

**Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer**

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**Week – 10**

**Lecture - 48**

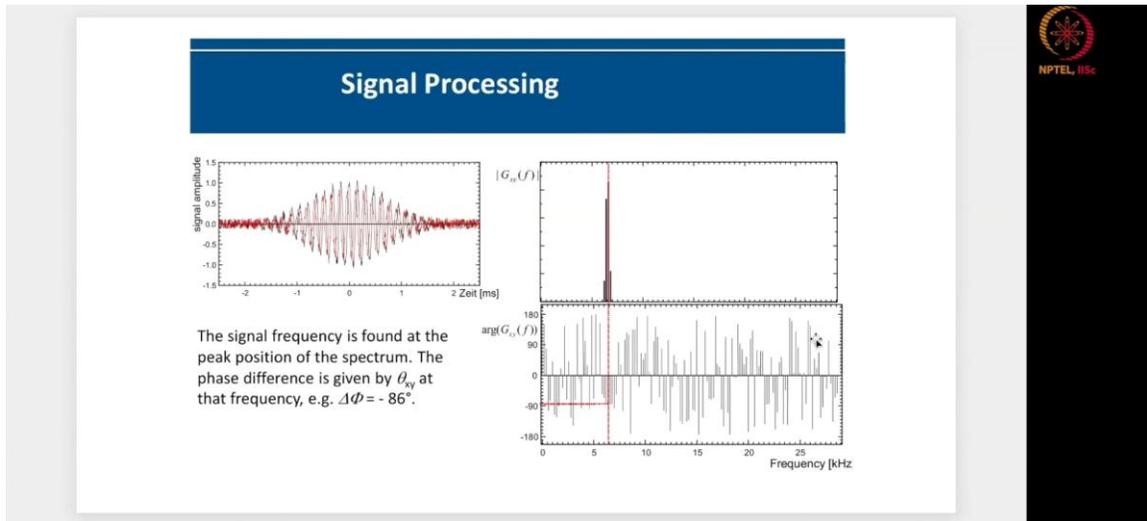
**Phase Doppler Particle Analyzer – 3**

OK, so we are going to stop with this. This will be the last lecture in the PDPA series. And if you recall that in the last lecture, we essentially talked about how the two laser beams intersect, and then you capture the signal from two detectors that have the same scattering order; they are coming from two different beams. And we talked about how frequency actually measures velocity, whereas the phase shift measures what the particle size will be. And this came from this particular equation. If I just move back a little bit.

So this was the expression. And there was a  $2\pi$  bias that we talked about. And that bias was addressed by using a third detector. So, the third detector was used.

Let me find that slide once more. The third detector was used to find the  $2\pi$  bias to relieve the  $2\pi$  bias, essentially. So this is what was done with the third detector. So this is the standard system. And then we talked about the possibility of a planar system that has zero elevation.

And then we got the, you know, we can actually do what we call a sphericity validation. So a lot of things like that can be done using this. And then you can also have—this is from Nicholas Apple's thesis—that all the points which are away from this line we kind of reject. And then whatever is in this band, we accept that as the spherical validation from the dual mode. Dual mode is basically standard and simple.



So that is how these things are done. One is along the meridional circumference, and one is along the equatorial circumference. So that is how this was done. And then the exchangeable spatial filters, and whatnot. Okay, so ultimately we talked about the data processing, what the coherence part is, and what the quadrature part is.

And when the signals are in phase, they all fall into the coherence bucket. If they are not completely out of phase, they go into the quadrature bucket. So basically, the angle between these two—the argument of arctan—is basically the argument of the cross-spectral density function, which gives you the phase. And that is what is used to extract the phase difference and hence the droplet particle diameter in this case. So this is how these things are going to pan out.

So let us look at some of the examples now. And this is once again from Nicholas Appel's thesis. This is a project in which I was also quite actively involved because it was part of an Indo-German science and technology center. The project on closed-coupled atomization involved the shock drop interaction, whereas Nicholas Apple worked on the full-scale closed-coupled atomizer operated with water and air, while this was supposed to be operated with liquid metal. That is how they actually create this metal powder, so to say.

