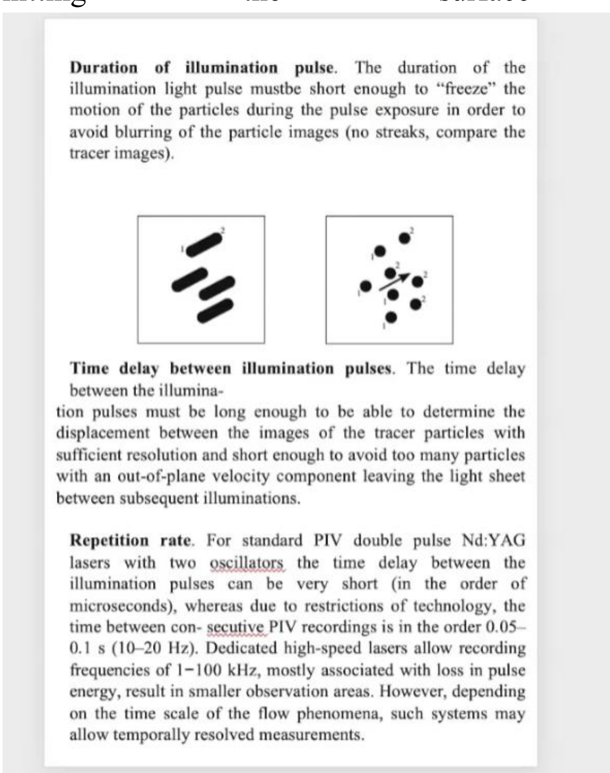
Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
Prof. Saptarshi Basu
Department of Mechanical Engineering
Indian Institute of Science, Bengaluru
Week – 07
Lecture - 32
Particle Image Velocimetry – 2

All right. We already talked about the duration of the illumination pulse. We talked about that the illumination duration of the pulse should be short enough to freeze the motion of the particle during the pulse exposure in order to avoid blurring of the particle images, that is no streaks. We also said that the time delay is important because otherwise if the time delay is too µch, then the particles may either go out of the measurement window if there is out of plane component it might go out of the plane and but if it is too short then the particles may not actually move so all these things are important and you know the rep rate of the lasers is also important So, other points are that, you know, the objects within the flow. So, for example, the glare may be present in the vicinity of the objects within the flow. such as wind tunnel models, due to the reflections of the light hitting the surface of the model.

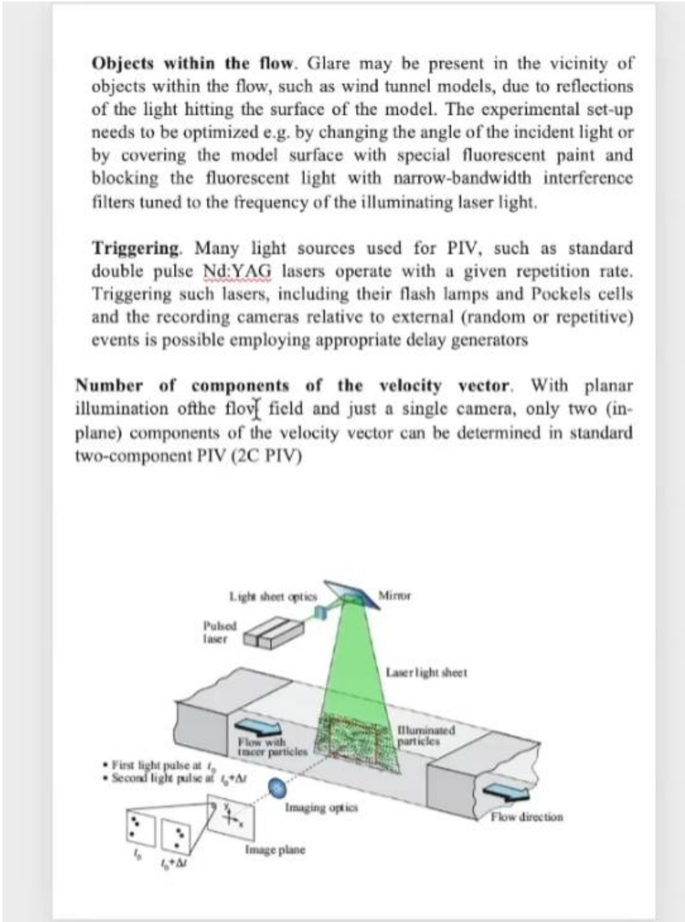


Duration of illumination pulse. The duration of the illumination light pulse mustbe short enough to "freeze" the motion of the particles during the pulse exposure in order to avoid blurring of the particle images (no streaks, compare the tracer images).

Time delay between illumination pulses. The time delay between the illumina-
tion pulses must be long enough to be able to determine the displacement between the images of the tracer particles with sufficient resolution and short enough to avoid too many particles with an out-of-plane velocity component leaving the light sheet between subsequent illuminations.

Repetition rate. For standard PIV double pulse Nd:YAG lasers with two oscillators the time delay between the illumination pulses can be very short (in the order of microseconds), whereas due to restrictions of technology, the time between con- secutive PIV recordings is in the order 0.05–0.1 s (10–20 Hz). Dedicated high-speed lasers allow recording frequencies of 1−100 kHz, mostly associated with loss in pulse energy, result in smaller observation areas. However, depending on the time scale of the flow phenomena, such systems may allow temporally resolved measurements.

So therefore, this acts as glare points. This is due to reflection. And this experimental setup needs to be optimized by changing the angle of the incident light or by covering the model surface with paints. Sometimes special fluorescent paint are applied and blocking this fluorescent light with narrow bandwidth interference filter.



Objects within the flow. Glare may be present in the vicinity of objects within the flow, such as wind tunnel models, due to reflections of the light hitting the surface of the model. The experimental set-up needs to be optimized e.g. by changing the angle of the incident light or by covering the model surface with special fluorescent paint and blocking the fluorescent light with narrow-bandwidth interference filters tuned to the frequency of the illuminating laser light.

