Experimental Methods in Fluid Mechanics
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Lecture 36
Measurement of microscale flow features – I

Good afternoon, I welcome you to the session of experimental methods in fluid mechanics. And today we will discuss the micro PIV analysis which is an important measurement technique for the flow characterization at microscale. If we recall that we have discussed about the PIV analysis, the operational principle, the method and to some extent the post processing of the images.

So, we are now familiar with the PIV that is the PIV is the particle image velocimetry. If we try to recall, following this technique we can characterize the flow, that means if you would like to measure the flow velocity, if you would like to obtain the pattern of the flow, then PIV particle image velocimetry is having a few advantageous features that we have discussed. PIV measurement is, you know I can say a non-invasive measurement technique.

For this measurement we do not require to disturb the flow filed, of course which is essential we need to consider, we need to select a few particles which are to be seeded to the flow and the seeded particles should have a few important characteristics. Except this particular point that the particles are to be seeded to the flow, there is no any other direct contact of any equipment, any measuring probe to obtain the flow characteristics. So, from that perspective this analysis particle image velocimetry is a non-invasive technique.

If we try to use particle image velocimetry technique in the paradigm of microscale transport processes to obtain the microscale flow feature, then we need to know what is micro PIV? That means, knowing rather you have understood the PIV, if you would like to include this analysis in the context of micro analysis, micro flow analysis, then do we need to consider any external feature or any other feature with the system or if we can

simply use the PIV setup to measure the microscale flow feature, even if we can, then what will be the system components and of course the measurement techniques.

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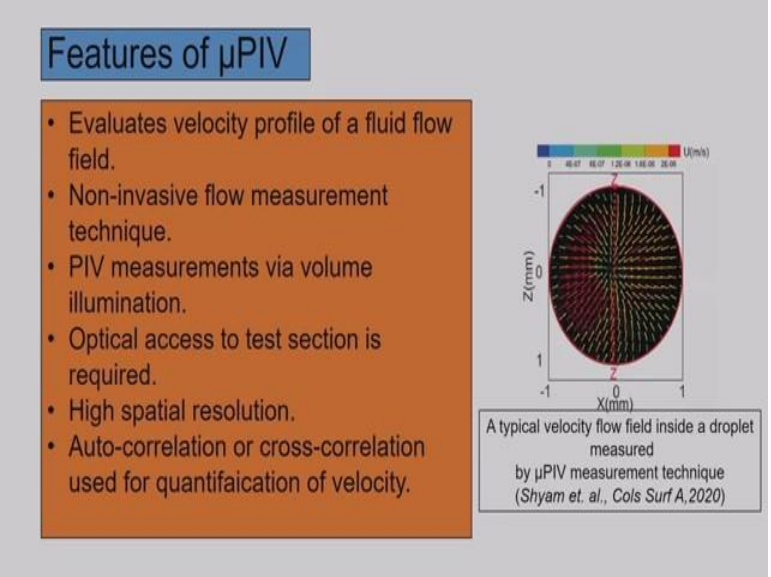

So here, I would like to discuss a few important features of the micro PIV analysis. At the right side, I have shown one figure, however, the flow, velocity flow field inside a droplet that we have measured from our group we have shown. So through experimental investigations, we have obtained the internal flow velocity field of a droplet using this micro PIV technique. So when we will be discussing about this technique, it is, either it would be better if we obtain insights about the flow field and that is why I have kept this figure.

What are the important features of this particular technique? As I said, similar to what we have studied in the context of PIV analysis, here also, this is micro so just one prefix is used micro, so this is micro PIV. We will see that for the micro PIV analysis further we need to include, we need to consider any other features which is or are not there for the PIV analysis.

So this PIV micro PIV analysis what we can see that if you would like to characterize the flow field, when you talk about flow characterization that means we are interested in measuring the velocity profile, velocity magnitude, that means the quantification as well

as the qualitative measurement of the flow. So PIV, micro PIV can, micro PIV analysis can be used to quantify as well as to provide the qualitative measurement of the flow field.