So this has a variety of parts. The video is not going to play, but I can take you through it. The characteristics of such an atomizer are that it has very high liquid mass flow rates, about 3 kg to about 9 kg per minute. It has a strong two-way coupling. Two-way coupling means that the liquid actually influences the airflow.

**Characteristics of Supersonic Gas Atomization**

- Representative example of a full-scale close-coupled atomizer operated with water and air.

**Characteristics:**

- High liquid mass flow rates ( $3 \frac{\text{kg}}{\text{min}} \leq \dot{m}_l \leq 9 \frac{\text{kg}}{\text{min}}$ )
- Strong two-way coupling ( $\dot{m}_l$  controller)
- Highly underexpanded gas nozzle ( $\frac{p_e}{p_a} \leq 6.2$ )
- Very high local gas velocities ( $u_g \leq 660 \frac{\text{m}}{\text{s}}$ )

Experimental challenges: short time scales, wide range of length scales, dense spray.

Supersonic Close-coupled Atomization: Experimental and Modelling Insights, 2023, Ph.D. Dissertation, Niklas Apell, TU Darmstadt, Germany

Airflow influences liquid flow. And stuff like that, and if you look at the different locations, which are marked as one, two, three, four, for example, four is a region of very high local gas velocities; it's about 660 meters per second, and three is a region of highly underexpanded. Expanded gas nozzle. So these are the different features. So, the experimental challenges were many.

It had short time scales, it had a wide range of length scales, and it was a very dense spray at the same time. And you know, there is a lot of feedback that goes on. The structures are very turbulent. And things like that. So the equivalent of that is even shorter timescales where the shock-droplet interaction, which we did at IISc, and some of those videos will be played at a subsequent time.

But essentially, what that also shows is that the timescale can be very short, even much shorter than this, and it is a challenge, therefore, to measure the droplet sizes and velocities in essence. So what was done was that Professor Tropia's group used a dual-mode phase Doppler configuration. So they had a standard system, a planar system, and the assessment of sphericity was that  $D$  should be less than 107 micrometers, and it's a three-axis traverse. So what happens is that these are the transmitters, these are the receivers, and then you have the velocity. So, you know, these are exemplary, I mean, measurement locations along the Z-axis.

This is how it comes out of the atomizer. So the average validation and spherical validation rates were about 75% and 70%, which is because you tend to get a lot of ligaments, flattened discs, and oblate types of droplets in such configurations, as you can see. And so 75% and 70%, honestly speaking, are pretty reasonable to begin with. And

the measurement location, if you look at it, is 500 mm downstream, and you can go radially from 0 to 100 mm, assuming that the spray has radial symmetry. Not always the case, but in this instance, with that assumption, you can obtain some example measurements in such a setup.

**Example Measurements  
Close Coupled Atomizer**

**Phase Doppler Measurement Setup**

**Dual-mode PD configuration:**

- Standard system ( $u_x \leq 486 \text{ ms}^{-1}$ )
- Planar system ( $u_x \leq 200 \text{ ms}^{-1}$ )
- Assessment of sphericity ( $d_p \leq 107 \mu\text{m}$ )
- 3-axis traverse system

**Measurement position:**

- Axial: 500 mm downstream
- Radial: 0 to 100 mm (assuming radial symmetry)

