Particle Characterization

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Module No. # 01
Lecture No. # 02
Introduction: Classification of Particle Characteristics

Good morning and welcome to the second lecture in the particle characterization course. In the last lecture, we primarily discussed the why part of it. Why should we learn about particle characteristics? How is knowledge of particle characteristics going to help us in terms of either doing a research or running our processes or obtaining whatever result that we are trying to achieve?

As I mentioned in the last lecture, the second thing you need to talk about, after you discuss the why part, is the what. What are we going to learn in this course? So, specifically the question is, what are particle characteristics that are of most importance and most interest to practical applications? And what are the tools and procedures that are used to measure these characteristics?

So, in today's lecture, I will give you an outline of various particle characteristics that are of interest to us and I will also briefly outline the methods or techniques for obtaining these characteristics. For the remainder of the course, we would then essentially revisit what we are going to talk about today and deal with each topic in much more detail. So, this lecture, will serve kind of as a summary of what we are going to talk about the remainder of the course.

Now, when we talk about particle characteristics, you know it is like the story of the blind man and the elephant. Depending on, you know, which part of the elephant you touch, you might describe the elephant differently, right? Similarly, a particle is such a complex object, that the chief characteristic of a particle can be very different for different people that are working with these particles, for some specific purpose; and therefore, one of the first things we need to do is classify these characteristics of particles in a way, that is systematic and which will enable us to get a better understanding of these characteristics as we go along. The reason is, there are at least a hundred characteristics of a particle that are immediately relevant.

Now, if you just randomly go through these hundred characteristics and also the methods used for characterizing these particles, as the minimum you will get confused, and you might get totally lost. Instead of that, what we will do is classify these characteristics in specific categories and we will try to approach it, one category at a time.

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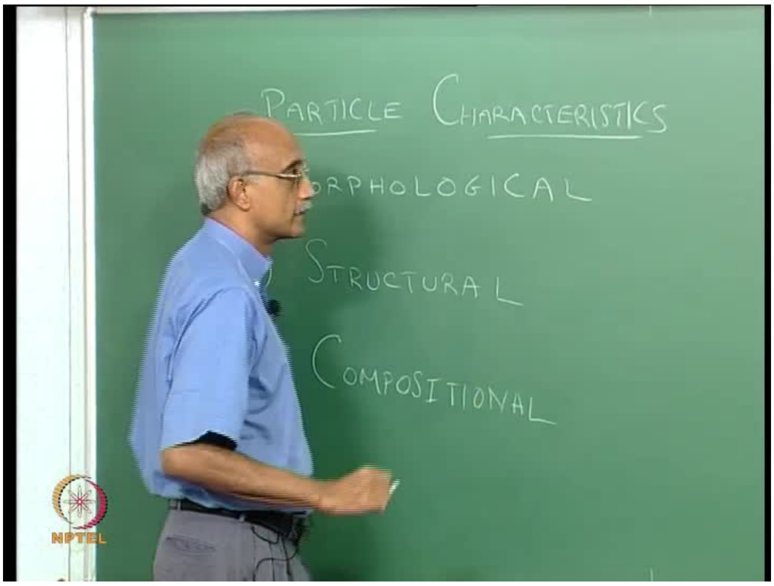

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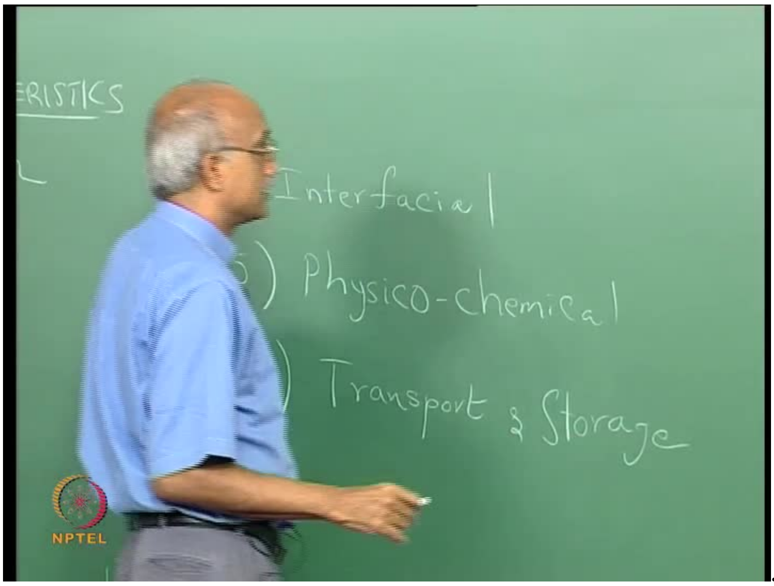

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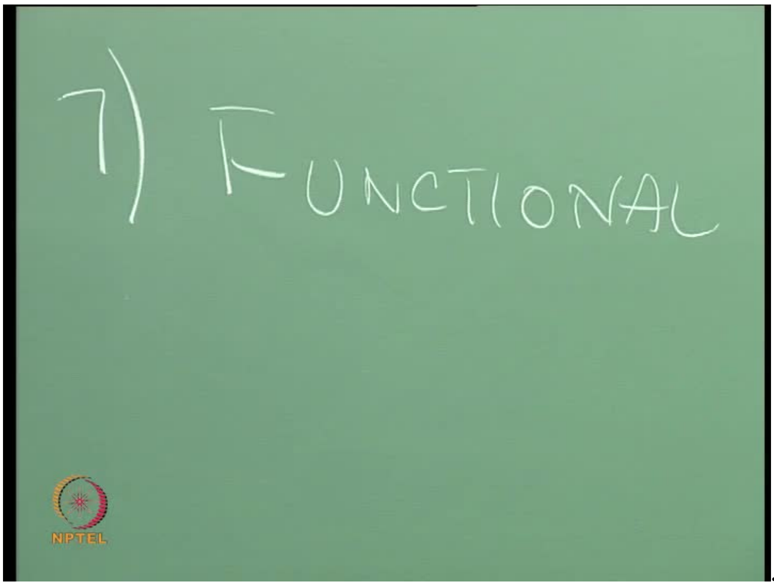

Broadly speaking, the characteristics of a particle can be categorized as follows - the first is morphological, the second is structural, the third is compositional, the fourth is interfacial, the fifth is physicochemical, the sixth is transport and storage and the last one is functional. This is the very broad classification of the characteristics of a particle. So, let us briefly talk about what we mean by each one of these.

