Spray Theory and Applications
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Lecture - 11
Simple measurement techniques

Good morning, we started to look at the air assist atomization, towards the end of last class.

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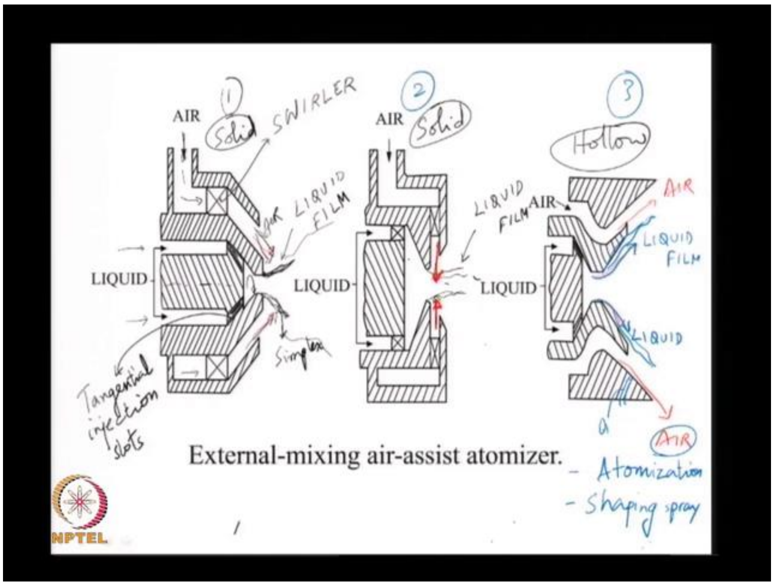

We looked at three different configurations of air assists atomizers, essentially varying and the angle at which the air is introduced towards the liquid sheet. And the advantage of the third design we said is that I can by varying this angle theta independently also control, the shape of this spray meaning like a spray angle. So, let us before we go much further make a list of a few different things that are different from spray nozzle to spray nozzle. And we will then use that qualitative related to differentiate the nozzle that are that we are going to talk about today.

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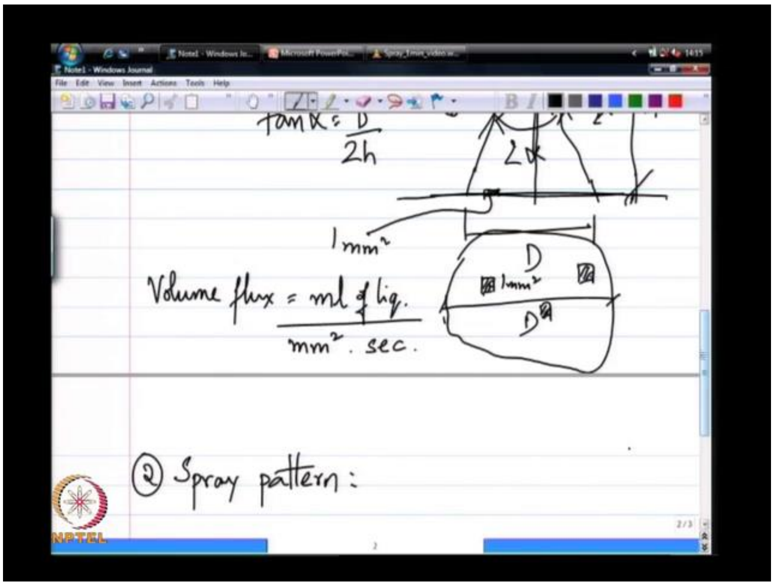

So, spray parameters, the first and one of the most widely used is called as spray angle. So, if I take a typical spray this sort of an angle, I can measure that by taking, by coming some distance downstream and looking at the diameter of that disk. That I make, I can define a tan alpha to be equal to h over D by 2 or rather other way round D by 2 h. This is one of the simplest sways of measuring this angle. Another one is to just bring a couple of bleeds of a proprietor, towards them and when these appear parallel to the human eye the angle between a protractor bleeds is equal to the angle over which spray angle.

So, these are sort of common ways of measuring the spray angle. Now you have to understand that there is no such thing as a spray angle like a geometric angle between two lines, it is what is visible to the human eye and what is visible to the human eye could be slightly different from person to person. So, it is usually very hard to define a spray angle you know any more accurate than let us say 3 4 5 degree it is let about as good as the human eye I can get.

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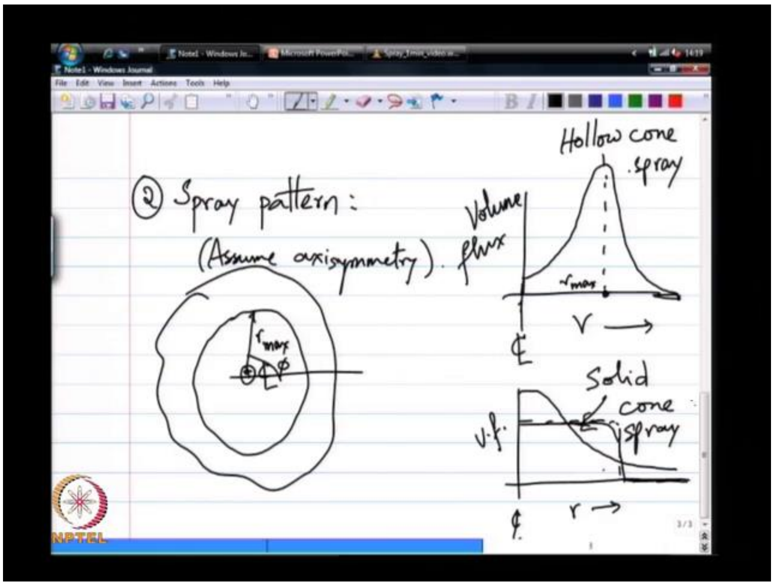

