Spray Theory and Applications
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Lecture – 01
Introduction to sprays and their applications

Hello, welcome to this class on Spray Theory and Applications.

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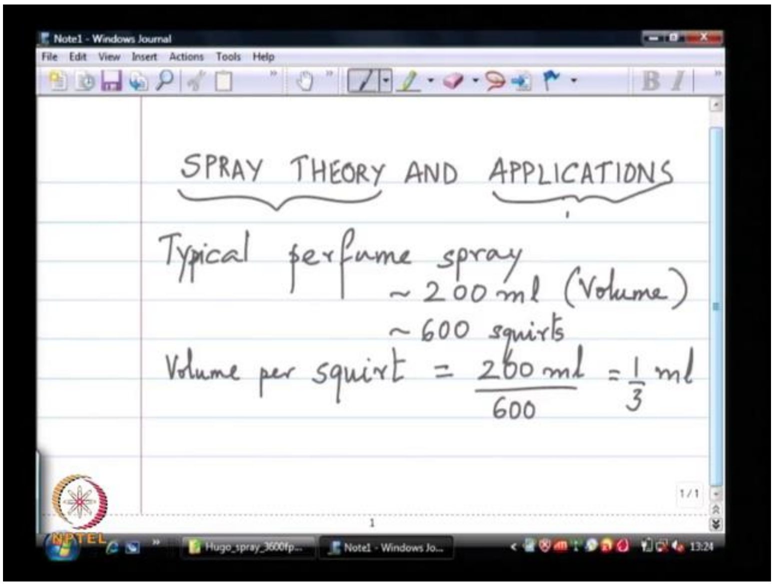

There are two parts to this class that we are going to focus on, they will sort of the in that order of sequence. The first part related to the theory of what a spray is and why do we need a spray and where would be a good place to use it; that is a segway into a talking more about the applications.

Although as users I am sure every one of us has seen a spray you know the simplest of the household sprays perfume or water cleaner that you used to clean glass, there are you know sort of more obvious uses of where you probably encountered sprays. What we want to do is actually build upon that, we do not want to take that away instant start of on a theoretical note. I want to sort of see what we already know from common knowledge and, but what we look but we do not see; in other words we look at something, but we do not completely understand what is happening. That is going to be our first objective for the next few lectures.

So, we will take a typical perfume spray. Let us say a typical perfume spray is about 200 milliliters in volume. So, that is how much perfume the manufacturer has promised you. And there are some ads I see on TV where they say they also promise 600 squirts. So, this whole bottle they promise 600 of those little waves of spray. So, what we want to do is understand what this really means as engineers and fluid mechanicians. So, what we and also gain a feel for some numbers around the sprays, how complicated are there or how simple are there both ways.

So, what I wanted to is start from this, and just say volume per spray, volume per squirt will be this 200 milliliters divided by 600 that is about one-third of a milliliter. That is how much volume of perfume is being delivered to you in one depression of the plunger. Now again from common observation we know what this looks like.

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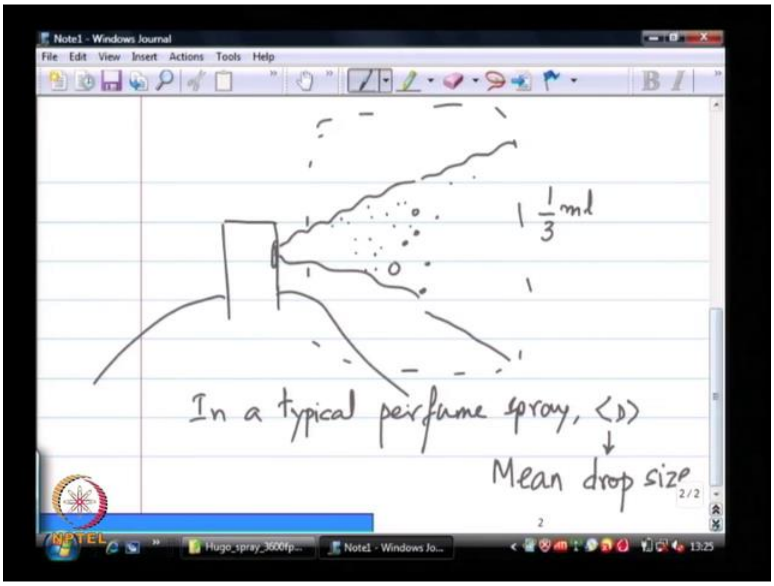

So, here is your plunger, this is the rest of the bottle that is usually fairly artistically shaped, and there is a tiny whole from which you get your spray. The spray itself has is a collection of drops; some big, some small, but there is a general Perry free of sorts. So, this one-third ml is distributed in this spatial region, as soon as I have squirted one delivery of the perfume I have dispersed one-third milliliter of volume in to this spatial region.

Now, in a typical spray we will come to see this towards end in a lot more detail, but in a typical spray say such as a perfume the mean drop size; that mean drop size is on the order of let us say 50 micrometers that is on average these drops are 50, let us say 100 micrometers typically less than 100 micrometer in diameter. So, this is also called the average diameter. We will come to talk about this later on in some more detail as to what we mean by an average diameter.

