Multiphase Microfluidics
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Lecture – 20
Particle Image Velocimetry

Hello. In this lecture we are going to discuss Particle Image Velocimetry. So, this is one of the most powerful techniques and very frequently used in recent years to measure the velocity in different configurations different systems including in microfluidics. For microfluidic applications there are some issues that need to be resolved and some changes need to be made in the experimental setup and the corresponding experimental setup is known as Micron Particle image velocimetry or Micro Particle image velocimetry.

So, as the name suggests that in particle image velocimetry velocity cimetry means; the velocity is measured and this velocity is measured by the images of the particle. So, where do the particles come, because what we are talking about is the flow of fluid? So, this flow or any flow that we are measuring the velocity in this flow is seeded with the particles. Seeded means particles are introduced in the fluid the concentration of the particles is small, the size of the particle is small, and one of the major requirement of a the technique is that the particles should follow the flow faithfully.

So, to get that once we have the particles such that these particles follow the flow faithfully, then the velocity by taking the images of these particles of the velocity of the particles is measured by post processing techniques or analysis or image analysis. And then the velocity, because the particles follow the flow faithfully the velocity of the flow is obtained as the velocity of the particles. So, the technique is called non-intrusive flow measurement techniques.

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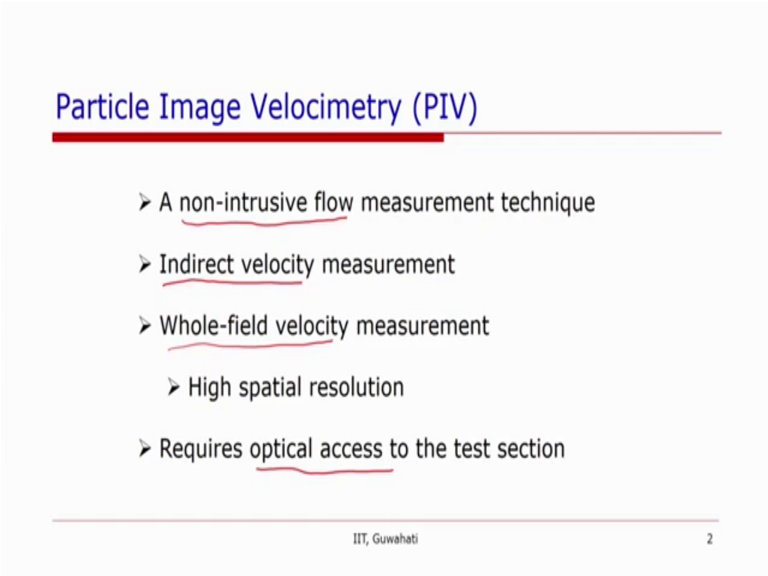

So, the non-intrusive means that in this technique no intrusion needs to be made in the flow. For example, in the pitot tube we need to insert the pitot tube in the flow or so that the measurement of the flow can be made at that particular point unlike that the particles are introduced in the flow; however, we have the requirement that the particles should not affect the flow. So, the particle does not affect the flow field and we do not introduce any sensor or any probe as such in the flow. So, the flow field is not disturbed and the flow can be measured accurately.

So, it is called non-intrusive flow measurement technique, then the velocity measurement is indirect as we are not measuring in the technique the velocity of the fluid particles or the fluid molecules directly rather, the velocity of the of the solid particles or the liquid particles or the tracer that is introduced in the fluid is measured and from that the velocity of the fluid is measured. So, that is why it is called an indirect velocity measurement technique.

The whole field velocity measurement so, if you have looked at some of the images in computational fluid dynamics; that means, you can get the velocity field at a particular cross section or a in the in the computational fluid dynamics, what one does is solves the navier stokes equations in the entire computational domain this computational domain might be 2 dimensional or 3 dimensional.

So, in this computational domain one obtains the velocity field at different points or in the entire computational domain for example, in a 2 d plane.

Similarly, in this technique one obtains the velocity field at a 2 d plane for the entire plane in which the measurements has been made, unlike the point probe method where the velocity at a particular point are measured apart from this there are very few other techniques, which can do the whole field velocity measurements.

Say for example, other technique is laser Doppler velocimetry which is based on the Doppler Effect and radioactive particle tracking, which can measure the velocity based on the attenuation of the radioactive material or radioactive particle that is introduced in the flow.

The special resolution of this technique is very powerful and is limited by the special resolution of the camera that is used to take the images of the flow. So, the more powerful camera one has the more number of pixels one have on the sensor and the more or the better special resolution one can get for the flow. The optical resolution will again be limited by the frame speed of the camera or the speed at which the camera can capture the images as well as the speed of the laser.

One of the limitations of the technique is that it requires optical access to the test section. So, the optical access means that the light should be able to enter the test section and it should be a transparent so, that the images of the test section can be captured. And this is not possible say for example, if one wants to take velocity measurements in an experimental setup or in an industrial conditions, most of the pipes or the industrial equipment will be opaque.

So, there is no optical access as such and one might either need to have an optical window to measure the flow or need to mimic that is in the industrial conditions in a separate experimental setup.

This can also be a problem the optical access can be a problem even in a transparent setup, when one have a multiphase flow and the visibility or the or the transparency of the flow is affected by the presence of the large number of dispersed, particles, or dispersed bubbles or droplet us. For example, in a bubble column where a number of bubbles are present in the fluid it might be challenging to take the images of the fluid in a in a bubble column.

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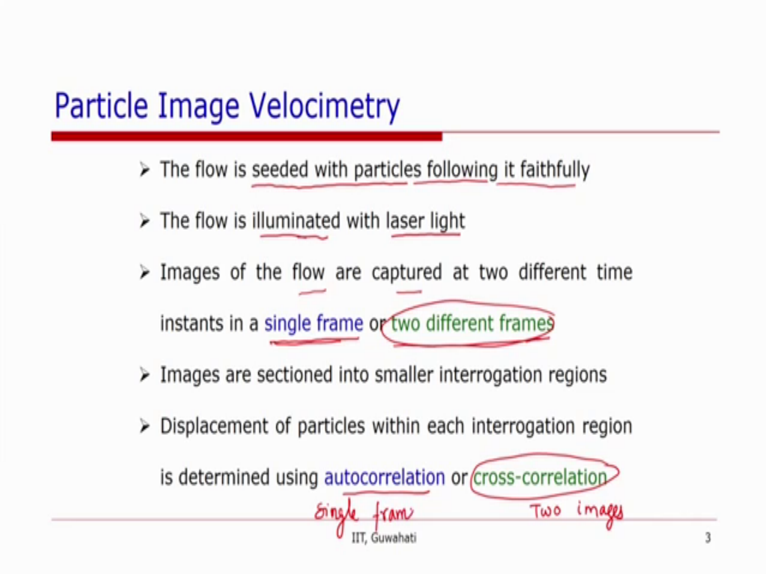

So, in this technique the steps are that the flow is first seeded with particles the particles they should be following the flow faithfully they should be moving with the fluid. So, the velocity of the particle should be the velocity of the fluid at that particular point, then this flow is illuminated this is often done using a laser light, but sometimes for a cheaper equipment one can also have white light or nowadays with the development of led lights led lights are being increasingly used for PIV applications.

