Spray Theory and Applications

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Lecture - 13
Spray measurement characteristics

Hello, welcome back. We are going to continue our discussion of sprays and atomization, but we are going to move on to little more practical a few more practical aspects and look at external spray characteristics and their measurements.

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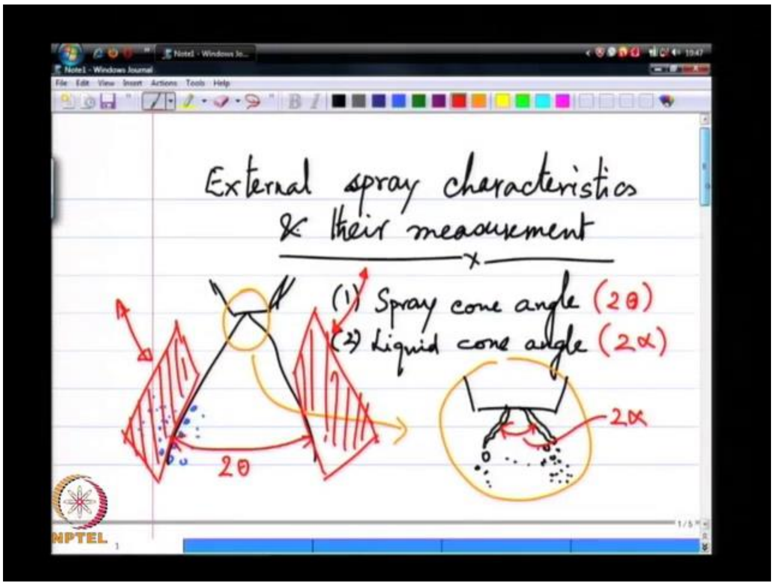

So, let us take a simple example of a spray. You know we looked at what the morphology of the spray is like in the earlier lectures. What we want a do today is understand how one could characterize these spray. Now, we did actually go through a make a list of a few different external properties of sprays; will start with the first one. We will start by making with distinction with between the spray cone angle and the liquid cone angle. The liquid cone angle if I zoom in to this near nozzle region what I have essentially is a fluffing liquid sheet of sorts; you have seen videos of this and then we start to get a spray where this drops form. This cone angle subtended by the liquid sheet itself is what is often refer to as the liquid sheet cone angle and what angle measurement that we can make of the spray part itself slightly, downstream is what we will often called call the Spray Cone Angle.

Now, how do you measure these two properties the liquid cone angle can be measured from high speed image snaps out of the spray at this magnification as sure and it is fairly spread forward and very clearly defined because, this is the liquid sheet that is that is formed at the exit and the angle made by the liquid sheet is very clearly defined. As suppose to the angle made by the liquid sheet, the angle made by the spray is not as clearly defined because the spray itself is essentially; a bens of drops and you have a lot of missed on the outside and it is not like a rigid object that as a clearly defined edge. So, measuring spray cone angle is always a matter of subject bit of a subjective decision, but in the industry typically one could use what is called blade protractor, so measurement devices for each of these.

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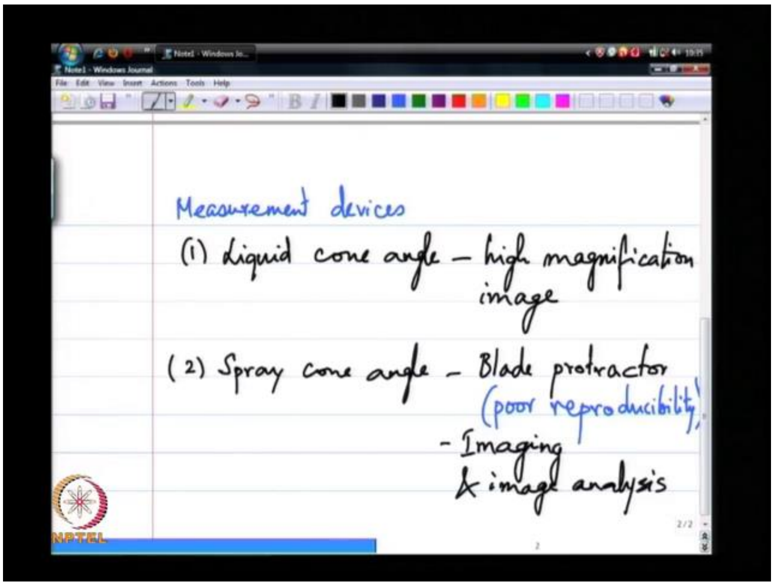

