Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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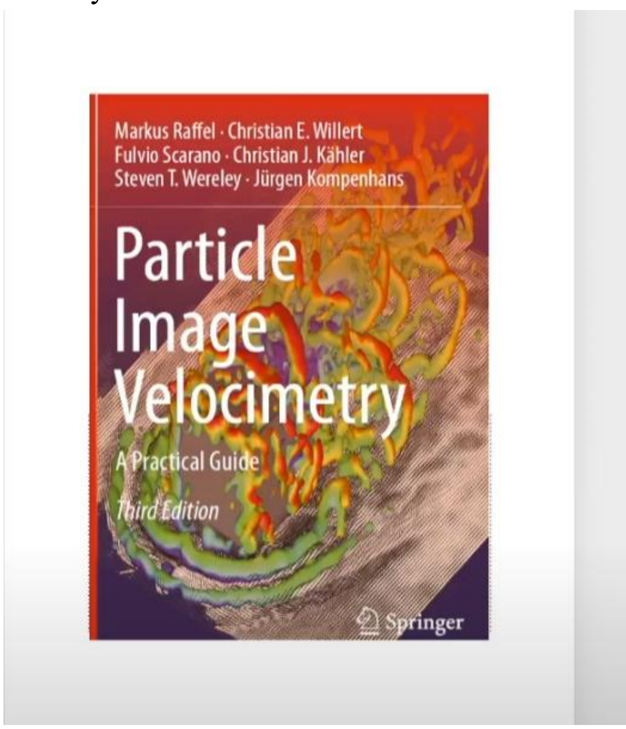
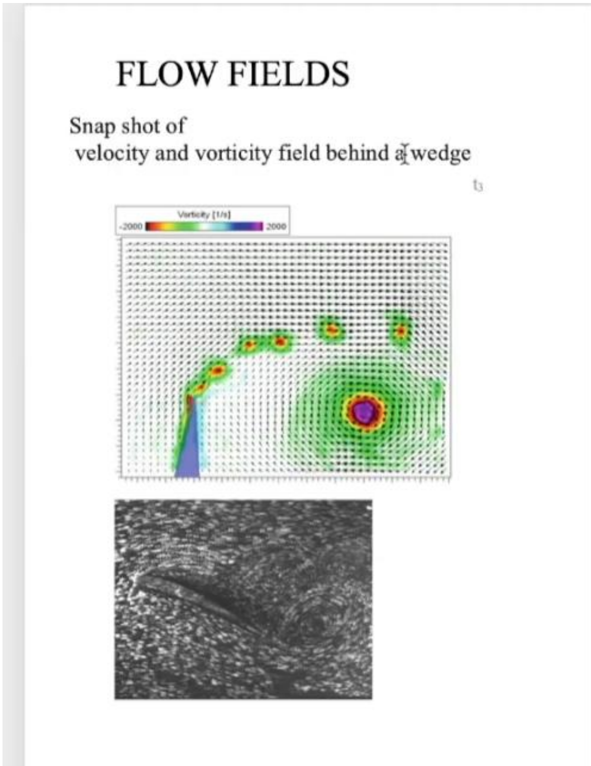
Week – 07
Lecture - 31
Particle Image Velocimetry – 1

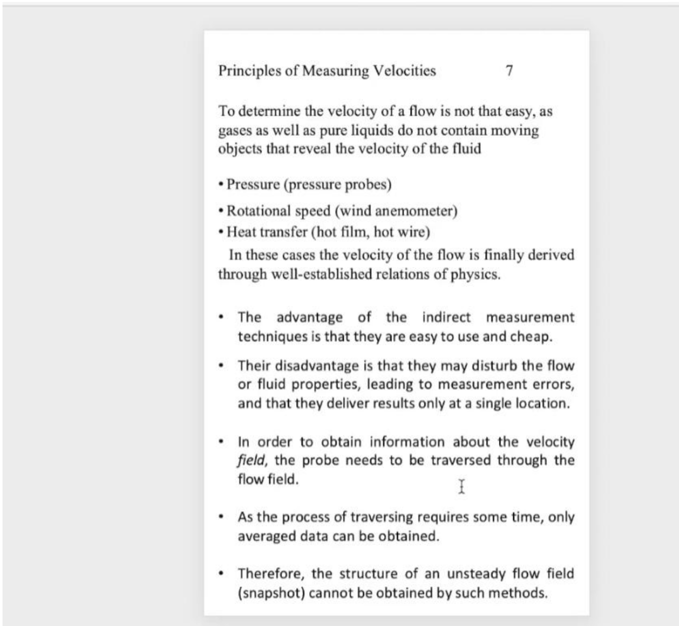
All right, so this is the first lecture on particle image velocimetry. So the book that we are going to cover will provide most of the examples, and there will be some examples from our own research. The book, Particle Image Velocimetry: Practical Guide, 12, 3rd and 4th. Published by Springer. So the idea is that if you take, this is, for example, a snapshot of the velocity field behind the wedge. And this is, for example, the unsteady velocity field and the vortices around an aerofoil.