As I said this is non-invasive flow measurement technique, following this technique we do not require to disturb the flow field except the incorporation of a few seeding particles. These measurements important point to note, that is what I was now talking about that, I was talking about that if we try to recall for the post processing part in the context of PIV analysis, in the context of the discussion of the PIV, we have discussed two important aspects, one is the constructional feature of the setup procedure and finally, the images which are captured using this technique need to be post processed, essentially to quantify the flow parameters.

And for that, I have mentioned many times that we need to have a light source and that light source provide light which is used to illuminate a particular zone and that is zone of our interest. And if we try to recall, then we will find that in the context of the discussion of PIV, we have discussed that light sheet so that means a sheet is particular zone that means a sheet that is what I have discussed that a light sheet and that is illuminating a particular zone.

In the context of micro analysis, sometimes we need to go for the volume illumination instead of zone, instead of a sheet, we need to go for the volume illumination. So this is one important point we should keep in mind. Then, optical access to the test section is required, that is obvious without light source we cannot measure the flow parameters using this method. So we need to have proper light source and that light source should have again a few important points to be fulfilled for this technique.

High special resolution is important because again I am telling we are focusing our attention on a particular zone. And that is the zone of our interest and we should have sufficient or high special resolution and if we do not have then we cannot track, we cannot quantify or we cannot, even if you can, if we cannot quantify and even if we try for the qualitative estimate but if we have lack in special resolution, we would not be able to predict the qualitative estimate for the flow parameters.

And finally, the images which are captured, again I am telling, what is done I will be discussing today again. Light is allowed to fall on a particular zone in the flow field then images are captured and light pulse which is used to illuminate a particular zone, there should be, the duration of the light pulse should be something of the order of nanosecond or microsecond. And the gap between to successive light pulse which will be used to illuminate, that also should be very small.

Now that means you are, we will be capturing different frames of different images, rather images at different frames. Now, the captured images will be used to predict the flow parameters, that is the velocity, that is what is important and to do that we need to go for the auto correlation or the cross correlation method. In the context of the discussion of PIV, we have discussed the difference between these two correlation methods and we have briefly task upon the cross correlation method in, which is used in quantification of the flow parameters.

So from the image which is shown here, it is clear that using this technique we can really qualitatively predict that the, what we can see from this image that the flow is readily inward. So what we can see from the direction of the arrow shown overe here that fluid is now trying to flow from outside to the inside, that is readily inward flow.

This is the qualitative estimate. Also from the direction of the velocity and the arrow, we can quantify the magnitude. So this is possible using this technique and for that, in fact from the color bar that was shown at the top of the image we can predict the velocity magnitude. So this method is, I mean I can say successfully can be used to predict the qualitative as well as quantitative measurement of the flow parameters.

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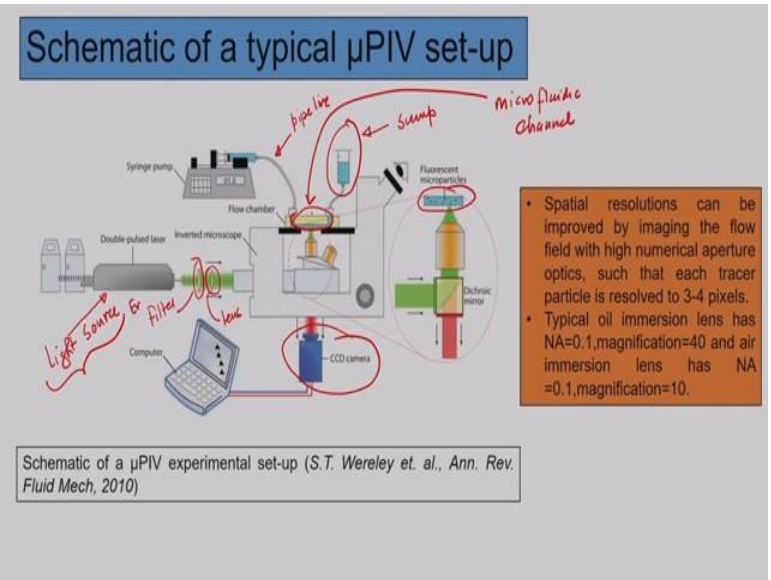

So this is a schematic of a typical micro PIV setup, that is very important to know at least because we are studying PIV in again micro PIV and what are the different components we have discussed? Today, I was thinking at least to show our schematic a typical schematic setup where we can see the different components which are integrated with this measurement method and of course then we will try to discuss briefly there a function.