So, first the liquid cone angle your best bet is a high magnification image the spray cone angle can be measured with what is called a blade protractor. This is technique that is widely employed in the industry essentially, if we will imagine a device that is got two mettle blades, that are allowed to swing back and forth and you and an operator brings these in to touch the so called edge of the spray. Now one persons edge is another person's periphery is another persons missed. So, there is subjectivity in what one would call the edge of the spray. So, one of the basic problems with using brade blade protractor is poor repeatability or at actually more precisely poor reproducibility.

So, operator to operator while, one operator working on one spray nozzle may be able to reproduce the same result may be able to actually repeat the same value of measurement. If you bring in several operators and have them test the same spray nozzle you are likely to get high variability. So, this is the device that potentially as high repeatability, but poor reproducibility. Reproducibility is important, if I want to convey my results to a fellow engineer and have him verify my findings. So, that is where the challenge lies with this blade protractor but, it is a very simple device sheet and is widely used and alternate way is again going back to imaging and using image analysis.

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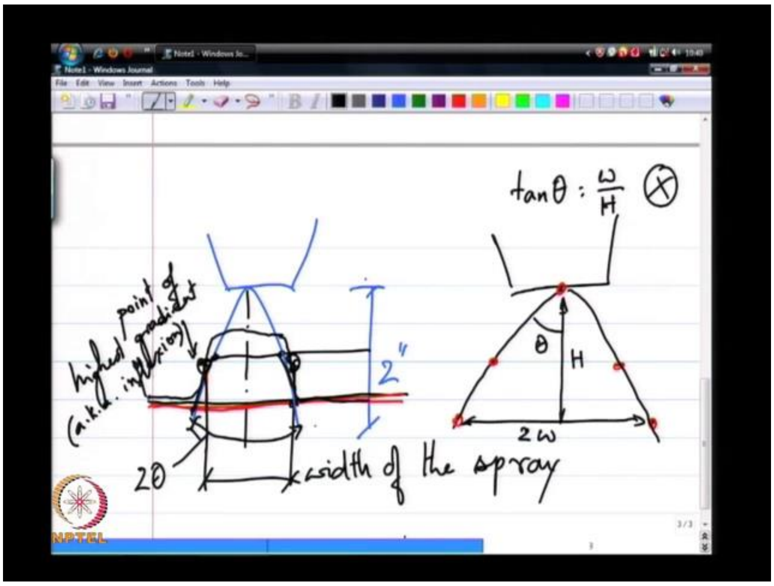

So, one way that imaging is often employed is if I take an edge of image of a spray let us say I take an image that is a sufficiently a large spatial representation of the spray cone angle. So, the liquid part is the liquid cone is very close to the nozzle here and then when I take the image I see all the missed and everything on the edge and if I take a line going across the spray and float the intensity in the image as a function of the position from the center line.

So, if this is the center line if I float the intensity in this particular photograph intensity of the drops of the image itself, one would see that there is a sharp rise right around the point that you would call the edge and this point here were the gradient is the highest also known as inflection point is one possible measure of what the edge should be like. So, essentially I look at the whiteness of these pixels of these lines of this line array of pixels.

So, whiteness as in a gray scale and it goes from nearly pitch black on the outside of the spray to where the liquid drops reflecting light back towards the camera look whitish at a higher gray scale number and even I float that quantitatively I get in, I get a float that looks like this and from these two inflection points I can get the width of the spray at this axial location. So, typically what is done is that you could get the width at a couple of different axial locations and through a cur fit figure out what the cone angle would be the two theta is calculated knowing what the spray width is here. Spray width is at an at another axial location and the fact that I have nozzle here using these three points, using these three data points if one could reach one could essentially reconstruct the spray.

Now a simpler variant of this is to just make this measurement at one axial location. So, if I know this width I will call this 2 w in if I know this height I will call this h I can define this theta to be h over w or w over h, but this is going to give you a higher source of error in comparison to making the measurement at two positions primarily, because most of the time the spray is sought of collapsing on to itself due to air entrainment not due to the gravity due to air entrainment.