**Site view:**

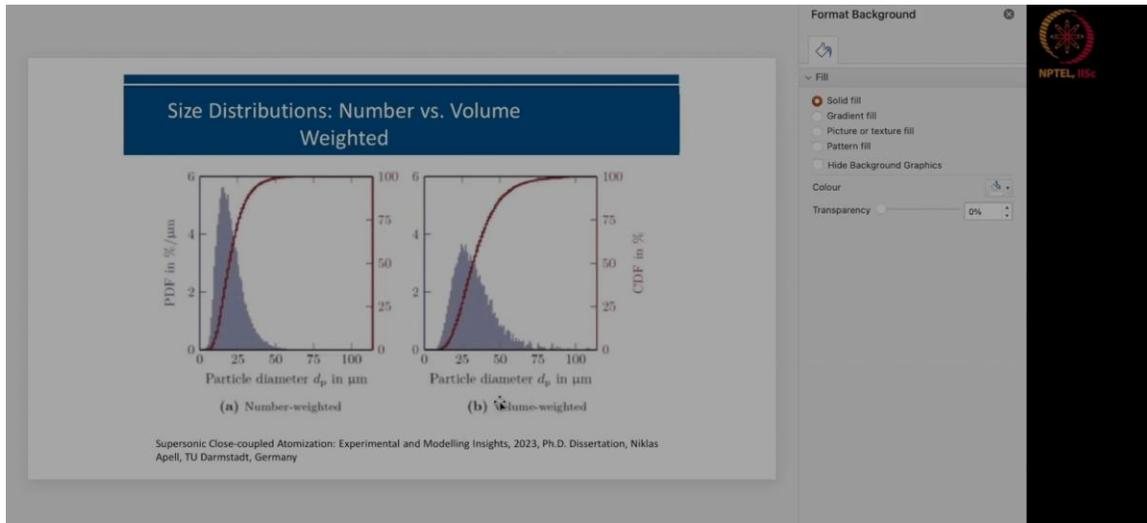
transmitter  
transmitter  
receiver

\* Exemplary measurement position

→ Average validation and spherical validation rates of 75 % and 70 %, respectively.

This is a setup where measurements were really tough. That's why it is being shown here. And using the PDPA in shock, you cannot use it at all. So there we will use something called the depth-from-defocus technique, which we'll cover in a later lecture. So the size distributions, which are number versus volume weighted, for example, this is the PDF.

And this is the particle diameter. And this actually shows the number weighted, and this shows the volume weighted. So you can see how that diameter actually, when you have number weighted, the peak diameter falls under 25 microns, more like in the range of 15 to 20. Whereas if you do volume averaging, it is always weighted towards the larger droplet size scale. As a result of that, you have this diameter of, say, 25 to 30.

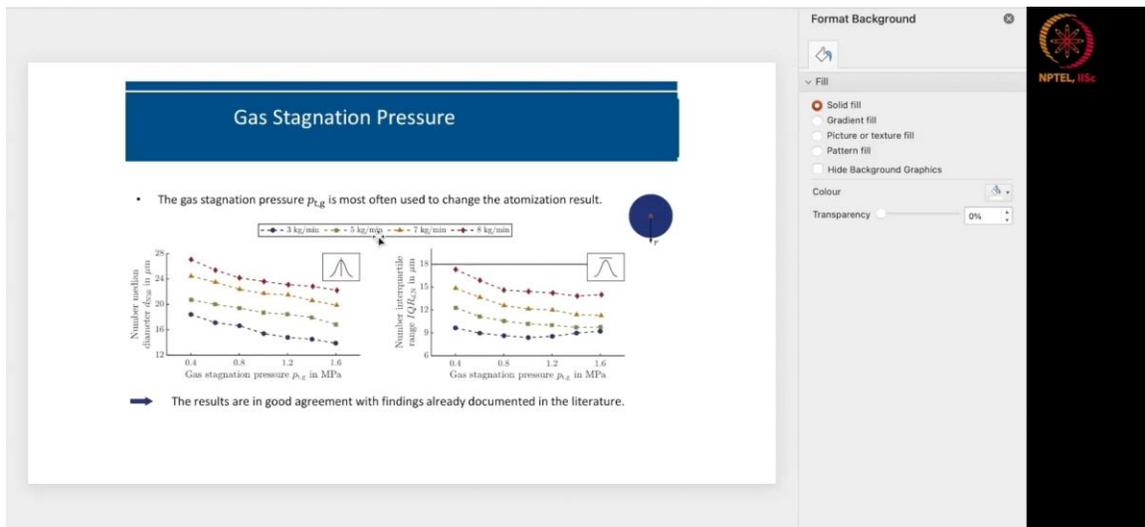


So these are the kinds of size distribution measurements that you get. Different droplet diameters are sampled, and then you do whatever statistics you want. So in this case, you can do a number-weighted average, or you can do a volume-weighted average. So all these things can be done in this way; any type of statistics can be generated. And why are they useful? Because it tells you how the nozzle is functioning.