So, the flow is illuminated with a light generally a lasers are used because the light from the laser is monochromatic light so, that is why the laser light is preferred and then the images of the flow are captured. So, generally the lasers that are used for PIV applications they are double pulse laser. So, the one light wave or light pulse is introduced or is sent to the test section and image is captured and within a small time duration another pulse is sent. So, the 2 pulses or 2 light waves are sent at a time instant or time difference of delta T and with this known time difference the images of the particles are taken.

Now, these images may be captured in a single frame. So, the images of the particles are may be captured for the 2 d 2 pulses in a single frame or they may be captured on 2 different frames. And then these images are sectioned into or divided into smaller interrogation areas and then the corresponding interrogation areas from these 2 frames are analyzed, in case of a single frame using autocorrelation and in case of 2 frames using cross correlation. So, cross correlation where we have 2 images and when it is captured in a single frame one uses autocorrelation technique.

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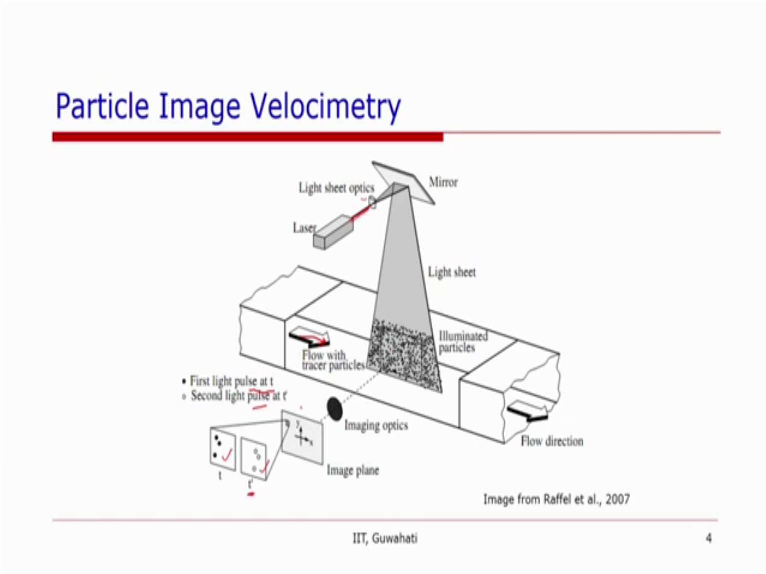

So, this is a typical schematic of a PIV setup, you can see that this is the test section in which the flow is happening from in this direction and this flow is seeded with the tracer particles. Now the laser light is introduced on it and you can see this that the laser light in a 2 d PIV system for a conventional channels or large channels the laser light is converted using light sheet optics it is converted into a light sheet.

So, it illuminates a 2 dimensional plane of a small thickness of a small order of small width in the test section and the velocity in this test section is measured this will be measured by imaging optics.

So, it is the velocity is measured at first light pulse is introduced at time T and another light pulse is introduced at time T dash and so, 2 images at time T and at time T dash are captured these are the particles which are illuminated. So, the light scattered from the particle is taken into the camera.

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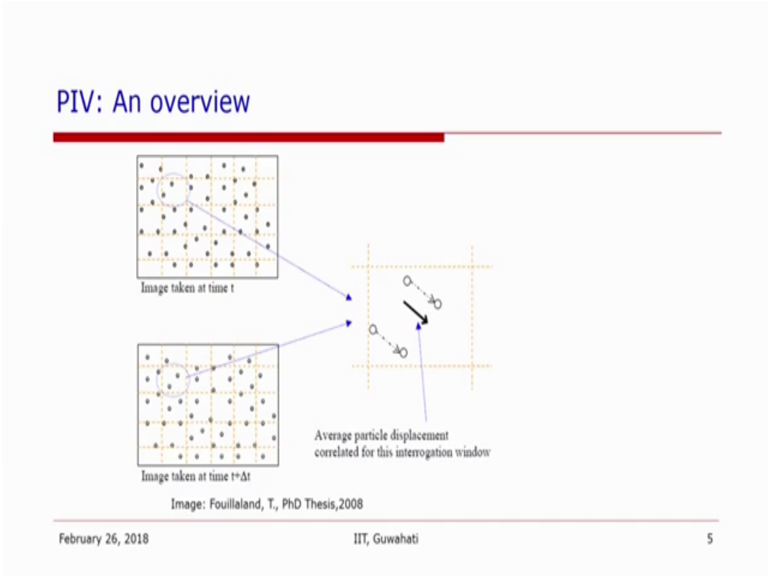

Now, these 2 images which are taken at time T and time T dash which is equal to time T plus delta T they are cross correlated and from that the average displacement of the particle is obtained for each interrogation window. So, the local velocity field in the each interrogation window is obtained by cross correlation technique.

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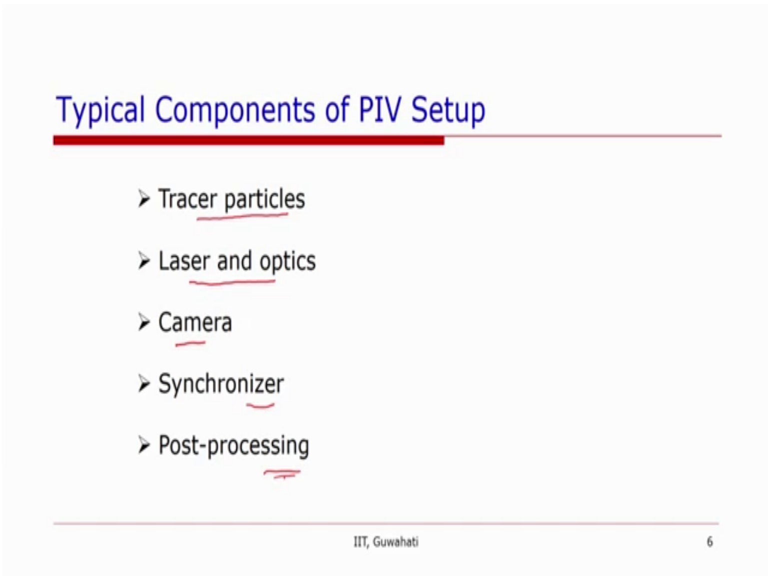

So, by looking at this experimental setup we can identify the main components of the PIV setup. It is important as the technique is dependent on the tracer particles following the fluid. So, it is important to have the tracer particles on a case to case basis depending on the fluid phase. For example, the a fluid is gas phase or liquid phase the density of the fluid or the size of the test section all those considerations needs to be taken into account when selecting tracer particle for a particular PIV application, then the laser and optics.