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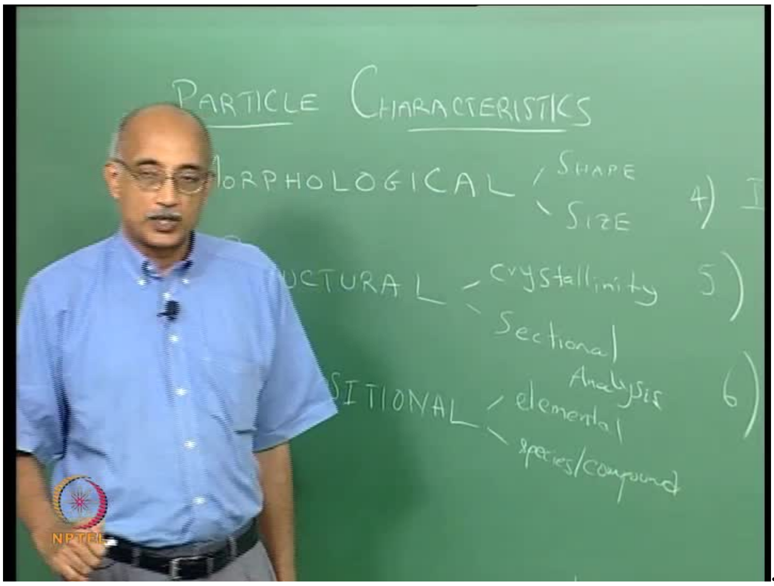

Morphological characterization refers to characterizing the morphology of a particle. By morphology, what we mean is primarily shape and size - the two things that hit your eye as soon as you observe a particle. So, shape and size are the two chief morphological characteristics of a particle, in the sense that, they give you the most direct impression of the appearance of a particle. So, in our discussions, we will begin by initially focusing on these two aspects. We will devote a few lectures to shape assessment and we will devote a few lectures to size measurement. It is the logical starting point in the study of the characteristics of a particle. Until you define the shape and size, you really cannot progress to some of these other characteristics that we are going to talk about.

The second category is structural. Now, what we mean by that is the appearance - the visual appearance of a particle - will only tell you shape and size. It does not yield any information about the nature in which the atoms or molecules or constituents of the particles are held together. So, when we talk about structural characteristics of a particle there are really two ways to approach that. The first is based on the macroscopic nature of the particle. Is it crystalline? Is it amorphous? Or is it something that has crystalline features in some spaces and is amorphous in other places?

So, the crystallinity is one of the most important structural aspects of a particle. Because it is the crystallinity, that really lends certain very important functional features to the particle. It imparts directionality, which is very useful in certain applications. In some cases, it also yields strength - toughness. So, the crystallinity of the material is a very important particle characteristic that we will deal with in some detail.

Now if you look at a single particle, the structure that is immediately obvious is, what I would term the macroscopic structure of the entire particle. But when you actually break it down, when you start sectioning the particle, you will observe that there are actually 3 distinct regions in a particle, from a structural view point. The outer most layer of the particle is called its surface. The next layer is called the sub surface and the bulk of the particle is called the core. So, essentially as you take a particle and move in towards its center, first, you will encounter the surface, then, you will encounter the sub surface region and finally the core of the particle. So, sectional analysis is an important aspect of understanding the structure of a particle.

The third aspect is compositional. Certainly, as chemical engineers, we are always interested in the chemical makeup of any material and particles are no different. So, you need to understand, for any given particle, what is it? Is it a pure element of some kind? Is it an alloy material? Is it a compound, a species? Is it a polymer? Is it a ceramic? These materials aspects are also very important in characterizing particles. At a very basic level, when you talk about composition, especially chemical composition, you can either describe the elemental composition of the material or the species composition of the material.

For example, if you have alumina as a particle, that you are looking at from an elemental view point, it has aluminum and oxygen, right? So, if you are using a simple SEM-EDX type of tool, all that it will tell you is, this particle has aluminum and this particle has oxygen, but it will not tell you anything about the actual species composition or compound information about the particle. For that, you need additional analysis techniques.

So, when we talk about chemical composition, we have to distinguish between elemental composition and species slash compound identity of the particle. In other words, in many applications, it is not enough for us to say that this particle has aluminum and oxygen. We have to know that it is actually a l 2 o 3 and the same tool may not be able to give you both information and here also, when we talk about elemental or species composition, there is a broad classification of all chemical materials as organic and inorganic and our analysis techniques will essentially depend on whether the material is organic in nature or inorganic in nature. So, any analysis that we do, to identify the compositional characteristics has to be based on whether it is organic in nature or inorganic in nature.

The next broad category is interfacial properties. Now, what do we mean by that? A particle, by its nature, is a discrete entity, which means all around its outer surface, it is in contact with an external medium. So, there is always this interface between the surface of the particle and the medium that it is suspended in.

So, for example, if you have a solid particle that is suspended in air, let us say, this interface that is most relevant is the interface between the solid surface of the particle and the air that is surrounding it. If you have a solid particle that is suspended in a liquid, the most relevant interface is between the solid surface and the liquid medium.