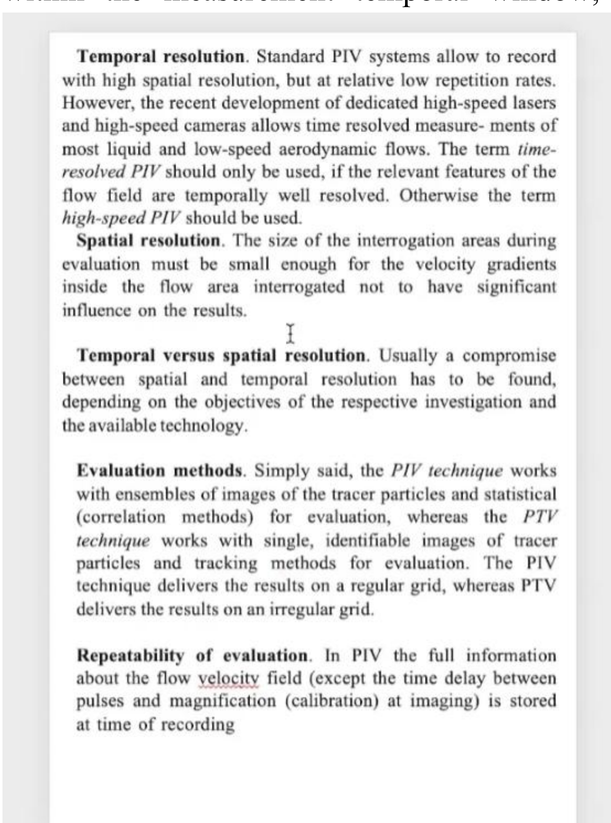
Triggering. Many light sources used for PIV, such as standard double pulse Nd:YAG lasers operate with a given repetition rate. Triggering such lasers, including their flash lamps and Pockels cells and the recording cameras relative to external (random or repetitive) events is possible employing appropriate delay generators

Number of components of the velocity vector. With planar illumination ofthe flow field and just a single camera, only two (in-plane) components of the velocity vector can be determined in standard two-component PIV (2C PIV)

We already know what those filters are. So these filters are placed, tuned to the frequency of the illuminating light. So therefore you capture only, you know, the light which has got the same frequency. When you coat it with a fluorescent paint, the emission signature will be at a different frequency or a different wavelength. Therefore, you are neglecting it.

But if there is a glare point present, it will have the same frequency as the scattering. As a result of that, it can create problem. So therefore, you coat it with fluorescence so that the emission, whichever light falls on that particular object which is painted, with a fluorescence paint that will now have a different emission wavelength as a result of that if you use a narrow bandpass filter you should be able to get only the collect only the laser light which now should be coming from the tracer particles Now, triggering, many light sources used for PIV, such as standard double pulse NDAG lasers, operate with a given repetition rate. Now, the triggering such lasers, including their flash lamps and POCAL cells, and, you know, the recording cameras, these are usually done by delay generators or customized, you know, timing units, which is programmable timing units, as they call it. So this can be kind of tuned to the nanosecond so that everything is kind of in sync because you want the laser light to come and the camera should also open at the same time.

So everything needs to be synchronized like that. so the number of components of the velocity vector if it's a planar illumination you can only get two in plane components you cannot get the out of plane components for that you need a second camera which gives you the stereo vision like your eye it should give you that the third component is possible all right So the temporal resolutions, so the standard PIV systems allows you to record with high spatial resolutions, but at relative low repetition rates, right? However, if you now look at the high speed lasers and high speed cameras, which allows time resolved measurements in most liquid and aerodynamic flows, The time resolved PIV should be used. But however, if it cannot resolve a flow field, which is very high speed, we can say high speed PIV. Time resolved means you are resolving all aspects of the flow field. Whereas high-speed PIV means you are probably resolving some aspects which are within the measurement temporal window, but you are not resolving everything.



Temporal resolution. Standard PIV systems allow to record with high spatial resolution, but at relative low repetition rates. However, the recent development of dedicated high-speed lasers and high-speed cameras allows time resolved measure- ments of most liquid and low-speed aerodynamic flows. The term *time-resolved PIV* should only be used, if the relevant features of the flow field are temporally well resolved. Otherwise the term *high-speed PIV* should be used.

Spatial resolution. The size of the interrogation areas during evaluation must be small enough for the velocity gradients inside the flow area interrogated not to have significant influence on the results.

Temporal versus spatial resolution. Usually a compromise between spatial and temporal resolution has to be found, depending on the objectives of the respective investigation and the available technology.

Evaluation methods. Simply said, the *PIV technique* works with ensembles of images of the tracer particles and statistical (correlation methods) for evaluation, whereas the *PTV technique* works with single, identifiable images of tracer particles and tracking methods for evaluation. The PIV technique delivers the results on a regular grid, whereas PTV delivers the results on an irregular grid.