So, the type of laser and the light sheet and other optical accessories they need to be taken into account or they need to be they are the main components of the setup. And the camera in which the images are to be captured the resolution of the camera as well as the frame rate of the camera will determine the spatial and temporal resolution. Of course, for the temporal resolution one also need to have a high speed lasers only then the time resolved PIV or very high flows can be captured, because until unless one have a high speed lasers high speed cameras will not be useful for capturing the flow at large velocities or high velocities.

A synchronizer will be required, which can synchronize the camera and laser. So, the pulse the synchronization between the light pulses, which are sent to the test section and the images that are captured they can be synchronized. And then finally, once the images has been captured lot of work needs to be done into analyzing the flow a number of a software's, open source software's are available on the web as well as all the OEMS all the a manufacturers of PIV systems. For example, Dan tech dynamics law vision as well as TSI, they have developed their own post processing tools to analyze a flow in these systems.

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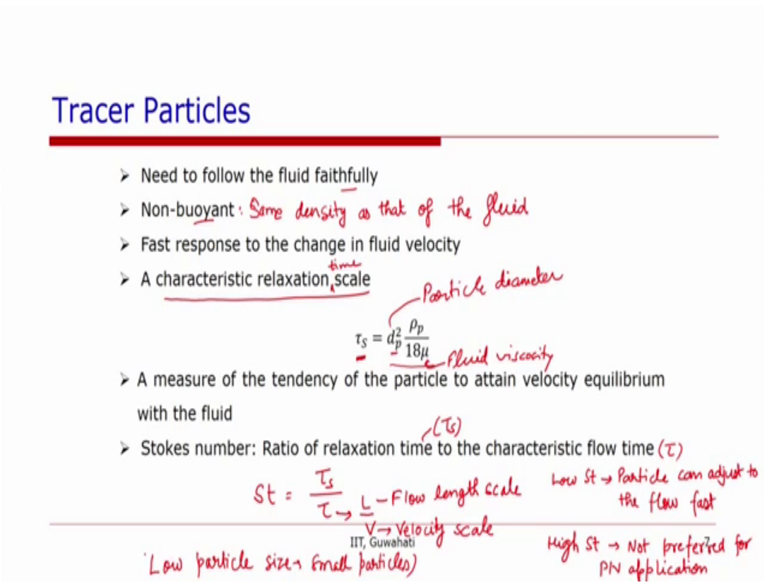

Now, we let us look at these components one by one. So, the tracer particles if they do not have the same density as that of the fluid, then the because of the buoyancy the particle will have a motion of their own in the fluid. So, it is often advisable that the particles are non-buoyant or so, they have the same density of as that of the fluid fast response to change in the fluid velocity.

So, the particles if they are in stokes regime then the particles can follow the flow faithfully. Now for a stokes flow one can derive the characteristic relaxation timescale that is the time, which is required for the particle to respond to the change in the velocity of the fluid.

So, the TS is the a characteristic relaxation time which is given as dp square rho p over 18 mu is fluid viscosity rho p is particle density and dp is particle diameter. So, this relaxation time is a measure of the tendency of the particle to attain velocity equilibrium within the fluid. Now a non-dimension number is defined, which is called stokes number ratio of the relaxation time to the timescale of the flow, which is the ratio of a flow length scale and the flow velocity scale.

So, the characteristic flow time is tau and characteristic relaxation time we write as tau S which is given by this. So, flow length scale for example, in a channel it will be the hydraulic diameter of the channel V is the typical velocity or the average velocity in the channel.

So, that gives us a measure of the tendency of the particles to attain the velocity of the fluid, low stokes number means the particle can adjust to the flow fast, because the characteristic that the relaxation time is smaller than the a flow time is high strokes number suggests that the fluid inertia will be important and it will not be good for PIV. So, this will not be preferred for and because it will take a particle will take some time or the relaxation time will be comparable to the flow time.

So, it will affect the measurement and particle may not represent the fluid velocity.

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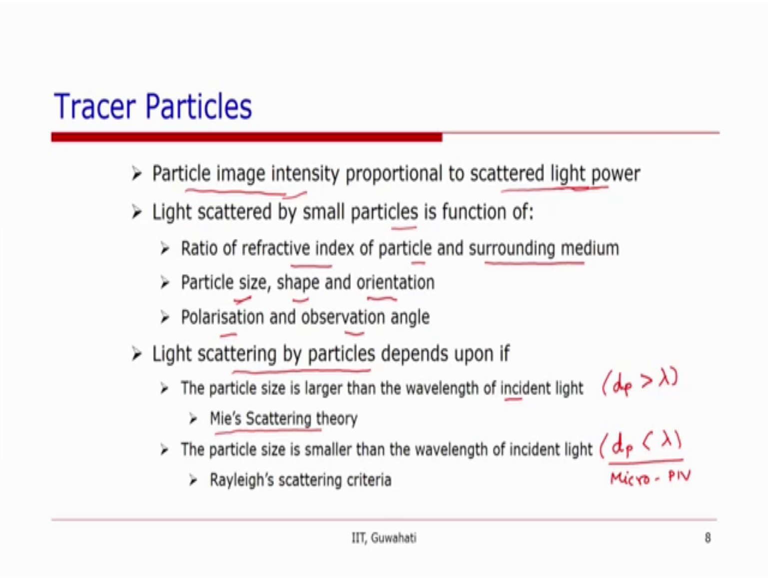

Now, so the considerations we just now discussed based on the stokes number, that is for from the fluid dynamics considerations which require that as we see from here that the relaxation time or the stokes number is proportional to dp square. So, one will prefer from these considerations that low particle size or small particles will be preferred so, that they can follow the flow faithfully.

However, there is another requirement which comes from the optical requirement. Now it is known that the particle image intensity the intensity of the image that is captured it is proportional. So, the better the image intensity the better contrast and better image one will get for post processing or for analysis post processing generally refers to process the image to obtain, the velocity field or to obtain the displacement and from their delta x over delta T one gets the velocity field.

So, the particle image intensity is proportional to the scattered light that is of light power. So, the light that is scattered from the particles, now the light is scattered by small particle that depend on a number of factors which are the ratio of refractive index of the particle and the surrounding medium, which is the fluid of which the velocity is being measured it also depends on the size of the particle, the shape of the particle, and orientation of the particle, while if the particle is spherical then shape and orientation will not matter. So, much, but the size of particle will do and it also depends on the polarization and the observation angles.

Now, there are 2 different criteria, which according with to which the light scattering by the particle can be they can depend upon. So, one is that the if the size of the particle let us say the size of the particle is dp is greater than lambda, which is wavelength of the incident light remember. We talked about when we talked about lasers we said the lasers are preferred, because in a PIV we would like to have monochromatic light. So, there is one particular wavelength of the light that is incident on the test section or on the sample.

So, if the size of the particle is larger than the wave of the a wavelength of the incident light, then one uses Mie's scattering theory or Mie's scattering criteria or when the particle it is smaller than the wavelength of the incident light which will be the case in a micro PIV, then one need to use a Rayleigh scattering criteria and this criteria have a different dependence of the scattered light on the particle diameter.