Another parameter that we want talk about this called spray pattern. So, if I take this spray same spray nozzle and I this distance a look at what this disk looks likes. So, I look at like there is a diameter to this disk, we know we saw that, but again it is not like a real hard geometric disk so the edges are fairly blurred out.

Now, if I look on the inside at every point here, if I take a small cross section let us say about 1 mm squared of this disk. And if I have a way of sampling all the liquid flowing through to that 1 mm square cross sectional area, there is drops flowing through there and over time I can define a volume flux, which is units of let us just say ml, ml of liquid per mm squared of a area per second. So, I sample for 1 second, how much volume of liquid flows through this 1 mm squared of area?

Clearly, that would be different over here and over here, in a general spray we do not know how much is flowing through here, here and here. Now, so, if I assume axis symmetry for a moment and I will see what this mean in a moment I will show you what it means. If I assume axisymmetric and draw this volume flux, verses radial position and this happens to my central line, if I get a pattern that looks like this, that is as I move away from the central line the central line happens to be over here, as I move away from the center line the volume flux first increases at some radial distance, the volume flux achieves a maximum and then drops of as you go towards the edge.

This would be an example of a Hollow cone spray, there is very low volume flux near the center line and most of the volume is concentrated around the around some thin rim inside the spray. If I make the same volume flux measurements, in a similar axis symmetric spray and it effect happens to show this kind of a pattern, this is more reflective of it being a solid cone spray. Ideally we wanted to be something like this, the volume flux is at some the value for little while and then drops of, and both of these are possible choices for it to be called as solid cone spray.

Now, I said I will assume axis symmetric, if I take this spray disk let us just draw a disk. This is my so called center line but remember it is not really a spray center line it is my nozzle center line that I am extending in to the spray, what is the chance that my spray is also symmetric about my nozzle geometrics center line. That nozzle as a nice geometric center line, because that was somehow somewhere drawn a not auto cad. So, it is a geometric object it has a center line possibly or at least an axis I should not say center line an axis, but if can I, when I extended axis in to the real spray. How much of an axis is it really. The answer to that lies in, taking one circle inside this spray; typically this could be the point where you have this maximum volume flux, and plotting the same volume flux, as a function of phi, the azimuthal angle around the circle.

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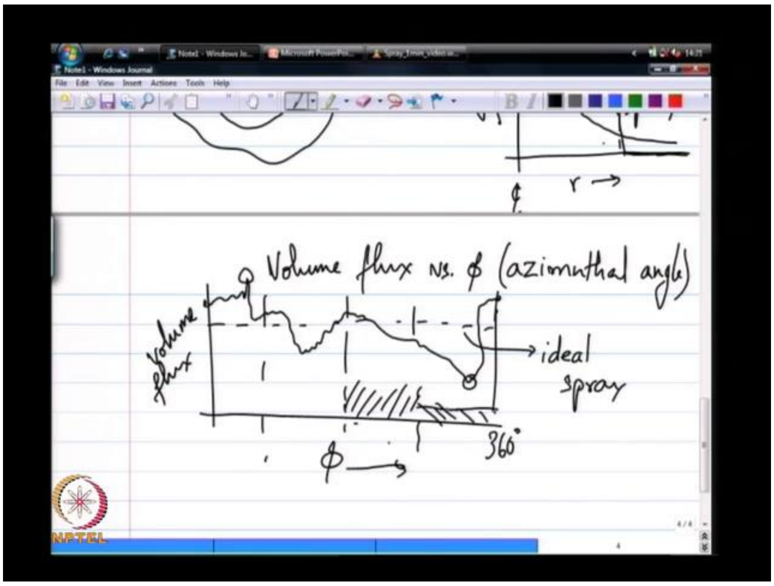

In the most ideal perfect spray this would be a constant. That is walking around a certain circle symmetric around the center, the volume flux at all the point on that circle are the same, but in reality I could get something that is slightly different, but this point and this point have the same volume flux essentially because of circular symmetric.

But see if this is my real spray, what its saying is that if I now divide this into 4 quadrants. I have somehow more flowing through this quadrant and let us flow in through the other quadrant; I have a higher volume flux in 1 quadrant in relation to the other. Now in most instances, this may not be desire able this is what causes non uniformity in your deposition if you work spray in paint for example, or non uniformity in the fuel vapor distribution if you are combustion system its extremely bad because you create were you have this high volume flux you can a creating a hot spot, which could burn through the combustor lining material if you are looking at some sort of a land base power generation. So, I want to avoid these kinds of hot spots and cold and low flux regions.