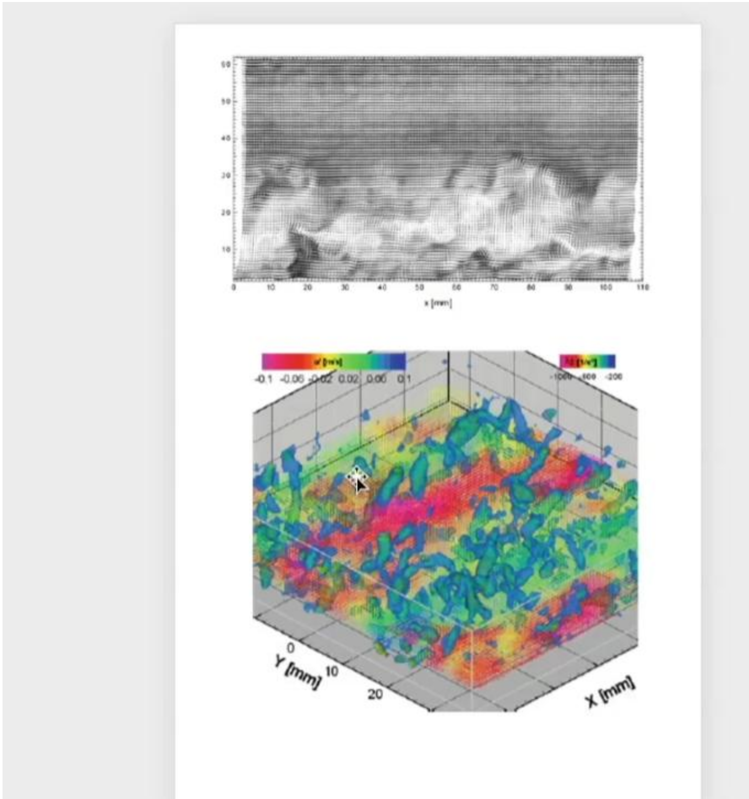
Repeatability of evaluation. In PIV the full information about the flow velocity field (except the time delay between pulses and magnification (calibration) at imaging) is stored at time of recording

It's like the turbulence, right? So you can resolve some and you are not resolving the others. But fully resolved means you are resolving all scales, right? So then comes the spatial resolution, which is basically the size of the interrogation areas during evaluation µst be small enough. for the velocity gradients interrogated not to have significant influence on the results. So it cannot be very large so that within the measurement window itself the velocity gradient is so sharp that within the measurement window itself there is a variation in velocity. Remember within that interrogation windows we are not assuming that there is a spatial gradient of velocity that is present.

So we have to make in those cases the window sizes really small, the interrogation window sizes really small for you to be able to resolve the flow field. So in the areas of strong velocity gradients like you would do in your CFD, you reduce the cell size, here also you have to do the same thing. Alright? Okay? Now, you also have this temporal versus spatial resolution. So this is usually a compromise between a spatial and the temporal resolution, depending on the objectives of your measurement. So as evaluation methods, when you go to evaluation methods, we already said that the PIV technique works on ensembles of images of the tracer particles.

and statistical correlations of the correlation methods for evaluation, whereas in the case of PTV, which is particle tracking velocimetry, it works with single identifiable images of the tracer particles and tracking methods. The PIV technique delivers results on a regular grid, whereas PTV delivers results on an irregular grid. You also need to be careful about the repeatability of the evaluation. So in PIV, the full information about the flow field is stored at the time of recording. And then you can post-process it in whatever ways you want.

So these are some of the examples. This is a highly three-dimensional flow field. And these are the flow fields. These are very complex flow fields that the PIV is able to resolve. So this is the power of particle image velocimetry.



Look at the types of velocity information and vorticity information that you can get. Now that we have done this, let us take a look at the tracer particles. We already said that it is the backbone of PIV measurement, right? The measurement technique is indirect. We already said that the velocity of the tracer particles is instead of the velocity of the fluid. Therefore, the interaction of the particles and the surrounding fluid has to be examined because we are talking about how the particles actually follow the flow field.

Therefore, the optical properties of the seeding particles also play an equally important role in the selection of suitable tracers. So let's look at the fluid mechanical properties first. The primary source of error is the influence of gravitational force on the velocity of the tracer particles because they are particles. They have some weight. As a result of that, there is a gravitational pull, and the particles may actually settle.

Physical and Technical Background

Tracer Particles

The measurement technique is indirect as it determines the velocity of tracer particles instead of the velocity of the fluid. Therefore, the interaction of the particles and the surrounding fluid has to be examined Therefore, the optical properties of the seeding particles play an equally important role for the selection of suitable tracers.

Fluid Mechanical Properties

A primary source of error is the influence of gravitational forces on the velocity of the tracer particles, if the densities of the fluid ρ and the tracer particles ρ_p do not match. Even though it can be neglected in many practical situations, we will derive the gravitationally induced velocity $\mathbf{U}_g$ from Stokes' drag law to introduce the particle's behavior under acceleration. Therefore, we assume spherical particles in a viscous fluid at a very low Reynolds number. This yields:

$$\mathbf{U}_g = d_p^2 \frac{(\rho_p - \rho)}{18\mu} \mathbf{g}$$

where g is the acceleration due to gravity, μ the dynamic viscosity of the fluid and d_p is the diameter of the particle. The equation implies that sedimentation of particles

Sedimentation can be avoided if the density of the fluid and particles is identical (neutral buoyancy). The latter is easily achieved in liquid flows.
In gas flows, the density of the particles is typically much higher than that of the fluid. Therefore, the particle diameter must be chosen sufficiently small in order to minimize the settling velocity

So if the densities of the fluid and the tracer particles do not match, say the density of the fluid is ρ and the tracer particle density is ρ_p, obviously they do not match in most cases, or ρ_p rather. Even though it can be neglected in many practical situations, we will now try to explain what happens when you have a gravitationally induced velocity that comes from Stokes' drag law. To introduce the particle's behavior under acceleration. So let's assume that there are spherical particles in a viscous fluid at a very low Reynolds number. So g is the acceleration due to gravity, μ is the dynamic viscosity of the fluid, dp is the diameter of the particle, and the equation implies that there is a tendency for sedimentation.

So ug is the gravitationally induced velocity. So this sedimentation can be avoided if the densities of the fluid and the particles are identical. So if this particular term goes to zero, which I ρ_p - ρ, then this u_g, which is the gravitationally induced velocity, would also be equal to zero, correct? In another way, these types of particles, which are identical in density to the fluid, are called neutrally buoyant particles. And this is easily achieved in the case of liquid flow. You can have particles that have the same type of density as the fluid medium.