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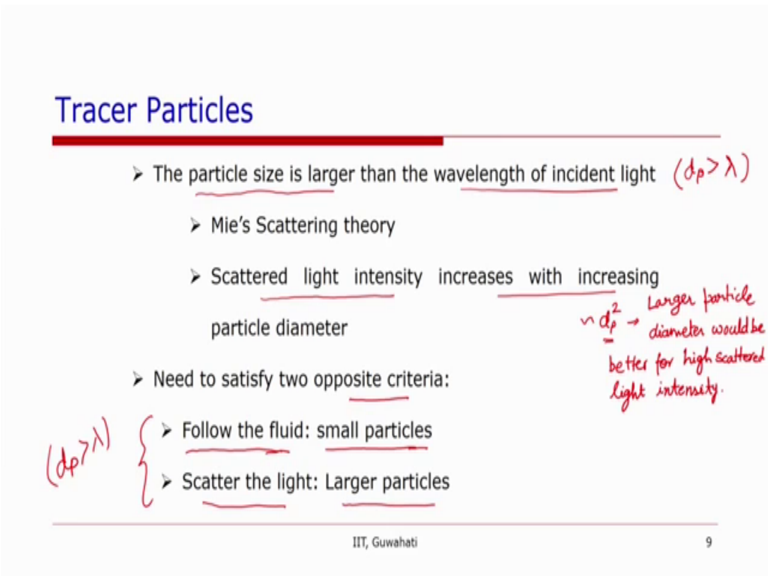

So, looking at the Mie's scattering criteria which is when dp is greater than lambda, when the particle size is more than the wavelength of the incident light, it has been observed that the scattered light intensity increases with increasing particle diameter it is probably proportional to dp raise to the power 2.

So, one would prefer larger particle diameter would be better for, now one need to satisfy 2 opposing criteria. For small particles the condition of that the particles should follow the fluid one should have small particles. And for the case when the particle size is larger than the wavelength of the incident light so, this criteria is when dp is greater than lambda. Then from the fluid dynamic considerations one would prefer a small dp and from the optics considerations one would prefer a larger particle diameters the one would need to have a balance between the 2 conditions and decide the size of the particles.

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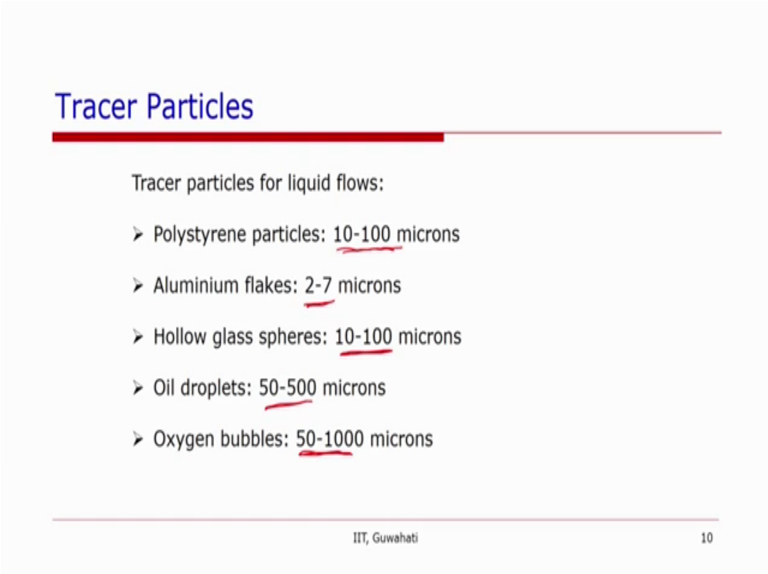

So, here are typical particles that are used for liquid flows in general or in conventional channels. So, polystyrene particles, which are of the size between hundred or 10 to 100 microns, aluminum flakes, size between 2 to 7 microns or the hollow glass spheres, which is where the size between 10 to 100 microns oil droplet us between 50 to 500 microns oxygen bubbles and the size can vary between 50 microns to 1 mm. So, these are some of the tracers that are used for liquid flow in conventional channels.

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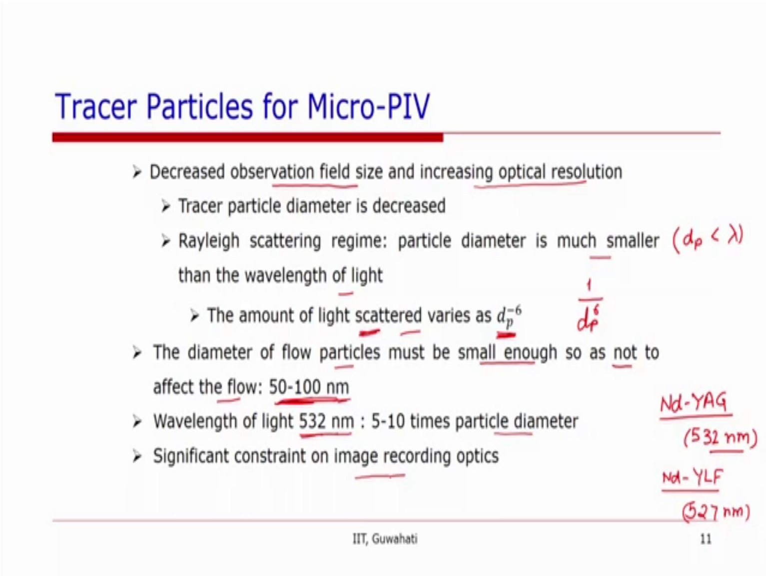

Now, when we come to the other criteria we have the tracer particle size is less than the wavelength of the channel, which will occur when the observation field size is decreased and increasing optical resolution is required. So, in this case for example, the best example for this is micro PIV applications or so, when one needs to measure the flow velocities very near to the wall. So, in such cases the size of the particles will be required for example, if we are looking at a flow in a 100 micron channel then of course, one will need to have smaller particles one cannot afford to use the particles which are of the size of say 50 micron.

So, in such case the particle diameter is smaller than the wavelength of the light. And the amount of light that is scattered the scattered light varies as dp raised to the power minus 6. So, the scattered light is one over dp to the power 6. So, the Rayleigh scattering criteria requires the particle diameter to be as small as possible, which is opposite to needs scattering criteria, when we were considering the particles sizes greater than the wavelength of the incident light.

So, for such cases the diameter of flow particles must be small enough. So, as not to affect the flow of course, smaller the particle it will be good, but one also need to take into account that it does not affect the Brownian motion.

So, we will briefly discuss that in a later slide. So, the typical particle diameter that are used is between 50 to 100 nanometers and the typical generally Nd-YAG laser are used in many PIV applications, which has and the visible light in which the wavelength of the light is 532 nanometers. So, the 532 nanometer light or the other laser that is used is Nd-YLF again the wavelength is 527 nanometer so, these are the 2 often used lasers.

Now, this the wavelength of light in this case is 5 to 10 times the particle diameter, if we are using 50 to 100 nanometer sized particles. So, this places is significant constraint on the image recording optics.