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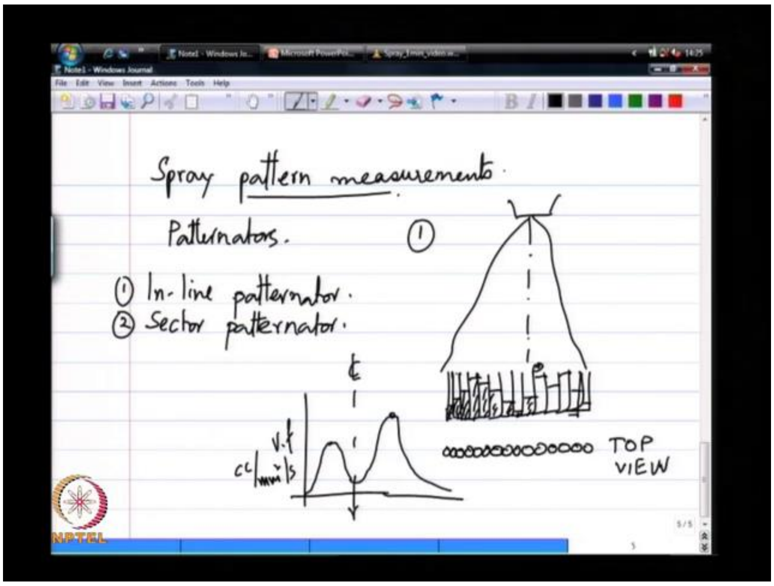

But before I go much further I need a way to quantify both of these spray patterns, the simplest way to make these measurements I using. What are called patternators? There are two kinds patternators, one is called an in line patternator and the other is called as sector patternator. We look at the in line partternator first. So, lest they say I have this spray, the in line patternator is a just series of tubes, when I expose the spray to this tubes this is sort of like a rain gauge essentially, I end of collecting some volume something like that let us say.

And these heights are indication of this spray pattern. So, I take a row of tubes move them in to the spray and then let volume be collected in the tubes for a fixed period of time over the entire tubes since that tubes are all of the same cross sectional area, what I have measured is the volume per unit cross sectional area per second if I take the volume divided by the cross sectional area of each tube and then divided by the time over which I collected all this liquid.

So, I can now plot this and that looks like volume flux in units of let us say cc of liquid or ml of liquid per mm squared per second as a function of radial position. So, in this case I am going to draw this lightly differently I am going to make this center line, somewhere in the middle and I could do this. I have intentionally drawn this peak to be higher than this, just to show you that this kind of patternator can detect these kinds of non uniformities in 1 diameter. So, I take 1 diameter of this spray and see if the uniform how much if a mirror image is one-half of the spray in comparison to the other.

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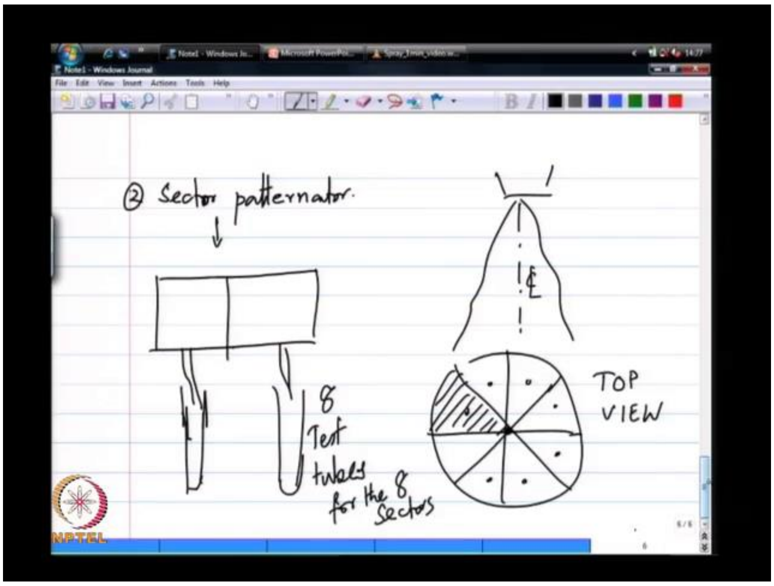

So, this is simplest kind of a patternators called the in line patternator. The other is called a sector patternator as you can now begin to see from the name, if I take a spray I insert the patternator, that I divided in to 8 sectors let us say or I could do more and each of these sectors drains in to 1 test tubes. So, typically this is the patternator with the top view shown here and each sector drains in to 1 test tube. So, I have 8 such test tubes, for the 8 sectors and if this is the cross sectional area and each sector and there the same for all the 8 sectors I can plot the volume flux in each sector. In a perfectly axis symmetric spray I expect that all the 8 sectors catch the same volume.

Now, this is a perfect place to talk of the spray center line, say if I take this sector patternator and displace it slightly so I am going to move the spray part out slightly, just about that for. So, this is my spray right now, where the center line of the patternator the patternator is also a geometric object. So, I can define an axis for it is only the spray that does not have a line that I can see right. So, if I now take the, spray patternator the sector patternator and align it and miss align it slightly with the nozzle geometries center line, what sort of a volume flux do will I expect.