This setup I have taken from a journal paper, so only to this schematic will help us to understand what is done in micro PIV analysis. So what we can see from this schematic is that one light source I will be showing again the different components through block diagram in the next slide but before I go to discuss that slide, at least I will try to discuss a few important points from the schematic.

What we can see from the schematic is that at the top we have one syringe pump, so typically this is a typical micro PIV setup so this is used to capture the flow parameters, I mean micro flow parameters to be precise. That means we will have, we need to ensure that there is a continuous flow in a micro fluidic channel or micro fluidic pathways. So from where the syringe pump is used to maintaining a continuous flow through a channel whose lens scale is of the order of micron. And the liquid is pumped and the liquid is taken from the other end into a sump that is shown over here. So this is essentially the

sump which is collecting the liquid, so this is sump which is collecting the liquid and this is syringe pump that is shown and this is the pipeline. And this is the micro PIV micro channel, so this is the micro fluidic channel. So our attention will be on this part, what we can see from the bottom? The setup that is the experimental setup which is the channel, essentially micro fluidic channel through which liquid is allowed to flow is in the syringe pump.

This is inverted microscope, now we have light source, so that is the light source, that is the light source and this is double-pulsed laser and this laser is used to supply light and the light is taken through one filter and then this is one filter and then one lens. And the there is an mirror which is inside the microscope and that is also shown in this zoomed in view.

So what we can see that this portion is shown through this zoomed in diagram and we can see that the light which is coming from the laser which is taken into a dichroic mirror and this dichroic mirror has two important functions that we will discuss very soon. So the dichroic mirror allows a particular light of having certain wavelength to be illuminated to be used to illuminate.

So dichroic mirror use a particular light of having certain wavelength to be used in illuminating the fluidic path and that is kept at the top and that is shown over here. So this is that micro fluidic device system through which liquid is allowed to flow using a syringe pump.

And since we can, here we can see from the schematic again that as an essential, pre requisite for this measurement technique is that we need to ensure that the liquid which will be allowed to flow through the micro fluidic channel, our objective is to characterize the micro flow parameters, then we will estimate the, to predict the micro flow behavior then the liquid will be seeded with a few particles and those particles will have a few important characteristics that is what we have discussed in the last class.

Now when light dichroic mirror is allowing a particular light of having certain wavelength which is falling on the seeding particle, the particle will now reflect, the light

will be reflected by the particle and that will be again taken by the dichroic mirror and mirror only, mirror will allow that a particular light to pass and it will be taken by a CCD camera that is shown over here and the camera will capture image, rather images at different frames.

And the captured images will be now taken for further post processing using cross-coalition algorithm to quantify the flow velocity. So this is what is the brief description of the micro fluidic setup. I have taken it from the standard literature and I hope the schematic is helped us to understand the basic process mechanism which is involved with the micro PIV analysis.

I have written something here that the special resolutions can be improved by imaging the flow field with high numerical aperture optics, such as each tracer particle is resolved to 3 to 4 pixels. And so now I will go to the block diagram or I will discuss the objective of different parts, that is the filter, then lens. Why we need to provide this filter, why we need to provide this lens and although I have discussed about the function, objective of the dichroic mirror but even then we will discuss what is done essentially using this dichroic mirror.

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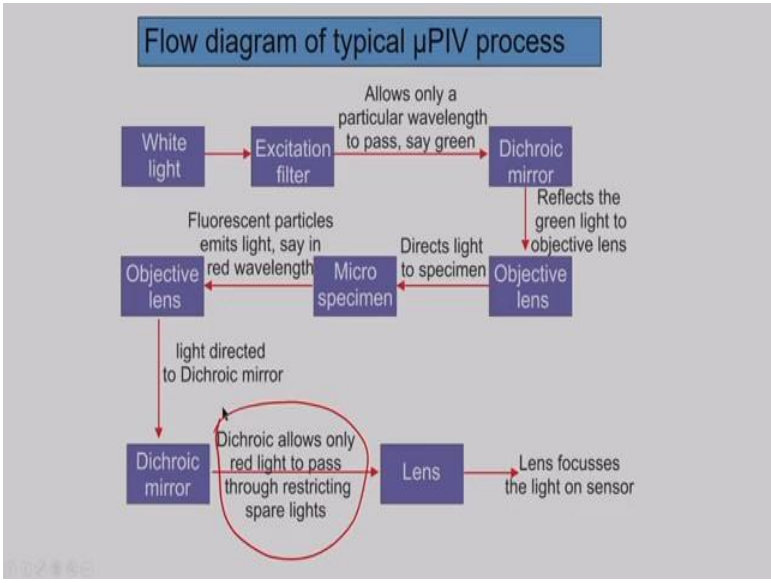