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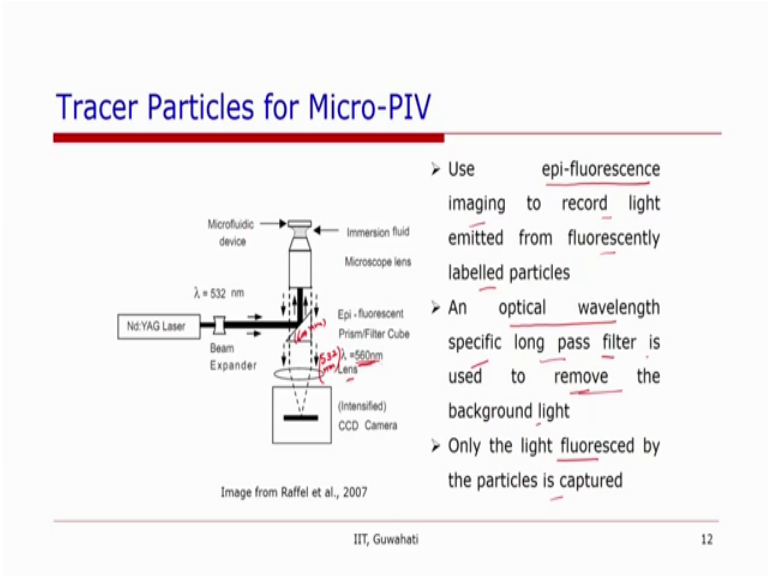

So, generally what is done in such cases or specially for micro PIV that a in place of the direct imaging one uses epi-fluorescence imaging to record light from the fluorescently labeled particle. So, the particles they are labeled flow by fluorescence. So, the particles are fluorescent particles and an optical wavelength specific long pass filter is used to remove the background light.

So, what happen that in micro PIV the particles which are introduced they are fluorescent particles. So, the fluorescent particles when the light is introduced over fluorescent particles they will emit a light with a smaller energy. So, we know that energy e is equal to hc over lambda. So, if a light of say 532 nanometer is incident on the particles the light emitted by the fluorescent particle will be of a larger wavelength. So, a long pass filter is introduced which allows only the larger wavelength particle say. For example, if 532 nanometer is the incident light and if let us say the light that is being reflected is 600 nanometer.

So, the filter will be such that it will not allow the incident light or. So, in this case say if we have a 560 nanometer lengths. So, this allows the light having wavelength larger than 560 nanometer to pass through it, but it does not allow the 532 nanometer large of 532 nanometer wavelength light. So, this a long pass filter removes the background light and the fluorescent light is sent to the image. So, the light fluoresced left floor by the particles is captured.

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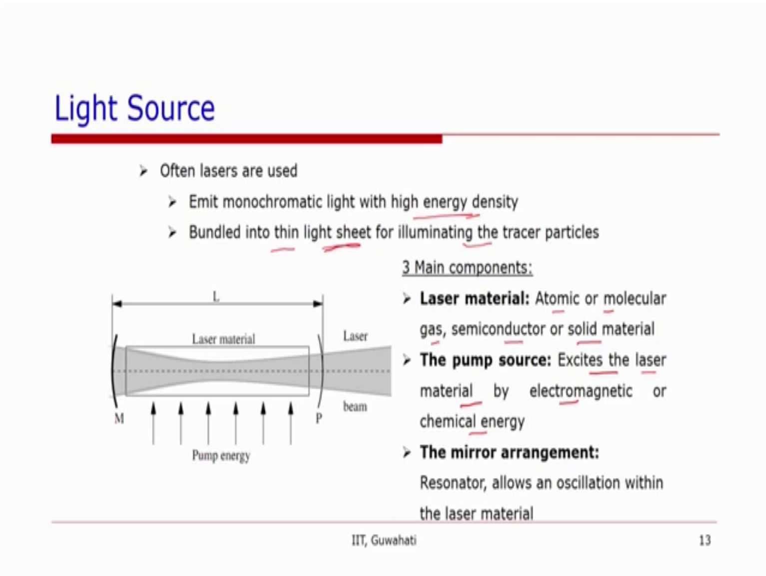

So, first we have discussed about the tracer particles and their sizes for a large channel applications as well as small channel applications and the 2 criteria, when the particle size is smaller than the wavelength and when the particle sizes is larger than the wavelength.

Now the light source that is used is often the lasers sometimes white light source is also used, but it is not monochromatic. So, there will be problems in terms of wavelength, but it is cheaper. So, for depending on the application and the accuracy required one can choose the light source, with the development in the light emitting diodes or the led lights in recent years then use of leds for PIV application is increasing and every day one have a new technique in which the led light can be used for a PIV applications is being developed.

Nonetheless the established PIV techniques generally use lasers more. So, because they emit monochromatic light and have high energy densities. So, for the lasers the wavelength of the light that is introduced and the and the energy density of the light is very important. Now this for conventional channels this light is converted using the light sheet optics it is converted into a light sheet to eliminate the tracer particles on a particular plane.

A laser, typically have 3 main components the laser material, which is which can be atomic or molecular gaze gas so, which will be the gas lasers or semiconductor or solid materials.

The pump source which excites the laser material by electromagnetic or chemical energy more and more lasers, which are used in PIV applications are diode pump lasers and the third component is mirror arrangement, which is a resonator which allows an oscillation within the laser material.

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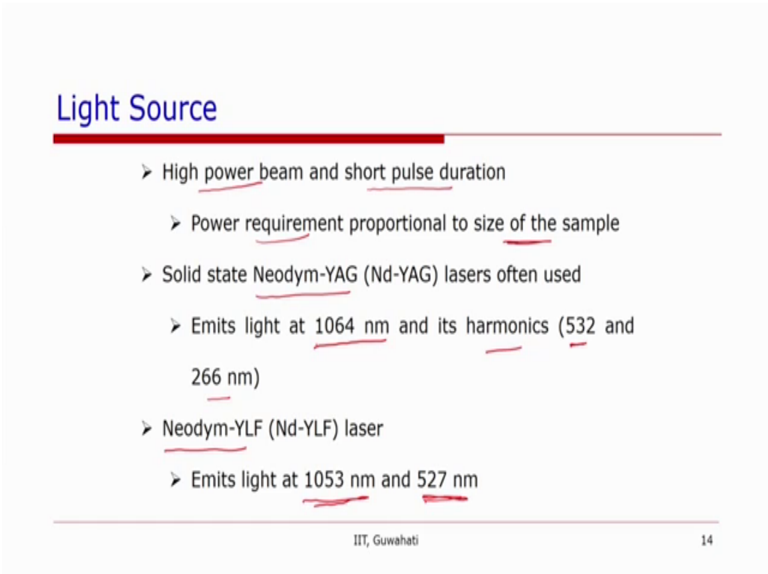

Now, so, the lasers this would have high power beam and sort pulse duration. So, the power requirement that is proportional to the size of the sample larger size more power is required. Now the 2 most often used lasers are Neodym-YAG laser and Neodym-YLF laser these lasers emit lights at the Nd-YAG laser they emit light at 1 0 6 4 nanometers and it is harmonics of 532 nanometer and 266 nanometers generally it is 532 nanometers that is used in the application.