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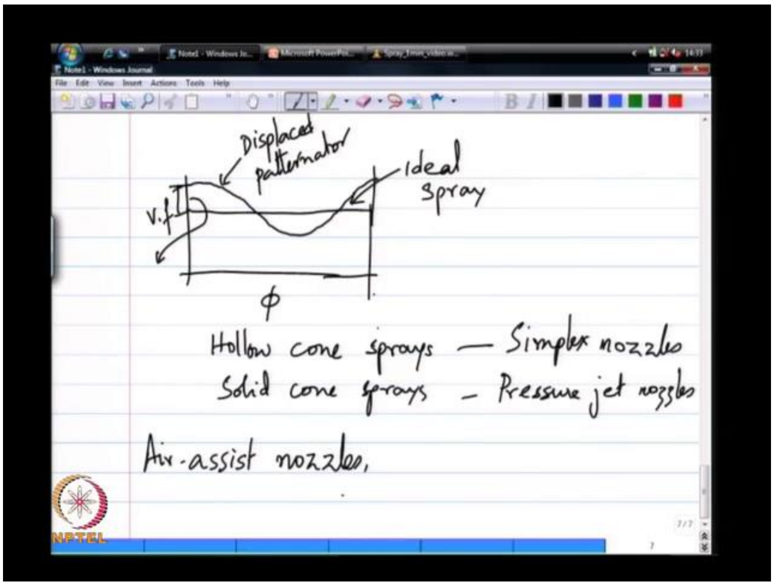

So, if I take the volume flux and plot it as a function of phi, I am expecting it in to be a dead straight line if it is in a perfectly ideal spray. Now if I took an ideal spray, but place the sector patternator slightly of axis, then what I will expect is that the diametrically opposite sectors get a minimum and a maximum of the volume flux. So, essentially if I take the sector patternator and displace it slightly, I am going to expect the spray volume flux to look like that. And these displace patternator. So, if I know, if I take the volume flux measurement and what is usually done is if I take the furrier components of that volume flux in this phi variable, any variation that is either like sin phi or cos phi is essentially due to miss alignment between the nozzle geometric center line and the patternator center line. Any other variation, that is outside of sin phi or cos phi is due to a real non uniformity in the volume itself. So, I can by looking at this magnitude sort of arrive at a degree of it is a center city of the spray itself to the nozzle geometry center line.

So, this sin phi or sin 1 phi and cosine 1 phi the magnitude of that is an indication of the eccentricity of the spray with respect to the nozzle geometry center line. That is assuming I had the patternator I used the example, where the patternator was misaligned, but if the patternator was aligned to the nozzle center line and I still saw a pattern like this it is essentially that the spray is slightly displaced in relation to the a nozzle center line. So, if you think of a simple example, where I am expecting this to be alpha, this to be alpha.

But if the whole spray was, shifted to one side sort of like that nozzle was nice and straight, but the spray was shifted slightly to the one side that would give me something that looks like this. So, these are all just simple diagnostic tools help us arrive at different metrics that we could that we could use to measure sprays. So, in most axis symmetric sprays I am expecting the sector patternator to give me the same amount of fluid in all the sector tubes and in the inline patternator measurement I am expecting whatever my design objective is to be achieved. So, if I am looking for solid cone, I want something that looks like this for the volume captured by each tube.

Now, these are all intrusive measurement techniques, there are non intrusive equivalents of these we will talk about towards end of the semester, essentially like optical ways of measuring some of these variables. So, we looked at spray angles, spray patterned of course, we talked about drop size in some detail earlier on. These are all indicators of what the spray, what are all the different variables that we used to characterize the spray. So, we looked at hollow cone sprays coming mostly from simplex nozzles and we have solid cone sprays arising most out of pressure jet nozzles and we looked at combinations of these.

We looked at, and then we will get to air assists nozzles. The 2 or 3 designs the 3 designs that we saw, prod have independent control over the spray patterned by controlling the angle over which the air is introduced like the third design here, produces more of hollow cone spray, in comparison to these two, these two will generally produce more of a solid cone spray. Because your intentionally pushing a liquid towards the center line we will most probably produce more of solid cone spray in designs 1 and 2, design 3, because of the nature of the air flow will most likely produce the a hollow cone spray. Now, these are all different designs of external mixing air assists atomizers. So, we are introducing the air and liquid in to the nozzle and they are allowed to come in contact with each other outside the spray nozzle essentially.

