Optical Methods for Solid and Fluid Mechanics
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Lecture - 16
Particle Image Velocimetry I

So welcome back. Now just to rewind in the last class we were discussing about tracer particles. We first discussed why in certain cases tracer particles may not follow the fluid flow. So by this time I hope you are all at a situation where you have a good intuitive feel of how to select tracer particles we will discuss that in a little bit more detail in the coming lecture.

But overall I hope you have got in a good idea of what goes behind selecting a proper tracer particle and then we talked about how particle tracking velocimetry is probably one of the most intuitive ways of understanding flow field or quantifying flow fields. We will also see in today's class that PIV which is particle image velocimetry although the names are very similar particle tracking velocimetry and particle image velocimetry so PTV versus PIV.

PIV is a far more evolved technique and is conceptually very different which is why I wanted to introduce to you the idea of PTV, I will continue that demonstrating PTV today with one example. So, let us take a look at this now this example I am taking from one of my own works that I did almost more than a decade ago and to just explain to you I will show you a video in the next slide.

What I am going to show you is the result of an imaging under a microscope in a flow in a micro channel and in the outside of the experimental box.

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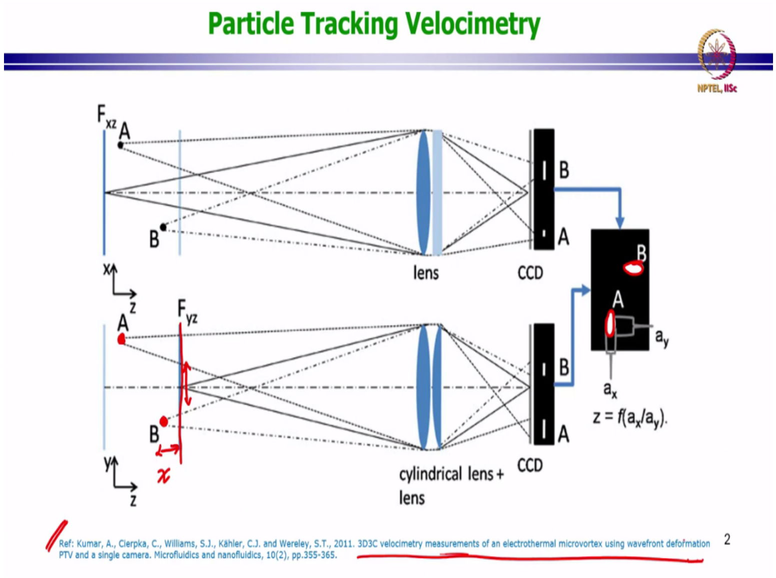

What we have is. We have a lens here and a cylindrical lens that have been put together and because of that what happens is the particles which are nice spheres when they are imaged on the image plane they actually look as ellipses. So and what happens is this is let us say the focal plane the further away the particle is from the focal plane the ellipse is of a slightly different nature.

So, by actually measuring this ellipse we can also measure this z direction displacement. We can also measure x and y and we can also measure z. Now this is the reference for this manuscript if you wanted to read this up. This is based on a technique that was demonstrated a few years ago by another set of our collaborators. So, you can look up both those papers all the references are there in this particular case.

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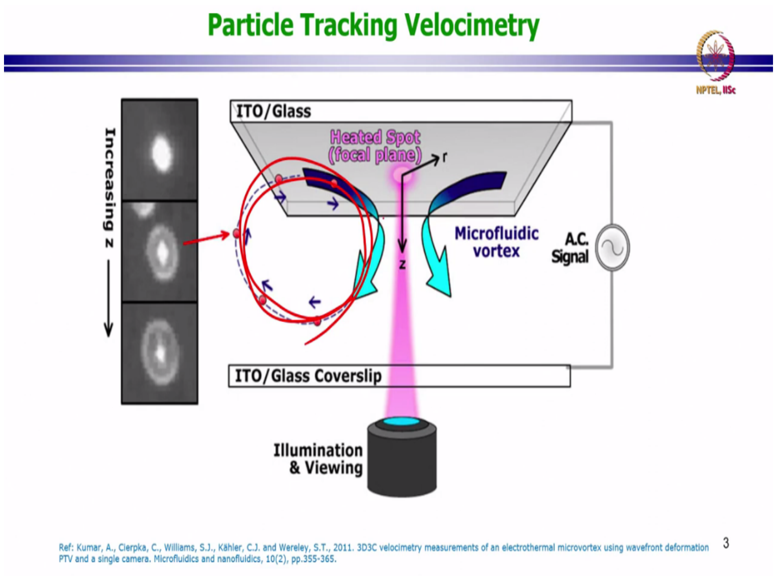

