Spray Theory and Applications
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Lecture - 16
Non-intrusive spray measurements techniques

Hello, welcome back. We are going to continue our discussion of optical diagnostics applied to sprays. We will look at a couple of different techniques today involving a laser diagnostics.

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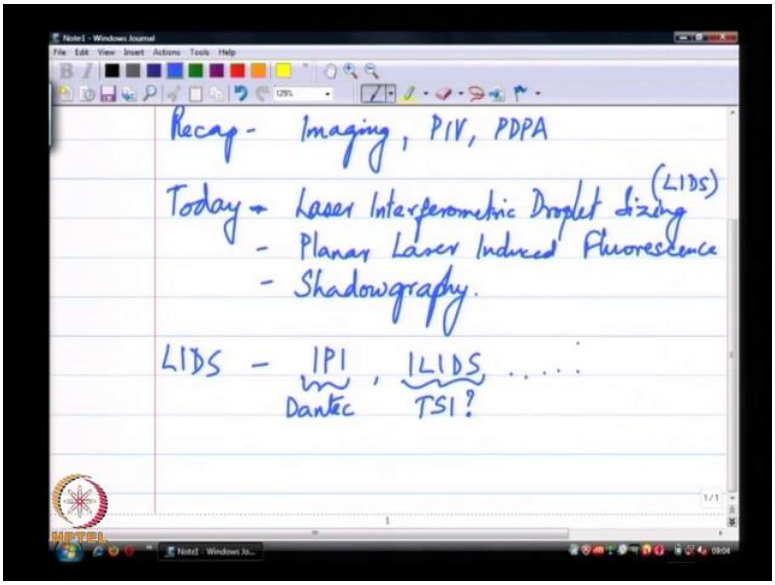

Just as a quick recap; in the previous classes we have studied basic imaging, although we did not really look at image processing. We looked at PIV; we looked at Phase Doppler Particle Anemometry, and started to talk about other techniques. Today we are going to discuss three more techniques; one called Laser Interferometric Droplet Sizing, will also look at Laser Induced Fluorescence, and end with Shadowgraphy.

Laser interferometric droplet sizing, I will use the acronyms LIDS is known by several acronyms commercially, IPI is an acronym that is use by a company called Dantec, ILIDS is a company is an acronym that is use by I believe TSI, I am not sure. And there are other companies that make this as well. The basic principle of operation is similar to a PDPA, in that in the sense that it takes advantage of coherence.

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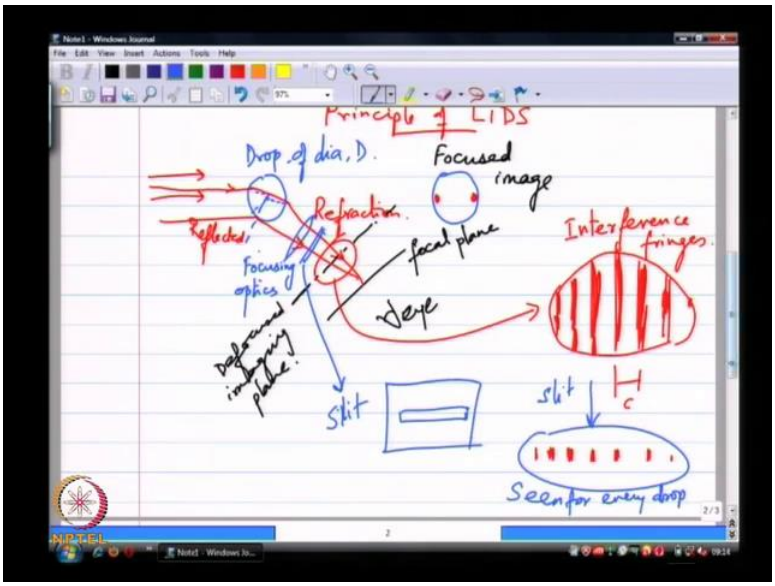

So, if I take a droplet and have a laser light source approaching the drop, if I do a very quick rate race, this is a typical ray that is twice refracted though the drop of diameter D. There is another possibility of light reaching this observer here. So, let say this is v the observer there is another possibility by which the same light can reach this observer which is through the mode of reflection. So, either a ray down here is reflected or it could reach the same person through the medium of refraction.

A combination of these two modes of transmission of light or scattering of light through this observer, if I focus when the light is focused you see drop with two bright spots corresponding to the two predominant sources of light coming to the observer. So, this is in fact common observation that; if I see a rain drop, if you see a picture of a rain drop that is in perfect focus you will see 2 points of bright light on either side of the rain drop.