In the gas flows, however, this density difference is typically much higher than that of the fluid because it is air and the particle is some kind of liquid or another particle. So air is one; the other particle may have a density closer to a thousand. So this becomes like a thousand. Therefore, the particle diameter must be made very small. To minimize the settling velocity because you see the other term here is dp squared.

So if you reduce the diameter by half, the settling velocity goes down to one fourth. So it's a square dependence, right? So if you decrease the particle diameter, you can achieve the same effect as reducing the density. So there are basically two players here: the difference in density and the diameter of the particle. Now this is the interesting part: in this case, if you are an experimentalist, what are you going to do? In the case of liquids, you can have the liberty of choosing larger particles, but in the case of gases, you have to make this very small to account for the thousand-fold increase because air is normally one. Particle densities are normally of the order of thousands, even if you use a liquid or a solid particle, right? So you need to reduce this by quite a bit to achieve the same; you know, minimize the settling velocity, so to say, right? So, with this, we can also derive an estimate for the velocity lag of a particle when it is continuously accelerating in a fluid, okay? So let up and u denote the particle and the surrounding fluid velocity.

ρ_p is the particle density. In case of sudden deceleration, the step response typically follows an exponential law. And if the density of the particle is much greater than the fluid density, then this is the expression that you actually obtain. So, in other words, what you can see is that the U.

We can derive an estimate for the velocity lag $\mathbf{U}_s$ of a particle in a continuously accelerating fluid:

$$\mathbf{U}_s = \mathbf{U}_p - \mathbf{U} = d_p^2 \frac{(\rho_p - \rho)}{18\mu} \mathbf{a}$$

where $\mathbf{U}_p$ and $\mathbf{U}$ denote the particle and surrounding fluid velocity respectively, where ρ_p is the particle density. In case of a sudden deceleration the step response of $\mathbf{U}_p$ typically follows an exponential law. If the density of the particle is much greater than the fluid density:

$$\mathbf{U}_p(t) = \mathbf{U}\left[1 - \exp\left(-\frac{t}{\tau_s}\right)\right]$$

vith the response time τ_p given by:

$$\tau_p = d_p^2 \frac{\rho_p}{18\mu}.$$

- If the fluid acceleration is not constant or Stokes drag does not apply (e.g. for larger particles or at higher flow velocities), the solution is no longer a simple expo- nential decay of the particle velocity.
- Nevertheless, τ_p remains a convenient measure for the tendency of particles to attain velocity equilibrium with the fluid.
- Knowing the response time of a particle tracer is not sufficient to determine if it will follow the flow with enough fidelity. For this purpose the particle Stokes number

$$\mathrm{Stk} = \frac{\tau_p}{\tau_f}$$

where τ_f stands for the characteristic time scale in the flow. The latter refers to velocity fluctuations along the particle trajectory. **A value of the Stokes number below 10^{-1} yields an acceptable flow tracing accuracy**

S. is the deficit; it is the velocity deficit. So U is the actual velocity, and U_p is the particle velocity. So this is suddenly accelerated by A. That is what you see. There is a sudden acceleration now.

On the particle. Now the surrounding fluid velocity, and ρp is the particle density. In this case, in the case of sudden deceleration, it typically follows an exponential law, where the response time is given by this: $\tau_p = d_p^2\ \rho_p/18\ \mu$. So if that fluid acceleration is not constant, or Stokes drag does not apply, for example, to larger particles or at very high flow velocities, the solution is no longer an exponential decay of the particle velocity. All right, because this is in the case of deceleration, remember. All right, nevertheless, this τ p remains a convenient measure of the tendency of the particles to attain velocity equilibrium with the fluid.

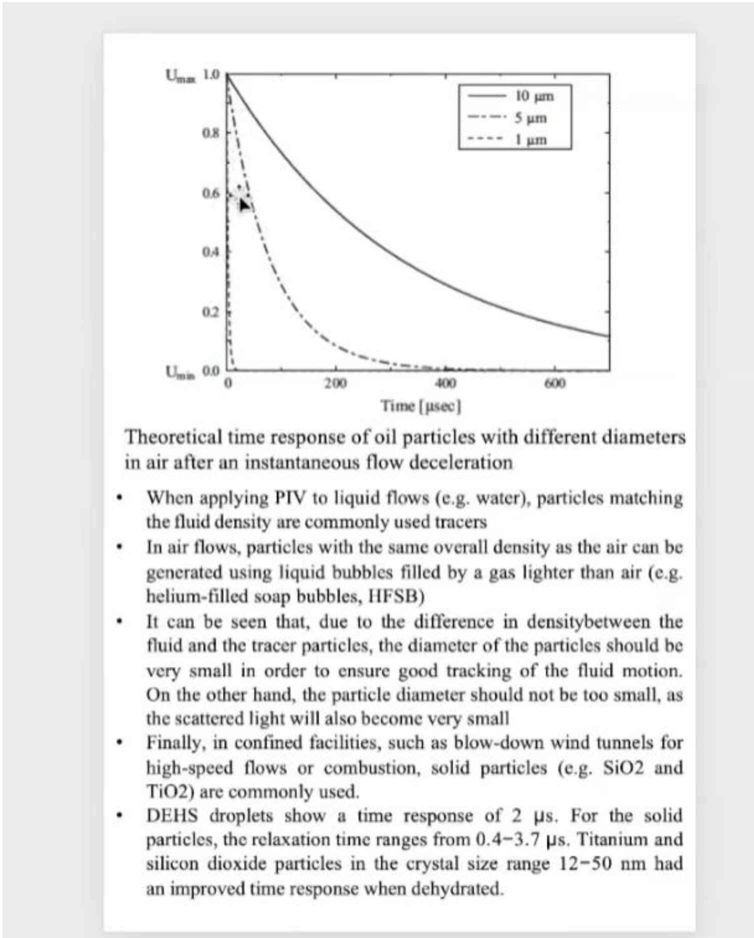
This is the timescale at which the particle attains equilibrium, the velocity equilibrium with the fluid. Okay, this is the timescale. This is the time scale that arises because there is an exponential. Okay, so knowing that the response time of a particle tracer is not sufficient, however, if we just know that response time, this is the response time of the particle tracer to an acceleration or a deceleration, right? Uh.