Similarly Nd-YLF the ultimate light at 1 0 5 3 nanometer and 526 or 527 nanometer and it is the 527 nanometer, which is used in the PIV applications ok.

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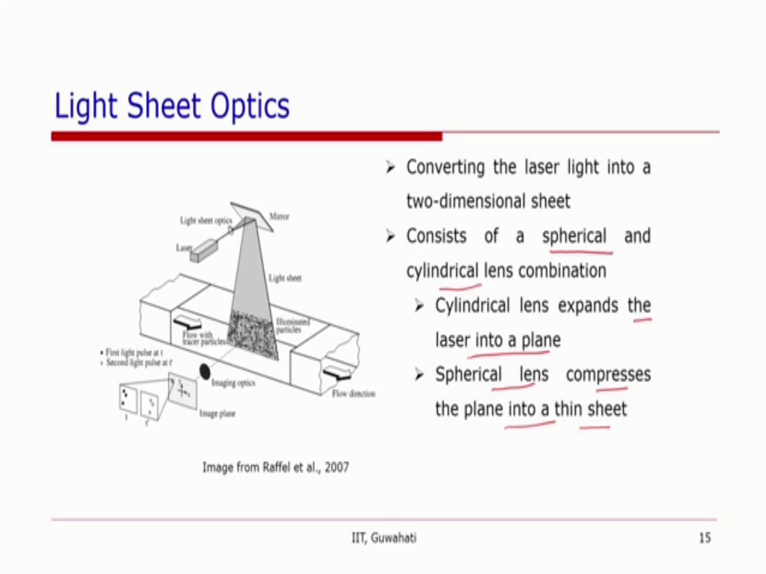

So, this laser is converted into a light sheet optics using a combination of a spherical and a cylindrical lens. The cylindrical lens expands the laser into a plane. So, that converts a laser into a plane and this a spherical lens it compresses the plane into a thin sheet. So, that is required for PIV applications in conventional channels whereas, the illumination is not a sheet illumination in micro PIV or to analyze the flow micro channels it is volume illumination as we have seen before.

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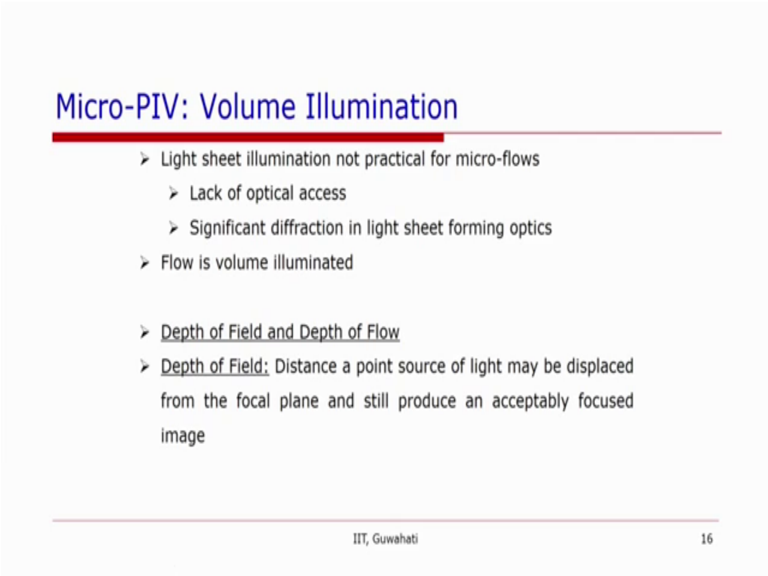

Now, the light sheet illumination is not used for micro flows because that light, which is generated it may be few nanometers thick. So, it is not practical to use a light sheet there and there will be significant deflection in the light sheet form optics. So, it is a volume illuminated flow is used in micro PIV.

Now the depth of field and the depth of flow the 2 things are compared when discussing the volume illumination. So, depth of field refers to the distance a point source of light may be displaced from the focal plane and still produced and accept we acceptably focused image.

So, the distance on the 2 sides of the focal plane where the and exactly we focused image is obtained is known as the depth of field.

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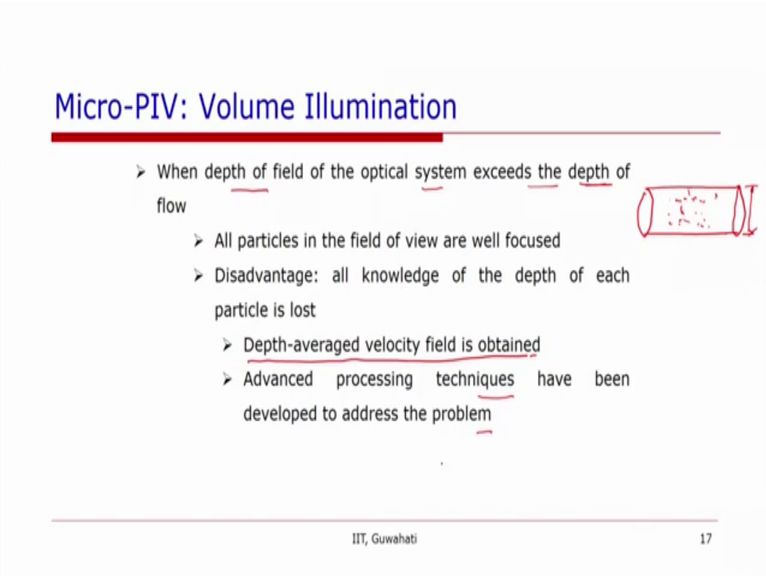

So, now the 2 cases can be there that when the depth of field of the system exceeds the depth of the flow. So, in this case what will happen that all the particles that are there in the field of view they will be illuminated, because all the particles are well focused. So, one will not have an idea for example, in a when one has a light sheet optics then a particular plane is illuminated.

But in case of volume illumination such is not the case and the entire volume is illuminated. And if the depth of field exceeds the depth of flow, which is the size of that the flow all particles will be well focused and so, the images will be captured of all the particles that are there.

So, one will not have an idea that one will be able to capture all the particles. So, if say one wants to take the velocity measurement, then one will know not know at what depth the information is from. So, what will be obtained is the depth average velocity field and the depth of the flow will not be taken into consideration.

So, depth is the third dimension of the flow will not be there; so to take into account this when the depth of the field exceeds the depth of the flow one need to have advanced processing techniques. So, this problem can be addressed.