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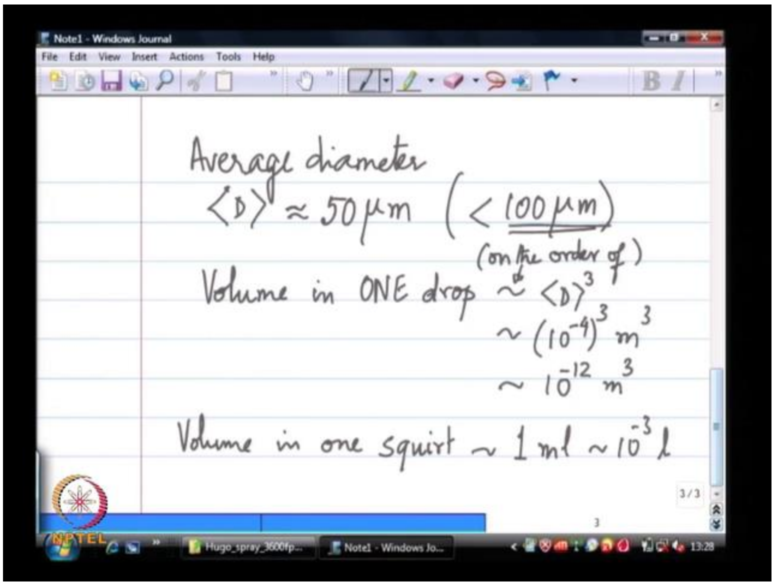

But let us say it is like an indication of the size of the drops. So, from this information and I will use this - 100 micrometers only because it is easy to do the multiplications. We want to calculate the volume in one drop and from here on I am going to drop the equality sign in place for the order of; so this is same on the order of. So, this symbol here is going to be used to me on the order of. Now essentially what this means is I am not really interested in the specific numbers as much as the power of 10. So, 10 micrometers is 10 power 2 micrometers or 10 power minus 4 meters. That is all I am interested in for now.

So, if I take this the volume in ONE drop is this average diameter cubed which would be 10 power minus 4 the cubed meter cubed; that is the volume in ONE drop. So, just to complete the calculation it is 10 power minus 12 meter cube. The volume in one squirt is on the order of I will say 1 ml because one-third ml is on the order of 1 ml. So, it is on the order of 1 ml which is 10 power minus 3 liters, which 1000 liters make a meter cubed. So, this is 10 power minus 6 meter cubed.

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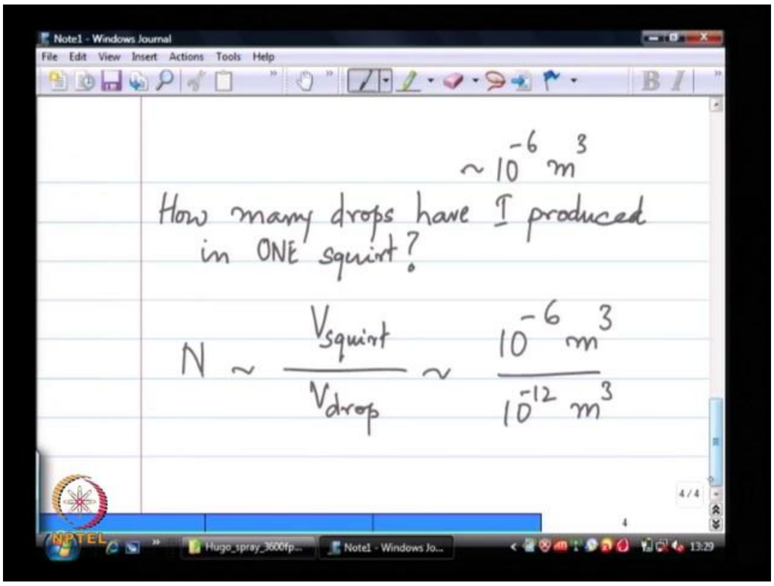

So, how many drops have I produced? That is simple that is the volume in each squirt divided the volume per drop that gives me the number. So, this is 10 power minus 6 meter cubed divided by 10 power minus 12 meter cubed. So, N is on the order of 10 power 6.

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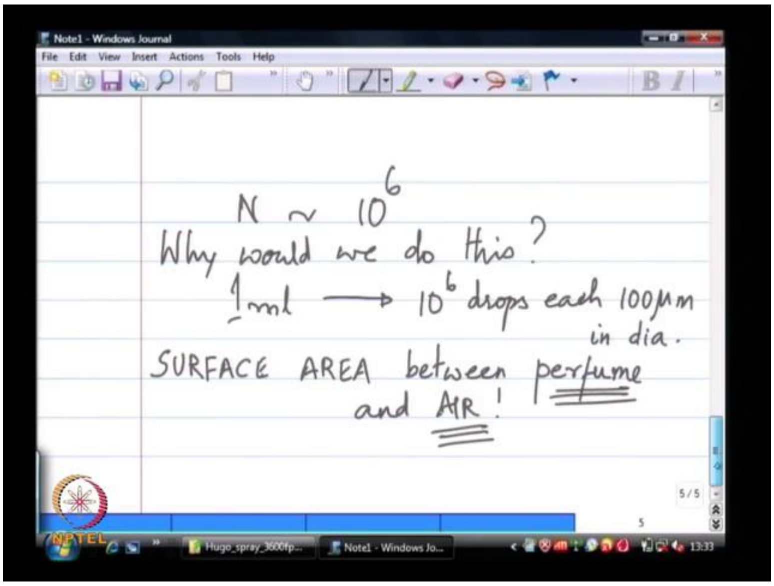

This is a simplest of sprays, one that we have a probably all familiar with. And every squirt produces a million drops each drop having a size on average about 100 micrometers and that is the purpose of a spray nozzle.

