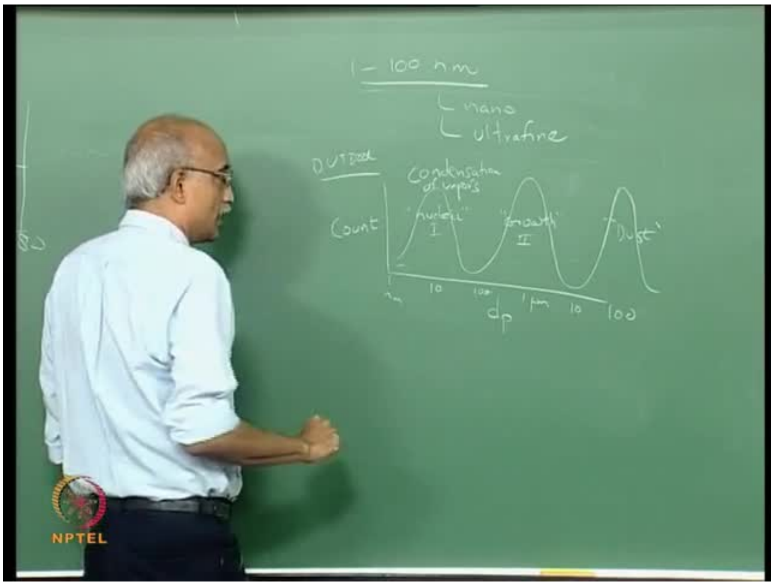

Homogeneous nucleation is very difficult in terms of overcoming the energy barriers associated with it. Heterogeneous nucleation can happen like that. So, in other words, even if conditions are very conducive to the formation of rain droplets.

If we do not have a sufficient amount of suspended particulates in the environment, rain would not happen. So, actually we need a certain amount of pollution in the atmosphere for rain to begin happening.

And so, the nuclei that we are talking about here can either form in homogeneous mode or in a heterogeneous mode, and heterogeneous mode always as a lower energy barrier and so it is much more feasible compared to homogeneous nucleation. The growth phase is essentially, the, they phase where that the initially form nuclei, find the nearest neighbor and start agglomerating.

The third phase now is distinctly different from these two, and it is actually most of the time not related to these two, it comes from an independent source. For example, this could be just your dust particles, or again it could be industry emissions that are, in a, in a larger size range compare to the types of emissions that are participating here, or this could also be due to spewing aero salts that are getting in to the environment. So, the source here is distinctly different from the source of particles in, in these two cases. As I mentioned this is for the outdoor environment.

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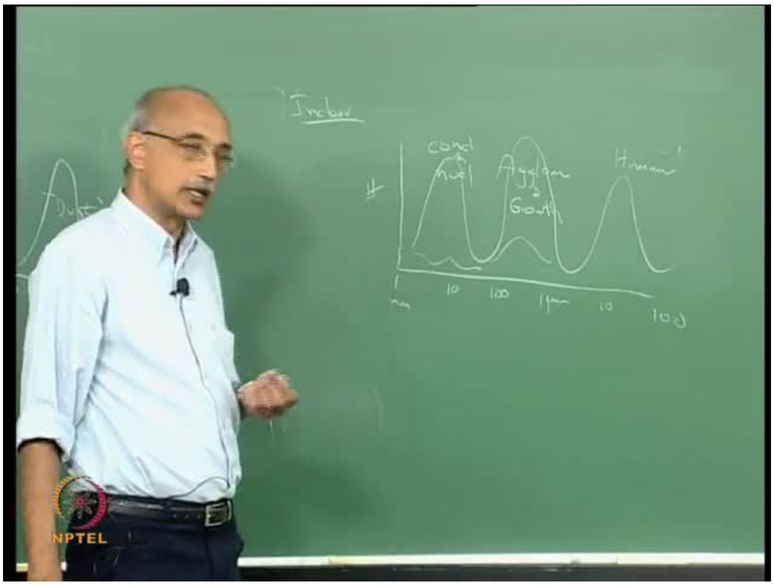

Now, how about indoor? What kind of distribution would you expect to see? Suppose, you take the sample here, in this room, what would be the size distribution you would expect?

Again, we go from 1 nanometer to 10 to 100 to 1 micro meter to 10 to 100 and you are looking at the counts. Do you think the same tri modal distribution will prevail in case of the Indore environment also?

Actually, the, again the qualitative nature of the size distribution remains the same. You still see a tri modal size distribution even in indoor environments. Again the actual magnitude of this peaks, the scale itself can change significantly. For example, if this is a clean room, cleaned room is facility that is designed to operate with a very fixed level of contaminants in air including particles.