So there are countless examples like this where we need to know, for example, what it is. And here it can also be steady. It can be unsteady. In all those cases, the flow may be sudden.

It can be impulsive. There can be many things. So all these things together, you see that this velocity field is composed of many transient structures, but you need to visualize the flow field in its entirety, and that is the pollutant particle. The principles of measuring velocity are quite simple; if you want to measure, for example, the velocity of a flow, such as gas or pure liquids. But how do you measure the flow? They do not contain moving objects that act as a reference for you to track and identify the velocity, right? So it is not that easy.


Principles of Measuring Velocities 7

To determine the velocity of a flow is not that easy, as gases as well as pure liquids do not contain moving objects that reveal the velocity of the fluid

- Pressure (pressure probes)
- Rotational speed (wind anemometer)
- Heat transfer (hot film, hot wire)

In these cases the velocity of the flow is finally derived through well-established relations of physics.

- The advantage of the indirect measurement techniques is that they are easy to use and cheap.
- Their disadvantage is that they may disturb the flow or fluid properties, leading to measurement errors, and that they deliver results only at a single location.
- In order to obtain information about the velocity *field*, the probe needs to be traversed through the flow field.
- As the process of traversing requires some time, only averaged data can be obtained.
- Therefore, the structure of an unsteady flow field (snapshot) cannot be obtained by such methods.

Therefore, how do you do? You use pressure probes, for example. Pressure probes, as we already saw, could be like your pitot tube. So it measures the pressure and links it to velocity. And there can be things like you can no longer use the rotational wind. It did not cover it.

And then it can also depend on heat transfer. For example, a hot film or a hot wire is a perfect candidate for it. In these cases, the velocity of the flow is finally derived from a well-established relationship in physics. For example, in the pressure probes, we use Bernoulli's principle. In the case of heat transfer, which involves hot film or hot wire and inventory, we use what we call heat transfer.

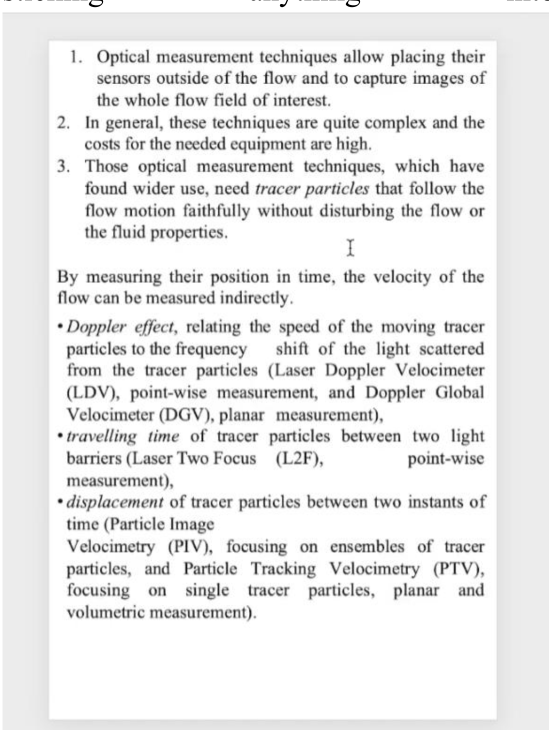
So use that; you know, the flow velocity is actually embedded in the calculation. So we can kind of relate the two indirectly. So this is an indirect measurement, but it is very cheap. You can see, well, the hot wire anemometer is cheap, but the pitot tube and, you know, the rotational wind anemometer are very cheap. But a hot wire anemometer is expensive because, you know, it gives you quite a bit of fast, high temperature.

So in general, the indirect measurement techniques are easy to use and cheap to begin with, but their main advantage is that these are probes which are actually physically inserted into the flow field; they disturb the flow, the very flow that they are trying to measure. This leads to measurement errors, and they also deliver results at a single location. These are point-based measurements. In order to have information about the whole velocity field, the probe needs to be traversed through the flow field. For example, you can never get an image like this.