So this is the block diagram, the flow diagram of typical micro PIV process. I have explained in the previous slide that light is taken, light is taken from a light source, it is taken into an excitation filter so this filter is essentially an excitation filter. So this is, I did not write, so this is excitation filter.

Now, then if we consider only white light is coming, if the light source is not laser that is laser is very costly. If the lights or the source of light for the investigation is laser, then we will get the monochromatic light for that we do not require this excitation filter. But if, this is not the case always because laser is very costly and if we use white light then the light is taken into a excitation filter, the objective of this excitation filter is only allow a particular wavelength, say green light.

That depends whether this will, whether we will need only the green light or we need red light that will depend upon the particles which we have considered to seed the flow that is the particles which we have considered for the measurement method, so the particles which are seeded to the flow will eventually depending upon the particle characteristics which are seeded into the flow, we can select this excitation filter.

Now, the white light which is coming from the light source, it will be taken to the excitation filter and for this particular case and it is, I can not say this is the case which is true always but it is normally taken that excitation filter will only allow the green light to pass, the wavelength of the green light to pass.

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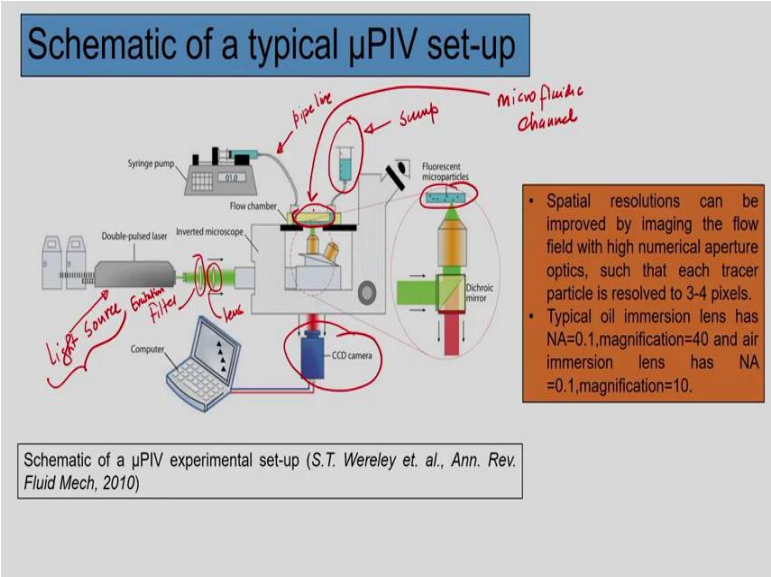

And if I now go back to the previous slide, after the excitation filter we have one lens. So what is the objective of the lens? Lens is taken so that since our objective is to analyze, to characterize the micro flow then the confinement of the micro fluidic device is very small of the order or micron.

So our objective should be and that too in the context of micro flow we are focusing on a particular volume. So it is not expected rather it is not advisable that the light which is used to illuminate the micro fluidic device for this purpose, should focus only the zone of interest.

So to ensure that the light which is coming from the excitation filter that means the light will now focus on a focal length, that is to ensure on a focal point. So the light which is taken from the excitation filter which is now taken into the lens only to ensure that we can focus a particular zone, particular point rather.

So for that this lens is taken. So that means light will be splitted into two parts and the light, the splitted light will be allowed to focus a particular zone. Of course, there will be some kind of I can say plus minus level a range of uncertainty but even then it is not advisable that light should be either light should not, light will only focus the our zone of interest and for that lens is taken here.