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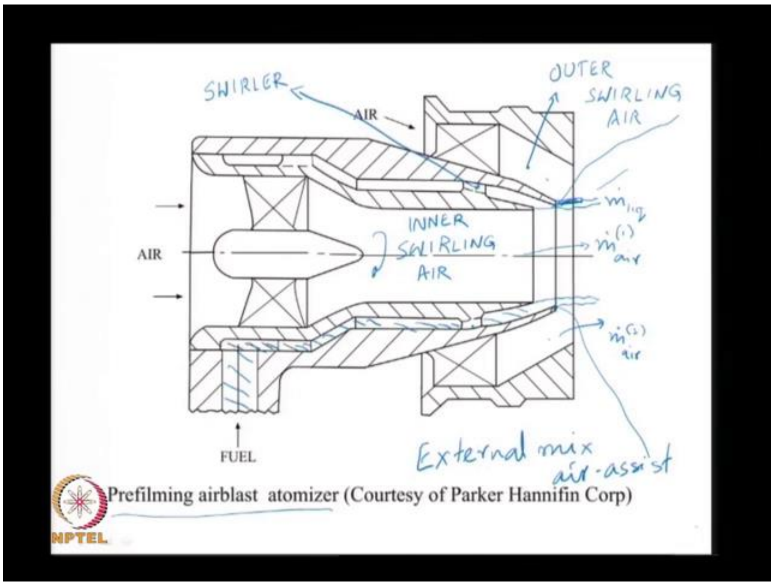

We want to look at another extension of these external air assists atomizers called the prefilming airblast atomizer. This prefilming airblast atomizer is again one of the most widely used spray nozzles that this is essentially a design that is used in most air craft’s. Now that this is liquid passage in the fuel goes through this passage, it is got a swirler pass, swirler slot in at somewhere here those are swirlers, but the purpose of the swirler is only to gently push the liquid outwards. So, what you see here is liquid film that is spilling out from this tip essentially, that is impacted by a swirling air stream on the inside often called the inner swirling air and, then this is called the outer swirl air.

So, this part these vanes are also at an angle. So, the air at in this part is swirling, and the air coming out of these passages here is also swirling. By controlling the ratio of the air coming in on the inside and outside, so I will call this m dot air inside. I call this m dot air 1, m dot 2 of the air, by controlling the ratio of this m dot air 1 and m dot air dot 2 we can essentially shape this spray. So, if I want a spray that goes very far out a wide spray angle I am going to introduce m dot air 1. So, it is essentially going push this spray further out.

For want the narrow over spray I can decrease m dot air 1 and increase m dot air 2. And in addition I can also increase or decrease the atomization quality the drop size by essentially varying the total mass flow rate that I introduced. So, if I increase m dot air 1 plus m dot air 2 I have put in more air per unit mass flow rate of the liquid and that generally means I get a finer spray or a lower drop size. So, I have a way in this design of independently controlling spray drop size, spray cone angle and spray pattern, pattern is whether it is hollow over solid, by these three different handles by essentially controlling the mass flow rates of the 2 air streams in relation to the liquid flow rate. So, this is m dot liquid.

As a result this is one of the most widely used nozzle designs for aircraft applications. The air coming in is essentially the compressor stage exit. So, it is set a very low pressure on the order of like may be, like compressor may be at like 5 times the 2 to 3 times may be the increase in the pressure, the pressure ratio of compressor stage. So, we are looking at fairly low pressure air and the liquid is also operated by a pump that is on the same shaft typically. So, that is also a low pressure liquid, but the flow rates of the air is very high and that is what, that is what gives us good atomization.

This is also an example; we are still in the realm of external mix air assists atomizers. Although, this particular design is patented by Parker and it is got the where it goes by the name Prefilming air blast atomizer. Because you are essentially creating a film, in fact, the specific design looks at there is a little lip that extends out, on its the film is it is like a little annular lip and the liquid film is sticking to the wall as it comes out. This is a design from the, I think early 50, just to give you some chronology of where these where developed. Parker is a company that used to be, that is based out of the US.

So, now there are other ways that we want to look at some of the more new or designs we will look at one of those newer designs here called the effervescent atomizer.

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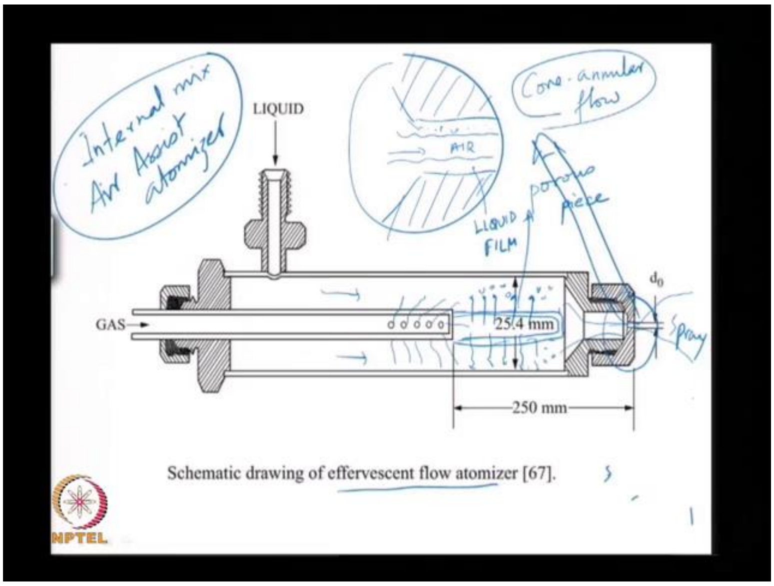

This is in fact, design from my masters work where we looked at the spray performance on this particular atomizer. That design itself is where you have liquid coming in through the side of a nozzle and it flows in through this annular passage and at the exit here you have a gas coming in and is being injected in to this liquid through a series of holes. In fact, another design could be extended this all the way down to the nearly the exit.

