

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

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**Week – 09**

**Lecture - 42**

**Laser Doppler Velocimetry – 1**

All right, so in today's lecture, we are starting to do something that is called laser Doppler velocimetry. Now, these lecture notes are courtesy of Professor Cameron Tropier, my long-term collaborator. And he's one of the pioneers of this particular technique, laser Doppler velocimetry. And so this particular talk heavily draws from his lecture notes in a workshop that he conducted at IIC. So let's do it and see that what we have for laser Doppler velocimetry. You know, flow visualization, and we will do several of them.

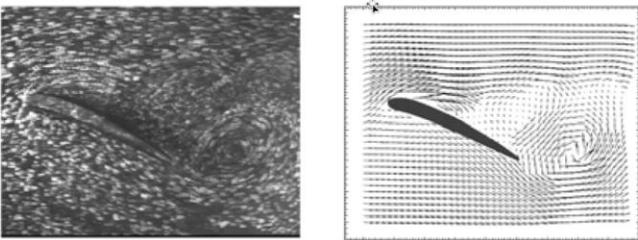
One is, of course, particle image velocimetry. So you can obtain tracer-based velocity measurements. That means you put something into the medium, and you start visualizing the flow field. So, in this case, for example, this is an aerofoil.

What we have done is, or what the experimentalists did, is put some tracer particles. It could be sawdust. It could be many things, anything. And basically, this follows the flow. And using scattering measurements, we are able to see how the streamlines look around this particular aerofoil, which is very important when we actually try to design aerofoils for, say, aeropropulsion or aerodynamics.

NPTEL, IISc

## Tracer Based Velocity Field Measurement

Qualitative Visualisation → Quantitative Measurement



Now, this is qualitative. So this roughly shows that, OK, there is a flow, and then there is, you know, a separation, and you get a vortex being shed over here. But you really do not know what the velocity is and what, for example, you know, derived quantities like vorticity are and stuff like that. So this can be done using, say, for example, PIV, where we actually try to determine what the velocity vectors would look like, what their magnitude will be, what their direction will be, and also derive quantities like, you know, here, as well as vorticity. So this is a tracer-based velocity measurement, extremely high throughput.

The image shows a presentation slide with a dark blue header and a white content area. The header contains the title "Methods of direct velocity measurement". Below the title, there are two sections: "Velocity" and "Vorticity". The "Velocity" section includes a definition of direct velocity measurement and the formula  $U_i = \frac{\Delta x_i}{\Delta t}$ , followed by the vector components  $U_1 = \frac{\Delta x_1}{\Delta t}; U_2 = \frac{\Delta x_2}{\Delta t}; U_3 = \frac{\Delta x_3}{\Delta t}$ . The "Vorticity" section includes a definition of vorticity measurement and the formula  $\omega_i = \epsilon_{ijk} \frac{\partial U_k}{\partial x_j}$ . The slide is presented in a software interface with a menu bar at the top and an NPTEL logo on the right.

And this is what we are going to cover in the PIV. So the method of measuring velocity basically comes in two flavors. One is a direct measurement of velocity. That means you know how much distance the tracer or any parcel of fluid actually covers in a particular amount of time,  $\Delta t$ . You basically resolve this displacement into the x, y, and z directions.

And then the  $i^{th}$  component of the velocity is nothing but the displacement in the  $i^{th}$  direction divided by the time interval that has elapsed. So this time interval could be very short, allowing you to essentially go to an instantaneous velocity calculation. It's almost like calculus for you, like  $dx/dt$ . In this way, you can calculate all components of the velocity. This  $U_1, U_2, U_3$  means  $x, y, z$ .

So it can be, this can be, and put it as  $u_x, u_y,$  and  $u_z$  as well. So this is more like calculus. Now, in order to measure, this is a direct velocity measurement, and sometimes it's doable. And then there is vorticity measurement. So this measures the rotation of a fluid parcel or particle.

And so, as it measures, you can see these are the cross derivatives. So this is the derivative of  $u_k$  with respect to the other coordinates. It's a variation of u with respect to x; if it's the x component of the velocity, it's a variation with respect to y and with respect to z.  $U_h$ , so in this case, of course, you need to know the slope; that means you need to know the change in velocity, uh, over very small distances because you can see this is a differential. So, this is a vorticity; this calculates the rotation of the fluid particle.