What are the functional characteristics of these nozzles? And that is very important because you need to know how the nozzle actually behaves. And whether it is good for closed couple atomization because it is used for metal powder production, for example, is unclear. So this determines what will be the.

.. Powder size, for example. Because these droplets are going to shrink, they will solidify and form this metal powder. So, this size distribution has a direct correlation with the powder. So that is very important, and that is what these particular measurements will actually show. And then, of course, you can also vary the gas ignition pressure, and by varying the gas stagnation pressure, you can actually measure the number of median diameter droplets. So, with an increase in stagnation pressure, this comes down.

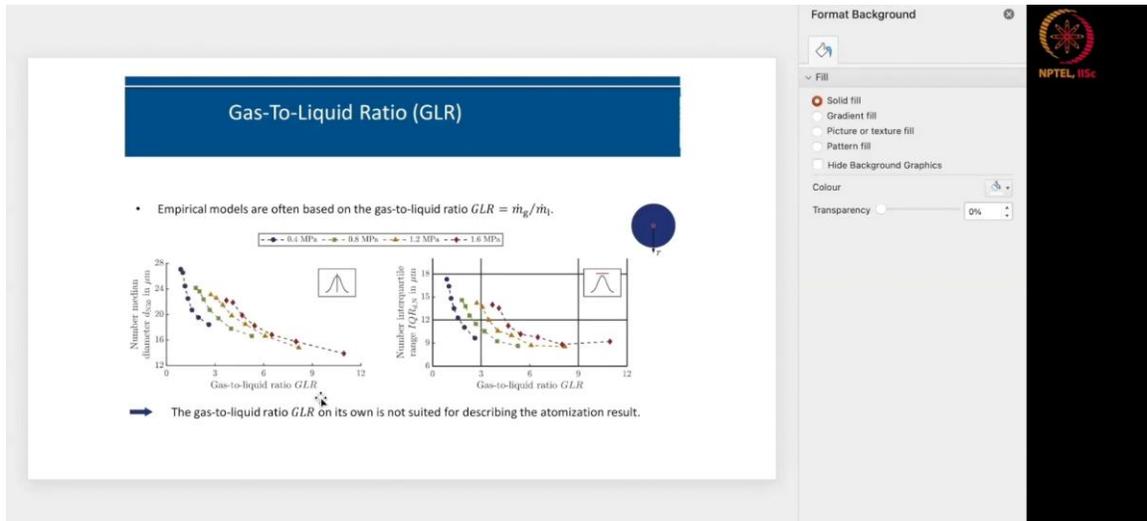
Okay, so you can use... You can vary the liquid flow rate, you can vary the stagnation pressure, and that is what is done. The liquid flow rate is varied here and here. So you can vary multiple parameters and try to find out what the median diameter number is, which is called the N15 that we can get in these kinds of measurements. It gives you the statistics, which are very important for actually optimizing the performance and even for characterizing the performance. So this is also the variation of the liquid mass flow rate that has been studied in detail, and this is again the number median diameter.



So the liquid mass flow rate has a strong influence on particle size and dispersion. So this also enables us to see that what functions or what parametric space one can play with to control the droplet diameter size. And this is only possible because you can use the PDPA to measure the droplet diameter. So that becomes a mission-critical part of this particular measurement technique, so to speak.

And this is very, very important. And so, this is one example. And, of course, you can also vary what we call the gas-to-liquid ratio.

So it is often touted as M.G. by M.L. And you can once again plot the diameter or the median diameter of the droplet in microns for different GLR values. For a low GLR, it means that the liquid mass flow rate is actually larger compared to the gas mass flow rate. Not larger with respect to the gas mass flow rate; sorry, the gas mass flow rate is always larger, but the liquid mass flow rate is lower. We can hold the gas mass flow rate constant, and you can, you know, decrease the liquid mass flow rate, or you can increase the gas mass flow rate while keeping the liquid mass flow rate constant.