Now, if I take the same light and instead of focusing it on to a plane. So, if this is my focal plane, when I create this focused image I see this, if I take the same modes of transmission and if I image the light; say this is a focusing lens. So, instead of placing the plane imaging plane at the focus I place it at a slightly defocused part. What you will see at the defocused part is a set of interference fringes. So, if I draw the doubt you are likely to see, and all of this is the envelope of a circle because that is what is scattering the light.

So, you see bright and dark interference fringes. These interference fringes, especially the fringe width contains information about the size of the drop, and it is really a hard signature that is coming directly from the sphericity of the drop and the size capital D of the drop. So, it is actually very rich in information this fringe pattern we will see how to take advantage of it will little later. So, this is the basic principle of operation of this LIDS; Laser Interferometric Droplet Sizing. Now how do I take advantage of this in a real system?

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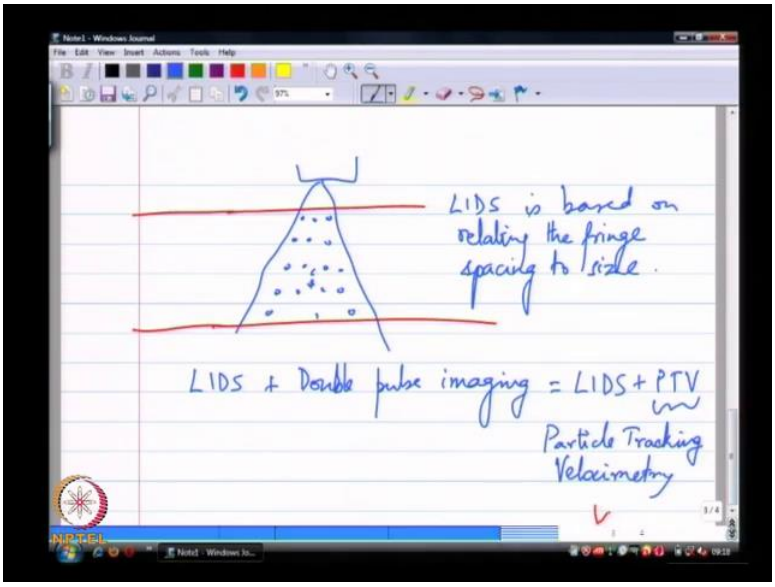

What we do; is I have a spray nozzle, I have a spray that is form; I take a light sheet passed through this spray. Now potentially I have a lot of drops in this light sheet of different sizes, and where your eye is currently is where the collection optics and the focusing optics are setup.

So, if I now look at the scatter light coming towards me with in a sort of a defocused sense, every one of these drops will create circular footprint and an interference pattern in that circular footprint. Because of this coherent light coming from two different optical path lengths the reflected light and the refracted light takes separate optical paths therefore, you create interference. Now when I view each of these drops I have a full circular pattern. So, if I have a I mean a light sheet of some finite thickness, which is say 1 mm and our drops are typically much smaller than that, if I have two drops that are one slightly behind the other they are both going to create an interference pattern. And this

circular interference pattern is going to interfere in some sense spatially in the image with the interference pattern created by the drops slightly behind it.

As a result you will see a whole set of interference fringes, but I need to identify a set of interference fringes with a particular drop in order for me to get to the drop size, the way this is done is by using only the information that is required, by only allowing the information that is required and discarding the rest. When I have a circular interference pattern, circular footprint with interference fringes along the length of the circle, along the vertical cross section of the circle, all I care about are the is the fringes spacing I do not care about the full circular footprint.

So, what is typically done at the collection optics level there is. So, I can place a slit and this is a in some sense a horizontal slit that looks like this. So, the vertical fringes when look when visualized through a horizontal slit essentially create you only see a part of the fringes that looks approximately like this; you will not see this vertical lines on top and bottom, but you will just see something like this for every drop, something like this you seen for every drop.

So, if I have multiple drops; even if I have two drops that are slightly behind each other I am able to only take a thin slice of the interference pattern created by each of the two drops, and as long as those two slices do not overlap I have enough information to get the size of each of the two drops even if they are close to each other spatially inside the light sheet. Once I know this fringe spacing, and once I have information related to the position; ones I know the fringe spacing and I have a bunch of these for every one of these drops, we are able to extract drops size information for every one of the drops.

Now, like I said these fringes actually if you do the even in some sense the wave calculation, optical wave transmission calculation through a spherical drop, you will find that this fringe spacing is not exactly uniform throughout and that contains information that is specific to that drops; in terms of sphericity for example or some kind of difference in the refractive index of the of the drop. So, I am able to relate every drop and by knowing let us say that midpoint of this pattern, I am able to determine the size and it is position uniquely. So if I use LIDS; which is laser interferometric droplet sizing along with double pulse photography, where I take two pulses and get two images lightly

a part in time, because I am able to uniquely identify every drop in this image we can calculate the velocity vector of every one of the drops.