So, these are more direct measurements. So there are other things, too. So there are, you know, we will cover, for example, the hot wire anemometry part. But the initial measurements were all done with pitot tubes. This is something that is very well-known.

When we cover the hot wire anemometry, we'll cover a little bit on the pitot tube as well. But the hot wire anemometry was also an extremely potent measurement technique, and it is still used today. And a very, very good measurement technique as well. It can come in constant current as well as constant temperature. We will cover more of this in a separate lecture.

Then, of course, the invention of lasers, which is an acronym for light amplification by stimulated emission of radiation. So this changed the scenario quite a bit because now we could have these very coherent lights, which could be used for, you know, the measurements that we are going to show. So this led to the development of laser Doppler velocimetry in the 1960s, Ye and Cummins in 1964, and in the 1980s, the more field-based measurements, which are particle image velocimetry, came into the picture. Remember, laser Doppler velocimetry is still a point-based or a small volume-based measurement. Particle image velocimetry is more of a field measurement, the kind of field that you see over here.

This is like particle image velocimetry. So the comparison of the different techniques will be as follows: So for point measurement, you have a pitot tube, hot wire anemometry, and laser Doppler anemometry, or LDV. And the whole field, which is basically kind of measurements like this, you can also have PIV, then variations of PIV, which is tomographic PIV; tomography we already saw in the Shillerine, and then magnetic resonant velocimetry, which is also, I mean, for biological purposes, if you want to measure something in your heart, for example, that would be a good technique. to

**Comparison of various techniques**

Pitot tube, HWA, LDA  
 Pitot tube, HWA  
 LDA, PIV, MRV  
 PIV, Tomo, PIV, MRV

- LDA, PIV are non-intrusive, tracer based methods (Volume concentration of particles < 10<sup>-6</sup>)
  - LDA: Time (Frequenz) for a **known displacement**
  - PIV: Particle displacement for a **known time**

follow. So these are whole-field measurements.

Then, of course, there are intrusive measurements like pitot tubes and hot wire anemometry. These are intrusive in the sense that you are physically putting a probe into the measurement volume. And what it does is that sometimes the presence of this particular element, though it can be made very small, actually disturbs the flow field in a non-trivial fashion. And then there are non-intrusive point measurement techniques as well as field measurements; of course, this LDA PIV, because this uses lasers, is kind of considered to be non-intrusive. So, for both probe-based as well as field-based measurements.

The LDA-PIV is a non-intrusive tracer-based method. The volume concentration of the particles is less than a million parts per million. And so LDA is a time-shift type of measurement. We'll see that in a few minutes. In for a known displacement, you know the displacement; you measure the frequency shift, and that's how you get the velocity.

We will see how this is done. PIV is, however, done for the particle displacement for a known time, so you fix the time over which, or basically fix the  $\Delta t$  over which you want to measure, and then you calculate the particle displacement. and more in line with what you saw here. Of course, not this easy. So once you do that, you will receive the field measurement.