The objective of a spray nozzle is to do just this, I mean we, but let us ask the next deeper question why would we want to do this in the case of a perfume? If we understand how a perfume works we are almost there to understanding how an IC engine works or how a gas turbine works, because essentially we are moving along in the same direction although the magnitudes of some of these numbers would be different.

So, why would we want to take? Start with approximately 1 ml of perfume and from there creates 10 power 6 drops each 100 micrometers in diameter. So, that is what the nozzle has just done. The objective of doing this is essentially to take perfume that sitting in the bottom of my bottle and disperse it in to an area, see my skin or a piece of clothing that can benefit as a whole. There are many ways of doing it, we will again stick the perfume and show how a spray is much more efficient then other ways of doing it. I can take a little bit of the perfume and spray it, I can take perfume and sprinkle it; these are all also available designs. But we all know the ease with which a perfume spray works especially in the context of uniform delivery. So, if I want to deliver a product uniformly in a certain space performing that delivery hydro dynamically. In other words, using fluid mechanics to deliver this product is what is the most beneficial as for as producing a uniform delivery of the product that you intend to delivery.

Now, what have we also done in the process of taking 1 milliliter and creating 10 power 6 drops each that is 100 micrometers in diameter on average. The biggest increase has been in the total surface area that is available to the drops. So, the single reason we do this; we will make an estimate of that, but essentially what we have done is this is not so obvious with the human use of perfume, but if I want to deodorize a room like this then I want to maximize the area of contact between the air in this room and the perfume itself.

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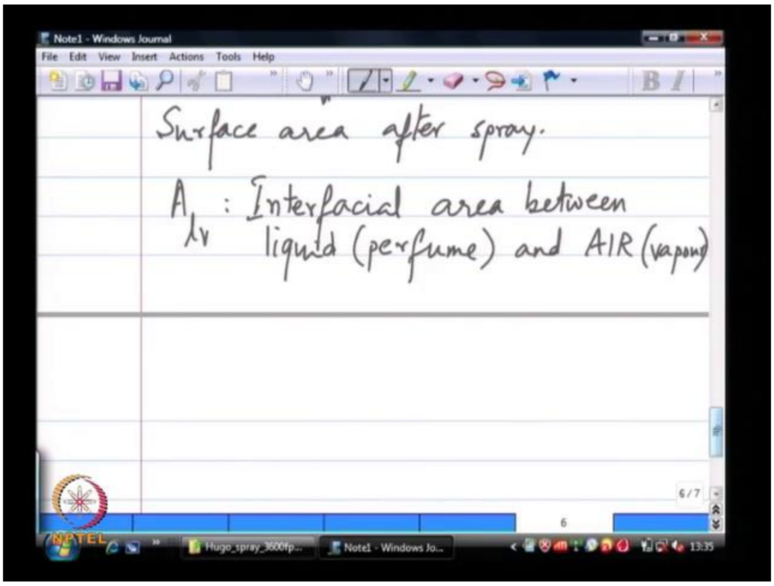

And this is the most efficient way of doing it as far as increase the surface area. So, let us see what we have done. So, the easiest way to understand this is to look at surface area before spray and surface area after spray. We will do the after spray part first. So, essentially if I take the total surface area we call this A lv standing for the interfacial area. So, if I try to estimate this A lv, it is N times the surface area of a given drop. So, I again I am only interested in order of magnitude.

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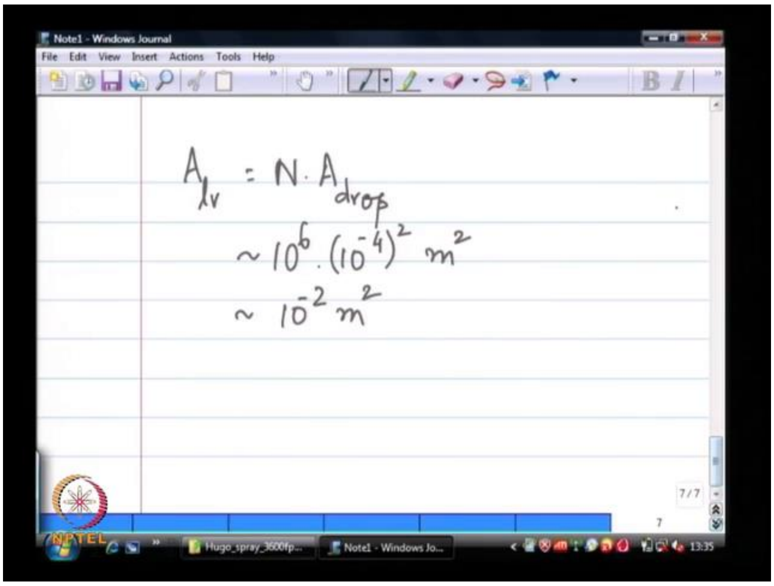

So, N is the on the order of 10 power 6, the area of the drop is 10 power minus 4 squared and the units on this is meter squared. So, if I look at this that is 10 power minus 2 meter squared that is 10 power minus 1 centimeter.