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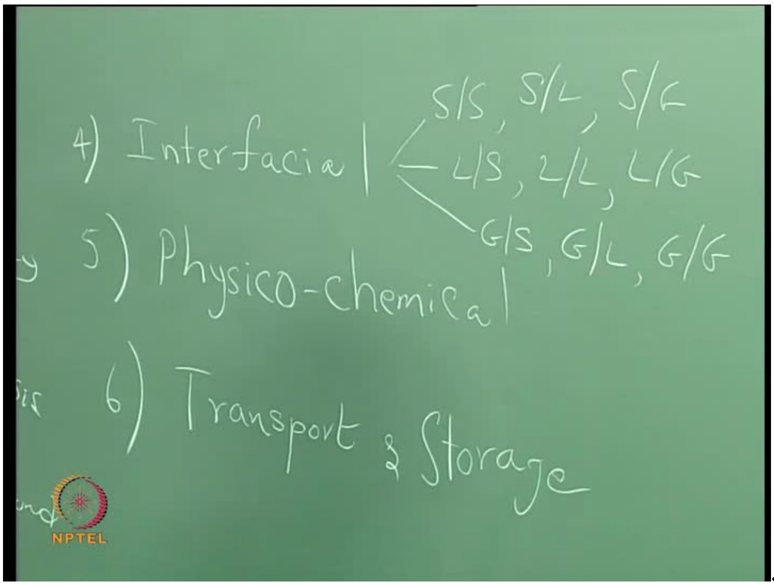

So, when we talk about interfacial properties, a simple classification is S/S S/L S/G or L/S L/L L/G or G/S G/L G/G. What do we mean by that? The particle that is suspended can be solid in nature or it can be a liquid particle a droplet or it can even be a gaseous particle, right and the surrounding medium can be liquid and gas in most cases. But, when you have two solids, for example, that are in very close contact, then actually, there may exist an interface between two adjacent solid particles that are suspended in a medium. So, essentially now, you have to concern yourself with two different interfaces - the solid to gas interface and the solid to solid interface.

Similarly, if you have a liquid that is suspended in a solid or a gas, there may also exist an interface between adjacent liquid droplets that are suspended in the medium and same thing with gas-solid, gas-liquid and so on. Is it possible to have a gaseous particle? What do we mean by that? Well, there is an interesting way to look at this.

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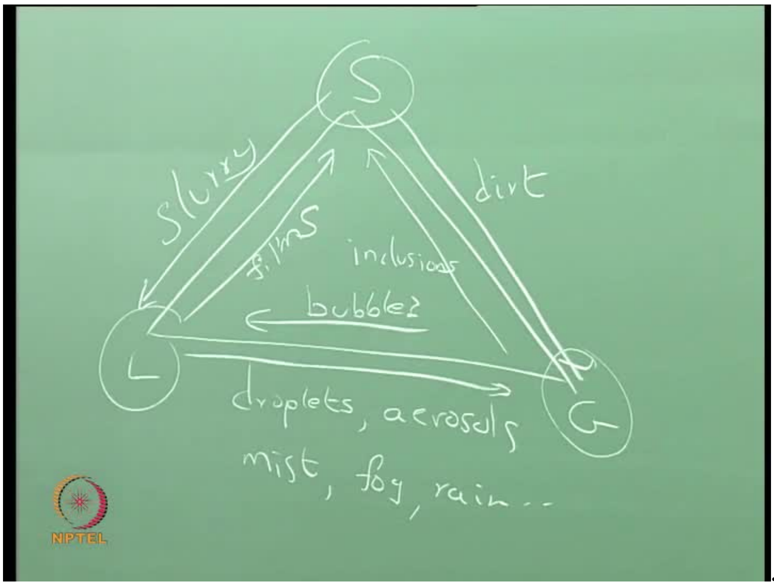

You can represent interfacial behavior in this triangular graph. Let us call one of the vertices solid, let us call this liquid, let us call this gas. Now, when you have a solid particle suspended in a liquid, it happens all the time, right? What are some names for solid particle suspensions in a liquid – slurry, for example, right? So, frequently it happens that you have solid particles suspended in liquids.

How about liquids and gases? Sure, I mean many examples you can think of; droplets of all kinds, aerosols, even things like mist, fog, rain, smog, all of these represent liquid droplets that are suspended in a gas. How about solids suspended in a gas? Sure, again environmentally you can think of many examples; dirt, let us say is a classic example. But, you could also have particulate emissions from automobiles, factories which get suspended, pollen from plants that are getting transported due to air movement, all of these represent examples of solid particles that are suspended in a gas. So, these are somewhat obvious.

Now, let us look at the other way. Is it possible to have, let us say, gases suspended in a solid? Well, it turns out that yes, there are what are known as inclusions - gaseous inclusions - that are present at distinct adsorption locations in a surface. So, your surface, the solid surface may not have equal adsorption capability at every location on its surface.

So, the gaseous material that is in contact with the surface, may be preferentially adsorbed at certain sites and these are called inclusions of gas in the solid and in such cases, these isolated gaseous species that are present in the solid are referred to as gaseous particles. They behave like particles in a suspension. They behave like droplets in air. They behave like particles in water. So, they can be characterized and described in the same way. So, gaseous inclusions would be an example of gas particles that are captured or present in a continuous solid surface.

How about liquids and solids? Well, similarly, you can have absorbed liquid that is present only at certain locations of a solid surface or you can even have films of water on a surface. Especially, if you have a hydrophobic surface, you may not have continuous film of water or hydrophilic material, but you may have beads of water or other liquids that collects on the surface. In such cases, they behave as liquid droplets that are suspended in a solid. So, these would be isolated collections of liquid that are present on a solid surface.

Now, this is an interesting one. Can you have gaseous particles in a liquid and what would they be known as? Bubbles. Bubbles are gaseous particles in a liquid and the interface between a bubble and the liquid that it is contained in can be studied using the same interfacial principles that we will be describing in our particle characterization course. So, the point with this triangle is two points - one is that when we talk about particles, we are not only talking about solid particles, they can also be liquid or gaseous particles. Secondly, when we talk about the medium that the particle is suspended in, they do not have to be only liquids or gases. They can also be solids. So, those are two important distinctions, we have to keep in mind. The third point is, you know, when you look at this triangle, it is obvious that for you to be an expert in the area of particle characterization, particle technology, particle science, you really need interdisciplinary skills.