So, this problem is not going to go away if you try to orient this spray upwards or horizontally it is essentially due to the fact that air from the outside is being entrain into the spray that there is the small collapse of the diameter or the cross sectional area over which the drops are distributed and then the last technique that you can use to measure spray cone angle is what is called a patternation processes.

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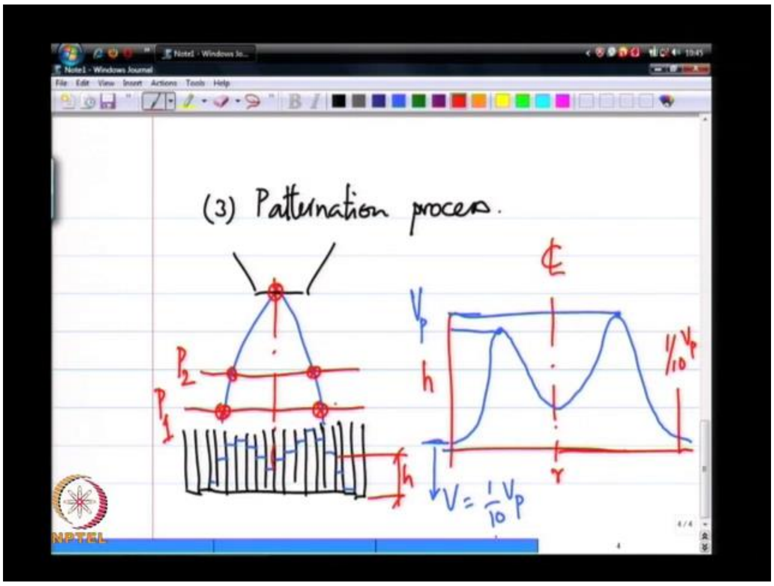

So, if I take a spray and place beneath this spray a series of tubes the liquid column in each of these tubes is going to be slightly higher and lower. If I were to quantitatively float that again as the tube height edge. So, if that is h is a function of r from the center line or replace this as a center line sorry, I have what looks like this from knowing this peak value of the volume flux and saying say if this is v peak I am going to a go to a point where the volume flux is one tenth of the v peak and call that my spray edge.

So, the point where the volume flux is one tenth of v peak is denoted as the spray edge. In other words I have to figure out some way to convert and otherwise blurred edge into a quantitatively repeatable sharp edge and in this is the case where I take this series of tubes inside them under need the spray and collect volume in this tubes from the spray over a fixed period of time and that gives me the tube levels and notice how the notice how I have intentional drawn the peaks to have different values on either side of the center line. So, in a real spray there is no reason to expect symmetry in this spray there is geometric symmetry in the nozzle, but very often your spray itself could be slightly off and there is would know theoretical reason that, they should always be exactly the same in a practical when apply to a practical spray nozzle.

So, I could take let us say the average of these two peaks as my peak value and the edge is where the volume in a given tube is one tenth the volume of the peak. So, essentially the edge is being defined as the point where the volume flux is an order of magnitude smaller than the volume in anyone given tube. So, once I know this I can essentially do what we did with the image. So, I get a pattern at one axial location pattern at another axial location, and from that knowing the spray edge at the two axial locations and knowing the origin of the spray I can fit a second order curve to these three points and from that calculate a spray angle it is always good to do this at two axial locations again because of this feature that sprays edge is are not linier entities.

If you look at what we have just done the difference between doing it we are the pattern nation process verses the image analysis process that I discussed earlier is that the image analysis gives us a snap short in time distributed over space. So, I am using spatial information, but at one instant of time whereas, the pattern nation process is where you are accruing the information over time at one axial location. So, it is the old spatial verses temporal measurement techniques, but in for this particular spray characteristic that, we are interested in both of these give reasonably the same answer size velocity correlation is not really was the reason why special and temporal measurements are independent. Whereas, when it comes to spray cone angle as a entity they it gives approximately the same values even if they are not quantitatively the same the techniques are very close the they yield very similar results.

So that brings us to the second the first spray characteristics is this cone angle. So, spray cone angle and liquid cone angle and the next spray characteristics is what we call spray pattern.