So essentially an extension of this; so first of all LIDS is based on relating the fringe spacing to size. Now if I combine LIDS plus double pulse imaging you can get LIDS plus particle tracking velocimetry which allows us to measure the velocity of every particle in the spray.

We will looked at several different techniques for a both particles sizing or drop sizing and velocimetry, let us quickly see the advantages and disadvantages of the various techniques. First of all; so let us list for each one the various techniques the advantages and disadvantages.

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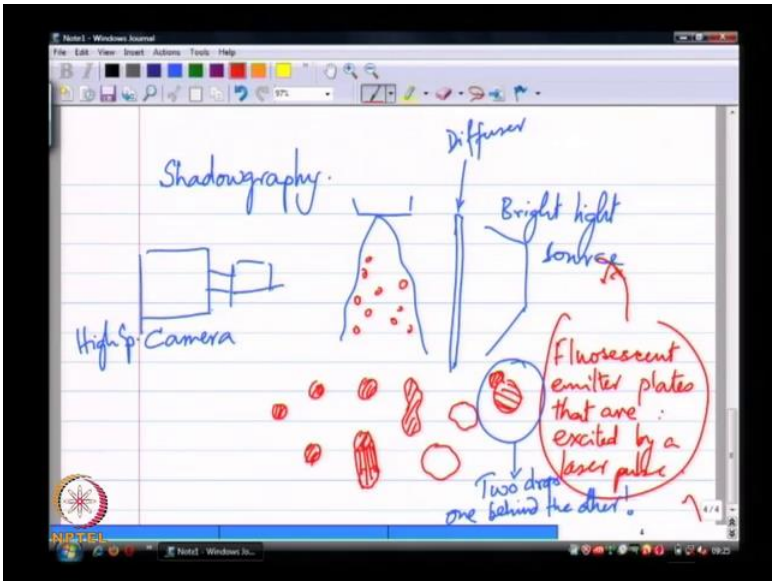

But, before we do that maybe we should look at one more technique called shadowgraphy, is similar to the one we use before, which actually in some sense the simplest of all imaging techniques. You put potentially have a very bright light source will passing through a diffuser, and on the other side is your camera. Typically, this has to be a high speed camera, in order to be able to image the spray.

The basic principle of operation you know when I am looking at a bright light directly in front of me I am going to see the shadow of any of object that is between me and the light and so the camera sees shadows of these drops. So, you might see drops that are

back here as well as drops that are in front all cast a shadow on the image, but I could have a specific plane in on which I focus the camera and only look at the shadows in that focused plane and discard the images on either side. So, essentially this is the clarity of the image depends on the depth of focus; the smaller the depth of focus the higher the clarity, but smaller the depth of focus the less chance I have of capturing a sufficiently large number of these drops in any one image, so though they are contrasting requirements of this system.

Once I have an image ideally I would like an image with like dark shadows that are circular, they do not have to be circular, but let us say they are of some very clearly defined shape. In reality what you will end up seeing one of two things; you will see a little bit of a blur where the drop is may be dragged through a certain distance, this is because in spite of using the highest speed camera the exposure time on some of the high speed cameras may be still long to get a crisp frozen image of the drops. So, the solution to that very often used is to have instead of a bright light diffuser their fluorescent emitter's, emitter plates if you will that are excited by a laser pulse. So, this would be a substitute to the bright light source.

The advantage of this light source is that you have first of all a laser light source that is infringing on a fluorescent, on an absorbing medium, medium that absorb that wave length and emits us slightly longer wave length, but the emitted intensity is relatively uniform and is only controlled by the concentration of the fluorescent agent. In reality of course, even that intensity is not important, the fact that that emission accurse over a very short period of time is what is important. So, the fluorescence life time of these agents is very short typically much shorter than the exposure times on your high speed cameras. So, if you can synchronize the high speed camera to the initiation of the fluorescing time or the pulse initiation time one could capture a very crisp image of the drop.

The biggest advantage of shadowgraphy is that I get, I am able to capture sizes of drops that are known to be a spherical. If you look at the previous techniques whether it is phase Doppler particle analyzer or LIDS, they all assume sphericity in order to get to the size. So, this is the technique since you are directly visualizing the blobs of liquid in motion frozen however, you are able to see images of drops that are not spherical and by appropriate image processing get you know shapes of like you are able to characterize the shape of the drop apart from just the size.

So, if I now look at an image coming from the fluorescing agent I am able to see drops like that are spherical, but I may also have a second drop that is slightly behind the first drop and in my image I may create a shape that looks like this. And both these drops may still be within the depth of focus of what of my imaging optics. So, I can now with my naked eyes see that they are two separate drops and I can use appropriate image analyses techniques. So, start with edge detection and look at sudden change in the gradients of the edge and from there identify this composite image of two drops on behind the other as actually being to separate drops, and you can ascribe a size to each of the two drops.