.. so it is not valid for very large particles or very high flow velocities, right? Okay, but if you know the response time of the particle tracer, it is not sufficient to determine if it will follow the flow with enough fidelity. For that, you need what is called a Stokes number. So the Stokes number is nothing but the ratio of the two time scales. One is the particle response time; the other is the characteristic time of the flow. So if the particle response time is much smaller than the flow time, that is the flow rollover time, for example, this particular characteristic time may be the shedding scale of a vortex, if that is what you are trying to measure.

And if the particle response time is much smaller than the vortex shedding time, then you should imagine that the Stokes number is a number that is much less than 1. And if it is less than 1, it should be able to follow the flow with sufficient fidelity. So the rule of thumb is that a value of the Stokes number that is less than 10 to the power of minus 1 yields an acceptable flow tracing accuracy. Remember that. Okay, so it is not enough just to know the response time; it is also important to determine the Stokes number to see whether this response time is lower than the flow characteristic time.

So you can imagine that if the vortex is being shed at a very high frequency for you to determine the vortex, it means that the particles can trace the vortex. That means that is what you are going to measure. So, if you are supposed to measure that tracer wiggling in the vortex, then the tracer timescale has to be much lower than the vertical timescale. Right, and that sometimes is pretty onerous. That means your τ_p, if you look at it, should have a time; it should have a diameter that is very, very small because the smaller the diameter, actually, if the diameter falls by half, the response time scale falls by one-fourth.

And you can also reduce the density, which is the basic paradigm anyway. You need to reduce the density. You also need to reduce the particle diameter if you are to track these high-speed flows or flows that have very low flow timescales. Right, so this is, for example, the u_{max}, and this is the relaxation time. For example, a one-micron droplet relaxes from U max to U_{mean} in a very short time interval; this is in microseconds.



Whereas if you see a five-micron droplet, it takes about, say, 200 microseconds to reach about 1.1. of the U_{mean}. And then it takes a very long time, a very, very long time, 600 to 800 microseconds for a 10-micron droplet to attain the same thing. This is the theoretical time response of oil droplets with different diameters in air after an instantaneous flow deceleration.

Okay, so there is a deceleration of the flow; it is a step function. Say that it is a step function, and this is the time it takes for the particles to respond. So this is the quickest, this is the longest. So in air flows, particles with the same overall density as the air can be generated by using liquid bubbles. Filled up by a gas lighter than air, like helium soap bubbles, for example, it is also seen that due to the difference in density between the fluid and the tracer particles, the diameter of the particles should be very small to ensure good tracking; on the other hand, the particle diameter should not be too small, as scattered light, as we will see later, becomes very small also.

Finally, in confined facilities such as wind tunnels and combustion chambers, we use solid particles. This is either silica or titanium dioxide. DHS is a class of droplets that shows a response time of about two microseconds. And for solid particles, the relaxation time is between 0.

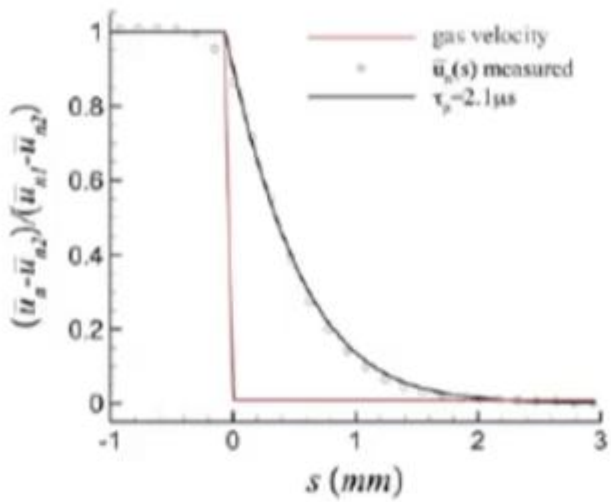
4 and 3.7 microseconds. So these are the different time scales with which we are operating. DHS is very good because it has a very long evaporation time. So these are some of the players. So DHS, silicon dioxide, these are a lot of tracers, you know, or seeders. And this is their mean, you know, response time scale that you can see over here.

They are all generated, I think, through certain fluidized bed dispensers or other types of methods. We will see some of them over there. And so these are the differences between hydrated and dehydrated substances and things like that. So you can see that in this particular case, it is a comparison between PIV measurements, which are circles, and the theoretical prediction, which is the black line of particle velocity of titanium dioxide tracers of 0.

Table 2.1 Time response of seeding materials and typical data dispersion

ID material	Seeder	Mean τ_p (μs)		$\sigma(\tau_p)$ (μs)	
		Stored (τ_H)	De-hydrated (τ_{DH})	Stored	De-hydrated
DEHS	A	1.92–2.02	–	0.40–0.38	–
SiO2R104	C	2.49	2.21	0.22	0.17
SiO2R972	C	2.64	2.29	0.19	0.28
TiO214	C	3.25	3.71	0.12	0.12
TiO230	C	2.56	2.20	0.11	0.07
TiO250	C	2.77	2.09	0.18	0.09
TiO250	C_F	–	0.56	–	0.10
SiO2R104	C_F	–	0.37	–	0.10
TiO250	F_L	–	1.36	–	0.05
TiO250	F_H	–	1.67	–	0.08
TiO2170	C	2.50	3.13	0.13	0.19
TiO2240	C	2.52	2.64	0.09	0.15
TiO2550	C	2.43	2.78	0.07	0.22
Al2O3	PG	–	0.18	–	–

Table after RAGNI et al. [52] - C cyclone, CF cyclone with 1 μm filter, A atomizer, F fluidized bed dispersion, L/H low/high mass flow rate, PG plasma generator (data from GHAEMI et al. [17])



Comparison between PIV measurements (circles) and theoretical prediction (solid black line) of particle velocity for Titanium dioxide tracers of 0.5 μm diameter across a stationary oblique shock wave. Result for the change of shock normal velocity component

5 microns along a stationary oblique shock. This is the gas's actual velocity because it's very sharp. And this is the velocity that is actually measured, along with the other velocities theoretically predicted. So you can see that there is a time; there is a certain time that it takes or a certain distance it takes. So, this is the result. Between the PIV measurements and theoretical predictions.