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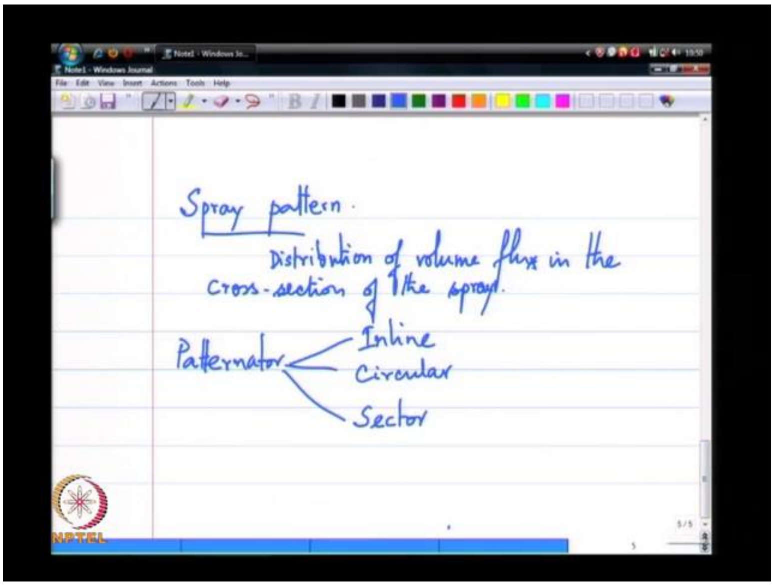

Spray pattern is an indication of the distribution of volume flux in a cross section of a spray now, depending on the internal flow in the nozzle I could get different spray patterns and like we discussed in the very early part of our discussion the example I have here would be called the hollow cone spray pattern. On the other hand, something like that would be called solid spray pattern.

Now, for the duration of today's lecture like we started we are only going to restrict tassels to mechanical measurements systems. There are optical equivalents of these in of course, imagining is optical, but is a fairly in expensive tool to use in a in any measurement setting. So, we will stick to mechanical measurement systems for the most part, because there a in expensive and b they give us reasonably accurate figures for the most part where, optical tools given as better estimates the degree of the quality of the measurement in an optical system is there is not justified by the cost incurred in many instances, we will I think these are still valuable research tools and certainly design level tools that one needs to be familiar with it.

So, will go to spray pattern one of the tools in that is often used is what is called a patternative we have already seen what this patternator is this three kinds of patternators. One is called an inline patternator the other is the circular patternator and the third is called a sector patternator will see what each of these are and what pieces information these yield. The one I described in the context of measuring co spray angle is what we would often called is what is called the inline patternator as you can see the tubes are all arranged in a straight line.

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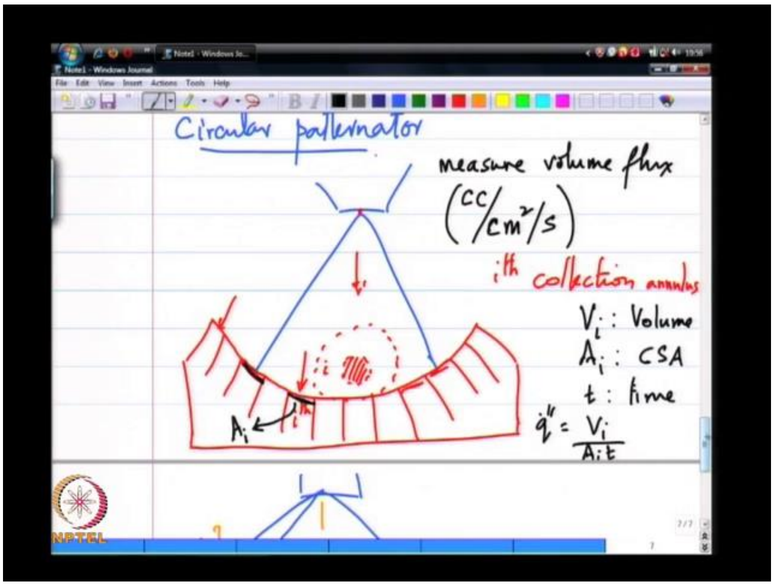

The circular patternator is where the tubes are all arranged as points on a circle which with each one of these collection points draining into. So, the i-th collection point drains into an i-th tube. So, I can this actually, if I look at the top view of this these are all circles. The middle one may be a circle this outside one will be an annulus of shorts, so the i-th collection annulus is the better way to put it actually.