Now if I have a ligament of sort, say typically like a if I am now very near the nozzle, I may actually see a drop that looks like this, I can use this technique to not only get the size of that drop in the plane of the image, but also get some feel for what sort of non equilibrium shapes are existing in the real nozzle region. So, this is the slightly more versatile technique in the sense that you are able to image drops that are not spherical.

One of the biggest disadvantages of these techniques is that you really still cannot go very close to the nozzle. In spite of you know talking about non spherical drops because, once your droplet number density becomes large tip classic case is a diesel spray it is very very difficult to image the real nozzle region in a diesel spray, to get to some kind of indicators of what sort of drops sizes may exists in that part of the in the near nozzle region of the spray.

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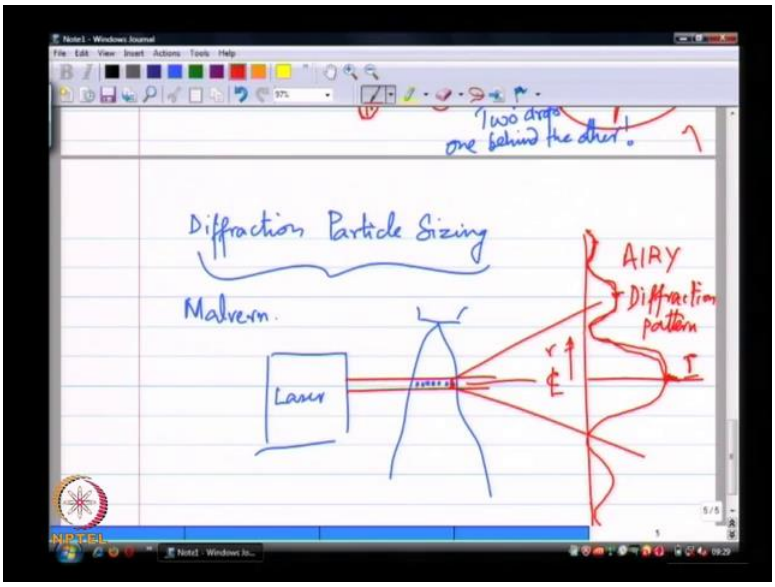

Now, we did not talk about another technique. In fact, one of the oldest techniques for particle sizing is what is called diffraction particle sizing? That the pioneer in this field is called was a company called Malvern. Which was? In fact, it preceded all other forms of optical diagnostics for sprays except photography. Now the basic principle here is that I have basic a laser source, that puts out a light beam, the light bream shine through a spray, and all the little drops that are in the light beam are scattering light. So, essentially by the medium of diffraction by the mode of diffraction, so, every drop again assuming sphericity creates what is called on AIRY pattern of diffraction.

So, I am going to exaggerate this part just to just to make the point, if I take this particular drop, the it creates a pattern where the light intensity versus radius takes on a pattern that looks like this. So, you see a very bright spot in a middle one more bright spot certain angular deviation away and the third bright spot. So, you see this clear peak this is called the AIRY diffraction pattern from a spherical drop. And this AIRY diffraction pattern has this clear peak and these peaks are responses are directly related to the drop size. If the way and remember this creates the diffraction creates an angular diverging pattern. So, with again some appropriating imaging optics, so it is quite usually it is just a single lens and the detectors are semi circular AIRY. So, I mean the l diffraction pattern for a circular drop in a laser beam is symmetric about the central line it is axisymmetric.

So, typically the detectors that are used to detect this light are photo photodiodes or photo detectors that not photodiodes, but photo detectors that essentially are arranged in rings around the axes, and these rings are the spacing between the first to peaks of the ring or the position of the first peak, on the ring position of the first peak of the AIRY diffraction pattern, tells us what the sizes? Now as you can see this worth if I have one drop in that long laser going through the spray, the I mean this principle of operation is clear, but if I have multiple drops, I will get a superposition of peaks and there are algorithms and that is Malvern's contribution, to take the intensity distribution from many different rings coming from many different drops, and obtain a mean diameter for the drop size for the distribution of drops in the resident in the laser beam. We will talk a little bit about this algorithm and continue our discussion towards the laser fluorescence laser induce fluorescence in the next class.

We continue our discussion of optical diagnostics, and towards the end of we have completed our discussion of the phase Doppler particle analyzer diffraction particle size, LIDS which is laser interferometric droplet sizing of course, our standard techniques associated with the PIV particle imaging velocimetry, and how PIV can be used to extract some averaged size information, averaged surface area information. Today we are going to talk about another technique called PLIF or planer laser induced fluorescence.