The result for a change in shock velocities is the normal component of the shock velocities. And these are the different response times that you can see over there. So when you have a neutrally buoyant particle, the density of the tracers approaches the density of the liquid they are immersed in, and you can see that the response time is basically given as delta ρ. In this case, delta ρ can be made several orders of magnitude smaller.

than the particle density. In airflow, for instance, the density difference of 0.1 kg per cubic meter can be easily obtained with helium-soaked bubbles, as we already said, compared to 10 to the power of 3 kg per cubic meter, typical of oil droplets. This condition allows to relax the constraint on particle size, which can be now chosen orders of magnitude larger with little detriment to their time response and tracing fidelity. The measurement of tracers' deceleration and the velocity slip now allow us to estimate the timely response of these tracers.

Neutrally Buoyant Particles

When the density of tracers approaches that of the fluid they are immersed in, the expression of the time response in the Stokes regime reads as:

$$\tau_p = \frac{d_p^2 \Delta\rho}{18\mu}$$

In this case $\Delta\rho$ can be made several orders of magnitude smaller than the particle density. In air flows, for instance, a density difference below 0.1 kg/m^3 can be easily obtained with Helium filled soap bubbles (HFSB), compared to the value of 10^3 kg/m^3 typical of oil droplets. This condition allows to relax the constraint on particle size, which can be chosen orders of magnitude larger with little detriment to their time response and tracing fidelity. The measurement of tracers deceleration and of the velocity slip allows to estimate the time response of these tracers:

$$\tau_p = \left| (U_{bubble} - U) / \left(U \frac{dU}{dx} \right) \right|$$

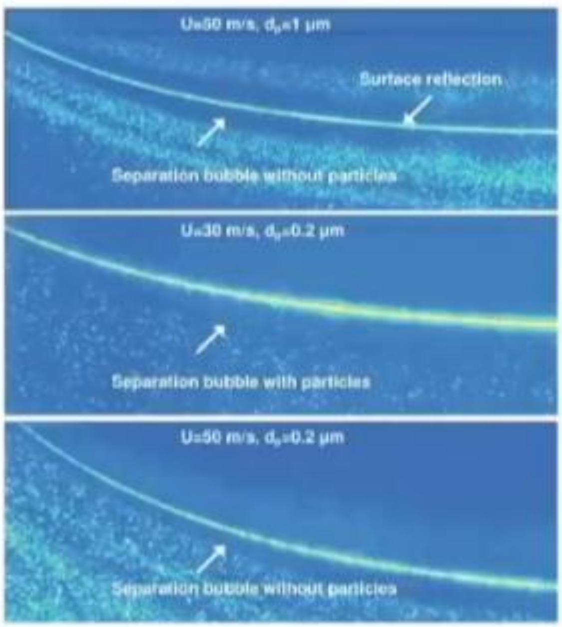
Particles of approximately 0.3 mm respond to velocity fluctuations within a time scale of 10–50 μs depending on their closeness to the neutral buoyancy condition

This is the time response. The particles of approximately 0.3 mm respond to velocity fluctuations within a time scale of 10 to 50 microseconds. Because you have reduced the density to almost zero. This depends on how close they are to the neutral buoyancy situation.

So this is great because you can deal with 0.3 mm particles, which are quite large compared to micron-sized particles. So even when the particle slip can be neglected for the purpose of velocity measurements, there are particle drifts that can happen, which can lead to undesired inhomogeneity of the tracers. Remember, we want a homogeneous medium distribution. Right? So in this case, for example, this happens when there are vortices and strong vortices and laminar boundary layers because of the presence of strong shear and vorticity; the particles tend to accuμlate in those areas. Okay? So this is, for example, you can see a separation bubble without any particles.

- Even when the particle slip can be neglected for the purpose of velocity measurements, the integrated effect of particle drift can lead to undesired inhomogeneity of the tracers spatial distribution.

- This is particularly evident in the case of streamwise vortices, strong vortices in high speed flows and for laminar boundary layers



Particle image concentration in the separated region for different free-stream velocities U and diameter of the tracer particles d_p (flow direction from left to right)

Time-averaged particles distribution in vortices

Okay. This is a separation bubble with particles. Okay, and this is separation bubbles without particles. So you can see that you may not always have the particles in the flow. And this is clearly an inhomogeneous distribution because you can almost see the structures. This is the average particle distribution in the vortices. Just because the particles are entrained in the vortices, they tend to stay there.

As a result of that, this leads to the inhomogeneity of the tracers and the spatial distribution of the tracers. And once we lose the spatial distribution of the tracers, your velocity measurement is going to suffer significantly. At the same time, let us now look at the polar distribution of the light scattered for oil particles of different diameters in air with a wavelength of irradiation of 532 nanometers, the most common NDAG lasers. The scattered light is a function of particle size, shape, orientation, relative refractive index, etc. So the contrast, as we know, of the PIV recordings is directly proportional to the scattered light power.