But this piece is a porous piece, this porous piece allows. So, it is like a porous it is made out of a porous metal, sintered metal let us just say, that allow this air flowing in to be injected in to the liquid. So, what you essentially create in the liquid are this tiny bubbles and that bubble laid in liquid, now flows through this atomizer comes out in the form of a spray here. There are 2 modes of operations of this, one where due to this convergent nature of this passage, some or all of these bubbles may coalesce in to 1 big bubble, which is usually in the middle of this injective.

So, if I take zoomed out view of this, I could have essentially created a thin liquid film with an air bubble in the middle, but the liquid itself may have some air a still trapped in it in the form of small bubbles, but most of the bubbles could have coalesce to create 1 big air bubble its sort of a like a core annular flow, in 2 phase flows this would be called a core annular flow. So, have an annular liquid film flowing down the walls in the middle is a core of air. This core annular flow design is like our old Prefilming air blast, because I now have an inner air except in this case I do not have an outer air, but I can always introduce another outer air stream to this.

But what people find is that is not required, because your mixing the air internal to the spray nozzle it is much more efficient at using the air for an atomization. In the previous examples, where we are using, where we are looking at external air mix the only place where the air in the liquid come in contact is at that interface that cross sectional area where the two are allotted exchange momentum is very small in comparison to the total surface area of the liquid. Where as in the case of an effervescent atomizer you created a sprays system that can be where the air and the liquid are internally mixed and they are very intimately mixed as a result giving you much more efficient transfer of momentum or and energy between the air and the liquid. Because the air could be at a slightly higher pressure, the air and the liquid coming in contact gives rights to this expansion of the air and that is essentially what gives rise to atomization what is energy source for atomization in this particular design.

Now, this is its really where it was first proposed in 80's came in with the loot of promise, because it uses about 10th of the air that is required for the air blast or air assists designs 10th of the air by mass. But it requires slightly higher supply pressures for the air. So, there is a slightly over head, but the problem is not that, the problem is that it is very prone to instabilities. So, I could for example, ideally I want this nice air flow in the middle and liquid film, sticking to the walls and getting a nice study spray, but what I actually end up seeing is that liquid may come flood this (Refer Time: 35:49). So, I get a big slug of only pure liquid that is being pushed out by some accumulated gas behind there and this big slug of poorly atomize liquid is followed by a slug of air with hardly any liquid in it. So, it is just like a big puff of air that comes out. So, this alternating slug of liquid poorly atomized and a puff of air is not a good. Because it gives rise to intermittency, that is one of the biggest challenges with this design.

There is a way to over come back; there are some advantages of this design even for diesel injectors. The big problem though is this intermittency, but this is one of the only concepts of internal mix air nozzles, internal mix air assists atomizer. So, if I need to classify this nozzle it would be as an internal mix, everything else external mix. The advantage of the external mix is that I get to control the liquid flow rate because that is the separate pump and that is not as much affected by the air. In this case if I increase the air flow rate for a moment keeping the fuel liquid supply pressure the same the liquid flow rate is going to go down slightly, because the pressure in this chamber will go up. So, the back pressure against to which the liquid is being supplied in to the nozzle goes up as a result the liquid flow rate goes down. So, if the 2 flow rates are more coupled in this problem in comparison to the external mix design, as for as robustness in an application is concerned this is not as good as the other for that reason. We will look at maybe one or two more other designs.

Now, we are moving away from we looked at liquid inertia as being a source of energy those where the simplex and just spell it on designs. We looked at air as being the source if an energy those are the external mix and the internal mix air assist designs, here is a case where the source of energy is a mechanical object.

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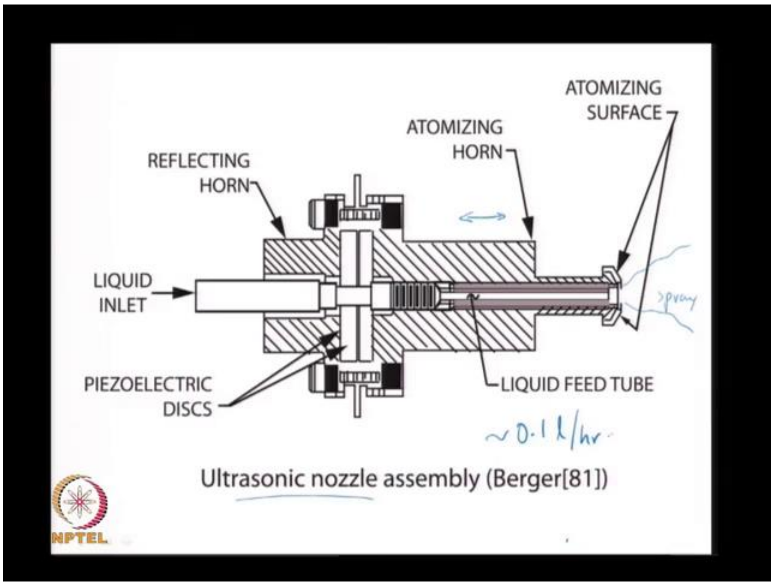