It is not enough to have a good understanding of liquids or solids or gases. You really have to have a very good understanding of how they come together, form interfaces and co-exist. So, the study of particles, in general, involves engineers from a variety of disciplines, not just chemical engineering. There is a lot of metallurgy involved here, obviously, lot of mechanical engineering, virtually every discipline of engineering has a role to play in the study of particle characteristics and by the way, when you start talking about nano-particles, the sciences become very important as well. In fact, the whole domain of nanotechnology is still predominantly within chemistry and physics. Much of the innovative work in nano-science, nanotechnology is still not occurring in engineering departments but rather in the science departments.

So, as the size of the particle shrinks, we are still in a mode where you are trying to understand the science of how it works. You know, the difference between science and technology is the science gives you the fundamental understanding, the technology is essentially taking that understanding that you have gained and putting it into practical use and at least, for the most part, nanotechnology is still in the realm of the nano-science. We are still trying to understand how nano-materials behave in a laboratory scale and we are still trying to figure out how to make it work in a larger scale.

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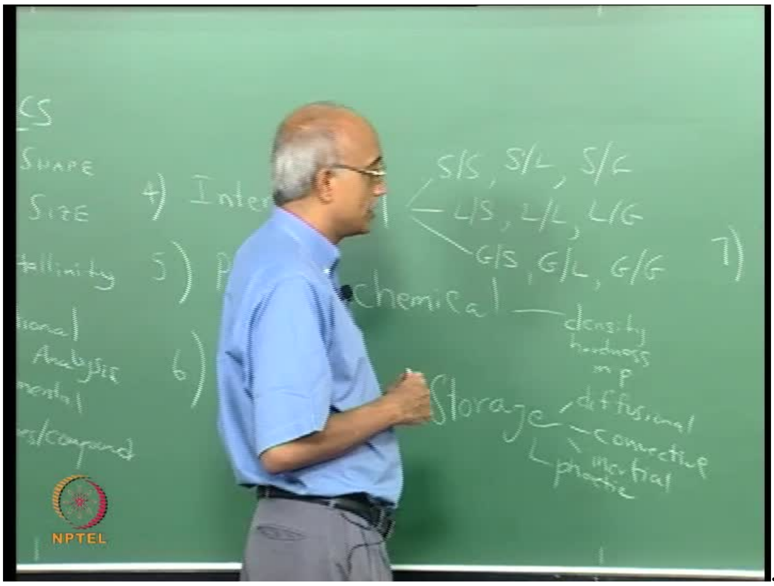

So, coming back to our list. Now, hopefully this makes a little more sense, that what we are talking about here is, when we will be describing interfacial characteristics, we are really concerned with nine different types of interfaces that we need to characterize.

Okay then, the next one is actually the largest of all. When you talk about physicochemical, what do we mean? Well, it is basically a combination of physical and chemical properties and the reason they are combined is, many of the physical properties have an effect on the chemical properties and vice versa. So, instead of studying physical properties separately and chemical properties separately, typically researchers combined the two and study them as physicochemical properties with particular attention to how the two interact with each other.

Now, what are some common physical properties of particles you can think of – density, hardness, roughness. Now surface roughness, you can actually classify it either as a morphological parameter, because the surface roughness of a particle can have an influence on its appearance as well, but certainly, it will affect many of the physical properties of the particle. So, you know you can write a fairly long list, but density, hardness, melting point or freezing point or boiling point - these are all very fundamental physical characteristics of a particle.

Now, this list will come back to an expand because, as I mentioned, of all these categories, the one that contains the most elements is this one and many of them are very relevant for people trying to work with particles. I mean, examples are thermal conductivity. Thermal conductivity of a particle plays a huge role in how effectively it can be deployed in many process industries. So, we need to have a good understanding of how does the thermal conductivity of a particle differ from the thermal conductivity of the bulk material.

In fact, many of the properties of a material change as you go from an integral or solid object to increasingly finely divided particles. The evolution of the physical properties of a material as the size changes from macroscopic dimensions to microscopic to Nano-dimensions is again, a very important aspect that we will deal with. Electrical properties, magnetic properties, virtually everything that you can think of, in relation to the physical property of a material is different in the case of a particle compared to a bulk material.

When you talk about chemical properties of a particle, obviously the reactivity is a very important parameter. The chemical reactivity is something that we typically try to maximize, by reducing the size. Essentially, as particles get smaller, they become more and more reactive and there are good reasons for this, that we will talk about later in the course. But, chemical reaction is one aspect of the chemical nature of the particle. But, it may also be physical phenomena that involve chemical change. For example, sublimation or dissolution. Do you call these physical processes or chemical processes? So, they really fit under this umbrella of physicochemical processes, because they involve some aspects of physical processes or physical changes and some aspects of chemical processes or chemical changes. And here again, it turns out that the chemical properties of a particle are very different from the chemical properties of a larger bulk material. Something you can imagine easily is that when you are trying to dissolve, for example, sugar into coffee or water or milk, you know that as you make the sugar finer and finer, it dissolves more readily, right? Larger particles take longer time to dissolve. Or if you are trying to burn something, how does the burning rate scale as size?

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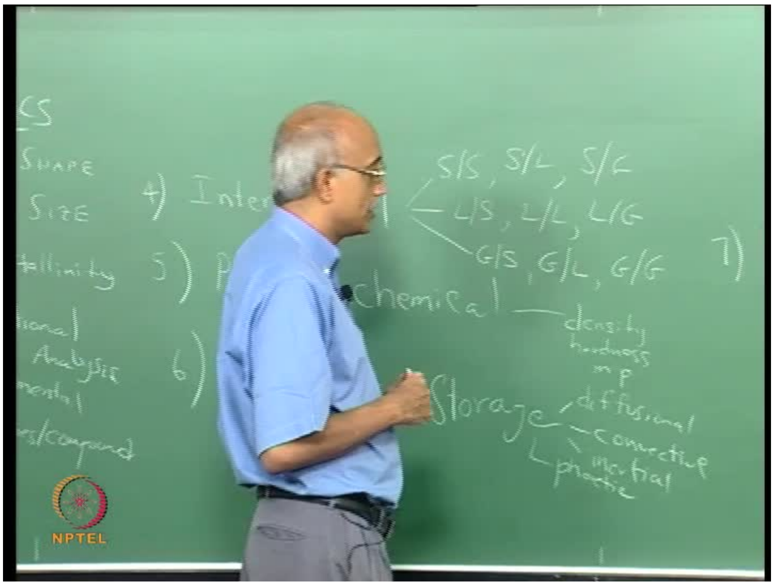

So, there are clearly some very critical dependences of particle characteristics on their chemical behavior. That is why, we again combine the two. Physical properties of a particle will influence their chemical properties and vice versa. So, you need to study them together as physicochemical properties.