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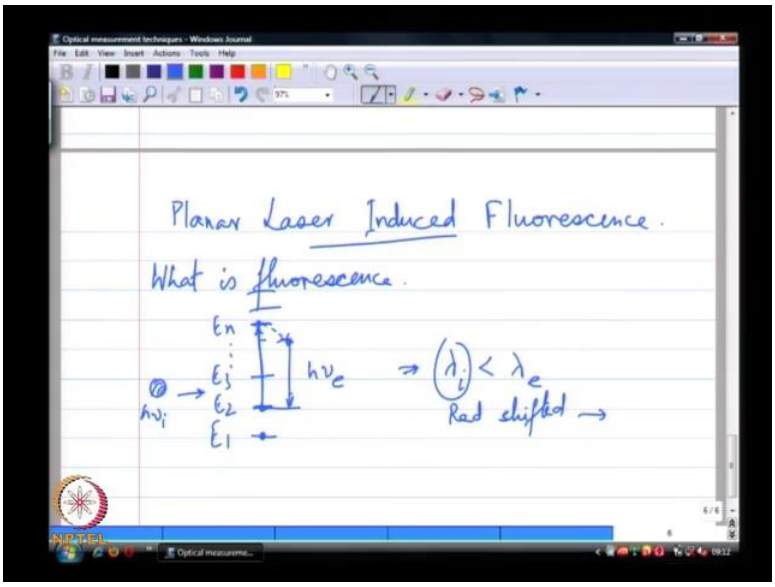

Planer laser induced fluorescence is a technique in that basically relays on the property called fluorescence. So, what is fluorescence very quickly typically when a photon interacts with a molecule, molecule as discrete energy levels for the electrons and an electron from one of the lower energy levels can absorb the energy coming from a photon, and be pumped up to some high energy level, but on the way back, but on the, but in the process of relaxing from this higher energy level down to the ground state, it may not emit a photon of the same wave length or frequency. There is some amount of inelastic this is essentially a phenomena called in elastics scatter because; the incident photon and the emitted photon are of different frequencies. The emitted photon has a lower frequency essentially lower energy in relation to the incident photon, which automatically means that the incident wave length of the light is less than the emitted wave length of the light.

So, this is also called in some sense this is slightly red shifted, that is shifted towards red on the spectrum. Now the way this actually works is you have to find the wave length, whose photon energy h nu is exactly equal to the spacing's, the between to discrete energy (Refer Time: 32:47) to discrete energy levels and. So, that in itself is a big field of research. So, for example, in the in some of the work that view done we views this. So, that to find a molecule that has a pair of energy levels one being the ground state another higher energy level, whose differences is equal to the photonic energy is the photon energy is basically an art of chosen what is called a dye.

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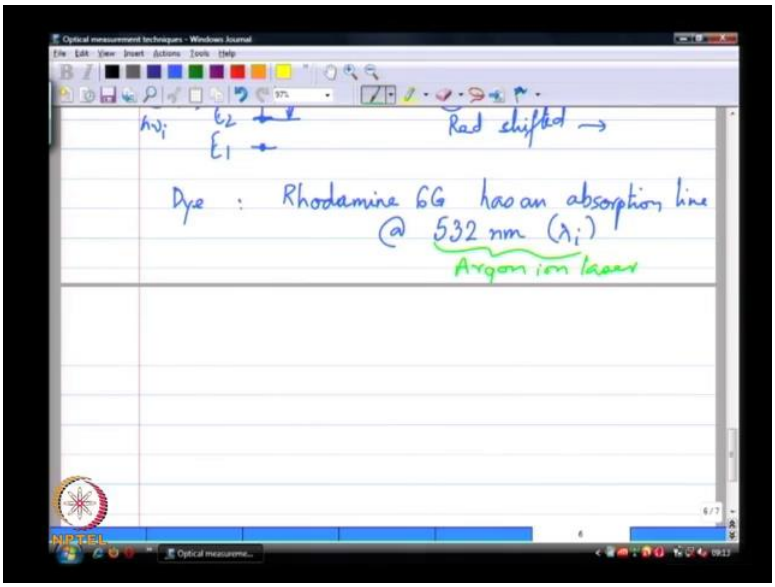

So, this kind of a molecule is often referred to as a dye. For example, there are many different dyes, there are many different classes of dyes, but say for example, Rhodamine 6G is a dye that is very commonly used in the spray community. In Rhodamine 6G has an absorption line at 532 nanometers wave length, which happens to be the wave length of argon ion laser. So, this happens to be green in fact, and it is happens to be the wave length emitted by an argon ion by an argon ion laser. So, if I take just to give you an idea, if I take a beaker full of water.