Table 2.2 Approximate scattering cross section for different oil particles in air

Particle diameter d_p (µm)	Scattering cross section CS [m^2]
1.0	$\approx 10^{-12}$
0.5	$\approx 10^{-12}$
0.2	$\approx 10^{-13}$
0.125	$\approx 10^{-14}$

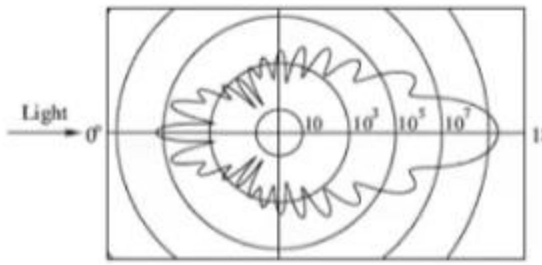


Fig. 2.7 Light scattering by a 1 µm oil particle in air

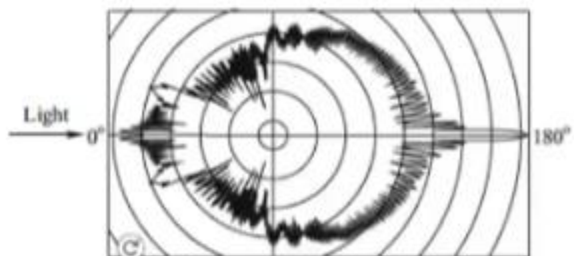


Fig. 2.8 Light scattering by a 10 µm oil particle in air. Intensity scales as in Fig. 2.7

Polar distribution of scattered light intensity for oil particles of different diameters in air with a wavelength of 532 nm. Scattered light is function of particle size, shape, orientation, relative refractive index.

Contrast of PIV recordings is directly proportional to the scattered light power

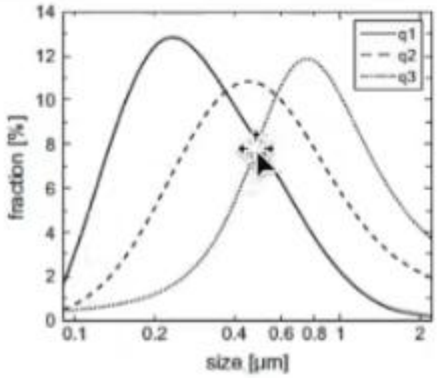
So the scattered light power, as we can see, if the particle is one, the scattering cross section is 10 to the power of minus 12. If the particle size is 0.

5, it goes to 10 to the power of minus 12. This is going to 0.1, 0.2, 10 to the power of minus 13, 0.125, and 10 to the power of minus 14. The smaller the particle diameter, though it might closely follow the flow, you get a two-order decrease in the scattering cross section. So this is, for example, a one-micron oil particle in air, and this is a 10-micron oil particle in air.

And these are on the logarithmic scale, as you can see. As we have illustrated, this is light from this end to the other end. As we know, forward scattering is always of high intensity, and these lobes are due to the interference between the different scattering orders or scattering modes. And so you can see that there is a lot of difference. Okay, it's a function of the particle size, of course the shape, orientation, and where you are measuring it. Forward scattering, I mean, back scattering is always inferior, but you are going to measure somewhere at, I would say, the right angle.

So this is what you are most concerned about. You are not going to do it there because your imaging in the case of PIV is at right angles to the light orientation. Okay, so you have to take this into account because the scattering cross-section drops by two orders for a size drop of about, you know, one to about point one. So, one order drop in particle diameter leads to two order drops in the scattering cross-section. Now, if you are dealing with polydisperse particles, this is like even a little bit of more complexity because these are.

Laskin nozzle; you will see what that is. This is the DHS particle distribution. And these are distributions based on length, area, and volume. So they are very different. So the particles with small diameters can only be used if the optical sensitivity is such that it is able to record images of the small particles; scattering performance, as we saw, drops quite a bit. Secondly, larger particles actually dominate the PIV signal because they scatter more.



Three representations of a Laskin nozzle atomized DEHS particle size distribution; solid line: distribution of length *(q_1)*, dashed line: distribution of area *(q_2)*, dotted line: distribution of volume *(q_3)*

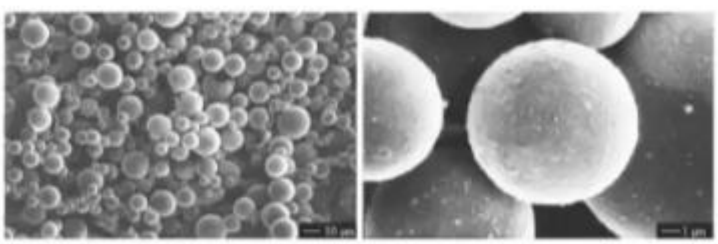
- Firstly, particles with small mean diameters can be used only if the optical sen- sitivity (laser power and camera sensitivity) is such to be able to record images of these small particles (scattering performance drops drastically with decreasing particle diameters as mentioned above).
- Secondly, larger particles dominate the PIV signal and in turn the measurement fidelity. The reduction of larger particles is therefore at least as important as the generation of small particles, when the velocity lag needs to be reduced.
- Thirdly, a quantification of the measurement error due to velocity lag of polydispersed particles cannot be determined easily with a calculation based on the particles most frequent size, but requires a more complex procedure, for instance based on in situ measurements with the same particles and optical settings.

So, in turn, the measurement fidelity. The reduction of larger particles is therefore also important. especially when cases with velocity lag need to be reduced. And thirdly, the quantification of the measurement error due to the velocity lag of polydispersed particles is not easy because you cannot base the calculations on the most frequent size; it requires more complex procedures. You may have to do in situ measurements with the particles.

We need to know the size distribution of the particles and so on. So these are the seeding materials for the gas flow. Just remember that polystyrene, alumina, and glass microspheres are all candidates. We have personally used all of them. You can also use liquids in the gas flow.