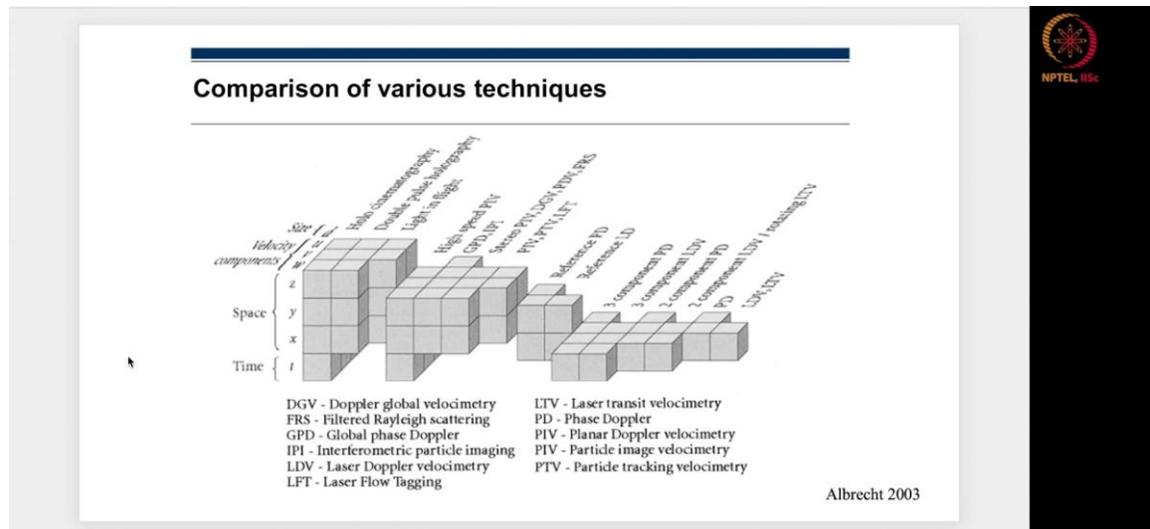
So it is like taking two pictures, and you know how much these particles have shifted between the two pictures, and you know the time duration that has elapsed between the capture of these two pictures. As a result, once you divide this  $\frac{\Delta x}{\Delta t}$ , you should get the velocity. Of course, it's easier said than done. LDA, on the other hand, when you fix the measurement volume in space, you have a fixed displacement, and you calculate the time,

or in this case, the frequency shift to know what the velocity of the particle is. So, in one case,  $\Delta t$  is fixed.

In the other case,  $\Delta x$  is fixed. So this is how these techniques actually work. So there are various comparisons regarding the kinds of resolutions that you can get. You have Doppler Global Velocimetry. You have filtered relay scattering.

You have global-phase Doppler velocimetry. You have interferometric particle imaging and LDV, of course, which we are going to cover here. Then laser flow tagging and laser transit velocity are used. Then phase Doppler, then planar Doppler velocimetry, then particle image velocimetry, and then particle tracking velocimetry. All these things happen in a spatiotemporal fashion.

As you can see, the field measurements will have the space and the time. The point measurements will have more resolution in time than in space. So each technique has got its own advantages and disadvantages, and it's also tailored for what you are actually trying to measure. So that is the part that is very important: what you are trying to measure and what kind of information you need. In one case, you can have a very high temporal resolution.



In the other case, you might have a very high spatial resolution. In some cases, you may need to see the field information. You need to see the entire flow field and how it evolves over time. In some cases, you can be interested in a particular location, and you might want to see what is going on in that particular location at a very high frequency. That means you measure the velocity at a very high fidelity.

All these things are possible, and depending on what you are trying to do, these things vary quite a bit. Okay, so there is no one silver bullet or any particular applications for the techniques. So in the case of tracer-based methods, the flow velocity is measured indirectly by measuring the velocity of the tracer particles or groups of particles. Okay, so in no case, for example, in the first, if you look at this slide once again, okay, these are tracer particles which we expect are following the flow field, but they are not exactly measuring the flow field per se. What it is doing is that it is measuring the velocity of the tracer, of the seeding particles or groups of particles, and it is not exactly measuring the flow, but the flow velocity we are inferring from the velocity of the tracers.

So the selection of these particles is basically then a compromise. You should first have two real situations: one is that the particles should follow the flow, which means this requires small particles. The particles that are density matched with the carrier fluid mean small particles, which have smaller inertia; as a result, when there is a sudden acceleration in the flow field, for example, these particles should be able to follow that flow field without much of a time delay. And the particles would scatter light well because unless they scatter, you cannot have sufficient measurement intensity. In that case, as we will see, the larger particles are obviously preferable, and we also need large differences in the refractive index between the particles and the fluid.

So these are the two caveats when we use any tracer-based methods. So when we do light scattering, the light scattering from small particles depends on a multitude of things. First is the relative refractive index, which means the particle to the medium. But if we call that  $m$ , it is the ratio of  $n_p$  to  $n_f$ , where  $n_p$  is a particle and  $n_f$  is the fluid. So it's a ratio; it's a relative refractive index.