I will just also explain to you what you are going to see. So, this is an example of a flow in a micro channel where this actually it is an electro kinetic flow there are two glass slides and actually this is Indium tin oxide. So, this is actually conducting glass slide and the distance between this is of the order of 50 or 100 microns and it is being heated by laser which is causing a strong electro thermal flow and the particles are moving in a vortex.

So, they are moving into this vortex loop and we are going to image this as the particles move at different locations in this vortex. So, this is what is being observed. So, the particle the overall flow is not changing with time or the overall nature of the flow, but the particles are just going in this loop again and again and again. **(Video Starts: 03:50)** So, I will show you the video right here so the center of this is now a view from the top.

So, you cannot see so it is somewhere here the center of the laser where these things are now caught in a loop and the loop is now outside of the plane of viewing. So, I will play this video. So, what you saw here is this particle is moving in different locations and now at one point if it is very far away from the focal plane the ellipse is bigger in this case whereas if it is nearer to the focal plane right here the ellipse is smaller.

So, from the size of the ellipse we can figure out the z direction location and x y is obviously known because this is the x y plane so this is the x y plane. Now if you recall in the last lecture we had said for particle tracking velocimetry the particle population has to be sparse. So now let us just look at this video one more time and I ask you to do one thing look at this video and ask yourself if you are able to intuitively follow each particle.

And as the video progresses and whether at any point you are confused about which particle went where. So, I hope you are able to follow it is not that difficult there are times when two particles start to overlap and there is a little bit of confusion, but if you go through the individual frames just figure it out very carefully which particle is where in each and every frame.

So, this is what we meant by saying that the particle population should be sparse and you should be able to follow each and every particle because we are measuring the displacements of each and every single particle. So, then you can reconstruct the vortex we have done that and you can look this up in the paper I am not going to go into the details of what the results were obtained.

But I just wanted to show you an example of PTV because now I want to contrast it with a video of PIV of something and this again I have shown you before, but I want you to look at this video one more time and specifically contrast this again a flow through a micro channel. So, it is a slightly different type of a flow is a two dimensional flow going from left to right and there is a micro channel here which will have edges.

And again this is the appropriate reference for this the PIV data that we have processed that is also available in this paper if you wanted to go through it again this the first author is it is me so this again from one of my works. I am going to stop this video for a second here and as this video progresses I am going to ask you again to do what I had asked you to do in the last video which is to try and see if you can actually look at particle centers.

And with your naked eye can you resolve a particle and where the particle is in the next frame. So, we are now going to magnify this. So, where you are able to follow the individual particles in this particular video my own answer is no. I mean it is some particles here and there you may be able to follow, but this huge number of particles it is impossible to try and follow each and every particle and see where it went.

However, just like the previous case the previous case also at tracers this also has tracer particles. In both the cases the movement of the tracer particle by the way the tracer particles have already been carefully selected so that you do not have to worry about particles not following streamline. So, in both the cases the particles are following fluid flow stream lines and however the two videos are very different in nature.

And yet even in the second one you are able to visualize the flow or at least perhaps hopefully get an intuitive understanding of the flow field. So, that is exactly what particle image velocimetry does and sorry so this is particle image velocimetry sorry this is a mistake. So, now in particle image velocimetry the idea now is to follow a large number of particles so this is this is a synthetic image that we have generated using a computer.