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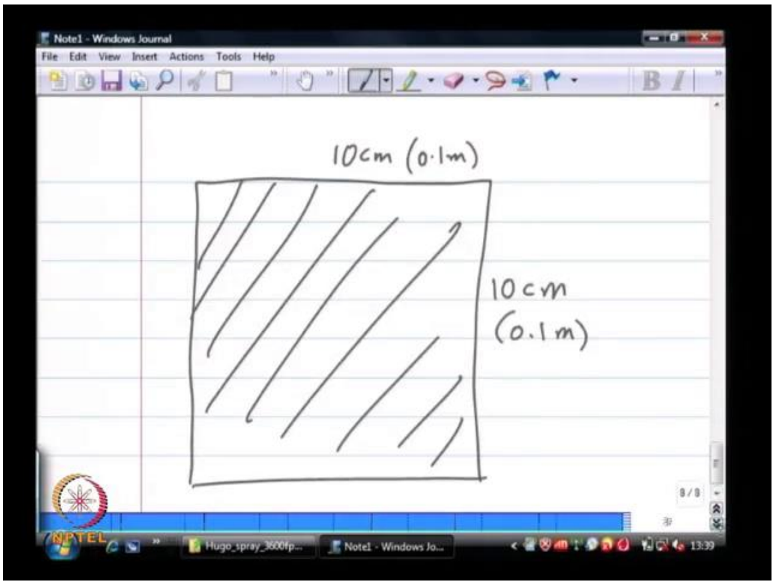

So, essentially if I actually look at it, is about 10 centimeters this way, 10 centimeters this way, this is the actual area that is available. So, this is 10 centimeters or 0.1 meters, this is 10 centimeters 0.1 meters. It is like I have taken 1 ml of liquid and smeared it over an area about this big. Imagine the rate at which that perfume would now evaporate. If I just took 1 ml of liquid and you know I have not even done the calculation of the surface area before spray, but you can see how even if I take a 10 centimeter by 10 centimeter window the actual content of a small qubit with 1 ml and the top area on there would be negligible compare to this. So, we are already at a point where we know we have increase the area so much that the initial condition does not even matter as far as the subtraction is concerned.

So, we have taken 1 ml which is about a tiny volume of liquid and create it and spread it uniformly relatively speaking over an area about that big with the simple action of pressing down on a plunger. And you can imagine that if you actually did this whether it is water or perfume; imagine the rate of evaporation because you now increased the surface area available for all this transport to happen. So, the single biggest reason why spray is find application in many different areas and we will talk about a few of those later on today is because you have this drastic increase in the surface area going from the before to the after condition.

So, all your surface area linked transport properties be it evaporation, be it drag, droplets are dragged by the air around and that drag is going to be much higher, if you had a higher surface area between the dragging medium and the dragged body. So, you can imagine how you can take a sphere would have a certain drag. If I took the same volume and created spikes on it I have essentially increase the surface area, and the higher this surface area the higher would be the drag on this body that is non spherical.

So, this increase in surface area has all these other repercussions with several transport phenomena be it momentum, be it mass through evaporation or energy through heat transfer, if I want to evaporate this fluid I can heat it up, but I can only heat the fluid up as fast as the interfacial area will allow me to. So, if I can increase the interfacial area I can increase the rate of evaporation by increasing the interfacial area the rate of evaporation goes up at the same temperature condition.

So, these are the wind falls associated with increasing the number of drops, increasing the interfacial area that we are all interested in, that actually drives these spray applications. So, this is sort of the basic sort of, so we want to understand what it is that we are talking about when we call a spray.

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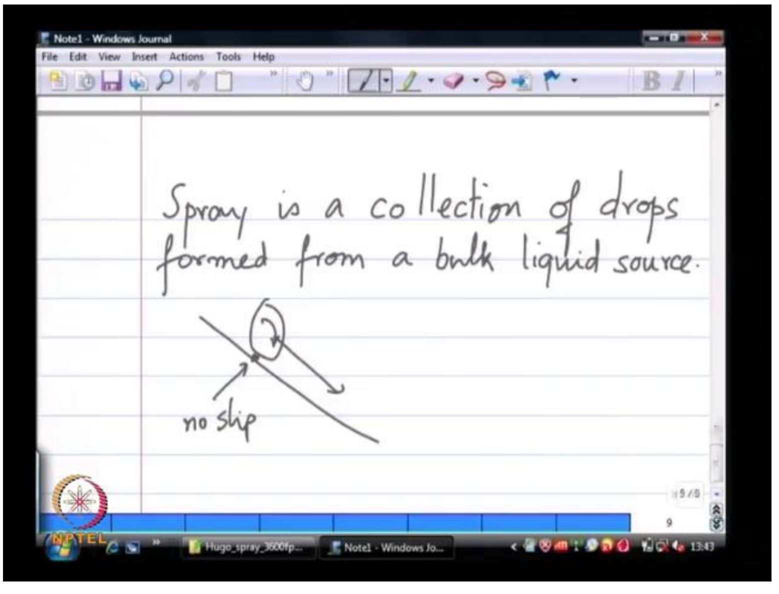

So, at least as far as our definition is concerned till now spray is a collection of drops formed from a bulk liquid source. So, I have created this collection of drops through some mechanical action in the case of a perfume spray we will talk about those as we go along. Those are all the details that we will get in to, but at this point we want understand what it is that we are talking about. So, at least we are talking about a collection of about million a drops these numbers that we saw or on we will see later on, or on the lower end of what a commercial spray or an industrial spray or an aerospace spray would be like.