The next category we have is transport and storage. Why is it important? Well, that we discussed yesterday. There are many process industries which require you to generate your particles in one place, but then move them to a different location, either for subsequent manufacturing steps or for consumer use. So, the way that particles are moved from place to place, the way they are stored, what happens to them during storage, all of these are very critical considerations and should be taken up in the context of particle characterization.

So, what do we mean by transport? Why is it important to study? Because it turns out that the transport characteristics of a particle are very much influenced by many of the parameters that we have talked about so far. The morphology of a particle, particularly the shape and size has a very sensitive effect on its transport characteristics.

For example, a very fine particle will move primarily by diffusion. A very large particle will move primarily by inertial effects, right? So, the size of a particle plays a critical role in determining the dominant transport mechanism in the prevailing system.

So, when we talk about transport characteristics, we have to talk about diffusional mode of transport. What are some of the other modes of transport? Convective, inertial, any other mode of transport that you can mention .There is something called phoretic transport, which is also very important to study. Phoretic transport essentially refers to the transport behavior of a particle which is induced by the presence of an existing field.

For example, if you have a thermal gradient in your system, that temperature difference can actually augment the transport of the particle. The particle will respond to the temperature gradient that is present. That is called a phoresis mechanism. Or if you have an electrical field or you have a charged particle, obviously the motion of the charged particle will depend on the electric field that is present. That is called electrophoresis. The motion in a temperature field is called thermophoresis. So, for every type of force field that is available, there is an associated phoretic motion of the particle and that is what we need to study under the phoretic mechanism of transport.

So, let us say that we have described the transport characteristics of a particle by dealing with these aspects and by the way, from a chemical engineering viewpoint, this is where our chemical engineering training will come in most useful. Because chemical engineering is the only discipline that really deals with mass transport in a lot of detail, right and that is exactly what we are talking about here. So, if you have already taken a course in mass transfer, then many of your learnings from that course will be directly applicable to the transport of particles as well. Especially, very fine particles behave just like chemical vapours. So, everything that you have read about quick fusion for vapours is immediately translatable to Brownian diffusion of particles.

Transport is followed by storage. Now, when you talk about storage, what are the major issues? One of the big issues in storage is agglomeration during storage. In other words, how does one particle interact with its nearest neighbors during the time that it is suspended or stored in a solid form or in a powder form. That has a huge implication for further use and processing of these particles downstream in the process.

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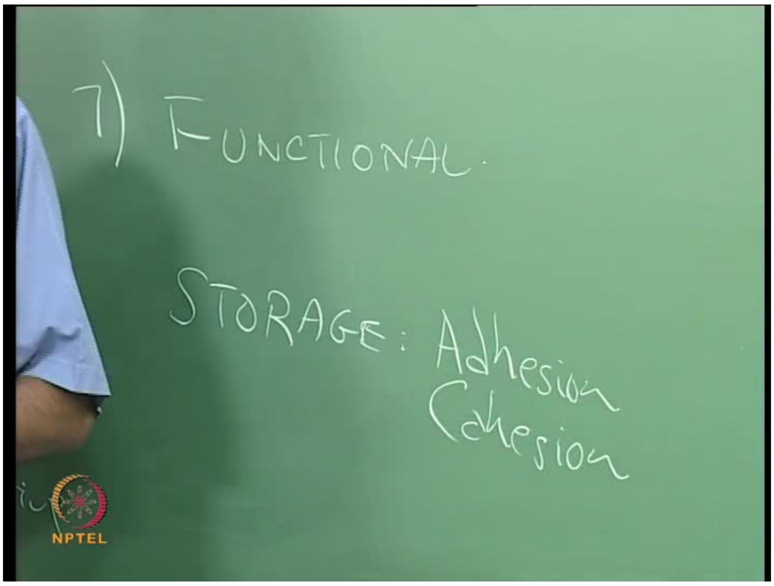

So, some of the aspects of particles that are important when we consider storage are first adhesion, the second is cohesion. Now, what do we mean by adhesion and cohesion? How are they different? Adhesion is the name given to the sticking of a particle to a contiguous surface. For example, if you were to describe the sticking of a particle to this bench, to this table, that would be considered adhesion.

So, what is cohesion? Cohesion is basically, adhesion between two particles. So, cohesion is something that affects, for example the flow ability of a powder or a slurry. If the particles remain completely separate, then the fluid will essentially flow like a Newtonian fluid.

On the other hand, as the particles start agglomerating, as the cohesive nature increases, the flow is likely to follow more Non-Newtonian pattern, right? So, clearly cohesion has a huge effect on the flow ability of the powder, transportability of the powder and certainly on storage also, because the more cohesive the particles, the more likely they are to form a clump and then they will have to be somehow disaggregated, deagglomerated before they can be used whereas if they do not a severe cohesive tendency, then they can be stored for a long period of time without agglomerating.

Adhesion is important, because again, when you are transporting powders particularly through pipes or tubes, if a particle has a tendency to stick to the nearest surface that it comes in contact with, its adhesive tendency is very high. You will quickly see a depletion of the particles as a fluid flows downstream. The lesser the tendency to adhere, the fewer the problems associated with loss of material, due to sticking to the walls of the chamber and this can become very important in processing industries that rely upon transport of particles from one place to the other.