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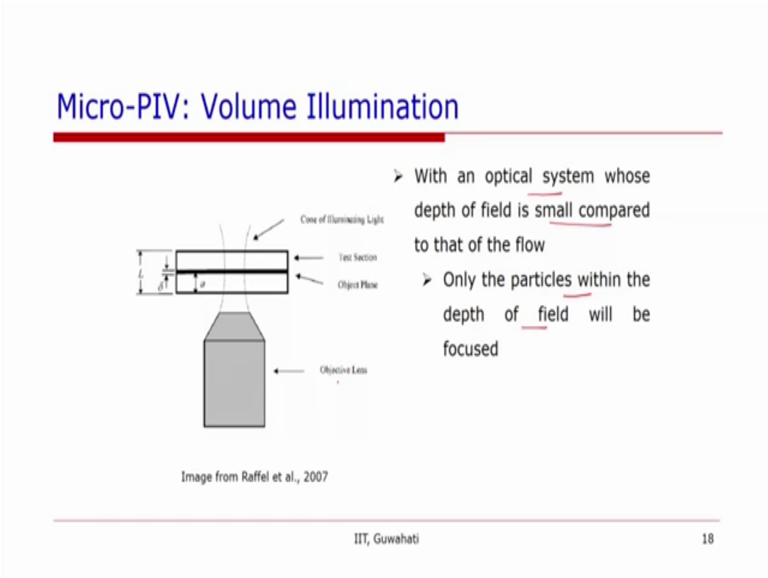

The other option is that one has an optical system whose depth of field is smaller, when compared with depth of the flow. So, only the particles that are there within the depth of field will be focused. So, in a volume illumination rather than the illumination the depth of the field from the optics are the from the objective lens is such that that if particular region in the channel is focused and of that particular region, the images will be obtained or they will be having a high intensity.

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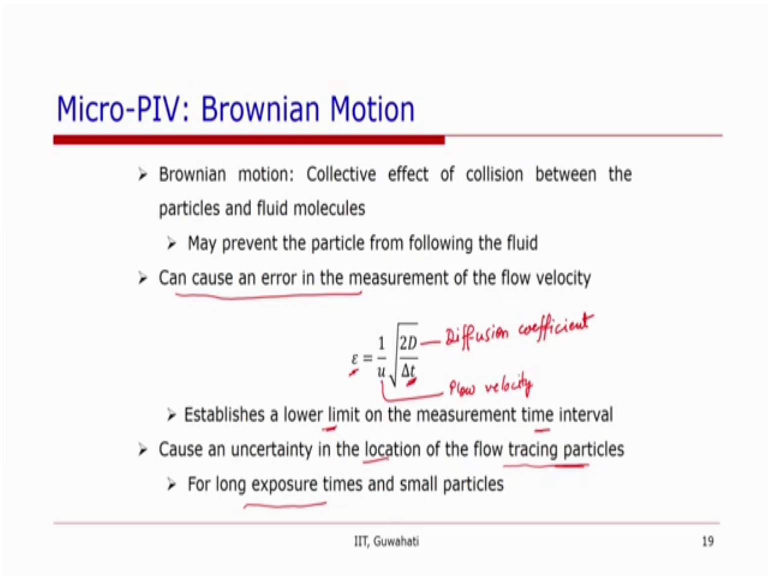

So, apart from the 2 considerations what we have discussed one is size of the particle especially the Rayleigh scattering criteria, which is applicable for micro PIV and the volume illumination. The third criteria that needs to be considered in micro PIV is the Brownian motion, because in the micro PIV the size of the particle is of the order of 10 to 100 of nanometers. Now Brownian motion is the motion of the fluid molecules of, because of the oscillations or the from the molecular mass motion the motion of the fluid molecules.

Now, if the size of the particles is comparable to that of the fluid molecules, then when they have collision with the fluid molecules, then the Brownian motion or the molecular motion of the fluid may affect the flow behavior or it may also prevent the particles from following the fluid carefully.

So, one need to take into account those considerations in micro PIV specially because the size of the particles is small. So, they can have 2 effects one is that they can cause an error in the measurement of the flow velocity. And it has been estimated that the error of the flow velocity can be estimated as epsilon is equal to one over u, root square root of 2 D over delta T, where D is the diffusion coefficient and u is the flow velocity then epsilon is the error that is introduced in the velocity.

And delta T is the temporal resolution on that or the time interval between the 2 images. So, this introduces a limit on the lower limit on the measurement time interval. So, delta T should be larger enough that this error is minimized in the measurement of the flow velocity. The, another error that may occur is because of a uncertainty in the location of the flow tracing particles, because the a Brownian motion it can especially for long exposure times, it can cause an uncertainty in the location of the particles for a small particles it can cause an uncertainty in the location.

So, this also needs to be taken into account the correlations have been developed for this case also. So, one can take into account these effects to avoid the significant on the Brownian motion of the flow.

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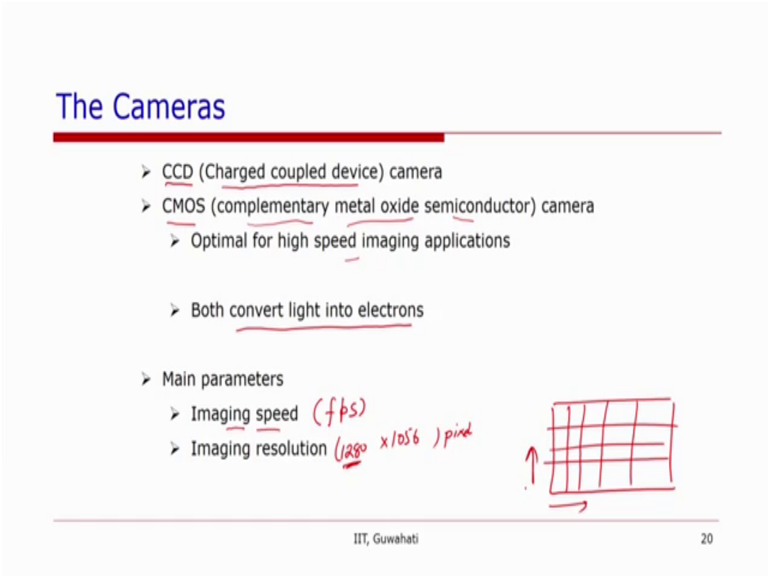

Now, the 2 things that we have discussed at the case of particles and the light source and the optical seat, if required or the volume illumination of the flow, now these images nowadays in most of the PIV applications these images are captured using either a CCD camera or a CMOS camera; both of these cameras convert light into electrical signals. So, CCD camera is charged coupled device, which goes and gives very good and accurate a special resolution.

The CMOS camera which is called complementary metal oxide semiconductor they are at high speed applications because the CCD cameras, they have a limitation with the a frame rates. So, CCD cameras are preferred at low temporal or a resolution or at low frame rates, CCD cameras are preferred. However, for high speed imaging applications only CMOS cameras or a complementary metal oxide semiconductor cameras are preferred and used.

So, when considering camera one need to look at the a light intensity, the imaging speed which is generally given as frames per second or fps and imaging resolution. So, it will be in terms of number of pixels in the horizontal and vertical direction. For example, a camera might have a resolution of 1 2 8 0 into 1 0 5 6 pixels or something like that.

So, this these numbers represents the pixels or the divisions in the horizontal direction and in the vertical direction on a camera or on a camera sensor. So, the numbers represent the number or division in the 2 directions.