This is simultaneous, right? Here, you cannot get that information. You have to basically traverse the flow field and move the probe across the flow field. So, in order to obtain information about the velocity field, the probe needs to be traversed across the flow field. So the process of traversing requires some time because wherever you go, you spend some time taking the measurements, and then you take time to move the probe to another location. Therefore, this can only give you averaged data.

It cannot give you unsteady flow information and definitely not the snapshots that you saw over here. You cannot get this kind of snapshot in probe-based. So this is the cannot get this. Right? Now you come to the next thing. Oh, what should I do? You go for an optical measurement.

Now optical measurements allow you to not intrude the flow. So basically, capture images. Or it can even capture the data, which we saw in LDV or PDPA, by placing the sensors outside the flow field. So you are not really entering the flow field. You are not sticking anything into the flow field.



1. Optical measurement techniques allow placing their sensors outside of the flow and to capture images of the whole flow field of interest.
2. In general, these techniques are quite complex and the costs for the needed equipment are high.
3. Those optical measurement techniques, which have found wider use, need *tracer particles* that follow the flow motion faithfully without disturbing the flow or the fluid properties.

By measuring their position in time, the velocity of the flow can be measured indirectly.

- *Doppler effect*, relating the speed of the moving tracer particles to the frequency shift of the light scattered from the tracer particles (Laser Doppler Velocimeter (LDV), point-wise measurement, and Doppler Global Velocimeter (DGV), planar measurement),
- *travelling time* of tracer particles between two light barriers (Laser Two Focus (L2F), point-wise measurement),
- *displacement* of tracer particles between two instants of time (Particle Image Velocimetry (PIV), focusing on ensembles of tracer particles, and Particle Tracking Velocimetry (PTV), focusing on single tracer particles, planar and volumetric measurement).

In general, these techniques are very complex, and the instrumentation cost is high due to the accuracy. So these optical techniques or measurement techniques, which have found wider use, actually need tracer particles. We assume that these tracer particles are going to follow the flow motion without disturbing the flow or the fluid properties. By measuring the position of these tracer particles over time, the velocity of the flow can be measured indirectly because you are measuring the tracer particles' velocity. You're not measuring the velocity of the flow; rather, the idea is that the tracer particles actually follow the flow field.

By measuring the tracer particles, you are measuring the velocity. And we are assuming that the tracer particles do not disturb the flow field or the flow properties. So these also come in different types. So one type we have already seen, which is the Doppler effect, relates the speed of the moving tracer, the frequency shift of the light scattered, and this is called LTV. It is a pointwise measurement.

There are other variations, like Doppler global, which we did not cover, okay? You can understand that you can use the Doppler effect. You can use the frequency shift to measure the velocity, right? You can also use what we call the traveling time of the tracer particles between the light barriers. This is called laser two-focus or point focus. To measure, it's like you are basically doing tracking. So at one light bit, there you have a trace of a particle crossing.

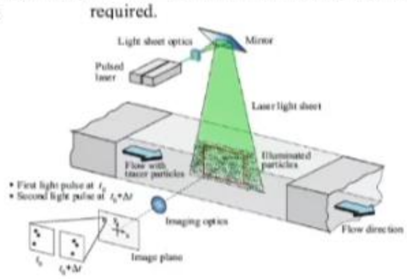
You see, when it reaches the next time barrier, you divide the distance by the total time, get the point measurement, which these light bits are very close to each other. Then, of course, the thing that we are going to do here is called the displacement of tracer particles at two instants of time. So, this is called particle image velocimetry. It focuses on ensembles of tracer particles, not on single tracer particles. But there are other variations which are called particle tracking velocimetry, focusing on single tracer particles.

Principle of Particle Image Velocimetry (PIV)

In the following, the basic features of the Particle Image Velocimetry (PIV) mea- surement technique will be described briefly.