Some of those sprays could run in to 10 power to 12, 10 power 15 drops being produced per milliliter, so huge increase in the surface area. If I took for example that 100 micrometers as the average diameter and I decrease that to, I had a way to decrease it down to 10 micrometers; I have come down one order of magnitude on the diameter which means three orders of magnitude more in number.

So, essentially I can take the same volume of liquid and disperse it in to a much larger number depending on some mechanical design of the of the nozzle. So, essentially what we are talking about is a collection of drops. Now if you were dynamists, you are all mechanical engineers and aerospace engineers. So, if you were dynamists, so you are looking at the dynamics of systems. So, let us take a very simple system a cylinder rolling down on inclined plane, let us say if there is no slip here how many degrees of freedom would the system have essentially that cylinder can only go up or down the inclined plane, it is a 1 degree of freedom system. A particle in air single point particle can move in three different spatial directions, it is 3 degrees of freedom. So, if I tell you the position and velocity of a particle in space that is I have to give you 6 numbers I have told you everything there is to know about the present condition of this particle.

So, that is what we need to know to completely determine the system of one particle I need 6 numbers. So, if I want to know the instantaneous state of a spray what do I need to know? I need to know the position and velocity of every point particle or every drop in the spray. So, we are talking of about 6 times million from the order of 10 million pieces of information, 10 million numbers to just know the instantaneous state. In fact, that is not the complete story every particle could be of a slightly different size correct. So, just as I want to talk about this idea of dimensionality in sprays.

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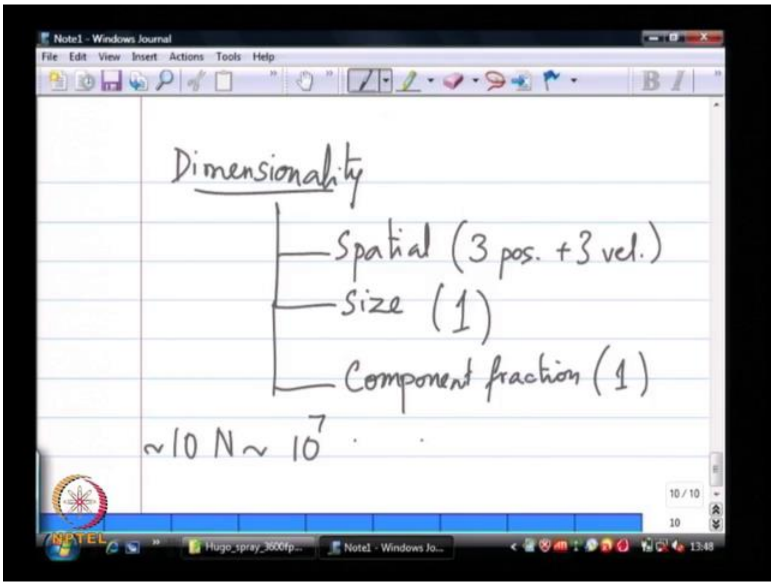

This is now an exercise to identify what are all the, what is like the most complicated way to look at a spray and then see how intractable that is and how we try to simplify our own understanding of spray, that is the idea of, that is the objective of this next few minutes here. So, this let us understand this idea of dimensionality.

Spatial dimensionality the something that is known to all of us three dimensions in space, if I include time that is four dimensions right. If I include velocities, I need to know where it is now and where it is headed. So, that is three more components of velocity in space. Assuming this drop is not big enough to have an identifiable rotation, so if I say rotation is also identifiable on the drop that is three more degrees of freedom.

If I say I am not going to go near rotation I will said drop is a spherical entity that is all most like a point particle. So, now, if we look at what dimensionality means. So, the first thing spatial, that is 3 position plus 3 velocity dimensions. So, I have 6 dimensions in space in the phase space to completely identify one particle. But I also need to know another dimension which is size. So, every particle in this spray could be and in general is a different size it is just it is a real number between say some lower limit of what is possible you will talk about those also like let say 0.1 micron, there is no way conceivable that this perfume spray would produce a drop less than that.

And there is also an upper limit or the upper limit could be infinity, the simplest understanding there is that our upper limit is as big as the whole on the perfume bottle I cannot produce a drop much bigger than the whole on the perfume bottle. So, I have a natural upper limit from in a perfume spray. So, between this lower limit and upper limit my diameter on any one drop could be a real number. So, in that sense it is no different from a spatial dimension, if I put up, if I place a perfume bottle here and spray - the perfume spray is starting here heading towards the camera and essentially all of the drops are constrained between these two lower and upper limits.

So, the spatial coordinate in this direction is bounded. Likewise the diameter coordinate, so I want you to start thinking about the size has been another coordinate; it is no different from a spatial coordinate as far as our idea of dimensionality is concerned. There are real differences between size being called a coordinate and space in the way we write our equations we will come to those later. But the point here is that at the moment if I want to completely describe this spray then I have to define one more dimension which is the droplet size. Now if this spray, if I am let us say I will switch hats and I want to now talk about a jet fuel, it is gas turbine aircraft spray where I am spraying jet fuel, jet is not single component fuel it is a multi component fuel.