So, adhesion-cohesion, also in terms of bulk properties; things like repose angle or the contact area between adjacent solids - all of these are characteristics of particulate assemblies. Another way we will later classify, virtually all of these characteristics is as single particle characteristics and particulate assembly characteristics.

The way that a single particle behaves is the fundamental starting point. But, in many cases in real life, you do not deal with single particles in isolation. You are always dealing with collections or assemblies of particles and when we talk about describing the characteristics of a particulate assembly, in many ways, it is a simpler task than characterizing an individual particle. So, in general as a particle technologist, you would want to avoid single particle analysis, single particle characterization, unless it is absolutely necessary. For example, if you just want to know how a suspension or a slurry will flow, you do not really need to do single particle characterization, right? You just need to do a bulk characterization of the flow behavior of the slurry.

On the other hand, there may be situations where single particle characterization is absolutely essential. For example, you know space probe goes out into outer space and brings back a sample from some other galaxy. You really want to know what each particle is, because there may be some very valuable information contained in that one particle, which may not be present in the other particle. So, depending on the need, you either do single particle analysis or bulk analysis and for many of these storage considerations and even transport considerations, bulk analysis would normally suffice. So, you have to be very careful not to extend the analysis beyond what is needed, because as we will see later on in particle science - particle characterization, the more you invest into it, the more information you will get, but you have to make a judgment call on how much is enough. When you keep throwing money at it and you keep throwing time at it, you can take a single particle and analyze it for, you know 10 years, and each moment, you will get some new information about the particle but, is it worth the effort? So, that is a judgment call that you know with the proper training, all of you should be able to make, if you go into an industry that requires particle processing to happen.

All right, so, the last part of it is the functional effect. Now, this is of most importance to the end user. They do not really care about all this. For example, if you go to a store and buy a tablet you know that you want to take for your headache, do you really care what its morphology is, what its structure is, what its processing is? You just want to know if it works or not, right? So, the functional aspect is the most important for the consumer or the end user.

However, how you achieve that functional effect depends on how you manage all the upstream processes. But, ultimately the characterization of a particle should have a link to its end use and this again, goes back to avoiding unnecessary or wasteful characterization. You want to characterize only those aspects that have a direct impact on the functioning of the product. So, for example, let us say that you are looking at industry emissions and one of the functional effects that you are concerned about is the toxicity of the particles that are emitted.

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So, toxicity is certainly an example of the functional effect of a particle. In other words, the effect that it can create on whoever encounters it at the end of the process. So, in terms of characterizing this particle, the predominant characterization should be for its toxicity, right? But, in order to minimize the toxic effects, in order to do process optimization, you still have to go back and do all these other characterizations that we talked about. But, always keep in mind, that what we are trying to do here is take this toxic emission and either keep it from happening or change the nature of the material, so that it become something that is non-toxic - that is being emitted. How am I am going to achieve that and what characterization do I need to do to achieve that? So, the link should always be backwards. You should always think about the ultimate functional use of the particular material that you are processing and then decide from this laundry list what are really the important and relevant characterizations that you need to do and what are not.

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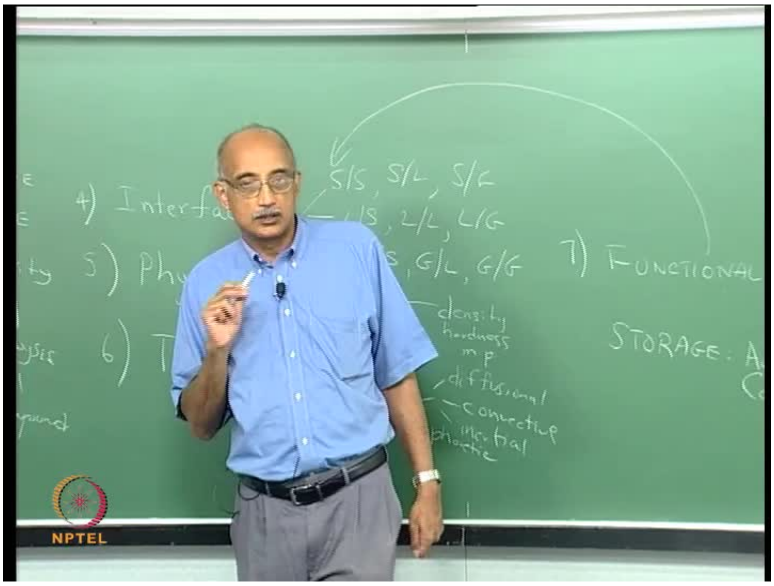

Now, when you talk about functional effects again, it can be something that is desirable or something that is undesirable. Something like toxicity is an undesirable functional effect. So, you would want to do your characterizations and other steps to minimize it.

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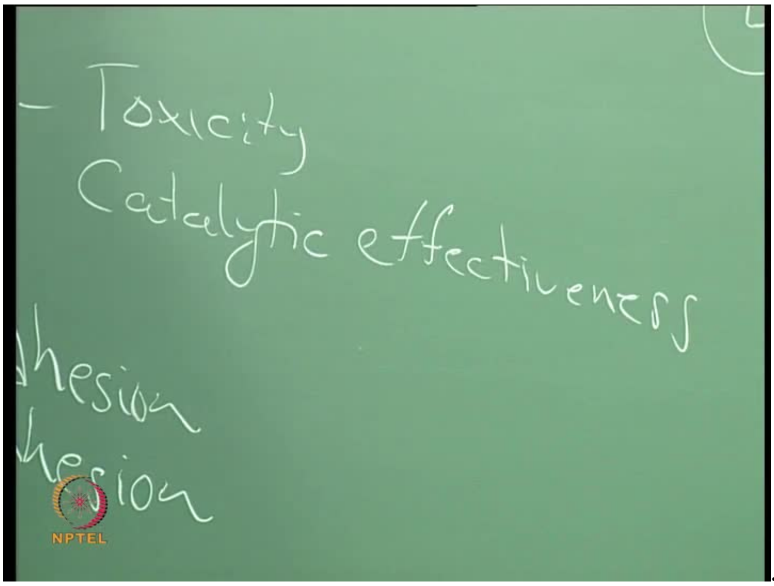

On the other hand, the functional effect may be let us say, catalytic effectiveness. Now, when you talk about catalytic effectiveness, obviously it is something that is very desirable and you want to maximize it. You want to have as much catalytic activity per gram of catalyst material that you can achieve.