Either way, this is perfectly feasible. And then the gas to liquid GLR on its own is not suited, for example, for describing the atomization results in this showcase. So this can also be used for even more in-depth fundamental studies, such as how atomization actually happens, what the atomization modes are, and how one can actually conceive of empirical models for this. So there are a lot of things that you can do in a complicated setup like this, which is high speed and uses a dual mode PDPA technique by measuring it across multiple sections, you know, and doing it at a very reasonable accuracy of 75 to 70 percent. So that is a great thing that we can get measurements under very harsh conditions, so to speak.

So, these are the empirical models that you see. So now that we have covered all these things, let's do a very quick run-through of interferometric particle imaging. So now that we know phase Doppler, we know LTV, we know scattering, and we know a lot of stuff, the interferometric particle imaging technique is something that will not be alien anymore. If you look at, again, go back to this particular picture where you have this particle or droplet, and then you have an illumination source, and then you have a receiver that monitors some scattering order. Now, if you look at this large particle or this particular drop, whatever it is, this is the first incident point of first-order refraction, and this is the first glare point of first-order refraction.

And this is basically the incident and the glare point of reflection. So, these are two different scattering modes. However, both of these will give rise to two glare points. So how about we monitor this, which is across two different scattering modes, remember, and try to get an idea of what the diameter of the problem will be. So the path from the incident wave to the detector is unique for each scattering mode.

**Incidence and Glare Points**

- The path from incident wave to detector is unique for each scattering mode
- Large particle images incident point onto detector through glare points
- Both points are unique for each scattering order/mode
- Both points lie in the scattering plane

The large particle images are the images incident at points onto the detector through the glare points. So both of these points are unique for each scattering order or scattering mode. And these are, assuming that these are coherent, okay? Both of them lie on the same scattering plane, so they are at the same scattering plane, but they are different scattering modes or different scattering orders, and they are coherent to begin with. You understand the difference. This is first-order refraction; this is reflection.

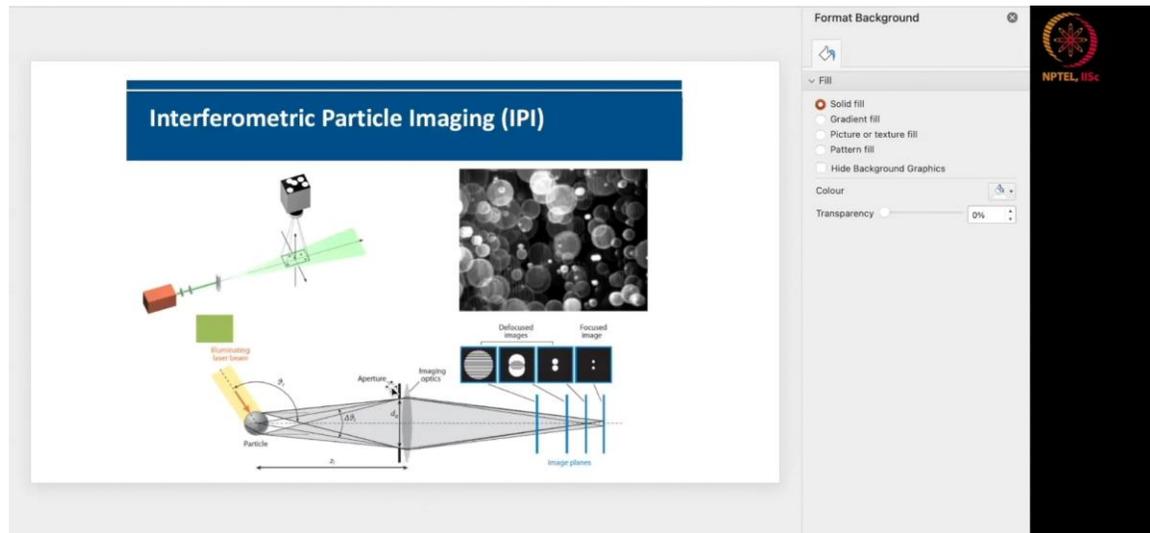
So they are two different scattering modes or orders, but they are coherent, and they lie on the same scattering plane. And when they are illuminated in a particular direction. And these paths are unique. And so you basically get two glare points from two different scattering modes.