So, if you will imagine an ultrasonic nozzle that has a set of piezoelectric disks around a supply tube. So, essentially what I am doing is, I could take this atomizing this horn as that is called and have it oscillate back and forth in this fashion. And what I end of doing on the end here is I am imparting that liquid, but by creating this transient motion of the liquid I can have liquid bump in to itself. Sort it is a very sort of crude way of saying it, but I think that describe the situation. I have fast moving liquid behinds slow moving liquid behind fast moving liquid, because of this oscillatory emotion of the horn because of which I have end of creating a spray here. It is not really a spray, in the sense of the previous sprays it is more like a drip, but a controlled drip this is. In fact, some of the very early inject printer out of IBM use the design like this. So, if you imagine the injected nozzle just oscillating it creates nice study streams of drops one behind the other and that studies stream of drop then goes hits your paper and gives you print. If I take it further, if I do not look at as study single stream of drops.

But I do not mind them disperse to over a certain area then I end up getting what looks like a spray. Now this is very efficient in the way it uses the energy because all I am all the energy that we put in the form of the ultrasonic nozzle is entirely transfer to the liquid. And, I the liquid inlet has a pump that drives the liquid through this nozzle that is independent of the energy source, the energy source in this case is the piezoelectric disks, that cause this mechanical moment of the horn.

And the liquid flowing through the nozzle is due to some other sources of push coming from the liquid inlet side. So, these two being decoupled is a good thing because I can put in whatever energy density that I need to get my desired spray quality. Because I can put in as much ultrasonic energy as I need to per unit mass flow rate of the liquid, because I have independent controls over the tool. The disadvantage of this practically it is not prone to up to any high flow rate. So, typically design like this can put out you know less than about 0.1 liter per hour very low flows. One of the places where you require low flows, but good atomization quality is in humidification applications.

So, this is in some humidifiers you see a design like this being used. Where I just want to in a very dry and environment, if I need to humidify the air in the room, I want to spray water in to the air, allow the water evaporate so as to saturate the air, and that process required some sort of a spray and that application this kind of a design is an often used.

Another mechanical design where the source of energy is mechanical in nature is what is called a rotating cup atomizer. We will look at this design.

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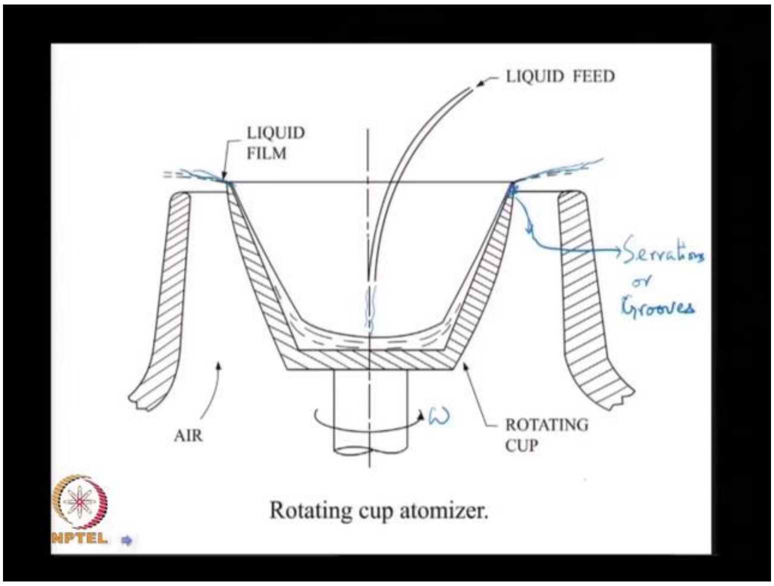

Rotating cup atomizer.

Essentially if you imagine a spinning cup, the spinning cup has a liquid feed, so just a little imagine a just like is shown in a schematic does not matter, do not have to get very fancy with this. If I keep dripping water in to the cup and the cup itself is spinning at some angle velocity omega. Then water is going to climb up the lip and come out in the form of a spray, the form of a sheet spilling over the edge. So it is just like a simplex nozzle except, the swirl for the liquid and the center fugal of the liquid is not due to the liquid swirl, but due to a wall swirl, due to wall motion it is the only fundamental difference.

Now, if I actually start to use this is now the top view of rotating cup except what is shown here, is where one-half of this cup in this part has serrations.