So, if I want to understand what is inside this drop, some drops could have more of the heaver component, some drops could have more of the thinner component or the less viscous component. So, I have now introduced another dimension and mind you these are all in some sense orthogonal dimensions in other words, if I tell you the position and velocity you do not have any idea of what the size is. If I tell you the size and position and velocity you have no idea what is made up, what the drop is made up of. So, they are all independent directions to describe the spray. So, if I now add one more, even if I am looking at the binary mixture I have one component direction percentage of component a for example, it is between 0 and 100 percent. So, they are all nice and bounded.

So, very quickly we can see that we are on the order of 10 times N or 10 power 7 degrees of freedom, so I want to completely describe and instantaneous snap shot of this spray I have to give you 10 power 7 numbers and then if I want to describe the evolution at to the next instant of time I have to somehow come up with these 10 power 7 numbers of all over again correct. Because the next instant could be related to the previous instant through some mathematically equations, but as far as I am concerned if I am making measurements they are completely new set of 10 power 7 numbers. So, this is the order of information that you need to before you can say I know everything about this spray, clearly it is out of our reach. In fact, it is not just out of our reach it is no where within our future reach; not just that is this level of detail important. So, that is the question that we have often ask ourselves not just as engineers of course, you know do I really need to know the position and velocity of every drop in this spray in order to use it.

As certainly did need all of this last 20 minutes of information to use of a perfume spray, but if I want to use an air blast atomizer in an aircraft I need a little more information, but not to this level, that is where comes our next level of approximations. So, what would some of these approximations look like? Instead of me telling you the diameter of every drop at every point in the spray, if I told you 1 number that is indicative would you have, you would have some idea about what the spray is going to feel like, but not to the level of detail that the full dimensionality would allow you. It will also, give you an estimate of the other things like of surface area; we were able to estimate a lot of the macroscopic parameters by simpler estimates. So, bulk of the time at least in the first one-third will be spent looking at these estimates, trying to understand what it is that the, what makes a spray and what sort of descriptors can I apply to these sprays that would make sense and that would be sufficient.

10 power 7 is like is not is sufficient, but it is like way out of the reach we do not need that much. So, what are the necessary descriptors? What is sufficient? How much information is necessary for me to start using a spray? So, this is just to give you an idea of what it is that we are calling a spray. We are calling on the order of about 10 power 6 to 10 power 10 drops, sitting together in a very close spatial region, doing something to the liquid that could not have been done without that sort of a morphology for that same amount of liquid - what it does, why it does and what are the uses of it would be the topics of discussion going forward.

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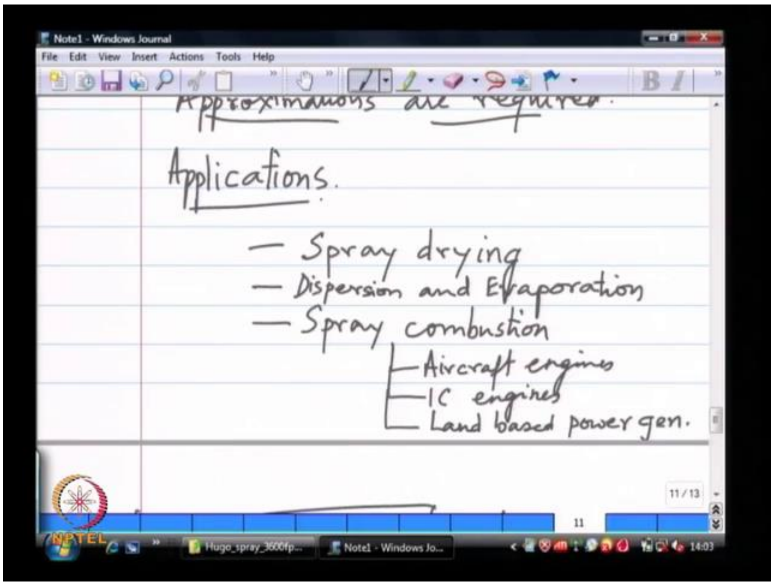

So, I think like we said some sort of an approximation is required as we move forward and before we start looking at what those approximations are that will tell us enough about the spray to start using it. Let us look at some of the uses of these sprays. So, like we said one of the objectives is to increase interfacial area that is quite sort of the most overriding principle on which sprays are applied.

So, let us look at the few different applications of sprays - one of the biggest uses I want to start with something that is not very obvious which is called Spray drying, say for example, if you take your coffee powder granules or tide or surf granules, a typical manufacturing process that produces a tide or coffee powder granules is where you first create the product in the form of a slurry. Slurry is like a liquid with these particles not in suspend, it is there only in suspension not in solution and this slurry is sprayed following up usually fairly a large bank of nozzles.

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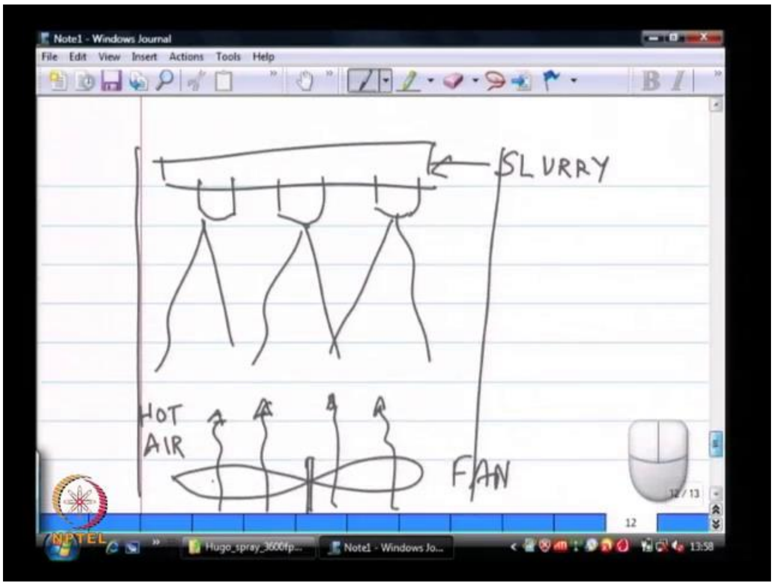