## Tracer based methods

- The flow velocity is measured indirectly, by measuring the velocity of tracer/seeding particles or groups of particles
- The selection of particles is a **compromise** between two requirements:
  1. Particles should follow the flow
    - This requires **small** particles or
    - The particle **density is matched** to the carrier flow
  2. Particles should scatter light well
    - **Large** particles are preferable or
    - Large differences in **refractive indices**  $n_p$  and  $n_f$

It depends on the particle size that we just discussed. We will see when we do a little bit of optics. That means the particle size is given as  $d$ . The particle form, shape, and orientation are also important. And the light polarization and observation directions are also important.

So the scattered intensity can be increased because we want more of it. By choosing suitable particles and increasing the laser intensity. Otherwise, if you increase the source intensity and crank it up, obviously the scattered intensity is also going to go up. And we also choose suitable particles for the job. So these are all prerequisite measurements when you are dealing with tracer particles in the flow.

It sounds very, you know, when you are trying to get quantitative information out of these things, that matters a lot. So for spherical particles with a diameter larger than the wavelength of light, which means  $d_p$  is greater than  $\lambda$ , the Lorentz mean scattering is applicable. This is one of the exact solutions of Maxwell's equations. So for spherical particles with a diameter that is larger than the wavelength of light.



## Light Scattering

The light scattering from small particles depends on:

- The relative refractive index (particle to medium),  $m = n_p / n_f$
- The particle size (diameter)  $d_p$
- Particle form/shape and orientation
- Light polarization and observation direction

The scattered intensity can be increased by:

- Choosing suitable particles
- Increasing the laser intensity

For spherical particles with a diameter larger than the wavelength of light,  $d_p > \lambda$ , Lorenz-Mie scattering is applicable (exact solution of the Maxwell equations)

All right. So... So let's look at it this way. So these are all plotted in polar coordinates. And these are particles of different sizes. And then there is an incident beam with a particular wavelength. Now, if the particle is roughly about, say, 20% of the wavelength of the beam, it will scatter light in this kind of fashion, where the direction of illumination is from this direction.

So this is how it will be scattered. If the particle size is the same as the wavelength, this is the scattering diagram that you will see. These are all plotted on a logarithmic scale. And when the particle is about 10 times higher than the wavelength, for example, a laser wavelength of 532 nanometers. So, this will be around 532.

This will be 532 divided by 10. which means it is in the nanometer range, so it goes into the micron range of five microns. This is of the order of half a micron. And this is basically very small. It's about 20% of the wavelength of the laser, roughly one-fifth. So, this is the polar diagram of the scattered intensity as a function of the scattering angle.

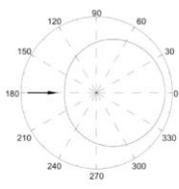
So these are the different scattering angles. Okay, this is the zero scattering angle; you can see this is the most, and these are, of course, zero and then 90 degrees. So these are the angles at which you can observe. Okay, this intensity is shown on a logarithmic scale, so this is how things get scattered in the Lorenz-Mie theory. So what happens is that when the particle size is greater than  $\lambda$ , it means the droplet diameter or the particle or the tracer diameter is larger than the wavelength; for example, 532 nanometers. So you can see that this is the light scattered by about one micron oil particle in air.

So you can see that 180 degrees scattering is like this and zero degrees. So the light is

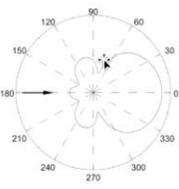
coming in this direction. This is basically your oil particle or oil droplet in the air. So the laser wavelength is about 532 nanometers, which is the most commonly used NDAG laser that you have. So, in the logarithmic scale, the neighboring lobes differ by factors that are more than 100.



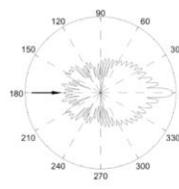
### Seeding: Scattered intensity



$d_p \approx 0.2\lambda$



$d_p \approx 1.0\lambda$

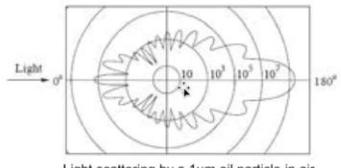


$d_p \approx 10\lambda$

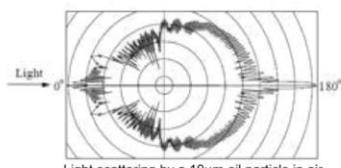
- Polar diagram of scattered intensity as a function of scattering angle
- The intensity is shown with a logarithmic scale.