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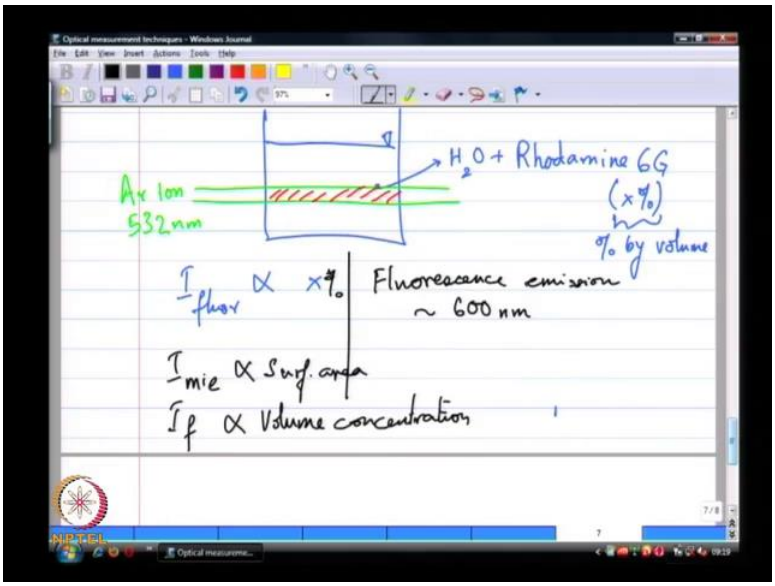

So, this is water with Rhodamine 6G in some concentration, and shine a an argon ion laser through there, and see it from where my I is placed, I will essentially at least to start with see green band going through that water, which is dyed with this Rhodamine 6G that is because of what we have already seen as mie scatter. So, this lot of particles and you know some entities in there that are scattering light towards the observer, and that is scattered light is exactly the same wave length as the incident light.

This is refers to as elastics scatter. So, the you have a lot of elastic scatter in any real system that has some scattering hobs, scattering entities in it and then if I wear safety glasses in any of you that has worked in the laser lab usually you have a pair of safety glasses that have a cut of filter for the wave length of the laser that you are using. So, essentially that wave length light would be invisible to you, if you wear that if you wear those safety glasses.

So, if I wear those safety glasses and look at these beam going through this water, which is a dyed with Rhodamine 6G, I will see a slightly orangish glow in the region where the laser is passing through the water and hardly any glow or hardly any light coming out of the rest of the beaker in all in other words, the rest of the beaker is practically dark the beam before it enters the beaker is invisible the beam after it comes out of the beaker is invisible, only the part inside the beaker when the beam is resident inside the beaker is responsible for this florescence emission from the Rhodamine 6G dye. The intensity of

that Rhodamine 6G dye, the intensity of that fluorescence emission is directly proportional to the concentration of the dye present in the solution.

So, the intensity of the light does not the wave length of the fluorescence emission, but the intensity is directly proportional to the volume concentration of the fluorescence of the dye in the solution. Now sometimes this fluorescence emission is a slightly broader banded in other words it is not a discrete wave length, because these molecules are typically very complicated. So, there are many energy levels from which you can get this fluoresce this inelastic relaxation. And because of which fluorescence is sometimes especially in the commercially used dyes is not one single wave length emission, but slightly broad band, but it is always red shifted.

So, it is always slightly longer in wave length then your incident light can never be shorter, and in and it also is much lower in intensity then your then your mie scatter. Because mie scatter is a phenomenon, which is where the intensity of the light is directly proportional to this scattering surface area. So, let us be there are two things happening here, one is I mie which is proportional to surface area and I fluorescence which is proportional to the volume concentration. So, let see how this is applied to a spray.

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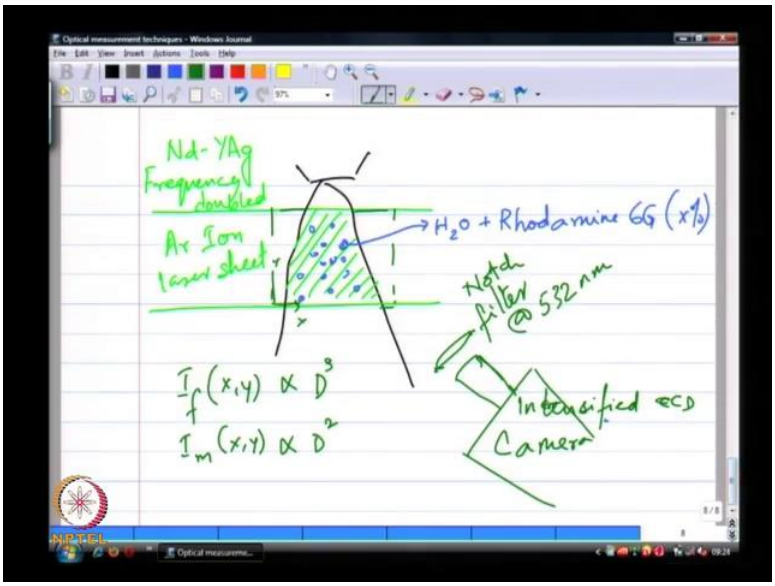

So, if I take a spray nozzle, and I take my argon ion laser sheet and in this sheet you know, you may have little drops of the spray that you want to visualize and these drops typically have these drops are of the liquid, where the you have the dye present in the

liquid. So, the drops themselves may be let say an equate solution of water and Rhodamine 6G, and your and the camera is placed were your eye is placed and typically the camera may have collecting optics, but it may also have a filter it is called a notch filter or at 532 nanometers.