But it shows you an example of what a typical PIV image might look like and this is a huge number of tracer particles so all these red particles, for example, here this is a tracer particle, this is another tracer particle and this is image 1 taken by the camera and this is image 2 I have deliberately colored it differently deliberately. I have deliberately colored the first one red and the other one gray because I want to show you a difference.

Now again I encourage you to try and see the same set of particles that would have moved somewhere in the second image, is it easy for you to follow intuitively which particle has moved where my own answer again is no it is very difficult. However, see what happens when I overlap the two images. When I overlap the two images you can see that there is a particle population.

So, you can see that there is a shift so this white particle here, this red particle here is shifted a little bit and similarly in many other cases. So, the white image is shifted a little bit compared to the red. So, in this small shift is where is the information located of this background flow and that is exactly what particle and again I am sorry this is a mistake this should have been image tracking.

So, with that what I want you to do now is to discuss the basic principle behind PIV. In order to do that what I have drawn is sort of an abstract diagram of a generic PIV setup I am going to explain to you all these different elements in this particular image in a second here. So, in order to discuss this better it is easier for me if I switch to my notepad. **(Video Ends: 11:42)**

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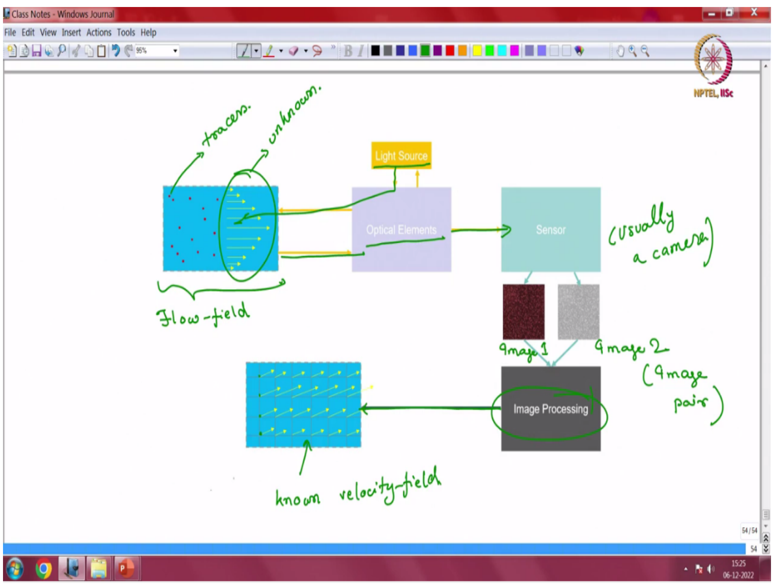

And this is the same image that I had shown you before. Now this here this showcases let us say a flow field so there is some flow that has to be measured these are tracer particles they have already been properly selected. There is some velocity obviously there is a velocity, this velocity is unknown. So even though I have drawn arrows like this we do not know these arrows or the value of these arrows a priori.

The entire idea is to figure out what this flow profile looks like. To do that we have to select the proper optical elements and I will tell you what the optical elements are when I show you particular examples and we have to select the proper light source. So, the light source sends light via the optical elements to my tracers. So, this light comes and it interacts with my tracer particles and then the light goes back from the optical element.

And then this light goes to the sensor. Once it goes to the sensor the sensor is usually a camera we have discussed this before and the camera takes two images. So, this is again image 1 and this is again the kind of image I showed you before and this is image 2 and it takes many such images. So, this is also known as the image pair and we will see why the image pair is important when we understand processing a little bit and these two images are now used by my image processing tool.

Once this image processing tool is used then I get a velocity flow field. So, what I get is an Eulerian velocity flow field where I divide my entire image into grids and each of these grid points I can determine my velocity field so this is now your known a quantified velocity field or the Eulerian velocity field. Now what optical elements, what light source, what sensor what image processing or what are the parameters of the image processing.