### Lorenz-Mie Theory



Light scattering by a 1μm oil particle in air.



Light scattering by a 10μm oil particle in air.

- $d_p > \lambda$ : Lorenz-Mie- theory
- polare representation of scattered light intensity
- Laser wavelength  $\lambda=532\text{nm}$
- Logarithmic scale, neighboring lobes differ by factors of  $> 100(!)$
- Lorenz-Mie theory works with the dimensionless particle size,  $x_M = \pi d_p / \lambda$ , known as the Mie parameter
- If  $x_M$  is larger, then the scattered intensity ratio forward-to-backscatter, also increases
- Mean scattered intensity scales with  $\sim x_M^2$

So the neighboring lobes differ quite a bit. So the Lorenz-Meis theory works with dimensionless particle size, which is given as  $X_M = \frac{\pi d_p}{\lambda}$ , known as the Mie parameter. This is the "Mie" parameter. So this is nothing but  $\pi d_p$ , which is one way of saying it is the circumference, or the perimeter. Of the particle divided by  $\lambda$ , now if  $X_M$  is large, then

the scattered intensity ratio of forward to backscatter also increases, as you can see. Okay, and the mean scattered intensity scales with  $X_M$  squared.

Okay, so as you can see over here, this is the light scattering by a 10-micrometer oil particle. So you understand this: if we have a non-dimensional number, and if  $d_p$  is much larger than  $\lambda$ , that means, you know,  $X_M$  is also large, then the scattered intensity from forward to backward scatter also increases. Okay, forward to backward scatter also increases. And the mean scattered intensity scales as the square of this particular parameter.

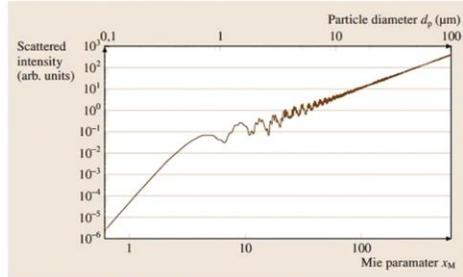
So this is the Lorenz-Mie theory in a nutshell. So in the Lorenz-Mie theory, if you look at it, this is the scattered intensity in arbitrary units, and this is the Mie parameter, which is  $X_M$ , the one that we defined over here; nothing but the perimeter divided by the wavelength of the incoming laser. You can see that this is the scattered intensity. And on top of this, you have the particle diameter, for example. As you can see, the scattered intensity is a function of the me parameter, okay, for a water droplet in air where, you know, this  $\lambda$  of the laser or the light is about 500 and at a scattering angle of 30 degrees.

So the 30-degree angle is the scattering angle. So all the scattering angles are given here. Okay, so you can see how the intensities actually change. So for a large particle size or a large me parameter or  $X_M$ , you have a very high scattered intensity that falls off pretty rapidly as you go down to smaller and smaller particle sizes, which also leads to a smaller E parameter because there's just that  $\lambda$ ; just that  $\pi$  and  $\lambda$ ,  $\pi/\lambda$  is the factor that multiplied over here. We can see that there is quite a bit of, you know, in a logarithmic scale; you can see that it goes like this, and then it kind of tapers off very fast. And from here to here, we have about six or five orders of change, you know, from a droplet particle diameter of 0.

1 micron all the way up to, say, 10 microns; we have a drop of almost 10 to the power of six. For  $10^5$ , you know, in the scattered intensity, so this is the kind of thing that we are talking about. All right, so this is, for example, German, so it is light scattering, as you can understand. So this is scattered light from a one-micron glass bead in water.

Okay, this is scattered light from a 10-micron glass bead in water. And this is the scattered beam from a 30-micron glass beam in water. So you can see how this works, and also remember the statement that when  $X_M$  is larger than the scattered intensity ratio, the forward to backward scatter also increases. And this is exactly what you see over here. OK, so this is not trivial. So you go down in the caveat is that you need to decrease your particle size if you want the particles to follow the flow.