So, for example and we will discuss this in more detail in future lectures. When we talk about a class 100 clean room, what it means is that per cubic foot of the air that is inside the room, you can have no more than 100 particles that are 0.5 microns and larger per cubic foot of the air.

So, under those conditions, obviously these peaks are going to be very small, because it is a well-controlled and a cleaned environment. However, it is very interesting and intriguing that in terms of the qualitative nature of the particle size distribution, it retains its try model characteristic, and the reason for that is that the first phenomenon of condensation and nucleation also happens inside even a room like this.

Now, why is that? Well, there is a couple of reasons - one is that all materials out gas. Out gassing is a phenomenon that is obviously not visible to you but any material that sitting here is constantly emitting molecules into the environment. Every material including humans is a constant source of emissions in the vapor phase. So, we are constantly adding vapor phase constituents to this room.

So, as that happens and again, as they find some heterogeneous sites to promote the nucleation, they will start nucleating very very fine droplets. Again, you cannot see it, but actually if I were to, let us say darken this room and illuminated with a fiber light, you can actually start seeing this very fine particles and droplets in the air, and of course, as long as condensation and nucleation are going on, agglomeration and growth are associated mechanisms.

Although the extent to which this happens again depends on how clean the room is. For example, in a well design clean room, particles are present in a very dilute form. The number of particles per unit volume is very low. So, the probability of 1 nucleated droplet finding another 1 is also very low. So, agglomeration kinetics are going to be highly slowed down in a clean room type of environment verses an uncontrolled environment. Also, in a clean room environment which has very directed air flow, these fine droplets that are being produced will be quickly directed to go in a certain way and removed from the room. So, they were never have an opportunity to find each other and start growing.

So, in a controlled environment the phase of going from here to here may only happen to a very limited extent. So, in a highly clean environment, you may get a peak like this which is very low compare to a room like this where this peak may be quite high. This room, for example, just in terms of clean room classes it is, probably about a million just to give a perspective.

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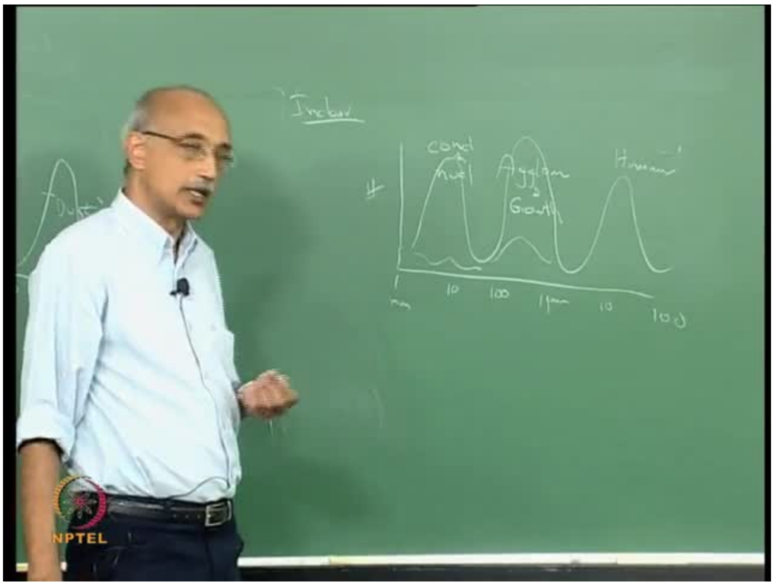

If we actually took a particle counter and major particles in this room, you will find there is at least one million particles per cubic foot, that is half a micron or larger. Even though none of them is visible, you know, you would think that this is the clean room but it is really not. It is a clean room but that is different from a cleaned room, you know, it depends on whether you write it as one word or two words clean room is something that is a very special thing.

So, where is this source? Actually that the most common source for particles in this region in an in indoor environment is humans, because again you may not realized it, but we are constantly shedding, we are shedding. We are skin flakes; we are shedding fibers from our clothing. As we speak, we are shedding saliva droplets; hair is falling out, you know, all these are contributing to large particles that are present, in a, in a, even in a semi cleaned environment.

Also if inside the indoor facility, you have tools that are operating or equipment that are in motion, or you have processes that are taking place. Each of these is a source of particles in this size range. Just as an example, if we take two metal surfaces and drop them against each other, you will generate a shower of particles that are all in this size range of 10 to 100 microns.

Again, may not be visible to you but you take a particle counter and you measure, it just get the huge burst of particles.