Then after that light is taken to the dichroic mirror. As I said the dichroic mirror is having two different objectives. First one, if we now come to this slide, the green light which is now coming, which is falling on the dichroic mirror, the dichroic mirror will now reflects the green light to the objective lens.

That means this is our objective lens. So this is our objective lens and this green light, the dichroic mirror will reflect the green light to the objective lens. So that means light is coming, now again we need to focus that light on the objective lens through the objective lens into the zone of our interest. So the dichroic mirror will do this job. Now when the light is coming to the objective lens, then it direct, the objective lens is now responsible to direct the light to the specimen, to the zone of our interest to the object. So that means now we are illuminating.

So now if I go to the previous slide, dichroic mirror is now allowing green light, our reflecting green light to the objective lens. If I say that light, dichroic mirror is allowing green light to fall, to illuminate, the green light to fall on the object to the specimen through the objective lens. So the green light which is coming from the excitation filter that will be reflected by the dichroic mirror and the reflected light will now illuminate the object, our specimen through the objective lens.

Then our specimen is micro specimen and that is there is a continuous flow, so we are focusing on a particular zone and there are few particles which are seeded to the flow. So when we are focusing a particular zone, a particular volume using the light, we are essentially focusing the light on those particles which are in the flow.

And these particles are basically fluorescent particles and when light is coming, the particles will emit lights and say the red wavelength, so the green light is now falling on the fluorescent particle. Fluorescent particle will now emit lights, emits light and the light is having wavelengths red.

Now the light will again come to the objective lens through objective lens it will be now direct to the dichroic mirror, the reverse path, same path but in a reverse direction. And then dichroic mirror now objective of the dichroic mirror is that earlier dichroic mirror

allowed the green light rather reflect green light to be objective lens now the light, the reflected light which is coming from the fluorescent particle will be now coming through objective lens into the dichroic mirror but now dichroic mirrors would not allow light to be reflected rather now dichroic mirror will only allow light to pass to the lens.

So that is what I have written. Dichroic allow only red light to pass through the restricting spare lights to the lens and lens of what that is the, if I go to the previous slide CCD camera and ultimately the lens focuses the light on the sensor and ultimately we capture image and the captured images are now taken for further post-processing essentially to quantify the flow parameters.

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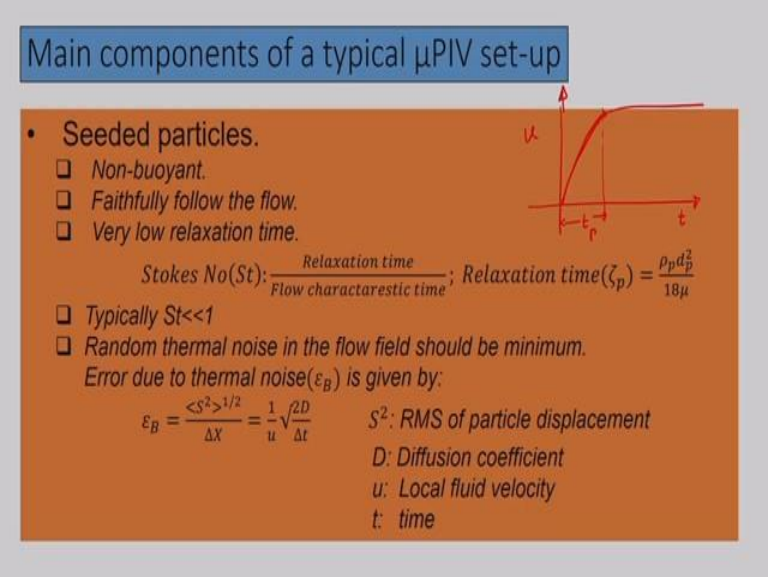

So this is what is the typical I know I can say process rather steps I can say of micro PIV measurement. Now the main components of the micro PIV setup, what is important again I am telling, seeded particles. I have discussed in the context of discussion of PIV that the seeded particles will have a few important features. Again I am discussing a few of them that it is neutrally buoyant, that means the seeded particle will largely follow the wall flow and the density of the particles will be almost equal to the density of the fluid.

Here one important point I have mentioned that very low relaxation time, which is characterized by the stokes number and that means Stokes number will be very less.