## Lorenz-Mie Theory



**Fig. 5.62** Scattering intensity as a function of the Mie parameter  $x_M$  computed for a water droplet in air ( $m = 1.333$ ,  $\lambda_w = 514.5$  nm) at a scattering angle of  $\theta_s = 30^\circ$  and a circular receiver aperture of radius 10 mm (after *Albrecht et al.* [5.356])

But it also comes with the caveat that, you know, your scattered intensity drops pretty rapidly as well. So you have to operate in a region where there's an optimization. That means you have an optimal. Scattered intensity of light, and at the same time, you have a sufficiently small particle diameter or tracer diameter that can follow the flow field without any lag. Because if there is a lag, then you are unable to measure the flow field properly.

That means the tracer velocities that you are going to measure are not going to be representative of the flow field in any way. So this curve therefore becomes very important in determining how much loss you have when you go from 0.1 to 10; this is like a two-order change in the particle diameter, which leads to almost  $10^5$ , or actually more than that, a  $10^5$  plus change in the lighting, or there is a decrease when going down

to smaller and smaller particle sizes for a particular laser beam. And on a relative basis. So if you see that these are the different seeding particles for gas flows, we have titanium oxide and titanium dioxide.



### Seeding particles for gas flows

**Table 3. Seeding particles in gas flows.**

Material	$d_p$ ( $\mu\text{m}$ )	Laser	Pulse energy, pulse time	Light sheet		Reference
				w (mm)	t (mm)	
TiO <sub>2</sub> ( $m = 2.6$ , $\rho = 3500 \text{ kg m}^{-3}$ )	<1	Nd:YAG	10 mJ, 20 ns	15	0.3	Reuss <i>et al</i> (1989)
TiO <sub>2</sub> , ZrO <sub>2</sub>	0.7–1	Nd:YAG	110 mJ, 12 ns			Paone <i>et al</i> (1996)
Al <sub>2</sub> O <sub>3</sub> ( $m = 1.76$ , $\rho = 3970 \text{ kg m}^{-3}$ )	0.3	Nd:YAG	400 mJ		0.2	Muniz <i>et al</i> (1996)
	3	Nd:YAG	9 mJ, 6 ns			Anderson <i>et al</i> (1996)
	0.8	Ruby	20 ns	150	$\approx 1$	Krothapalli <i>et al</i> (1996)
Polycrystalline	30	Nd:YAG	135 mJ, 6 ns			Grant <i>et al</i> (1994)
Glass	30	Ruby	30 mJ, 30 ns			Schmidt and Löffler (1993)
Oil smoke	$\approx 1$	Ruby	5 J			Stewart <i>et al</i> (1996)
Corn oil	$\approx 2$	Nd:YAG	100 mJ			Jakobsen <i>et al</i> (1994)
Oil	1–2	Nd:YAG	120 mJ		0.4	Westerweel <i>et al</i> (1993)
Olive oil ( $m = 1.47$ , $\rho = 970 \text{ kg m}^{-3}$ )	1.06	Nd:YAG	70 mJ, 16 ns	200	0.5	Höcker and Kompenhans (1991) Fischer (1994) Raffel <i>et al</i> (1996)
DEHS	0.2 $\mu\text{m}$					
water	4–5 $\mu\text{m}$					

Melling (1997), *Meas. Sci. Technol.*

The  $d_p$  is less than one. You use an NDAG laser, which is roughly 10 millijoules with a 20-nanosecond pulse width. And these are the different light sheets that we make. So oil