These all depend upon the particular circumstance which is why PIV it is important to understand the basic principles behind PIV in order to appreciate that. **(Video Starts: 14:35)** So, what I am going to do now is I will show you two examples of particle image velocimetry. So, this is a gif image is taken (()) (14:47) somewhere else, but this is a very nice illustration of a particle image velocimetry there is a laser source.

This laser is not a continuous wave laser it is actually a pulsed laser. So, it emits a laser pulse, there is a cylindrical lens. We have been discussing cylindrical lens quite a lot and this is the reason for it. This laser comes out as a cylinder or a small beam and then it becomes a light sheet. We will go into light sheet optics also in a moment, but first this is a mirror which just directs this light sheet.

So, the flow is coming in from left to right and the particles are coming along with it and there is this bluff body that the particles or the flow passes over and then you have a special camera called also the cross correlation camera. This camera in a single exposure takes two frames. So, it has taken two images which is image 1 and image 2 which is why we were talking about image pairs.

And then we will see how we do the image processing which is the cross correlation bit. This is the image processing here and then you process it and finally get the velocity field the known velocity field. So, this is a very good example of a large scale or lab scale PIV setup or a macro scale PIV setup that is often called and I will contrast this a little bit with the conventional PIV setup with the micro scale sorry this is microscale or microscale PIV setup.

In a microscale PIV setup differs in the sense that you might have flow in a micro channel so this could be a microfluidic device or a lab on a chip device which is a very small device. Now this device is small enough that it has to be mounted on a microscope for you to see and you have a double pulsed laser just like before it also passes through some optical elements. So, this is this optical elements here, but now this optical elements are very different than the optical elements you saw before.

So, here you have a different set of lenses this is a diffuser etcetera that are there and it goes into and shines on my tracer particles here and then the images are recorded by a camera and again the post processing is actually very, very similar because it uses the same idea of cross correlation. This particular image is taken by a book chapter that I wrote quite some time ago. Again the exact reference is given here this is the book chapter name of the book chapter optical flow characterization.

Micro particle image velocimetry and the name of the book is Methods in Bioengineering, Biomicro Fabrication and Biomicrofluidics published by (()) (17:39) and to show you the difference between the two setups. So, you have seen how this same idea of having optical elements, having a sensor image pairs, etcetera is how it is very different in these two cases.

So, here the set of optical elements that you might use or even the light source you might use might end up being very different.

The tracer particles between conventional particle image velocimetry and a microscale particle image velocimetry can be very, very different. **(Video Ends: 18:16)** So, this hopefully gives you an idea of the different, aspects of particle image velocimetry. So, we are now ready to discuss different aspects of this particular diagram. As you can see the foremost issue right now is the issue of tracer particles which we have been discussing for some time right what tracer particles why.

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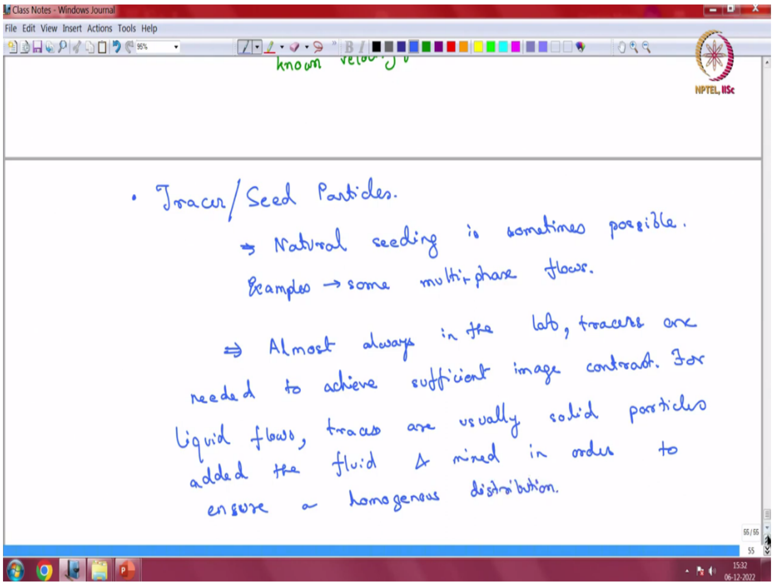

So, the first and the foremost issue is the use of tracer slash seed particles. We have been discussing the idea of tracer seed from a theoretical perspective, but now we will come to the practical perspective here. Now natural seeding is sometimes possible not always. So, natural seeding is sometimes possible by which I mean that you need not have to add an external tracer particle example is some multiphase flows.