So, except the one right in the middle all other collection regions are shaped on an annulus except they are arranged in a circular pattern where I could placed this patternator concentric with the orifice on the spray nozzle. Now the advantage of this is, that each of these collection annuli or at the same distance from the spray nozzle. So, you are likely to collect. So, essentially the cross section a cross sectional area of this annulus that is facing the nozzle is exactly the same as the geometric area.

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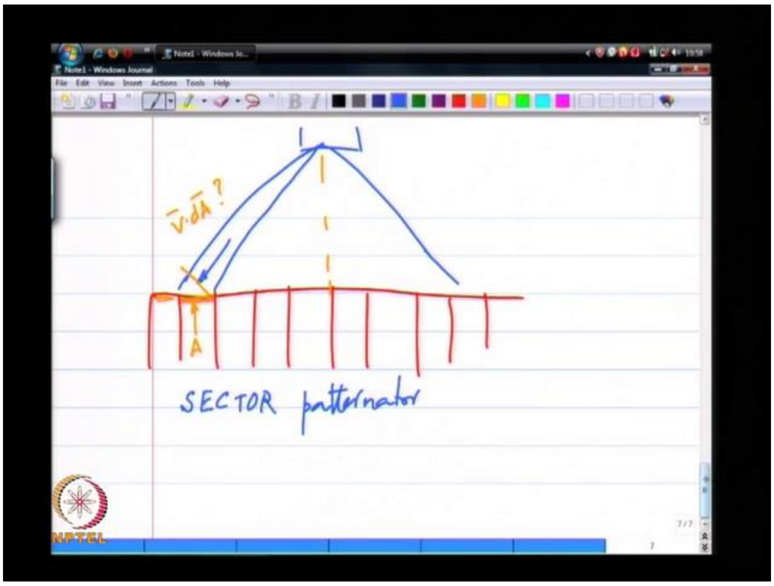

Let us make sure we understand this point if I did this same exact thing in an inline setting and I had a spray nozzle that is spraying, let us say I will intentionally draw a wide spray the collection going into this sector as a mean velocity in this direction which automatically means that, the collection area is not this area, but more like the area perpendicular to the velocity vector. So, essentially V dot d A, is what is responsible for the mass getting collected into the i-th chamber.

So, in an inline design the V dot d A the angle between the velocity vector and the d A vector and the area vector are different and that causes even though, I am thinking that I have am exposing the liquid to the same cross sectional area the cross sectional area that is that the flow actually seizes different depending on how far out away from the center line that particular sector is located whereas, if I have them all arranged in the form of a circle then the area, that the V. The angle between the area vector and the velocity vector are is essentially close to being 0.

So, before I go much further what to this patternator measures they measures volume flux. Let us see let us make sure we get the units right on this say I run one of this for a minute and in that minute I collect so many cc of fuel or liquid, if I divide this by the area and then by the time I have taken to collect the liquid, this forms the unit of measurement. So, if the area of cross section of the i-th annulus is A i, if V i is the volume collected let me write it on the side here if V i is the volume collected in the tube, if A i is the cross sectional area of the of the annulus and if t is the time. Then the volume flux call q dot double prime is given by V i divided by A i t. So, it is in this quantity A i that the problem arises. If I have 20 annuli at in across the circle and if I want to calculate A i for the i-th annulus by the geometry of that annulus.

So, in a radius of the annulus outer radius of the annulus I am essentially assuming that the flow is, entering the annulus nearly perpendicularly, which will be the case if I have them on a circular arrangement if I have them on an a circular arrangement them it does not necessarily be the case and for what kind of sprays does this error become higher and higher the wider the spray angle. We can see the angle between the velocity vector and the area vector increases and the further away I am from the spray from the spray origin the angle also is likely to exist.

So, if I am interested in measuring large sprays paternation on large sprays in line patternator is the bad choice I have to go to what is looks like circle of patternator. Whereas, if I am looking at a small spray, that is say I am only 3 inches way the entire spray width is only let us say, 2 or 3 inches in diameter and I have a sufficient resolution of tubes in that region then an inline patternator may not be very far off from the circular patternator, but you do have the source of error.