So, certainly you should characterize this and this, you do by a functional measurement. Essentially, you would run your chemical reaction with and without the catalyst and look at the enhancement in the rate of the reaction, the yield of the reaction, conversion and so on. But then, what do you have to do? You have to link this characteristic to fundamental characteristics of the particle. For example, the catalytic effectiveness will probably have a very direct link to its morphological properties, to its crystal, to its structure, to its composition, certainly the interfacial properties, chemical properties, may be not so much of transport properties.

So, you have to somehow clearly delign it - what is the link between all these characteristics that we are talking about and for every measurement that you make, always ask yourself a question, “I am characterizing this particular property of this particle. Why am I doing it?” You know, that ‘why’ question should be something, that is always in your mind. Is this going to give me some knowledge that I am going to be able to leverage in order to make a better product, something that will give me a higher profit or make a consumer happier in some way. So, always, think about it in the practical sense. There is a tendency, among particle scientists to throw the sink at it, you know, do everything. So, first thing you do is put it in SEM-EDX or put it in XRD or AFM, you know there are so many wonderful tools that are available for you to do these characterizations. But, what you need to do, is only as much characterization as is needed.

For example, when we talk about shape analysis, you know, what are the tools? By the way, for each of these characteristics, there is an associated set of characterization tools that we can use. But that list again is very exhaustive. For example, if you want to do shape analysis, there are about twenty different techniques that you can use for analyzing the shape of a particle, depending on how sophisticated you want the analysis to be.

What is the simplest shape assessment technique? Your eye, you know the human eye. You can just, say, look at this and say "It looks like a cylinder", right. That is a reasonably good description of the shape of this chalk. But, if you want to, you can completely digitize the profile of this object, put it into your computer and get a very precise mathematical description of the shape. Is it really necessary for a chalk? You just want to know, is it cylindrical or is it spherical or what, right?

So that is what I mean. You know, especially because as mentioned in the previous lecture, many of the characteristics of a particle are not absolute measures. They are relative measures, which means that you have a lot of flexibility, in terms of how extensively you want to capture that characteristic.

If I just want to know something, that is fairly general about the object, then I want to do the easiest, the fastest and the cheapest test. On the other hand, if I want to do a very detailed characterization, then I make a conscious investment in the additional effort that is needed to achieve that level of description of the object.

So, when we talk about shape analysis in particular I will dwell on this aspect quite a lot that depending on how much effort you put into it, you can get a more and more precise description of the shape of the object, but you have to know when to stop.

Size analysis, again, you will see that size is not an absolute measure. Size is always related to something. I mean, as the object gets larger and larger, the uncertainty in size measurement decreases. As the object gets smaller and smaller, the uncertainty in its size measurement increases. It is essentially a signal to noise ratio. An object like this has a large signal, that it emits from its surface and the noise is very small, the noise is kind of fixed whereas, you can imagine, as a particle gets smaller and smaller, the noise will become comparable to the signal and even start exceeding the signal in many cases.

So the precision in the size description of an object, again is something that you have to make a judgment call on. How precise, how accurate, what is the resolution that I need, what is the repeatability and reproducibility that I am looking for - all of these are important aspects that we will cover, when we talk about characterization of the size of an object.

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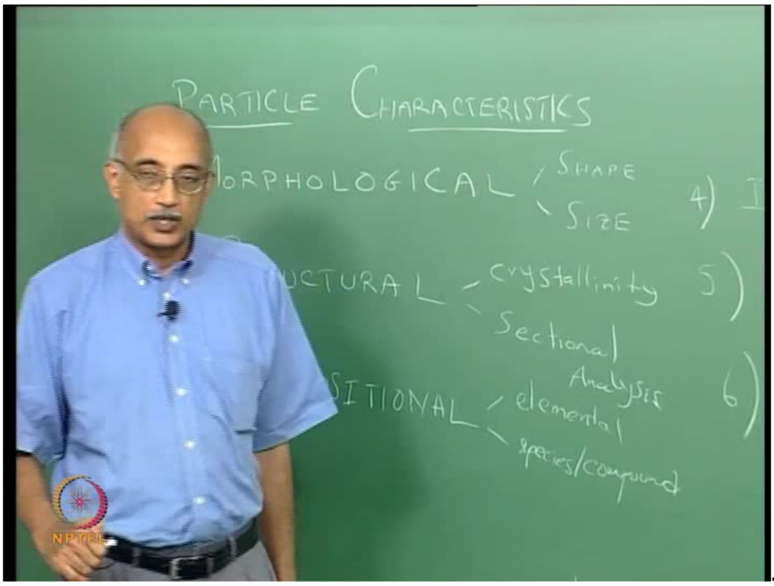

So, when we talk about crystallinity or when we talk about sectioning a particle and do a depth profiling of its structure, is that truly of relevance to your application or is it something that is strictly of academic interest? You always make that call in your mind as to how much characterization is enough for the problem at hand.

When you do compositional analysis, elemental analysis is the easiest. You can always use something like an energy dispersive x-ray analysis technique, to get the element to break down. But, to identify the specific species, particularly if it is an inorganic material or even if it is an organic polymer, may be very difficult. Is it worth making the effort to understand exactly what the composition of that material is or is it enough to have an elemental description of the compound?