So, any sliding motion, any abrasive motion generates a huge number of particles in this third peak. Same thing with spewing of aero salts, if you are using equipment, that is using oil or a grease or a lubricant, these lubricants are constantly being spewed in to air as the process takes place, as the equipment operates.

Again, even though these may not be visible to you, you can detect them using a particle counter. So, clearly particles that are present either in an outdoor environment or in an indoor environment; either in a controlled environment or in an uncontrolled environment. All have distinct sources of particle that are spread across this entire size spectrum, and that is why it is important to measure particles that are below 500 nanometers, because otherwise, you are going to miss these very fine droplets and particles that are present.

Now why is it important? Well, in a way they are the pickers to everything that happens after words. If you are trying to minimize the particles in an atmosphere, what you should do is eliminate this process, you can eliminate the condensation and nucleation process, then this process would not even get started, and usually the larger particle range is much easier to handle. That are very well identified and fixed sources for such particles and I would not say it is trivial but it is relatively easy exercise to get rid a particle from this size range.

But in this size range, again there is a saying that if you cannot measure something, you cannot control it. You have to be able to measure quantitatively in order to be able to control.

So, that is why the measurement ability in the sub 100 nanometer size range is very important in many particularly precession manufacturing industry such as semiconductors and so on.

So, how do you do it? Again it is goes back to the problem that we started talking earlier. Given that there is this steep fall in scattering intensity as a size drops below 100 nanometers, how do you measure it?

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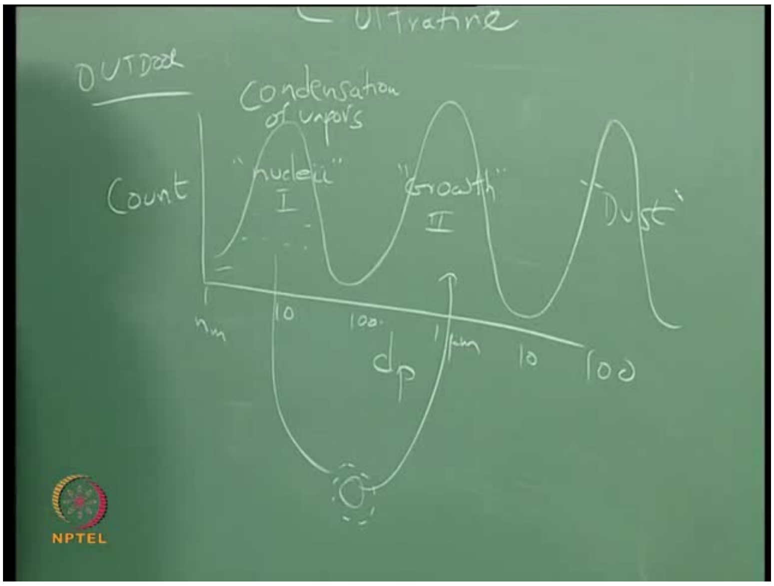

Well, going back to these curves, essentially what we try to do is - if you are trying to measure the size of a particle in this size range, you introduce a vapor which condenses on top of this particle and grows as sufficiently thick layer so that this particle size is migrated from this range to a more measurable range. So, if you have a collection of particles in this size range and you do this condensation process on top of all these particles, they are all going to grow to a size we are now, they are detectable.

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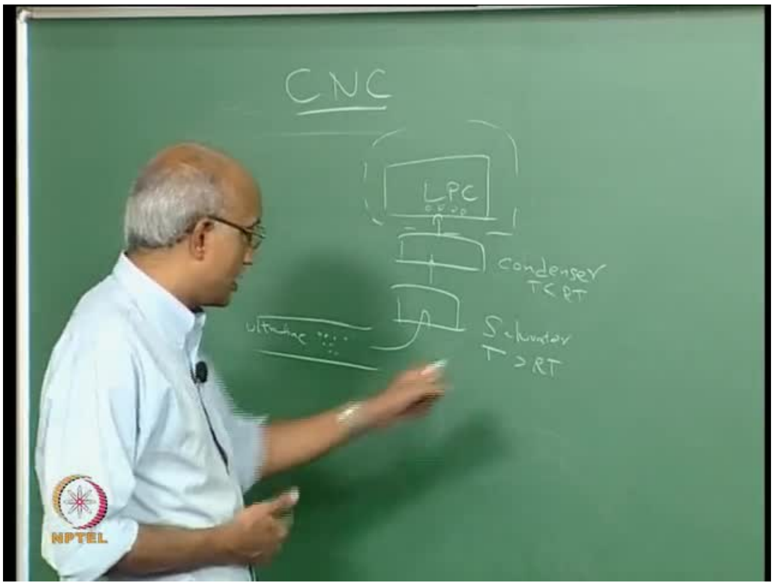

And so that is how basically these condensation nuclei accouters or condensation particle counters work. So, condensation particle counter is very very similar to the laser particle counter that we have been discussing so for. It includes that as one of the stages in it is in the process but it adds a couple of stages to it.