What is that? So if I try to draw here, so if I, say this is the velocity u and t, so what is relaxation time? The stokes number is defined by the, as a ratio of relaxation time to the flow characteristics time.

We know the flow characteristics time from our undergraduate fluid mechanics knowledge, but relaxation time now, when the fluid has start flowing, say we are just switching on the syringe pump if I go back to the, if I rather if I try to recall the schematic which I have depicted in the previous slide that the moment when syringe pump is allowed to, whether a syringe pump is allowed to run, then liquid will start flowing through the micro fluidic device channel.

Now the particles are also in the rest, so if the particle inertia is very high then what will happen? So if I switch on the syringe pump, liquid will now start, liquid will start to flow through the fluidic confinement and the particles will also starts flowing with the liquid and that is why we can ensure that the velocity of the particles will be equal to the velocity of the flow. If you try to recall again, I have discussed in the context of micro PIV discussion that in this technique essentially we are essentially measuring the particle velocity, particle which are seeded to the flow.

So by measuring the velocity of the particle we can predict, we can correlate the velocity of the fluid when we can. Now when the liquid is start flowing, ideally particle will start immediately to flow with the liquid and that is why they are neutrally buoyant. But in reality that is not.

So, we need finite although of the order of micro or nano but we need finite time gap that the moment when syringe pump is, syringe pumps which dissolve then liquid will start to flow through the micro fluidic device, particles also will start to flow but liquid will start to flow and say I am drawing this will, particle velocity is initially zero, liquid velocity is here.

So it will take certain time to reach the liquid velocity. And then liquid velocity and particle velocity will be equal.

So if I say, this time tr, so if this is the velocity of the liquid that is set by the syringe pump, particle velocity is initially zero. The particle will state finite time which is of the order of nanosecond but even then this time which is taken by the particle to move with the flow and this time is known as the relaxation time.

So what we can say from this understanding that this time will be very small, smaller this time we can ensure that the particle will largely follow the wall flow. And that is why the Stokes number will be very small and that is what I have written, much, much less than one. Finally, the random thermal noise in the flow field should be minimum and that is one important point for the measurement technique using light.

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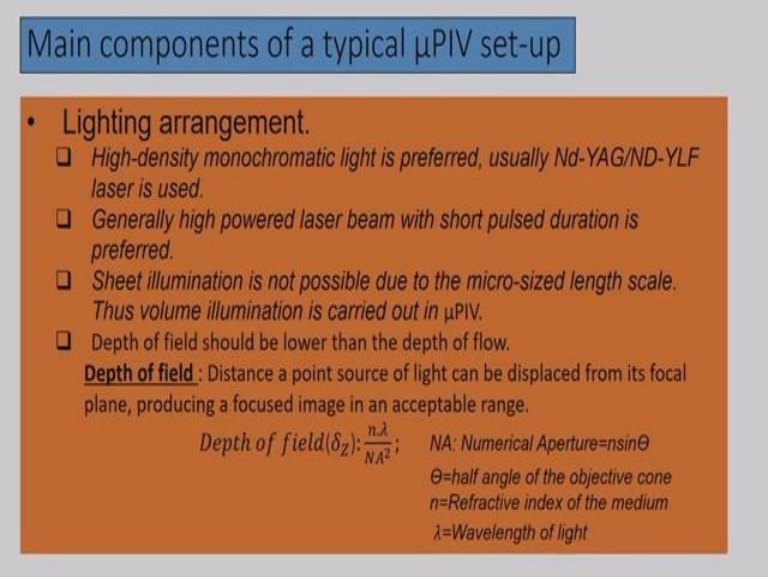

Next is lighting arrangement. So here are few important points that high density monochromatic light is preferred. Considering this point, laser light source is preferable for this measurement technique. Generally, high powered laser beam with short pulsed duration is preferred, again I am telling that laser is used to illuminate and we are having pulsed laser that means it will illuminate, stop then again illuminate, stop like this, kind of time periodic.

But the time gap between two successive light pulses will be very small, otherwise I mean because our objective is to measure the velocity of the fluid of the flow velocity,

we have, we need to seed a few particle to the flow and what we are doing, we are receiving, we are measuring the velocity of the particle.