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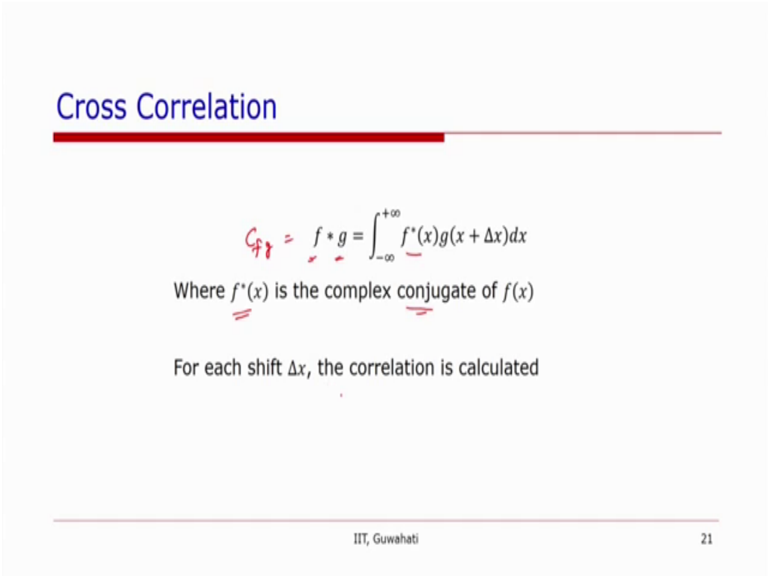

So, once the signals have been obtained and the images has been captured then one need to post process these images using cross correlation. So, cross correlation have to say for 2 functions f and g in the cross correlation Cfg is defined as a minus infinity to infinity s star x gx plus delta xgx, where f star x is the complex conjugate of fx, but because we have real signals here. So, f star x is same as fx.

So, the cross correlation is given by this formula and using the cross correlation one can get the peaks, in the signal and estimate delta x from there.

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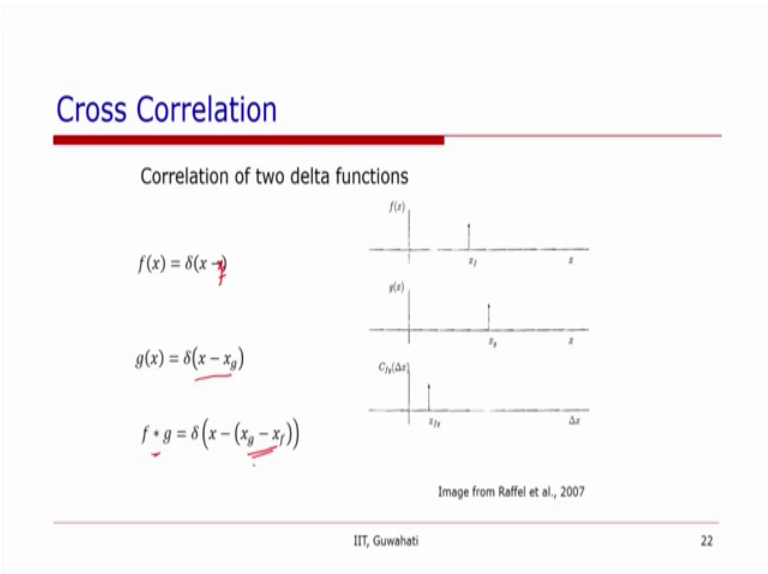

So, let us say for fx is equal to delta x minus xf the first function, which is a delta function. And another delta function gx, which is given as x minus xg the multiplication of 2 is given by a x minus xj minus xs. So, one can get the displacement as xj minus xf. So, one gets a peak here.

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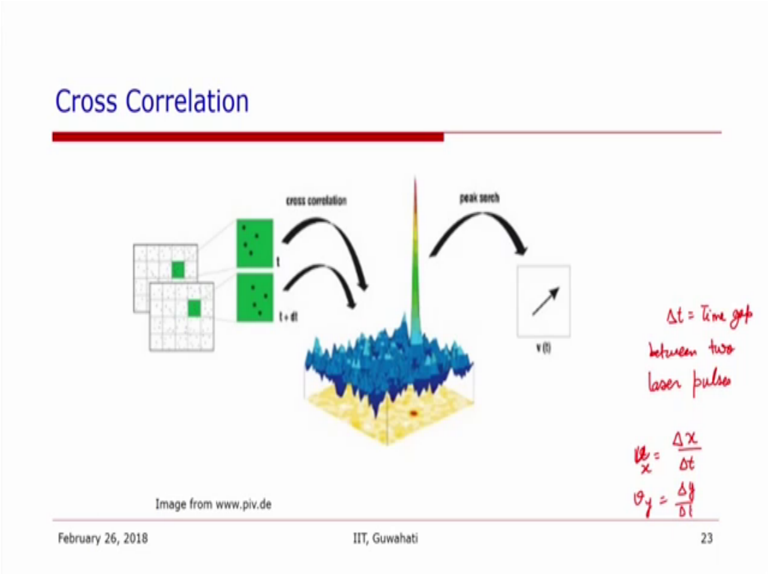

So, using this technique one can obtain the delta x and we already have we already know delta p is the time gap between 2 laser pulses and delta x is estimated from the or cross correlation of the 2 images.

So, one can estimate the velocity as delta x over delta T or x component of the velocity let us say vx is delta x over delta T. And vy as delta y over delta T now the technique has also been extended for a number of other applications for example, another technique, which is known as a stereo stereoscopic PIV where 2 cameras are used and the planar imaging are images are taken and one can get the 3 velocity components, which is known as stereo scopic PIV or the volumetric PIV again here the entire 3 entire field measurements are taken or the time resolved PIV their high speed camera, and high speed lasers will be required and the and using high speed camera and high speed lasers one can also measure the velocity at now the high velocities.

Now, furthermore one can also use temperature sensitive or the concentration sensitive fluorescent dies to measure the velocity at the temperature field or the concentration field using the same principle as I used in micro PIV that one introduces a fluorescent dye, which is temperature sensitive. And then using a long pass filter, the light only which a an light above a certain wavelength is allowed to pass through the filter and in go into the camera. So, the images of this is taken and from there one can have an estimate of the temperature field or the concentration field for heat and mass transfer application.

So, in summary what we have discussed today is the basic principle of particle image velocimetry technique and the considerations that one need to take into account for micron particle image velocimetry. We have a main components of the experimental setup is a laser, which should be a dual cavity or double pulsed laser, which introduces 2 pulses at a time interval of delta T and illuminates the flow at 2 different time instants, with a synchronizer the camera triggers at these 2 time instants and take 2 pictures of the flow, which is seeded by the tracer particles.

These particles are supposed to follow the flow faithfully and should be able to scattered enough light that the particle images or good images of the particle can be captured. And by analyzing or by cross correlating, the intensity of the particles in the 2 images captured at time T and T plus delta T 1 can have estimate of delta x in different regions of the images. And from that one can get the local fluid velocity of the flow a local velocity of the fluid in the tracers and under investigation ok.

So, that is all for this lecture.

Thank you.