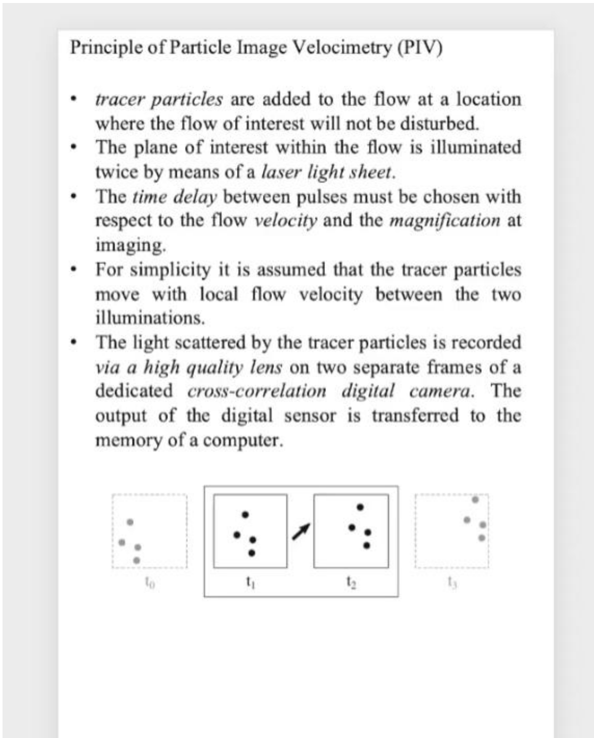
The experimental set-up of a PIV system typically consists of several subsystems.

- **Seeding**: In most applications tracer particles have to be added to the flow.
- **Illumination**: These tracer particles have to be illuminated in a plane or volume of the flow at least twice within a short and known time interval.
- **Recording**: The light scattered by the tracer particles has to be recorded either on two separate frames or on a sequence of frames of a camera.
- **Calibration**: In order to determine the relation between the particle image dis- placement in the image plane and the tracer particle displacement in the flow, a calibration is required.
- **Evaluation**: The displacement of the particle images between the light pulses has to be determined through evaluation of the PIV recordings.
- **Post-Processing**: In order to detect and remove invalid measurements and to extract complex flow quantities of interest, sophisticated post-processing is required.



Experimental arrangement for planar 2C-2D PIV in a wind tunnel

And these measurements can be both planar and volumetric. There are also measurements that are called laser speckle velocimetry. It basically tracks the displacement of tracer particles between two instances in time. It is usually between two laser flashes. So this is actually in PIV; remember, it is ensembles of tracer particles.



Particle tracking velocimetry focuses on single tracer particles. So there is a difference between the two. Right? So, this is basically the principle of BNP. Look at this particular diagram to scale. Expand this a little, blow this up.

So you can see that, you know, in this particular case, basically eight follows. It consists of several subsystems. Now, these subsystems are basically the seedings. Seeding is needed, as we call it; these are basically tracer particles added to the flow.

Then you have illumination. The tracer particles have to be illuminated in a plane or in the volume of the flow at least twice, with a known time interval between the two. So, for example, if this is the laser sheet, it is basically passed through the fluidic system under consideration, and this is pulsed twice; therefore, each laser sheet has a time on the order of nanoseconds, and then you have a pulse separation, which means there is another laser sheet that comes on the order of microseconds or milliseconds, and illuminates the same location of the flow field. Right. So this is the illumination. So it can also be volumetric illumination, as we will see in the case of micro PIV.

But normally it is a pulsed laser. It is converted into a light shield. You already know how to make it. We use a mirror to direct the light sheet into the flow field, where there is a flow that contains all the tracer particles. These particles are, therefore, illuminated, and so they scatter.