So, what you do is you take this ultra-fine particle population which is suspended in it is some fluid, whether it is gaseous or liquid and you take it through a stage that is called as saturator, and another stage, that is called a condenser, and then, this stream is input in to the particle counter, and the rest of it essentially follows the same light scattering principle that we have outlined earlier.

So, in a condensation nuclei counter or CNC, the part that we have added is really this upstream part. So, what exactly are we doing here? We are taking the ultra-fine particles that are, for example in air, you are introducing here a condensable vapor and but you keep the temperature slightly high.

So, this temperature here may be slightly greater than room temperature. At a next stage, you just slightly lower the temperature which is sufficient to believe the saturation that is present and cause condensation to happen. So, condensation will then happen on all these ultra-fine particles and they will be introduced in to the particle counter as enlarged particles because of condensation that has taken place.

So, this is fairly simple in principle. What is the problem with this methodology or what are some other draw backs? One of the difficulties is you can measure the size distribution of the grown particles, but from that, can you actually extract the size distribution of the original particles? Well, you could but it will take a lot of work. Essentially you have to do a calibration. You have to do this process and possibly use an independent measurement technique to look at the kinetics of how the vapour that you are introducing condenses on particle of various sizes.

So, if you were to do the exercise, then you could essentially take the data you get from here and extract the original size distribution that was present, but there is actually a cleaner or smatter way to do it which we will discuss very soon.

Before that, should talk about, how do you do the saturation? What are some of the vapors that are commonly used to make these, to grow these ultra-fine particles to a fine particles size range?

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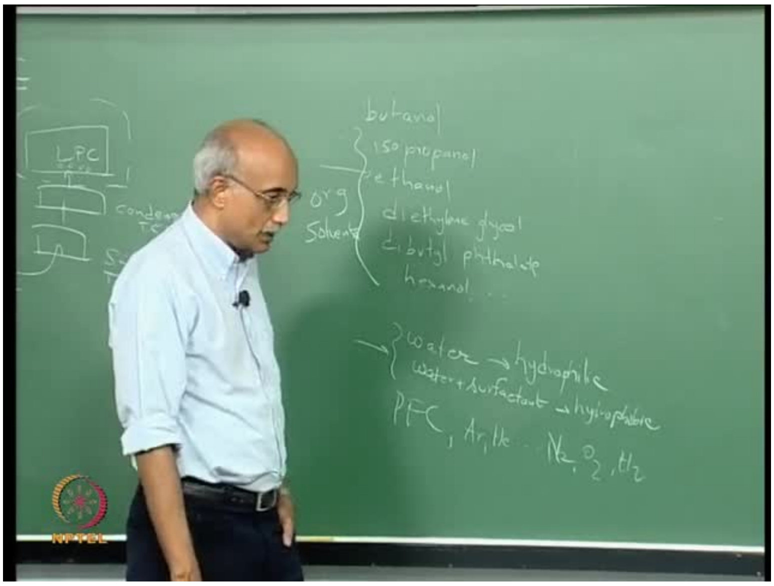

You typically do that using organic solvents such as butanol, iso propanol, ethanol. Now, the problem with butanol and isopropanol is they are toxic and they also have a kind of a bad smell, but they are very very good. Now, what are the features you look for in this type of vapor? It should be easily condensable and it should be able to condense both on hydrophobic as well as hydrophilic surfaces because of particles that we have suspended may or may not be hydrophobic. So, water may not always work as a medium to condense on the particle.

Where as many of these alcohols have a hydrophobic part and hydrophilic part. So, they are able to condense on either hydrophobic or hydrophilic particles. In the case of the hydrophobic particle, the hydrophobic portion of this molecule will attach it is self to the particle, whereas in the case of hydrophilic particle, the hydrophilic portion of this molecule will attach itself to the particle.

So, it can, they can condense on both types of materials. Other commonly used solvents are di ethylene glycol, di butyl phthalate, hexanol and so on. So, these are all organic solvents that have high vapor pressure. See the other requirement for these materials is once they have condensed and you have done the particle size analysis, you want to be able rinse this off also, you do not want them to permanently stay attached to the particle because then they become a contaminated in the process.