Like, I could have several nozzles that produce that spray this slurry and you have on the bottom side we have a fan that blows hot air. So, this slurry sprayed as it settles down to the bottom of a kiln of some kind, essentially loses it is solvent typically water and you start to get agglomerated granules, whatever particles where in a single drop now sort of agglomerate to form a cluster which gives you the feel of coffee granules.

So, you can take a single granule and crush it and get powdered, but if I sold you powder it would not taste as well as granules. So, this is the process by which most granulated materials of powder is manufacturing, spray drying is very efficient. You have talked several 1000s of pounds per hour or flow rates, extremely high flow rates and several nozzles, because productivity and production rates depend on that. So, these are commercially used quite widely. So, this is an area where again what determines the height of my kiln the drop size.

If I can make the drops smaller the water in them evaporates faster, because for the same volume have increase the surface area by decrease in the diameter. So, the faster evaporation means that faster rate of evaporation means that the I get powder, I recover powder from my slurry much faster which means I do not need to make the kiln as long as or otherwise. Also another way of looking at the same thing is that if I make the droplets too small then I start to get in to granules which are not what my customer is used to see take the granules feel more like powder. So, there is also a lower limit on drop size that I do not desire. So, the point of this is to show you that very often there are conflicting requirements in any design process. In the case of sprays, these are in the case of spray drying these are the conflicting requirements that I do not want drops much smaller than a certain critical size because they produce product that is not what the customer is used to see. On the other hand if I produce too large drop I may get wet product coming out at the bottom of my kiln. So, these two extremes essentially dictate how the kiln design works, a spray dryer design works and this is the basic principle of operation.

Now another application this is of course, in spray combustion. We will talk about this in some detail because there is lot more to, lot to learn theoretically from looking at the spray combustion as an application. Again spray combustion is area where sprays are applied, but the actual applications range from aircraft engines, IC engines as well as land based power generation have all these different applications where I create a spray of some liquid fuel, burn it and from the products recover heat to run a turbine or run an engine or some sort.

Again the objective of this is to increase the surface area. So, really speaking I want to go as small as possible on the drop size, but the conflicting part of the requirement comes from the geometry of how you want to design this combustor. Say for example, I do not want a combustor that is too short and flabby, I want a slightly longer combustor which means if I create a mist at my spray nozzle that is very, very fine, these drops may not penetrates in sufficiently far in to my combustor as the result I could get hotspots very close to the nozzle itself. So, I do not desire complete pulverization of my liquid I want some large drops in there as well give me this spray, this flame geometry, I want that flame itself to have a certain designable length associated with it. So, these sorts of conflicting requirements you will see in every one of these applications and we will talk about how to resolve them as we go long as well.

Another application is in simple evaporation - dispersion and evaporation. This is where my perfume spray comes in right I want to just disperse the perfume and I want to evaporate it that is how I deodorize a space. So, again the conflicting requirements are that if I spray a perfume here, I want the far end of this room also to see some effect or at least I do not want the effect to be completely localized in a small region right (Refer Time: 40:13) in to the nozzle. So, again I want some large drops that will remain in flight for a little while to give me this spray, this length and penetration to the spray because I do not want to be working around every look and cranny of this room to be sprayed. So, these are the different conflicting requirements as far as dispersion and evaporation is concerned.

So, as you see the overriding theme in all these three applications that we just wrote down, is that there is a typical lower end of drop that I do not desire below. There is also low upper end of drop size that I do not desire above as well and a spray nozzle designer and manufacturer has to take these in to account and be able to design spray nozzles that fit these constraints that is a challenge, alright. So, we talked about three or four of these, three of these applications. Let us look in to one of them some detail and see what is happening.

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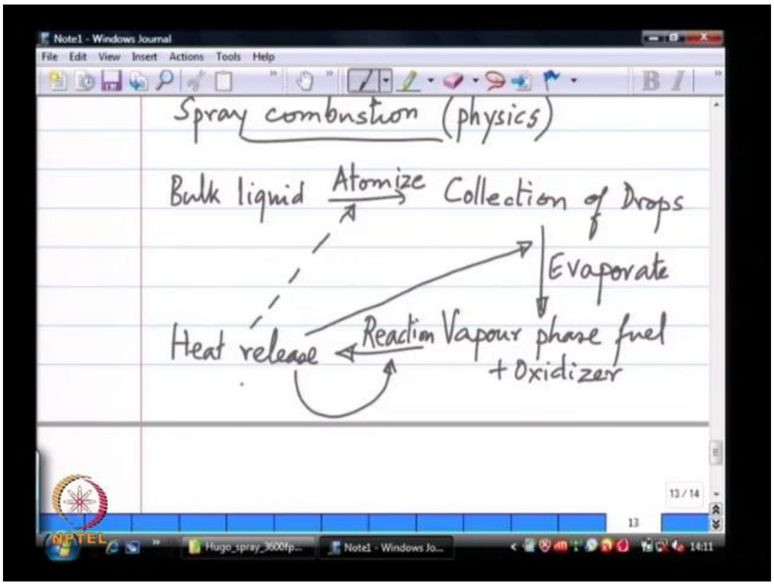

Just the physics of spray combustion, so the first part is where I take the bulk liquid, I atomize this is the first time I am using this word in to produce the collection of drops. You will see this word atomize used in a context of sprays, very often nozzles are called atomizers, it only it comes from some old British engineers who were used to colorful language that they started calling nozzles atomizers.