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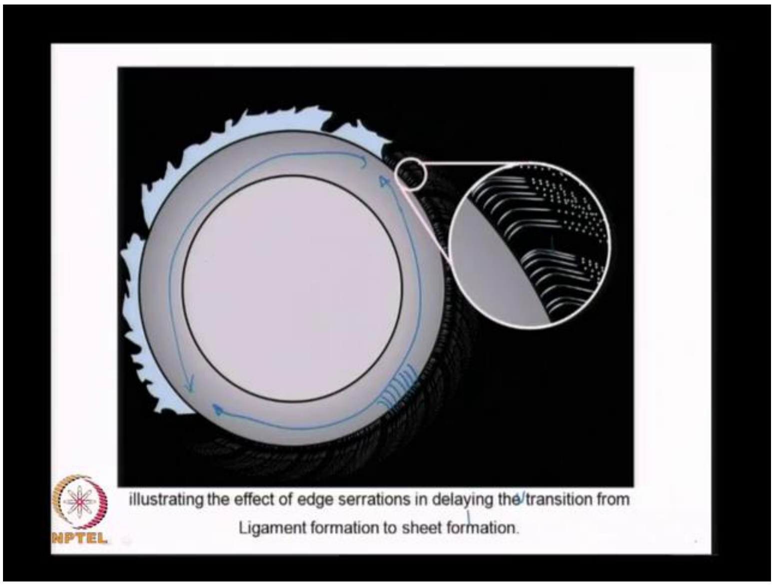

So, if you imagine little groves like that. So, it is like I have groves, on the edge on this rim of the cup. When I put those groves, what I end of doing is the liquid flows only through those groves, as it spills over the cup and each of the liquid that is spilling in through one grove is like a little jet that breaks up into drops. Now the size of the drops is comparable to this size of the liquid jet, so this liquid, this diameter d there. So, essentially by controlling the diameter for the depth or the width of the groves, I can control the drop size a by controlling the rpm, I can control the cone angle of this spray, the angle over which this you know the angle over which the conical sheet that is speed over the lip is at.

Now what is also shown in the schematic is where, if I take the cup and do not put these groves, what I end up getting is actual film spilling over, but looks like is shown in this schematic. So, it is like a liquid film itself, but spill over the edge of the cup that is not atomized at the point where it spills over. The problem with that is now I have no control over the drop size, as much as I had in the other design.

So, the more; this sort of serration on the groves does, serrations of groves does two things - one it allows me to control the drop sizes and two I have control over the width of the drop size, because of the nature of the primary atomization process. The fact that I have each individual jets spilling over through over the groves and each jets spilling over through each grove is going to be a responsible for breakup and if I make sure that all the groves are about the same width I have the same fluid mechanic process happening in all the groves.

So, the particle is that I get the drops I get or all going to be comparably very similar in size. So, this gives me much better control over the width of the distribution than any other design of sprays (Refer Time: 47:27). Consequently this design is used where width control is very important much more than drop size control, I can live with the size being of a little bit, I do not want the sizes to be far apart in there on width, in those kind of a application this is used one example is powdered food manufacturing, tide in the spray drying process in tide or any of these drying process is you see rotary cup of atomizers use. There is actually another reason why rotary cup atomizers are used in drying process is because drying by nature involves slurry. So, these are particle laid in fluids and you do not want the particle to be clogging fine features on a spray nozzle.

Here, is a design you where the finest feature is the groves, otherwise everything else is big right. So, essentially the groove size is sufficiently large that it does not clog up and, it is very resistance to clogging and gives you good control over the drop size distribution width. So, this is another mechanical source of energy based design of spray nozzles. Now, again this produces essentially a hollow cone spray really know way to produce a solid cone spray from a design like this, but if I am only interested in drying particle a solid cone is actually bad, because I have get unsaturated air to the middle of this spray if I have a solid cone spray, I have a hollow cone spray, I have to get unsaturated air only to near the drops which is only on the periphery. So, it is any way good.

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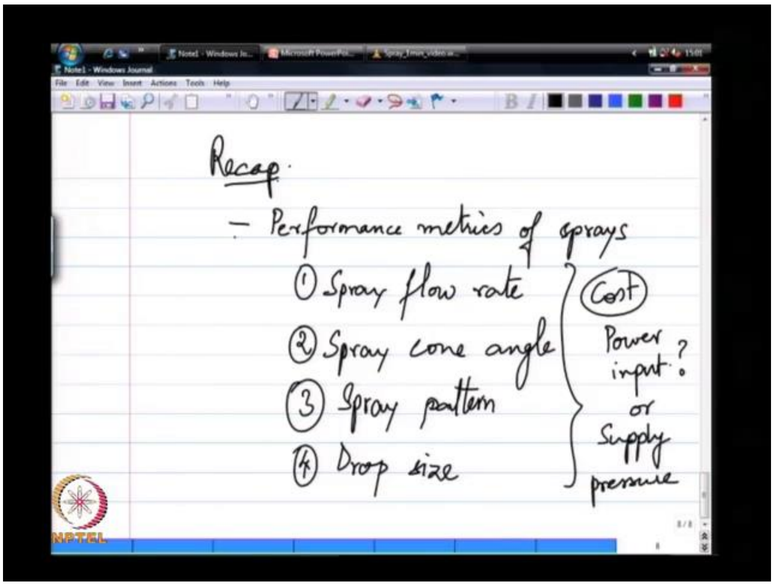

So, let us quickly recap, we looked at performance measures, performance metrics. The one I did not mention, but I know we did we talked about with earlier, is the actual flow rate this is very important, the second is spray cone angle or the third is spray pattern. We also have drop size as one of the metrics and the cost to incur all this is in some sense power input or supply pressure. So, at what supply pressure to I have to operate the certain nozzle in order to get these desire satisfied.

We will continue this discussion in the next class.