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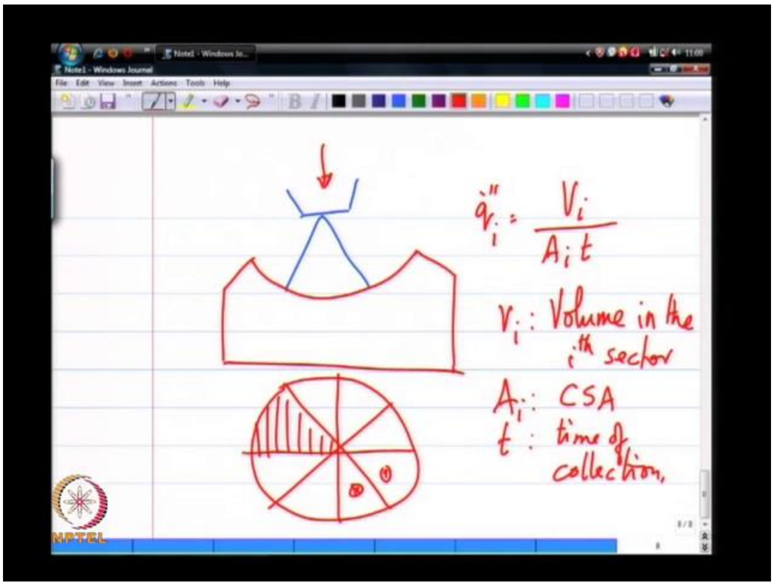

The third is what is called a sector patternator. So, this is essentially like a circular patternator, but except if I look at the top view of this circular patternator it is not a series of annuli, but a series of sectors. So, the each of these sectors is responsible for collecting volume in that sector. So, if V i is the volume collected in the i-th sector A i is the cross sectional area of that sector as the flow size it. And if t is the time of collection I can define same q i double prime which is given by V i divided by A i t and I expect q i double prime over all the sectors to be the same if I have a relatively uniform spray.

So, this is the patternator that measures the degree of axis symmetry of this prior degree of uniformity of the spray in the azimuthal direction. Now again you can create an equivalent of this that is, that does not have this sector that does not have curve nature to the surface, but it could be flat by again you running to the same issue of the area of visible to the floor except that it does not really matter in this case because the error due to the angle between velocity vector and the area vector is the same for all sectors.

So, it really you essentially still are able to measure the degree of azimuthal uniformity in the spray, but this is a typical construction. So, these are all mechanical or inclusive methods of measurement I take this device stick it under need the spray and from knowing the volume collected in each of this eight sectors, then drains into a separate measuring tube and by knowing the volume collected in each of the separate tubes I am able to estimate the degree of non uniformity in the spray.

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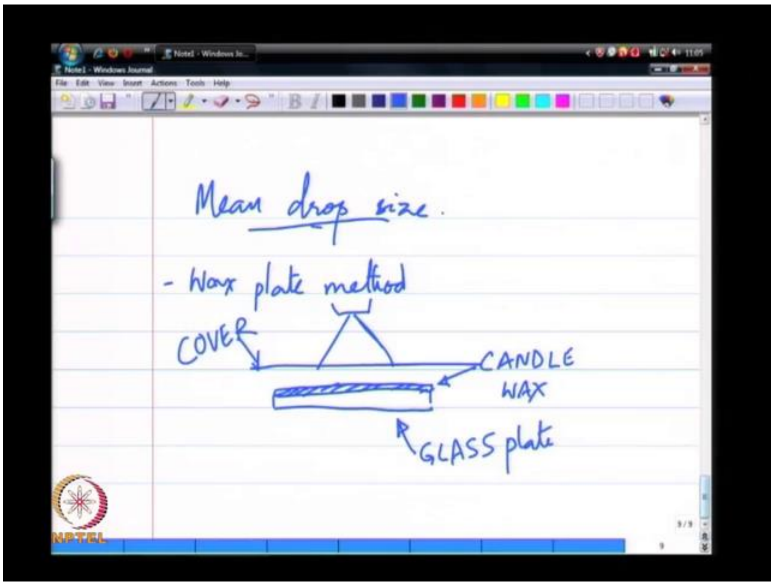

The last quantity that we want a talk about will define will call mean drop size. Mean drop size is a parameter that really is very difficult to measure, but it is an important parameter especially, when I want to estimate like the rates of evaporation or the rates of mixing of some vapor phase these are all phenomena that are greatly influenced by the by the rate of evaporation itself. So, if you look at by the drop size. So, if you look at mean drop size the oldest way of measuring mean drop size is what is called the wax plate method.