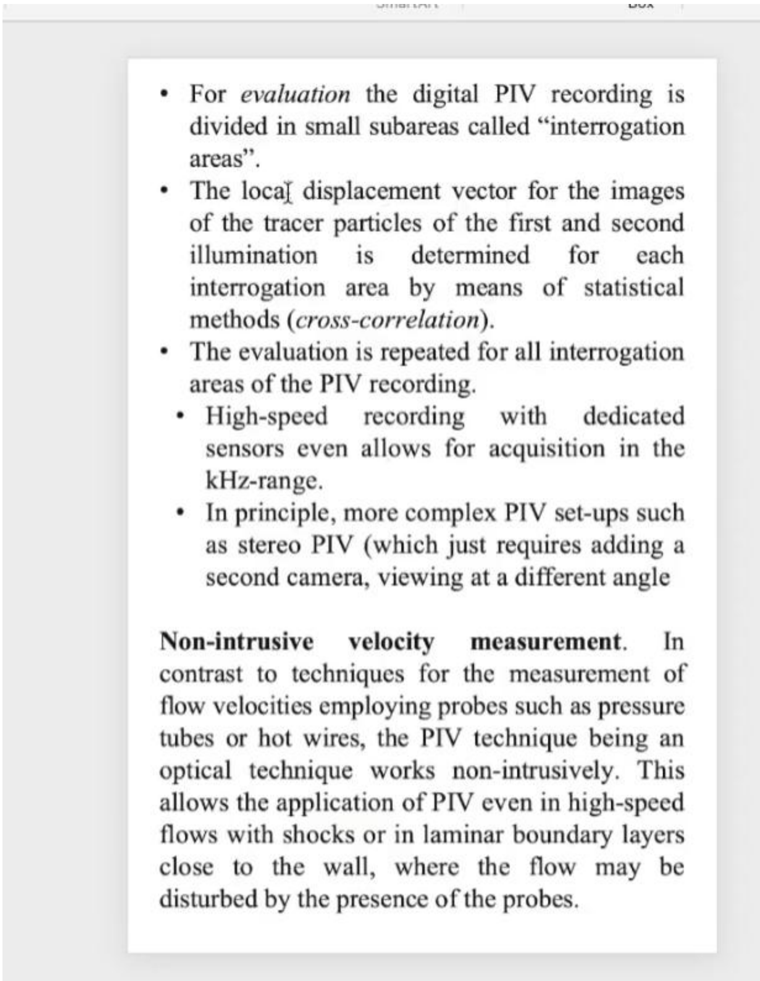
You already know a little bit about what scattering is. Then you have an imaging optics, which basically monitors the image at two points in time: the first light pulse is at t_o , and the second light pulse is at $t_o + \Delta t$, so you can actually see how much the particles have moved in between the laser pulses, and this will enable you to calculate velocity. So the recording of light scattered by the tracer particles has to be either recorded on two separate frames or on a sequence of frames from the camera. So the calibration in order to determine the relationship between the particle image displacement and the tracer particle displacement is required.

I mean the relation. So, usually, you have a calibration target. And the evaluation of the displacement of the particle images between the laser pulses, I mean, the evaluation of the PIV recording. And then we typically do a lot of post-processing to detect and remove invalid measurements to extract complex flow quantities, for example. For example, in the wall shear, there are a lot of things we can calculate, so you essentially get images of the particles in the flow field, and by looking at the displacement of this image over a known time interval, Δt, this is a component of the wind tunnel. You should be able to see what the flow velocity is.

Okay, so this is the very basic setup; it uses a laser and camera system. You can also use a camera system. So this is, in general, a nutshell of what is here. The second is that the principle of particle image velocimetry is that tracer particles are added to the flow at a location where the flow of interest will not be disturbed. This is the first important statement already said.

So, the flow cannot be disturbed. A plane of interest within the flow is illuminated twice by means of a laser light sheet gain. Then there is a time delay between the two pulses, which must be chosen with respect to the flow velocity and the magnification. The higher the flow velocity, the lower the time delay between the two pulses. And it also depends on the magnification. For simplicity, it is assumed that the tracer particles move with the local flow velocity between the two illuminations.

So it moves between these two pulses that are so close to each other that it moves with the local flow velocity. That is what the consideration is. And the light scattered by tracer particles is recorded by a high-quality lens on two separate frames for a dedicated cross-correlation digital camera. The output of the digital sensor is transferred to the memory of a computer.



- For *evaluation* the digital PIV recording is divided in small subareas called "interrogation areas".
- The local displacement vector for the images of the tracer particles of the first and second illumination is determined for each interrogation area by means of statistical methods (*cross-correlation*).
- The evaluation is repeated for all interrogation areas of the PIV recording.
- High-speed recording with dedicated sensors even allows for acquisition in the kHz-range.
- In principle, more complex PIV set-ups such as stereo PIV (which just requires adding a second camera, viewing at a different angle

Non-intrusive velocity measurement. In contrast to techniques for the measurement of flow velocities employing probes such as pressure tubes or hot wires, the PIV technique being an optical technique works non-intrusively. This allows the application of PIV even in high-speed flows with shocks or in laminar boundary layers close to the wall, where the flow may be disturbed by the presence of the probes.

So, this is not equal to zero. This is T_1 and this is T_2. This is one of 12 pulses; okay, you can see that the images move, so the particles may have a little bit of movement with respect to each other. You can see this very clearly, and this is what is used for the cross-correlation. Okay, now, for the evaluation, the digital PIV recording is divided into sub-areas, which we call interrogation areas.

These are the boxes that you see. These are called interrogation areas. The local displacement vector for the images of the tracer particles from the first and second illuminations is determined for each interrogation method. We will see what it is. It is called cross-correlation. The local displacement vector of the tracer particles during the first and second illumination.