How this can be used is the main purpose. So let's look at this, where we say that this is, for example, a laser. Now this has expanded into a sheet. So this is a laser that is expanded into a sheet, and then there is a particle. So this particle, what will happen if you look at it? This will be kind of the reflection, and this is the first order refraction. The lower part is the first-order refraction; the upper part is the first-order reflection.

So they will give rise to two glare points. Again, they are at the same scattering angle. Say that this is what we are monitoring it with. OK, so this is usually at 90 degrees. OK, so what happens is that you have an aperture, and then you have the lens. The aperture cuts off a part of the beam that skips the measurement region under check.

And then if you use imaging optics, normally you can focus them tightly and you will get these two very focused glare points. These glare points are nothing that comes from

this point and this point, again on the meridional plane, but they are from two different scattering orders. Remember, this is the point at which these two images are very tightly focused. Now, what you do is say that this is very hard. This is looking at one particular particle and focusing on it like that.



What you can do is move the plane either this way on the right-hand side or on the left-hand side intentionally, which is away from the focal plane. So it is no longer tightly focused. So, what do you expect? You expect the images to become blurry. Okay, as you move it more, the images start to interfere with each other; the two modes start to interfere with each other, and if you move it further, you will get full fringes because of the interference of the two scattering modes. So these are basically the defocused images, and these are basically the scattering.

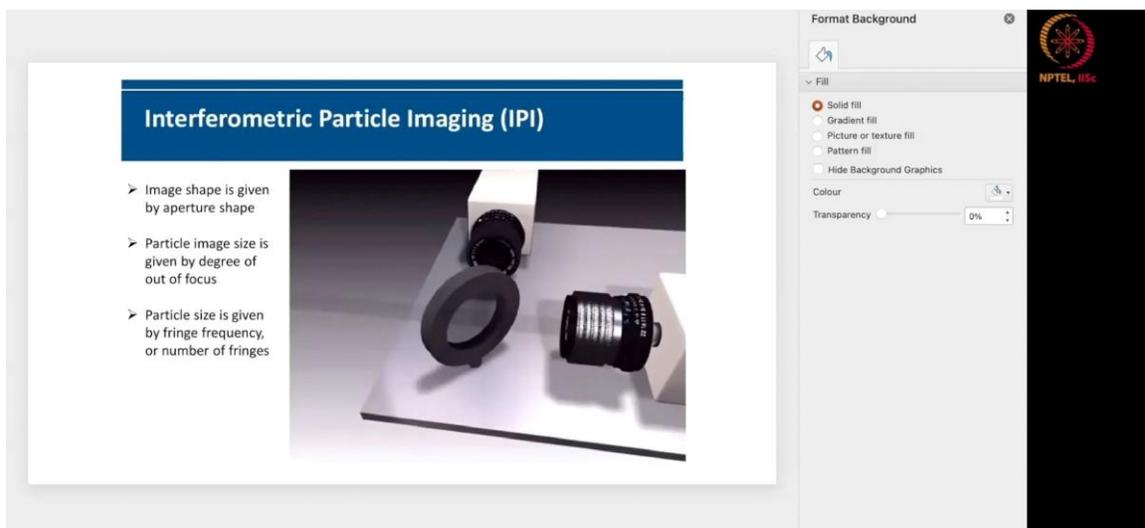
These are the fringe patterns that you form because of the interference of the two different modes. Now, if you now know the fringe spacing, okay, and if you can imagine that you can find out what the particle size will be because they are coming from two distinct glare points from each particle, correct? So what you see over here are all these things and the fringes, right? You see those fringes, right? So these round colored things that you see, or this round, basically, are not particle size. These have nothing to do with particles. This is basically an image of your lens.

If the lens is square, this will be a square object. So this has nothing to do with the particle or the droplet size; this particular profile, this particular image that you see, has nothing to do with it. What the information that is inside these spots, or inside these spots that you see over here, strewn all over, is the fringes. And these fringes, or the fringe

spacings, actually give you an idea of what the particle size is, or what the droplet size will be. In other words, here you're using a single laser.

A single laser is expanded into a beam. This beam actually forms a sheet, and then the particles are in that sheet, going in or out. As it happens, the particles or the droplets will actually have reflection and first-order refraction. Two glare points. You can focus the glare into two distinct points as well. And this will also enable you to measure the droplet size, by the way.