### Seeding particles in gas flows

Material	$d_p$ ( $\mu\text{m}$ )	Laser	CW power or energy, time	Light sheet		Reference
				w (mm)	t (mm)	
TiO <sub>2</sub>	3	Nd:YAG				Longmire and Alahyari (1994)
Al <sub>2</sub> O <sub>3</sub>	9.5	Ruby	2 J, 30 ns	100	0.8	Liu <i>et al</i> (1991)
Conifer pollen ( $\rho = 1000 \text{ kg m}^{-3}$ )	50–60	Ar ion	1–2 W			Westergaard <i>et al</i> (1993) McCluskey <i>et al</i> (1995)
Polymer ( $\rho = 1030 \text{ kg m}^{-3}$ )	30	Ar ion	0.5–5 W		0.5	Gallagher and McEwan (1996)
Phosphorescent polymer	80	Ar ion	5 W		1	Draad and Westerweel (1996) McCluskey <i>et al</i> (1996)
Fluorescent	50	Nd:YAG				Hart (1996)
	20	Cu vapour	45 W		1	Roth <i>et al</i> (1995)
Polystyrene ( $\rho = 1050 \text{ kg m}^{-3}$ )	500					Khoo <i>et al</i> (1992)
Thermoplastic ( $\rho = 1020 \text{ kg m}^{-3}$ )	15	Ruby	25 mJ, 20 ns			Zhang <i>et al</i> (1996)
	6	Nd:YAG		50	2	Hassan <i>et al</i> (1994)
Reflective ( $\rho = 1010 \text{ kg m}^{-3}$ )	60	Ar ion	18 W			Grant <i>et al</i> (1992)
	30	Ar ion	12–18 W	200		Grant and Wang (1994)
Metallic coated	4	Ar ion	2 W		2	Magness <i>et al</i> (1993)
	14	Ar ion			1	Johari <i>et al</i> (1996)
Microspheres ( $\rho = 700 \text{ kg m}^{-3}$ )	<30	Ar ion				Graham and Soria (1994)
H <sub>2</sub> bubbles		Ar ion	1 W		0.3	Dieter <i>et al</i> (1994)

smoke, for example, has about one. This is what people normally use. In very crude applications, you use a Ruby laser, which has a five millijoule pulse.

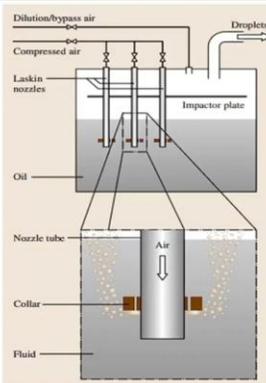
So you can see that this is quite high. And then you actually have corn oil which is about one to two microns. And then, olive oil is also very regularly used in flow measurements. Titanium dioxide is usually used for measurements in combustion applications, for example, because oil will vaporize. DHS is also something that is routinely used in many measurement techniques and in water droplets as well.



## Seeding Generator: Laskin Nozzle

The Seeding-Generator works by feeding air into a fluid through a series of Laskin nozzles at almost sonic speeds. Each nozzle produces micro-bubbles (ca. 1  $\mu\text{m}$ ). These bubbles reach the liquid surface, where they collapse, creating micro-droplets. An impact plate is used to filter out the large droplets. The number density can be varied with the air flow rate or the number of nozzles.

Schematic representation of a Laskin nozzle used to generate seeding particles, e.g. olive oil in an air flow)



So it depends on what kind of application we are actually looking at. So this is more on you: you can also use things like microspheres, hydrogen bubbles, polystyrene, and even fluorescent particles routinely used, for example, in a variation called micro-PIV; you can use phosphorescent polymer dye—lots of things—and these are the corresponding laser types that are routinely used. References where you can find more information about these applications. And particular attention is given to the droplet sizes. The particle sizes are more or less in the micron range, specifically in the tens of microns, in most applications when you seed the flow. All right, so these are, for example, the glass particles using liquid flows, as you can see.

So these are the magnification and the different magnifications. You can see how this flows and how these glass particles look. So the choice of your tracer particles, keeping this in mind, as well as just going to this, should ensure that the particle follows the flow. These two parts are the most important parts when you go for this kind of measurement. How you do this is basically you can also use, you know, seeding generators.