Seeding materials for gas flows

Type	Material	Mean diameter in μm
Solid	Polystyrene	0.5–10
	Alumina Al_2O_3	0.2–5
	Titania TiO_2	0.1–5
	Glass micro-spheres	0.2–3
	Glass micro-balloons	30–100
	Granules for synthetic coatings	10–50
	Dioctylphathalate	1–10
	Smoke	< 1
Liquid	Different oils	0.5–3
	Different propylene glycols	0.5–1.5
	Glycerine-water mixture	0.5–2.0
	Di-ethyl-hexyl-sebacate (DEHS)	0.5–1.5
	Helium-filled soap bubbles	200–3000



Micrographs of silver coated hollow glass spheres: ×500 and ×5000

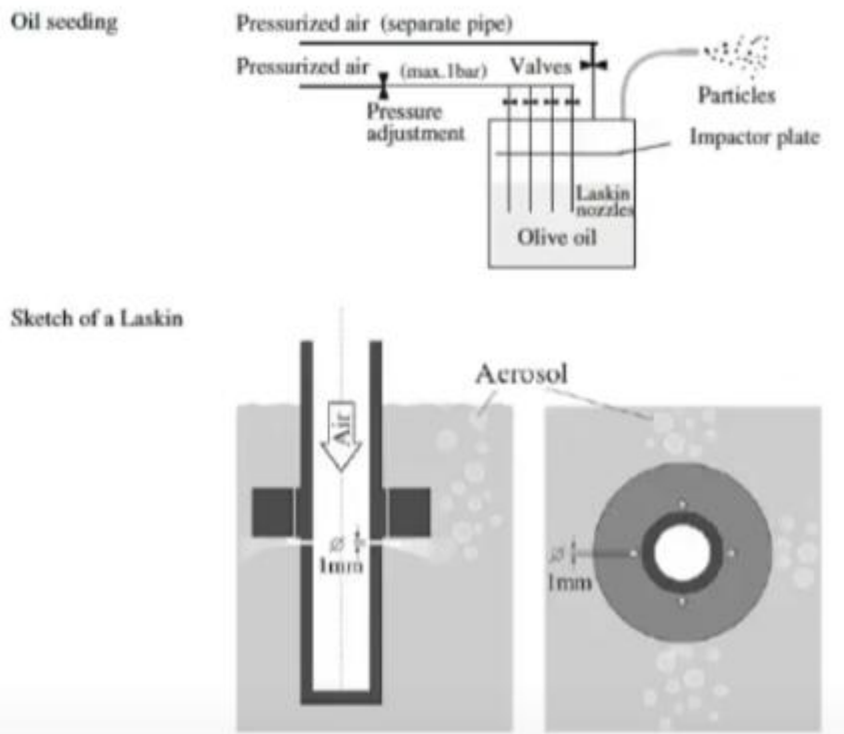
From a practical standpoint, particles slightly lighter (few percent) than the liquid will tend to accumulate on the upper edge of the facility (sometimes a free surface).

This is DHS, which is diethylhexylsebacate. And this is also used. This is about 0.5 to 1.5 microns in diameter. These are all within three microns, so to speak.

Glass beads or microballoons are typically smaller. Because they have the same density as air. So that's why you can go larger by the same principle that we mentioned. From a practical point of view, particles slightly lighter than the liquid will sometimes tend to accuµlate on the outer edge of the facility.

That can also happen. And this is an example of droplet seeding. This is for most of the PIV measurement. The Laskin nozzles are used. We have already discussed a little bit about the Laskin nozzles. This offered the advantage of being less harmful than solid particles because it stays in the air but doesn't change in size due to the longer evaporation time.

Droplet seeding of air flows. For most of the PIV measurements in air flows, Laskin nozzle generators supplied with oil have been used. These particles can offer the advantage of being less harmful than most solid particles, staying in air at rest for hours and not changing in size significantly under various conditions.

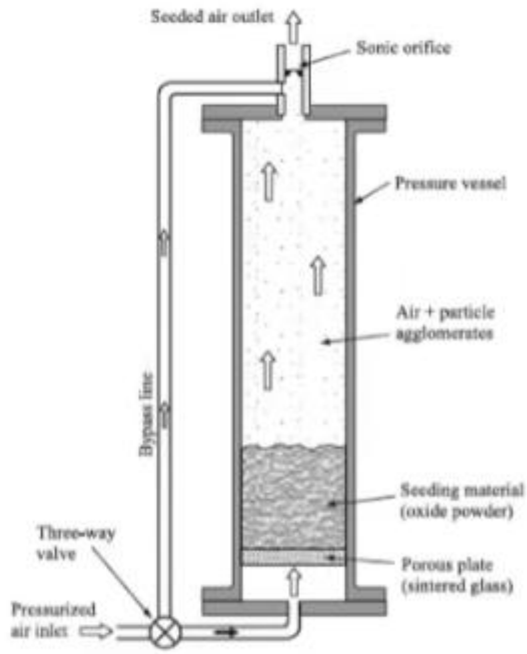


Vegetable oils and DEHS are the most commonly used liquids, since vegetable oil droplets are believed to be less harmful than many other particles and DEHS offers the advantage to evaporate in the long term

It takes a long time to evaporate. So vegetable oils and DHS are something like that; that is what we use. We pressurize, and then these particles come out; these droplets come out as a fine mist. This is the Laskin nozzles, which we already covered a little bit in the PDP and the LDB lectures. And this is a fluidized bed.

For example, if you want to generate solid particles, this is a powder-based seeding. So you pass the air through a fluidized bed, and what comes out of it is basically the particles. In these cases, metal oxide powders are routinely used because of their inertness, high melting points, and low cost. This is particularly important when you are actually dealing with combusting gases because the reacting flows you need cannot use oil in those cases. okay so we will stop here in in the next class we will take on the lasers and then continue with our piv

Fig. 2.23 Fluidized bed seeding device for high pressure applications



Powder-based seeding of air flows. In cases where the stability of the seeding mate- rial cannot be guaranteed due to increased temperatures or reactive environments, droplet-based seeding is no longer feasible. In these cases, seeding based on solids must be used. Metal oxide powders are especially well suited for this purpose due to their inertness, high melting point, and rather low cost.