But in lab cases almost always in lab tracer particles have to be added almost always traces are needed to achieve sufficient image contrast a signal and for liquid flows sorry not liquids for liquid flows tracers are usually some sort of a solid particle added to the flow added to the fluid and mixed well in order to achieve homogeneous distribution. This homogeneous distribution is obviously very important.

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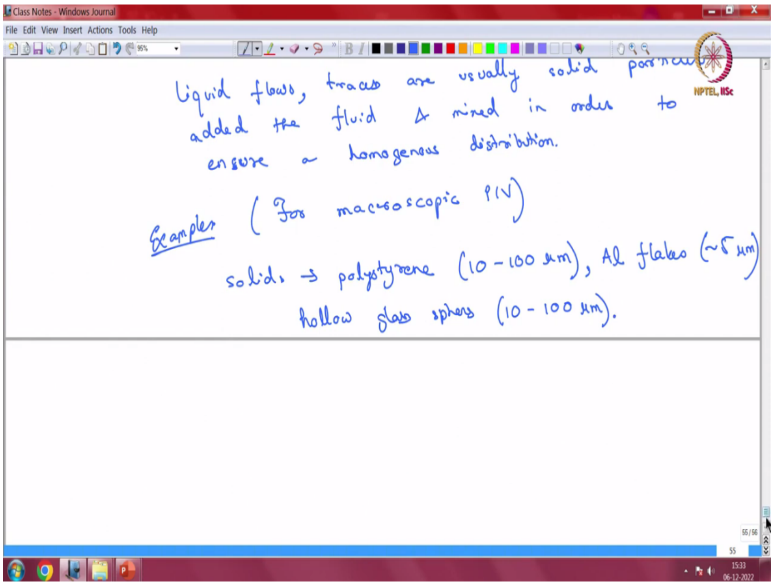

Now examples of this for macroscopic PIV; so macroscopic PIV, examples for solids are polystyrene particles sometimes between 10 to 100 micron it obviously the size is dependent on the type of flow and your particular case aluminum flakes are also used sometime around 5 microns. Bigger aluminum flakes can sediment which is why it can be a problem, hollow glass spheres by the way these numbers in the brackets these are just indicative.

So, this is usually what is done in every case has to be understood and evaluated on its own merit. So, I am not going to say that these are just suggestive numbers. So, hollow glass spheres of the order of 10 to 100 microns are often used in different experiments.

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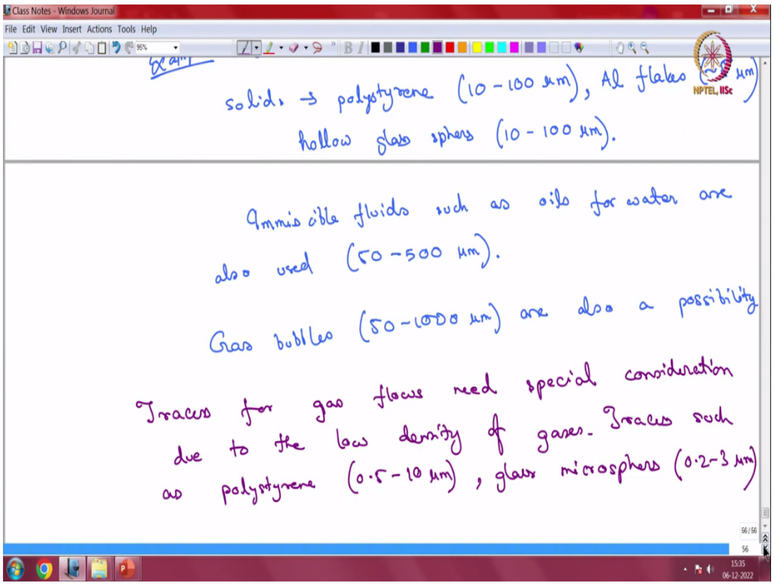