In other words it passes all wave lengths below and above 532 nanometer this is called a notch filter or I could use a low pass filter or high pass filter that cuts out anything bellow 532 nanometers or slightly above 532 meters. So, I am only going to see wave lengths that are longer than the cut of wave length. But a notch filter is fairly commonly used because, that is easy to make it using diffraction patterns. So, essentially if I place a notch filter in front of my emerging optics I see I do not see the mie scattered light I will only see the fluorescence emission coming from the drop themselves. So, if I create an image of the fluorescence emission this is essentially an image of the volume concentration of the Rhodamine 6G.

Now for most commercially available pulsed argon ion or frequency doubled Nd-YAg both give you very close to this same wave length. So, either argon ion or it could be frequency doubled Nd-YAg laser. So, both of these even at some even at the highest pulsed pulse energy of the light sheet coming into this spray the fluorescence intensity is. So, weak that it may not be visible on a regular CCD or a CMOS array. So, very often we have to use what is called an intensified CCD camera. So, this is like very low light imaging, so that is essentially the reason you require some way to intensify the image. So, your regular CCD camera is able to detect.

So, this intensified CCD camera with the notch filter will be able to visualize the fluorescence intensity distribution in the light sheet and the fluorescence intensity distribution, I f which is now a function of let us say some spatial if this is my image, this is proportional to the volume of the drops. So, if I for a moment assume that I only have mono sized drop or if I look at this phenomena at the single drop level the fluorescence intensity is proportional to D cube, and the mie scatter intensity which I can visualize without the intensifier and actually without notch filter is proportional to D squared.

So, if do multiple double pulse images, one pulse giving me the fluorescence intensity distribution and the second pulse giving me the mie scatter intensity distribution, from that I can get essentially and if I do a time averaging of those pulsed images am accruing

sigma D cubed in time in one sequence of images and sigma D squared in time on the other sequence of images, and if I ratio then I am actually directly getting the sauter mean diameter that is the advantage of using PLIF in sprays, that you by this appropriate ratio in you may able to get the sauter mean diameter directly.

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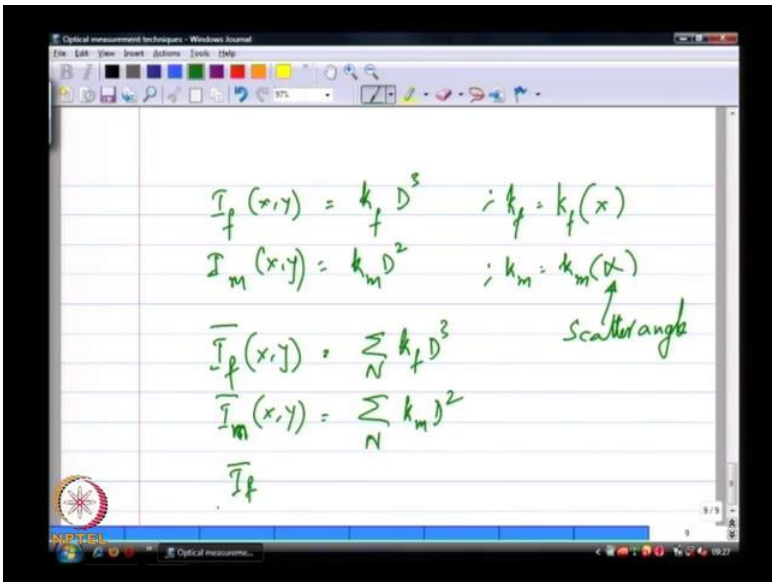

So, let us just quickly write that down, I f which is the function of x and y is equal to some k f times d cube this k f is a function of the volume concentration, which is the I mean at this level you will just say it is a function of the concentration of the Rhodamine dye in the liquid. So, this is like the concentration of the dye in a tank setting upstairs somewhere above your spray nozzle right.

The mie scatter on the other hand in some k m times D square to be found that this k m is slightly more complicated we have already done this calculation to show that it depends on this things the alpha your scatter angle, between the laser source and your imaging plane and your image it is the angle made by the ray coming in from the source and the ray going towards the observer and that angle could be different for different parts of the image. So, that complication which was which apply to any kind of a mie scatter imaging also applies to using PLIF for droplet sizing.