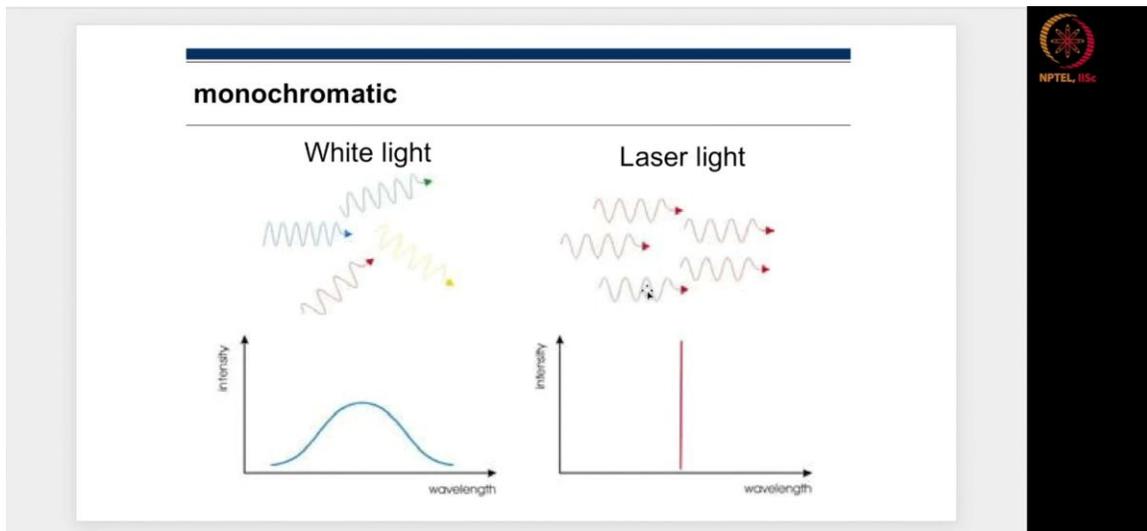
So one such thing is called a Laskin nozzle. So the Laskin nozzle works by feeding air into a fluid through a series of Laskin nozzles at nearly sonic speeds. So each nozzle produces these microbubbles, about one micron. These bubbles reach the liquid surface, collapse, and create what we call micro droplets. And these microdroplets collapse on the surface and create more microdroplets.

An impact plate is used to filter out the large ones. The number density can be matched. And these microdroplets are then actually fed into the main flow. So these are usually olive oil in an airflow, which is very commonly used. In every research work that we do,

we use olive oil a lot. So the Laskin nozzle is a very commonly used technique for generating these micro droplets, which are used for seeding the flow field.

Just a little thing about the laser. So the laser is, as we can see, of paramount importance when you do all these kinds of measurements, either PIV or LDV. So this is light amplification by stimulated emission of radiation. So this is actually an inversion problem. So how does it differ from normal white light? It has coherence.

It is polarization, and it's monochromatic. It's highly focused, high intensity, and we can do extremely short pulse lengths in time, which is essential for measuring high-speed flows; for example, there you need really small pulse widths because you need a stroboscopic type of effect. In order to achieve that effect, your pulse width for the laser during the time the laser is active has to be very small. So this is what monochromatic white light actually looks like. It has all kinds of wavelengths.

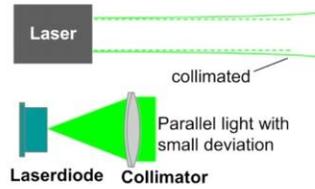


You know, the intensity is typically distributed in a manner like this. Then you have the laser light where all of them are kind of, you know, face-matched. And you have an intensity that is across a particular wavelength. So it is very narrow. Though it seems like a line, it has a little bit of width, mainly because of many non-radiative decay processes.

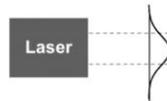


## Demands on light source for LDV

- monochromatic
- Spatial and temporal coherence
- Linearly polarized
- Well focussed



Lasers exhibit a Gaussian intensity profile across the beam



But compared to white light, this is very sharp. This allows us to focus the laser, send it over long distances, and perform a lot of manipulation. The demands on the light source for LDV laser Doppler velocimetry are that it needs to be monochromatic, it needs to have spatial and temporal coherence, it should be linearly polarized, and it should be well focused. So this is what a collimated beam of light actually looks like. Okay, this is actual light; this is the desired profile, and so you know.

This is parallel light with a very small deviation. And the lasers also exhibit something that is called a Gaussian intensity of the beam. So this is how the intensity actually varies across the beam diameter and across the beam cross-section. So these things have to be kept in mind. So the demand for the LTV is very simple. It needs to have that monochromatic light, a single wavelength, and then the spatially and temporally coherent light should have, you know, this collimated profile that should have very small deviations with respect to each other. So in the next class, we will cover more on this.