Although we are nowhere near the atomic limit of these liquids, we are not atomizing the liquid in that sense, we are heading in that direction but we are far away from that. Just to give you an estimate again one drop of this liquid is about let us say 10 power 18 meter cubed and 18 grams of water contains 10 power 23 molecules again, order of magnitude right 18 grams is a atomic weight of water, 18 gram is the 18 milliliters - 18 milliliters contains 10 power 23 molecules of water.

So, we need to sort of understand that this drop is nowhere near the atomic limit. So, we are talking of each drop containing on the order of you know 10 power 10 molecules still, 10 power 10 or even more you should do the number, but it is they are nowhere near the atomic limit, but will see, you see this use quite a bit. The collection of drops then evaporate and that evaporation gives rise to vapour phase fuel that is now mixed in with your oxidizer; your vapour phased fuel, that is mixed in with your oxidizer. So, this is where reaction happens, reaction is essentially you know let us say if I were to simply approximate the liquid fuel by say hexane or octane, you have a certain reaction between octane vapour and oxygen in the air giving rise to carbon dioxide water vapour and a lot of other by products, but essentially that is the reaction.

The reason you have reaction happening, the reason we facilitate reaction is because I have heat release that is what I am after, in all these application at least the combustion applications I have want to somehow convert the chemical energy in this fuels in to heat. So, this gives me heat release. Now the heat release is not going to keep quiet, it is going to further affect this evaporation process for sure; it is going to affect the reaction process also. Because the same pair of molecules says, octane and oxygen have a different rate of reaction at different temperatures. So, as the mixture temperature goes up the reaction rates go up typically. So, you start to see different rate of reaction and therefore, different an increased rate of heat release. Now there is also a possibility that this heat release affects the atomization process itself, this atomization is essentially what is happening close to the nozzle that is the process of converting bulk liquid into a dispersion of drops or collection of drops.

So, that process itself is a fluid mechanic process there is some motion happening and it is quite possible that fluid mechanic process is affected by the temperature environment it is embedded in. So, this heat release could also affect your atomization. This is a simple sort of arrow diagram indicating the different physical interactions that could take place between the spray and the environment. Now the atomization clearly affects evaporation through the drop size, the evaporation is also affected by; the reaction is the affected by the evaporation rate. Because if the rate of evaporation is faster the reaction rates depend of course on the concentrations of the two reactants, so the higher the rate of evaporation those concentrations are now different. So, you essentially have a highly coupled problem in a simple process like spray combustion. So, this from an applications perspective this is what makes the design of spray combustors very challenging.

So, with the spray dryer all of the above are still true except the reaction part. So, you have one piece of this block removed, but the rest of it is essentially the same likewise with droplet dispersion and evaporation I have at the same atomization and evaporation part that come in. So, we looked at a few different applications, let us quickly recap what we learnt today.

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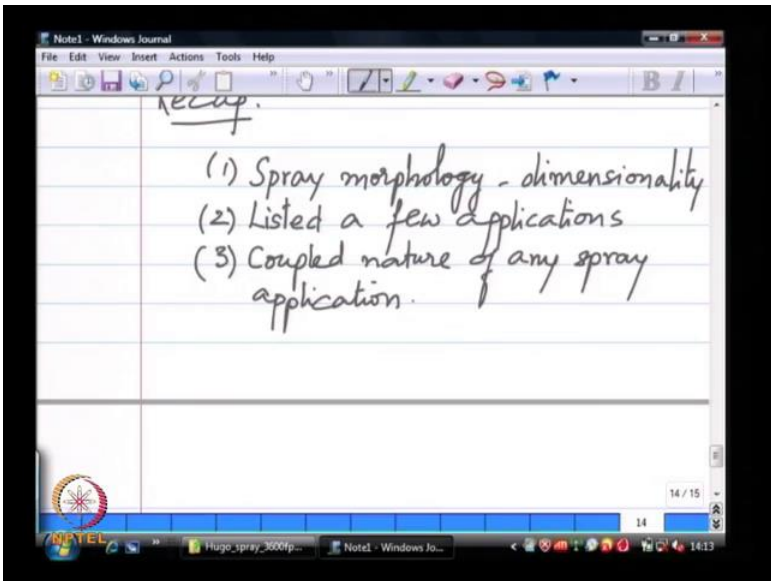

So, first thing we understood spray morphology or dimensionality. Some feel for numbers associated with the real spray and then we listed a few different applications, I wrote down the different challenges in each of these applications and then we started to study the coupled nature of any spray application. So, if we have to apply these sprays intelligently in any application we really need to get a hold of at least the third part, we need to really get a hold of the coupled nature of these applications.