Now you will probably not find anybody using this today because, there are optical tools that will do this for you, but I still think there is value in this it is a very simple technique that you can use that in a day's time you can built something on your own and get an estimate of what the drop size maybe. So, how does this work you essentially take a plate let us say, like a glass plate and quoted with candle wax. So, it is your simple candle wax and this could be like a glass plate, glass or some kind of a metal plate or something that you can easily heat and then you insert this plate. You first heat it up slightly until you have the wax in some molten state and then cover this plate with the piece of plastic and expose it to the spray itself.

So, essentially you have the wax the liquid wax now, because the plate is slightly warm you only need like 50 degree c heat to melt wax. So, you have molten wax on this glass plate and on top of that you have a cover of some kind the cover is removed for a removed and replaced back for a very short period of time.

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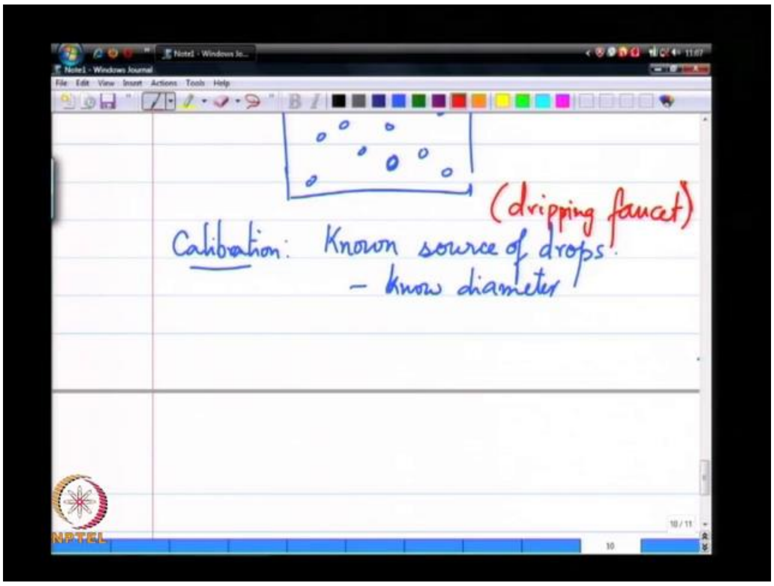

So, what you create on the glass plate are indentations wherever your liquid drops heat the wax and just by the liquid hitting the wax it immediately solidifies right around where the liquid as the hit and that is the only two pieces that is the only place where you do not want further flow of the liquid wax. So, as soon as the water drop hits the wax surface it causes the wax to freeze at that point with the indentation in it.

So, once you once you have recover this plate with all this indentation on it we can then go to each one of these indentation and measure the size either under a microscope or in a or just by simple by placing it against a known measure like a ruler. So, how can you finally, get drop size from this what you need to do is that this instrument now require some sort of a calibration. So, what I have at the end of the day is a size of this indentation, but not the size of the drop. So, if I take a known source of drops, the calibration processes start with the known source of drops.

So, you know the diameter what is the simplest such source of drops it is essentially, your whole dripping faucet you can analytically calculate the size of the drops that will result from this once I know the size of the drops that are impacting the plate in my calibration experiment.

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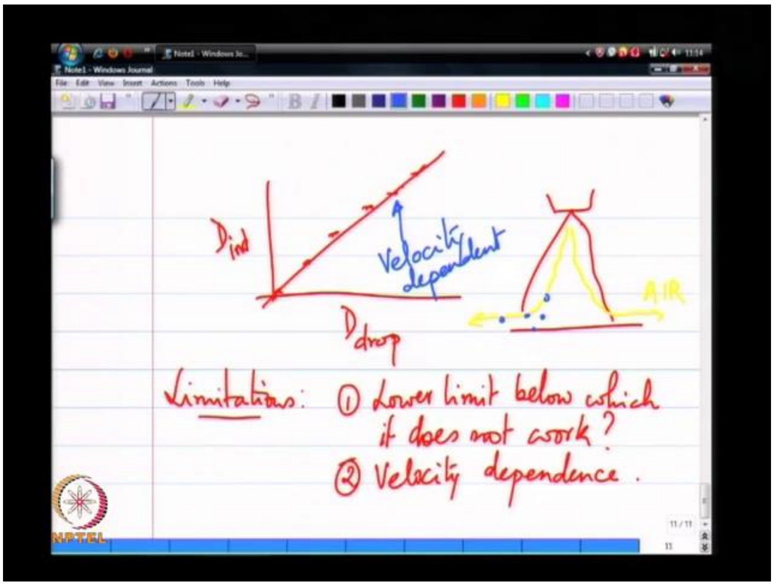