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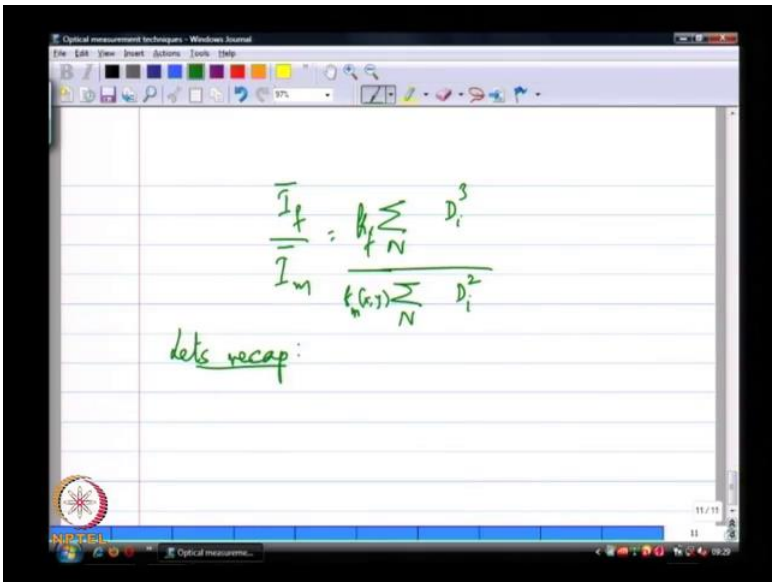

So, if I do a time sequence on these, remember if we said this k f is only a function of alpha I can factor that out, if k sorry k f is only a function of x I can factor that out if k m is only a function of alpha, I can, factor that out and make sure I have still retain the fact that it could be a function of my x and y coordinates in the image, because different parts of the image have different angle to which like a scatter. So, if I can get this sauter mean diameter at one point in the image, but that valve is not comparable to the sauter mean diameter at another point in the image, because the denominator k m is a function of x and y and that is not very easy to get in a real situation this it still a somewhat, active area of research to identify that.

So, this while in principle works it is still not been implemented fully commercially there are people who claimed to have done it and you can actually buy this PLIF mie sizing instrumentation, but as far as I know this is not been implemented commercially in a very robust situation at, so there some room for you to play round with and do some development work there. Let us quickly recap all the different measurement techniques you have studied, we have refer to this both as non intrusive and optical.

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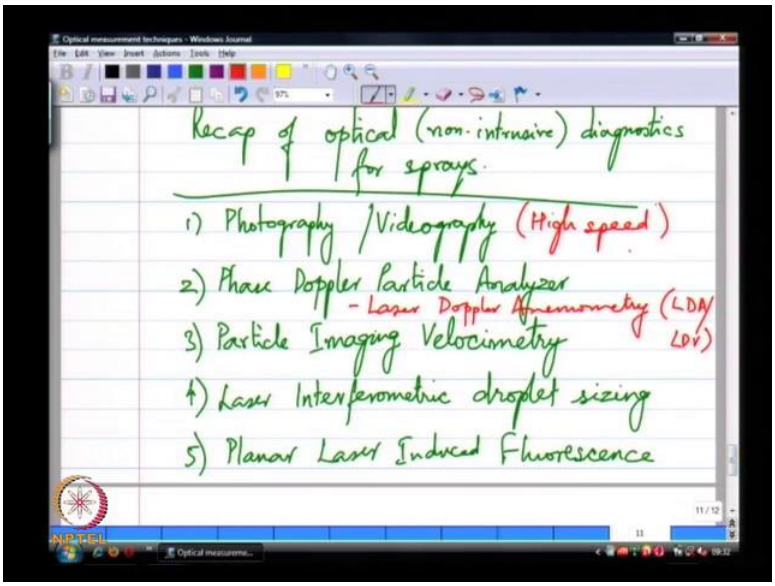

We started with simple Photography, Videography and then we looked at Phase Doppler Particle Analyzer, this may not be in the same order as the lectures, but it summarizes all of the all of the techniques we have discussed, Particle Imaging Velocimetry, we looked at Laser Interferometric Droplet Sizing, and then we looked at Planar Laser Induced Fluorescence.

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Your phase Doppler particle analyzer is a super set of our standard laser Doppler anemometry, or LDV or LDA. So, if you discard the particles sizing part in the particle in the PDPA you have essentially an LDV or an LDA, and somewhere along the way I think we also photography, videography, we also intended to mean high speed imaging. So, these sets of techniques are fairly widely and commercially used. In the last let say 20 to 30 years, the prevalence and use of these I instruments in spray and to understand spray related issues as really revolutionized our idea of what we can do in combustion systems, especially if not in other spray applications.

We will continue our discussion in the next class.