Immiscible fluids such as oils for water are also used again between 50 to let us say 500 microns. Again these are all indicative numbers gas bubbles 52,000 microns are also a possibility. So, we can see we are discussing some of the practical aspects of adding a tracer and you will have to figure out your tracer particles for yourself. So, now traces for gas flows are slightly different.

Gas flows they often need special consideration because of the density mismatch, the low density of gases. So, tracers again such as polystyrene 0.5 to 10 microns again a suggestive number glass microspheres again a smaller value let us say 0.2 to 3 microns.

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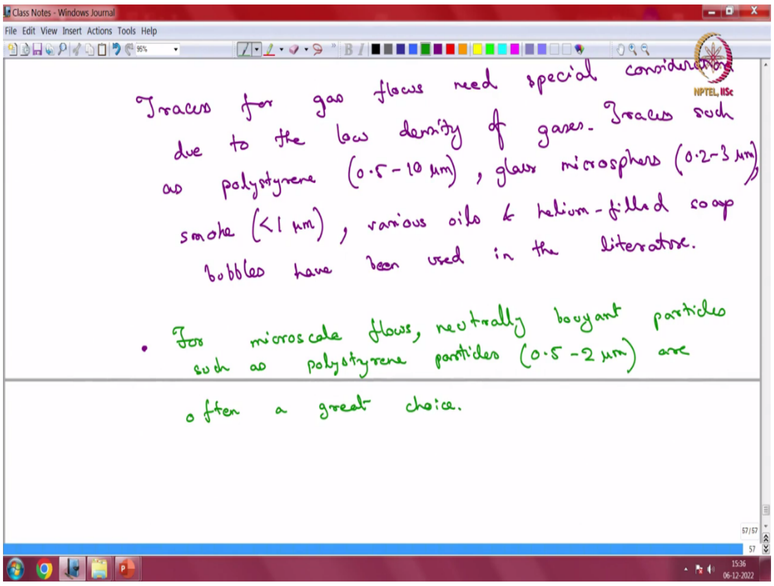

Smoke can often have particles that are very small so they can often be less than one micron various oils and helium filled soap bubbles have been used in the literature. Now for micro scale flows we are just going to use a different color for microscale flows. Again the particle size has to be small enough compared to the channel size neutrally buoyant particles such as hollow polystyrene particles I am not going to write hollow just write polystyrene particles.

The size again is really dependent upon the geometry you are using, but again I am just giving an indicative size. They are often a great possibility a great choice. They are often fluorescent also in microscale flows. So, microscale flows quite often applies fluorescent particles. So, now I will contrast this. So just here we said that hollow glass microspheres are used for microscopic PIV.

So, if you recall this particular video which you have already seen this is a flow. So, these are hollow glass spheres of the order of some 9 to 14 microns. So, hollow glass spheres whereas in the videos that you saw before, for example, in this particular video these are 2 to 3 micron particles polystyrene again and in this case again these are very small particles polystyrene suspended in water in both this video and the previous one these are both fluorescent imaging cases.

Whereas in this case the glass spheres are not fluorescent they are just scattering of light that is shining upon them. So, there is a laser that is shining from the side and the glass hollow spheres are just scattering that light and appearing on the green in the image because the imaging has been done with a DSLR camera which is a color camera. So, hopefully we can see that there are many different aspects of conventional PIV setup.

And the first and the foremost was the issue of tracer particles and in the next lecture we are going to talk about different light sources and some of the other aspects of particle image velocimetry. So, we will end here and we will take this up, we will start off from exactly where we left in the next lecture. Thank you.