So, these are materials that can be easily re evaporated. You can simply take the temperature high and you can essentially recover the virgin particles, or worst case, you can you can use another solvent to essentially remove this condense layers on the particles. So, that is one of the requirements.

Now, so, these are the organic solvents that are typically used in a condensation nuclei accouter or condensation particle counter, but there are alternative fluids we can use also. Water certainly is very attractive because even if we talk about liquid solvents in general, water is the most convenient medium to use. The problem is water cannot be used for hydrophobic surfaces. So, the use of water is normally limited to surfaces that are known to be hydrophilic easily wetted surfaces.

However, more recent work has led to the development of surfactance which can be used that promotes the betting even of hydrophobic surfaces using water. So, water plus trace amounts of surfactant are now being used to condense on particles that are even hydrophobic. Other materials that are used in this application are inert materials, for example, per fluorocarbons.

Even noble gases like organ helium and so on. Nitrogen can be used; even O 2 and H 2 have been used, but if you look usage of solvents in condensation particle counters in general, the most popular once are water either with or without surfactant and ethanol.

The only problem with ethanol is it has beautiful properties, it has very high condensation potential and high evaporation potential, they are not toxic effect. Only difficulty with the ethanol is sometimes procurement. Methanol is much easier to obtain compare to ethanol. So, prices are higher; availability is lower, but you only require really small quantities to do this test. So, it is not such a big issue as for as doing this testing is concerned.

Now, this method that we have been discussing so far - the condensation nuclei account a method - really works for fine droplets or ultra-fine materials in air and other gases. How about if they are in a liquid? Can you still use this technique? It is actually not possible to use a condensation nuclei accounting technique for particles that are suspended in liquids.

So, the alternative is essentially to measure the fine particle level using quantitative methods, typically gravimetric methods that estimate total non-volatile residue in the liquid. In other words, just boil of the liquid and look at what is left. Look at the non-volatiles that are present in the liquid. A substantial fashion of those non-volatiles will be particles that are in the ultra-fine size range.

It is not a perfect method but the ability to count and a size ultra-fine particle in liquid is not nearly as well double as ability to characterize them in gases. How about surfaces? If you are trying to characterize presence of ultra-fine particles on a surface like this, again the same difficulty is exists. Light scattering, now you have actually a double (( ))

Light scattering intensity from the particles is very low, but at the same time, the noise which is scattering from the surface itself is very high. So, use of light scattering techniques to detect ultra-fine particles on surfaces is even harder than detecting them in gases or liquids.

But lately variant of this technique has emerged where you do what is known as surface condensation again of condensable vapors, and the principle is the same, you take this ultra-fine particles and by condensing vapor on them, you grow them to a size where they now become large enough that the signal, the scattering do not from them is comparable to or larger than the noise that you get from the surface itself.

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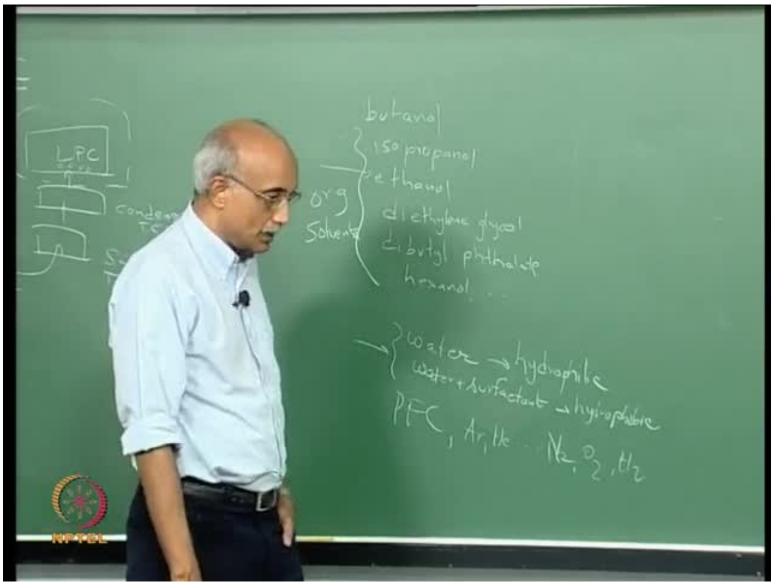

So, the use of condensable vapors to grow particles, ultra-fine particles on surfaces to a larger size range in order to do scattering technique base measurements is gaining in popularity, but we still comeback to the fundamental question of how do you translate the sizes that you measure with a condensation nuclei accouter to the sizes of the ultrafine particles that we are present to begin with.

So, just think about that. In the next lecture, we will start out by describing a method that enables us to do that. Any questions? See you in the next lecture then.