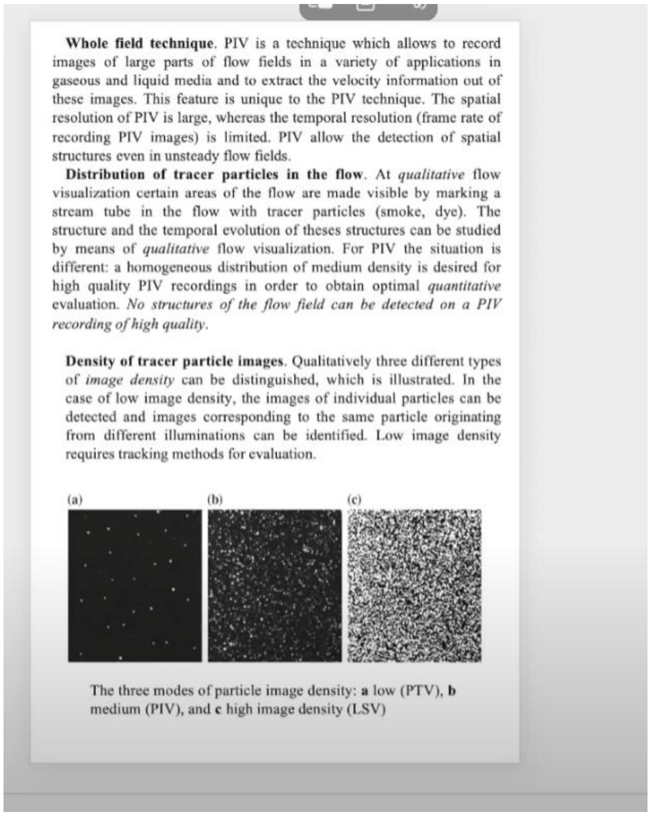
These are 12 pulses, right? It's determined for each interrogation. For each of these interrogation areas, we have to determine this. So it is divided into small subareas. So this particular image, the whole image is divided into small sub-areas, which you see. Right? Evaluation is, therefore, repeated for all interrogations.

Now we can use high-speed recording with dedicated sensors. This allows for acquisition in the kilohertz range. So that means you can actually now measure a very high-speed flow. In general, more complex PIV setups, such as view PIV, even tomography PIV, adds a second and a third camera viewing at different angles. All of this tomography we already saw a little bit in your Shillerin POS.

So, non-intrusive velocity measurement, in contrast to techniques for measuring flow velocity employing probes such as pressure tubes or hot wires, is a PIV technique, which is an optical technique. Therefore, it depends on the scattering of light. It is not a spectroscopic technique, by the way. There is no energy transition involved. So this allows the application of PIV even in high-speed flow, shocks, laminar boundary layers, and very close to the wall, where the flow can actually be very sensitive to the presence of probes, especially in the case of shocks because the shock is such a small zone.

In order to actually determine the location of the shock, you cannot put probes right there because they can actually, you know, severely compromise the flow field. So it is non-intrusive. Velocity measurement. There lies the beauty of it.

So PIV is a whole-field technique, therefore. It is a technique that allows you to record images of large parts of the flow field in gas or liquid media. And you can extract the velocity components out of these images. So this feature is the PIV technique. The spatial resolution of the PIV is high. As you know, it is taking a large full field, and it depends on the resolution of your camera and optics to determine what kind of spatial resolution.



Whole field technique. PIV is a technique which allows to record images of large parts of flow fields in a variety of applications in gaseous and liquid media and to extract the velocity information out of these images. This feature is unique to the PIV technique. The spatial resolution of PIV is large, whereas the temporal resolution (frame rate of recording PIV images) is limited. PIV allow the detection of spatial structures even in unsteady flow fields.

Distribution of tracer particles in the flow. At *qualitative* flow visualization certain areas of the flow are made visible by marking a stream tube in the flow with tracer particles (smoke, dye). The structure and the temporal evolution of theses structures can be studied by means of *qualitative* flow visualization. For PIV the situation is different: a homogeneous distribution of medium density is desired for high quality PIV recordings in order to obtain optimal *quantitative* evaluation. *No structures of the flow field can be detected on a PIV recording of high quality*.

Density of tracer particle images. Qualitatively three different types of *image density* can be distinguished, which is illustrated. In the case of low image density, the images of individual particles can be detected and images corresponding to the same particle originating from different illuminations can be identified. Low image density requires tracking methods for evaluation.