I can establish a correlation between the size of the indentation and the size of the drop itself and typically this is the linear correlation. So, knowing the slope of the curve you can go to an unknown sized indentation and establish the size of the drops. So, this is actually like I said a very simple and reasonably accurate measure, but like in every other case we need to understand the limitations of these measurement techniques.

So, what are the limitations of the wax plate technique first is there is a lower limit below which it would not work. Now where it is this come from essentially, as soon as I take a spray and place an abstraction in the way of the spray the smaller drops in the spray are likely to just follow the airstream which is going to go around this way and that airstream is going to carry the smaller drops with it. So, you essentially require the drop to be of ascertain size before which it will not make this turn with that with the air. In fact, come and form an indentation you do not want the drop to be carried away by the air, but instead. In fact, the plate in cause an indentation this lower limit is one reason why you will only tend to overestimate the drop size. So, if you have some fine particles in your spray those will not be measured by this and, you will only tend to overestimate the drop size. So, you do have an upper bound, so this provides an upper bound on over the real drop size the second problem is the velocity dependence of the indentation.

In other words I can take the same dripping faucet in my calibration experiment and I can get indentations at different heights below the faucet and get different indentation sizes depending on how far below the faucet my wax plate displaced just because the same size drops is now impacting the plate with the higher velocity. So, the size of the indentation is now not just a function of the size of the drop, but also a size also a function of the velocity with which the drop hits the wax surface.

So, if I want to know I only have the indentation spot size as a measure, but I can get the same indentation size by a larger drop that is moving slower or a smaller drop that is moving faster and I do not have the enough information to tell from the other. So, there is we do know that there is the velocity dependence of this slope. So, this slope here is velocity dependent, but how does that really cause a problem in our measurement system it come from the fact that, if I have different sized drops in the spray moving at different velocities then I am likely to get into this issue of not knowing what the indentation size is meaning for a given velocity the slope is fixed the indentation size verses drop size slope which means that, as long as all of my drops are moving at relatively speaking a similar velocity am likely to get a good correlation back from the between the indentation size in the drop size.

So, as simple technique as this is an exceptionally use full way and it is fairly robust it is which took the test of time for almost 40 to 50 years before the advent of lasers. So, this was the first way by which drop sizes are measured and I think there is still value in performing these kinds of measurements.

So, that is the story as for as mechanical patternation systems go now as you found from both of those instances both from the cone angle patternation and the drop size there all intrusive measurement techniques whether it is, your circular patternator or sector patternator there all they have an intrusion error associated with their presence in other words the spray pattern in the undisturbed spray is not the same as the spray pattern with the patternator inserted, this is what we will call intrusion error. And it is very often difficult to characterized and quantify the intrusion error, but it is possible to estimate the direction of that intrusion error which is sufficient.

So, if I know whether I am over estimating or under estimating my volume flux in let us say the inline patternator I can use the measurement as either an upper bound or a lower bound and that may be sufficient for most engineering applications specifically for the case of the inline patternator again if I place a tube in a spray I am assuming that all the drops passing through a certain area of cross section go into the tube and become deposited and I measure that as volume in cc terms.

But if some of these drop where to meander away due to the air currents am only going to measure the once that actually went in and depo and got deposited in the bottom of the nozzle bottom of the test tube which means that, the inline patternator or for that matter any patternator under estimates the volume flux just as we said the in dental on the drop size over estimates the drop size this the mean drop size because it is going to leave out some of the smaller drops. So, these are ways of bounding the measurement or bounding the error on the measurement which is always the useful exercise.

We will stop here, will continue this discussion and sort of become more current in the next few classes where we are going to discuss optical and non-intrusive measurement devices for measuring external spray characteristics.

Thank you.