But intentionally, for the sake of comfort, you move them so that these two scattering orders start to interfere with each other. As a result, you get these fringe spacings or these fringes. And by looking at the distance between the fringes, you can extract the particle size. So, one thing you should remember is that these sizes, these spots that you see, are not the droplet sizes but what is contained inside them; the fringes are what give you the droplet sizes. All right, so this is basically called interferometric particle imaging, or IPI, so to say.



Okay, this was also done by Professor Tropa for Dantec Dynamics. So you can actually improve particle image recognition by using two detectors. One is in focus, and the other one is out of focus. So you can kind of locate the particles and then get their size.

That is also possible. to do by these kind of measurements. So this kind of acts as a starting point for where the particles are, because sometimes you may not be in a good position to see where all those particles are. So, the image shape is given by the aperture shape. That is the shape of the image that you see over here. That's the shape of the

aperture.

The particle image size is given by the degree of out-of-focus. The particle size is given by the fringe frequency and the number of fringes. So, once you know the fringes and the spacing between the fringes, you can calculate the particle size. So, this is very important. This is what IPI actually does.

Now you can go one level further and use high-speed cameras. So once you use high-speed cameras, the IPI technique can be combined with the PIV technique to provide both the size and velocity of droplets in an illuminated plane. So how does it do that? It captured the first image, then determined the defocused image sizes and positions. Then you capture the second image, determine the sizes and positions for the second illumination, and compare the two illuminations and the determination of the particle velocities. Since these days, everybody has got high-speed cameras. So the IPI technique can be routinely combined with high-speed cameras to also provide particle velocities as well as size information.

The image shows a presentation slide titled "Interferometric Particle Imaging (IPI)". The slide text reads: "Using high-speed cameras the IPI technique can be combined with the PIV technique for providing both size and velocity of droplets in an illuminated plane." Below the text is a photograph of droplets with colored circles overlaid on them. To the right of the photo is a list of steps:

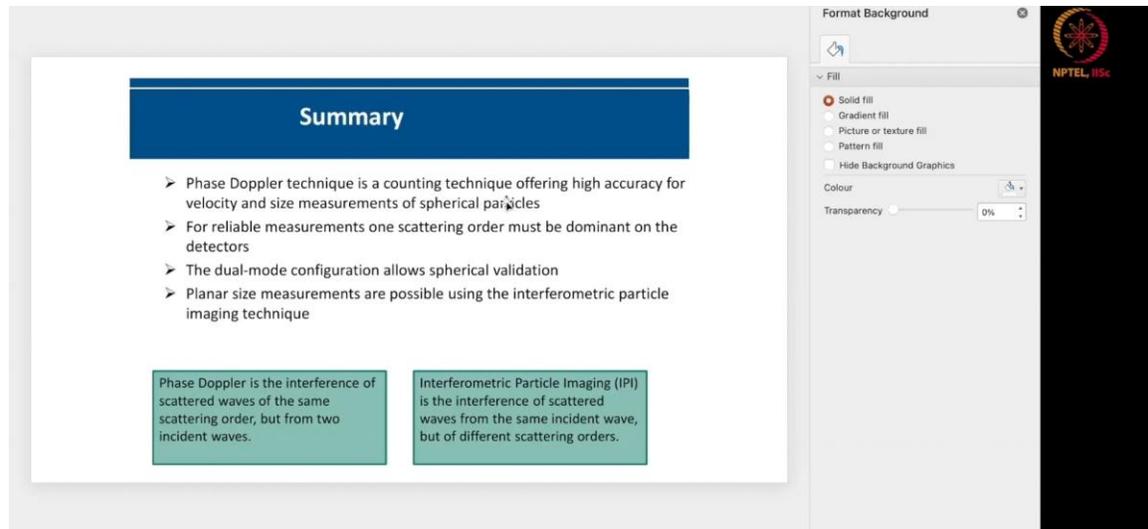
- Capture of first image
- Determination of defocused image sizes and positions
- Capture of second image
- Determination of sizes and positions for second illumination
- Comparison of the two illumination and determination of particle velocities

On the right side of the slide, there is a "Format Background" panel with a "Fill" section containing options: "Solid fill" (selected), "Gradient fill", "Picture or texture fill", "Pattern fill", and "Hide Background Graphics". Below this is a "Colour" field and a "Transparency" slider set to 0%.