(a) (b) (c)

The three modes of particle image density: **a** low (PTV), **b** medium (PIV), and **c** high image density (LSV)

Temporal resolution, which is the recording rate, is sometimes limited, unlike LDB or PDPA, which can be very, very fast, but 100 KHz PIVs are not yet available. So we are getting there. The PIV allows for the detection of spatial structures, even in unsteady flow fields. But the temporal resolution part is also important because if it's a very rapidly moving flow field, then if the PIV framing rate cannot match, there will be a problem. In those cases, we'll rely on phase averaging, mode locking, and all those kinds.

The other part is the distribution of tracer particles in the flow field. Now, in qualitative flow visualization, certain areas of the flow can be made visible by, for example, using smoke and dye. This is like if somebody has seen this Reynolds experiment; you can see there is a dye injected that then wiggles. You can also insert smoke.

You can see these very nice vertical structures, among others. But that structure and the temporal evolutions can be studied through qualitative flow visualization. So you do not really know the magnitude. You do not really know the directions and the nuances, but they give you an idea of what the flow field should look like. and therefore this can form a prelude to the actual measurement.

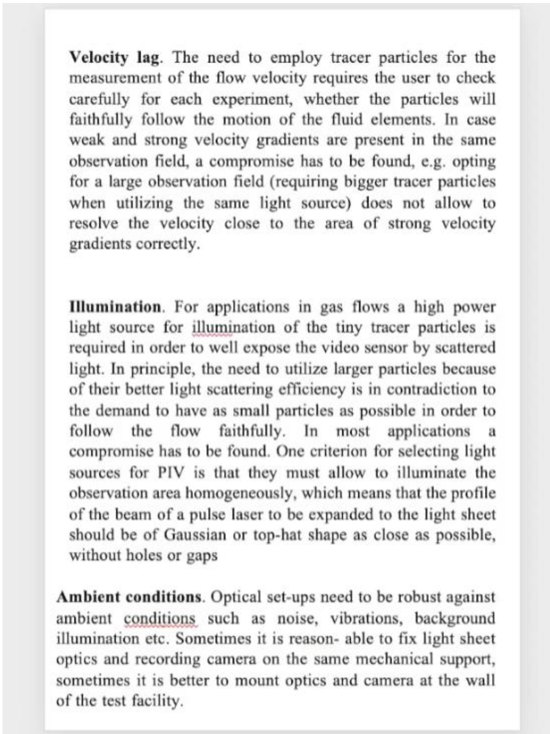
Now, for PIV, the situation is very different. You need a homogenous distribution of the seed density for high quality PIV recordings. In a high quality PIV recording, from looking at these raw images, for example, at the lower side, on the lower bottom, see any flow structure, cannot see structures that can be detected. It was only after processing that we were able to detect this. So, because it's a homogeneous distribution of the medium, it does not really preferentially show in structures that have a qualitative imaging paradigm.

So now comes the density of the tracer particles. So there are three densities here. This is the particle that is clearly visible. They are almost distinguishable. Here, the particle has medium density. So you cannot really; it's a very hard, onerous task to basically track these individual particles.

Here, the particle numbers are so large that their images basically overlap, and you get the speckles. So basically, you can see that when the particle density is really low, in this particle tracking velocimetry, you track each particle and can calculate. It's more like a Lagrangian method of detecting the particles. Particle image velocimetry is, of course, medium density. So you can see this is medium, so it is very hard to find individual particles and track them.

So we use the interrogation windows that we talked about, sub-areas within this image, and then we use ensembles. Then we used statistical methods like cross-correlation to find out the displacement. And here, of course, you have speckles. This has a very large density.

The lights actually overlap with one another, so you get speckles. And this is therefore called laser speckle velocity. So all of them add a tracer particle, and all of them, you know, you measure the scattering of the particles coming out. It's the density of the cedar that makes all the difference. Now, the other thing is that when you employ spacer particles for the flow velocity, you need to check for each experiment whether these particles will faithfully follow the flow field or not. Otherwise, the purpose is defeated because if the particles do not follow the flow field, you are measuring the velocity of the particles and not the flow field.



Velocity lag. The need to employ tracer particles for the measurement of the flow velocity requires the user to check carefully for each experiment, whether the particles will faithfully follow the motion of the fluid elements. In case weak and strong velocity gradients are present in the same observation field, a compromise has to be found, e.g. opting for a large observation field (requiring bigger tracer particles when utilizing the same light source) does not allow to resolve the velocity close to the area of strong velocity gradients correctly.