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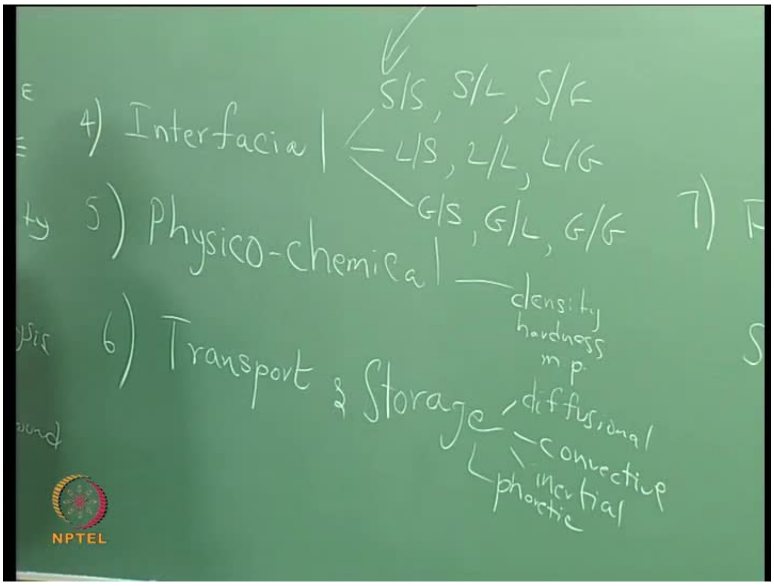

When you talk about interfacial processes, the interface between the particle and its environment is not simple. It is actually a very complex interface, because it is not really a two dimensional interface. Typically, we tend to think of an interface as a two dimensional object. But, when you look at the interface between a particle and its surroundings, it is three dimensional in nature, because the outer surface of a particle is not two dimensional, it is actually three dimensional, because it has a depth profile also. Especially, as the particle becomes rougher, the third dimension becomes very important.

So, you are talking about doing a very sophisticated three dimensional characterization of the interfacial behavior. Is that worthwhile, or can you assume two dimensional and make your analysis in that fashion? When you talk about physicochemical processes, how do you measure something like the hardness of a nano particle? Again, some of these measurements are reasonably easy to do for larger particles, but as the particle shrinks in dimension, the complexity in the measurement procedure increases almost exponentially. For measuring the hardness of a nano particle, you need a Pico indenter, something that is much smaller than the nanoparticle in question, with which you can make an indentation and measure it using AFM or some such technique. So, even though the principle of the measurement method may be the same, the difficulty in the analysis procedure is much higher as the particle dimensions shrink.

Transport and storage characteristics - When we talk about diffusional, convective, inertial, phoretic means of transport, these are not easy to measure. When you look at the three different transport phenomena – mass, energy, momentum; momentum and energy transport are reasonably easy to measure. The momentum flux or the momentum distribution can be measured simply by measuring velocities. The energy distribution can be measured, simply by measuring temperatures. There is no easy way to measure the mass conservation and mass transfer phenomena in a system. It is much more complex than measuring heat or momentum. How do you characterize mass transfer phenomena in the case of particles? With great difficulty.

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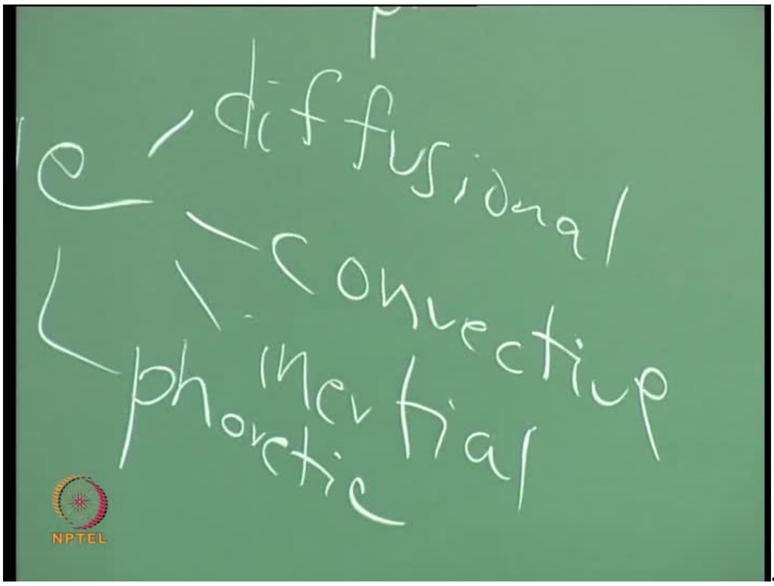

Especially again, as the particle dimensions shrink, the diffusional, convective and phoretic mechanisms all become roughly, equally important. Except the inertial mechanism, all the others turn out to be very important. So, how do you de-convolute them? Is it worth making the effort to understand? If you look at the total transport flux of particles, how much of it is coming from the diffusive mechanism, how much is coming from convective, how much is coming from phoretic and so on. It can be done if the need is there and finally functional effects.

Of all the characteristics that we have talked about today, the functional characteristics are the ones that you will definitely want to invest in, because that is what is going to sell your product at the end, if you work in industry. Or if you work in academic research, ultimately, it is the functionality that you can demonstrate, that will delineate how important or relevant your work is or is it only of academic importance.

So, looking at all these characterizations that are needed, if I were to prioritize, I would say that the functional aspects are the most important. That is where you would want to put most of your money into. All the other characterizations that you do upstream, will then depend on what you find, when you do your functional characterization.

As a particle scientist, you should have the ability to base your upstream analysis on your findings from the final functional characterization. That is where you get to use your expertise and hopefully, what you learn in this course, will enable you to make the kind of judgment call in a rational, logical and reasonable manner.

All right. So, what we have done today is essentially, list and categorize particle characteristics in general. We have not really dwelt in detail into equipments and methods, that are used for these characterizations. But, we will do that during the course as we go along.

So, the way I would like to approach this course is, we will start with morphological analysis, we will talk about what is involved, the what and then, we will talk about the how. How do we analyze for these characteristics? What are the chief features of the various methods that we can use? What are the advantages and what are the disadvantages and then we will basically make our way down this list towards the end. Okay. All right, let us stop at this point.

Any questions? Okay. I will see you at the next lecture.