Okay, so in this case, remember we are using only one laser, and the idea is to have them interfere with each other so that we know the fringe spacing and the fringe frequencies from which the particle sizes can be extracted. But in summary, The phase Doppler technique is the interference of scattered waves of the same scattering order. Remember, you are doing first-order refraction with first-order refraction, but this is the interference of scattered waves from two incident waves. There are two incident waves that are interfering. Okay, so two incident waves are being scattered by this particle, and those waves actually interfere, but they are of the same scattering order, which means that they

are coming from either first-order refraction or reflection or whatever.

Interferometric particle imaging is the interference of scattered waves from the same incident wave, not two, because you need only one laser. But they are of different scattering orders. That means you are observing the scattering order from refraction, first-order refraction with reflection, for example. It's not first-order refraction with first-order refraction.



The image shows a presentation slide with a 'Summary' section. The slide content is as follows:

### Summary

- Phase Doppler technique is a counting technique offering high accuracy for velocity and size measurements of spherical particles
- For reliable measurements one scattering order must be dominant on the detectors
- The dual-mode configuration allows spherical validation
- Planar size measurements are possible using the interferometric particle imaging technique

Phase Doppler is the interference of scattered waves of the same scattering order, but from two incident waves.

Interferometric Particle Imaging (IPI) is the interference of scattered waves from the same incident wave, but of different scattering orders.

The 'Format Background' panel on the right includes a 'Fill' section with options: Solid fill (selected), Gradient fill, Picture or texture fill, Pattern fill, and Hide Background Graphics. It also has 'Colour' and 'Transparency' (set to 0%) controls. An NPTEL logo is visible in the top right corner of the slide.

It is first-order refraction with reflection. So that is the difference between the two. In one case, you require two lasers, need to form a spot size, and stuff like that. But it is the same scattering order; it is coming from two different beams. But here it is coming from a single incident wave; however, it is of different scattering orders. This is done during simple imaging using a camera, and it can also use a laser sheet.

This is like a measurement volume, what we talked about, like the cigar-shaped measurement volume that we used routinely for LDV. The phase Doppler technique is a counting technique that offers high accuracy for velocity and size measurement of spherical particles. Sphericity determination is an important parameter that we talked about earlier. For reliable measurements, one scattering order must be dominant in the detectors. That's why you have to look at the scattering angles and the relative refractive index, determine which one you are going to use, and accordingly park your laser and receiving optics.

The dual mode configuration allows this spherical validation, which is a very important part because spherical validation is what we need for doing this kind of measurement.

Because you know, non-sphericity and non-spherical particles are routinely rejected. By using three detector assemblies, you could actually remove the two pi ambiguity. The planar size measurements, because they are on a sheet, are possible using the interferometric particle image technique just by counting the interference fringes and the spacing between them.

That is what IPI is all about. But the techniques are kind of similar in many ways; however, there are differences because both are interference-based techniques: both phase Doppler and interferometric particle imaging. All right? So there is a lot of literature that one can go through. There is a ton of literature on this. Feel free to look at all the literature and more. And this comes from Professor Tropy, as I said before the start of this lecture series, who is one of the pioneers of this PDA technique.

And these lecture notes are courtesy of him. So there are, of course, more details, more analysis, and more things that can be learned from these particular, you know, these particulars. In the particular mode of measurement we have covered just a few, and of course, we will try to give a lab demonstration of the same. But I think, more or less, you get an idea of how the techniques actually work and how it is tightly linked with the optics. So, the optics lectures were very useful, I would say, for both LDB as well as for PDPA. We also conducted this interferometric particle imaging, IPI, as we call it, by just twisting around with the measurements.

There are more twists that people have done. They can combine, mix and match the measurements, and then try to see if they can get more information out of it. But the PDPA lectures actually end over here. We'll try to see if a lab demonstration is possible, and we can look into the instrumentation side of things a little more. Thank you so much. Thank you.