Illumination. For applications in gas flows a high power light source for illumination of the tiny tracer particles is required in order to well expose the video sensor by scattered light. In principle, the need to utilize larger particles because of their better light scattering efficiency is in contradiction to the demand to have as small particles as possible in order to follow the flow faithfully. In most applications a compromise has to be found. One criterion for selecting light sources for PIV is that they must allow to illuminate the observation area homogeneously, which means that the profile of the beam of a pulse laser to be expanded to the light sheet should be of Gaussian or top-hat shape as close as possible, without holes or gaps

Ambient conditions. Optical set-ups need to be robust against ambient conditions such as noise, vibrations, background illumination etc. Sometimes it is reason- able to fix light sheet optics and recording camera on the same mechanical support, sometimes it is better to mount optics and camera at the wall of the test facility.

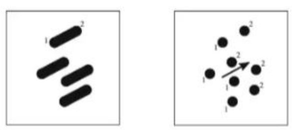
In the case of weak and strong velocity gradients, when there is a very weak velocity gradient and a strong velocity gradient, okay, in the same observational field, you have to reach a compromise. That means you can opt for a larger observation window. It requires bigger tracer particles because you know you have to get the light; the bigger the particles' scattering, the more you are going to use the same light source, and it does not always allow you to resolve the velocity close to the area where there is a very strong velocity gradient, okay? Because bigger particles may not be able to follow the flow if you are observing a large observation window. Now, for applications in gas flows, a high-power light source for illuminating the tiny particles is required because high power means a lot of scattering. As a result of that, you will eventually increase the visibility of the particle.

And you also have to expose a video sensor or camera. In principle, there is a need to use larger particles because of their better scattering, but this is in contradiction to the demand to have small particles because they have to follow the flow field. As we know, the smaller the particles, the more intuitively they should be able to follow the flow field faithfully. Now, in most applications, we need to arrive at a compromise. So the compromise is that one criterion for selecting a light source for DIV is that it must allow for the illumination of the observation area homogeneously, easier said than done, which means the profile of the beam will be expanded into a light sheet. It will be a Gaussian or a top hat profile as closely as possible without any holes or gaps.

So we already know what Gaussian beams are; you need very high-quality lasers. And the ambient conditions are also important in the sense that the optical setups need to be robust against ambient conditions. Vibrations, background illumination—all these things are important because if the setup, for example, is vibrating, what do you do? Because of everything, the image quality will be pretty bad. Sometimes you mount everything on the optical tables, breadboards, and even stages to minimize the duration of the illumination pulse. Now, if the pulse is short, the duration of the light pulse must be brief because you want to freeze it.

This is like a stroboscopic effect. That means in the theaters, if you see these stroboscopes, which freeze, you see the camera in this case, and your eye, like the camera, sees that the particles are frozen, right? So that means they do not really move during the pulse exposure. If they do move, you will see blurring or streaks. So, in this case, for example, you get streaks. In this case, you get a well-separated particle.

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 you need this rather than that. So, the duration of the illumination pulse is very important. That means it is short enough to freeze the motion. And have no streaks. Then, of course, the time delay between the two pulses is important because, you know, it must be long enough to detect the displacement between the images of the tracer particles with sufficient resolution, and short enough to avoid too many particles going out of the field.

Okay, because the particles are continuously moving, it should be very short. If this is a high-velocity event, then you have to make the time delay very short because there can be off-plane components where the particles can go out of plane or might go out of the interrogation window and stuff like that. The time delay between the illumination pulses must be long enough to determine the displacement. But it should not be so short that the particles do not really move, either. So you need to have a priori knowledge of the flow velocity or the kinds of velocities that you are actually dealing with.

So the repetition rate is another thing. For standard PIV, we use double-pulse NDAG lasers with two oscillators. The time delay can be very short, on the order of microseconds. you know, consecutive PIV recordings can be done, but you generally get it in 10 to 20 Hertz. However, high-speed lasers allow recording up to 100 KHz. These are mostly associated with a loss in pulse energy, resulting in very small observation areas.

So you cannot observe large areas because the laser power will not be sufficient. It will distribute it because we are making a sheet. So basically distributing the power everywhere. However, depending on the timescale of the flow phenomena, such systems may allow for a temporarily resolved measurement. I think it's a big thing because you sometimes need to resolve the flow physics at very high temporal resolutions.