So we are focusing a particular zone, what we do? By focusing a particular zone, we say that the particle location is, a few particles will be captured in the first frame. Second pass will come we will capture the second frame, a few particles which are captured in the first frame of reference will be there in the second frame of referrals only then we can calculate what is distance traverse by the particle which were there in the first frame are now in the second frame and from there we can calculate delta x and delta y and I know the time gap between two successive laser pulses and from there you can correlate what will be the velocity.

Now to ensure that if the flow velocity is sufficiently large, then our duration of light to ensure that the same particles will be there in the second frame of, the image which is captured in the second frame, our duration of the light pulse between two successive light pulses will be very less, very small. So that is why short pulse duration of the laser if preferred.

Sheet illumination is not possible due to micro-sized length scale. Thus velocity illumination is carried out in micro PIV. See, this is an important point and that is what I was talking about in the beginning of this class that in the PIV analysis we are focusing on a particular area, not volume, that is a sheet, light sheet illumination.

But for the micro PIV analysis, if we just try to illuminate a particular small area, then it is very difficult to ensure that a sufficient number of particles will be there in the fluid in that particular zone. And that is why it is better to illuminate the volume so that we can have at least sufficient number of particles present in that volume and the entire objective of calculating flow parameters will be ensured.

And final point is the depth of field should be lower than the depth of flow. That is very important. Distance a point source of light can be displaced from its focal plane, producing a focused image in an acceptable range. To explain this, what is the meaning of this? The depth of field should be lower than the depth of flow. If the depth of field is

larger than the depth of flow, what will happen? That is what I was explaining, again I am telling.

If we try to illuminate a particular portion of a micro fluidic confinement through which a liquid is flowing. Instead of focusing the required area, required portion of that micro fluidic confinement, if we try to focus rather if the light pulse is light source is such that it is focusing larger then what will happen, the calculation of flow velocity or flow parameters will be erroneous. Why?

And because the particles which are, I mean there in micro fluidic channel the confinement because of the most narrow confinement the zone itself is very small. Now instead of focusing on that particular zone if you try to rather if the light source is such that it focuses little bit larger area larger zone then the calculation may not be the correct one.

What is done? To ensure that the light which is coming from the light source which will be taken to the lens and it will try to focus the required portion rather it should focus the depth of the flow. If it is equal to the depth of the flow, it is okay, if it is higher than the depth of the flow there will be error in the results. It is always better that the depth of the light should be always less than the depth of the flow, so that our objective of accurate prediction of the rather quantitative prediction of the flow parameters will be justified.

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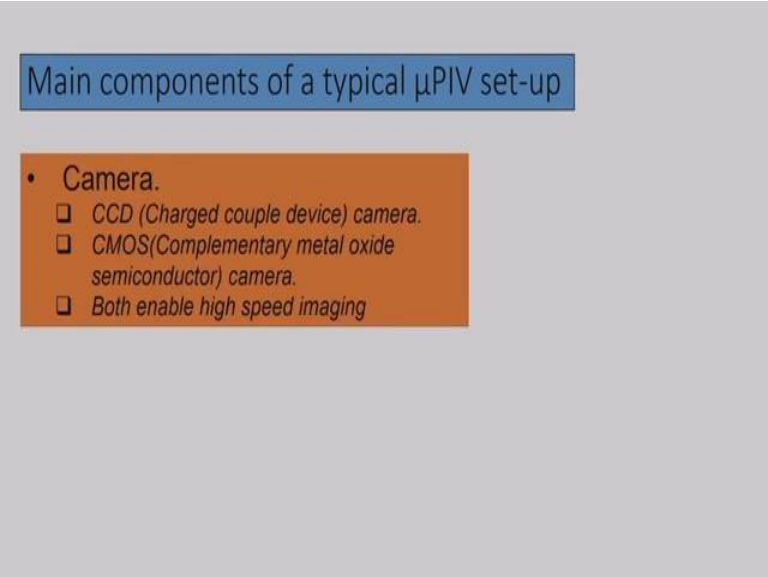

Next is and if we try to recall the schematic, the main components of the setup is, one is light source, and finally we need to capture images and from the captured images through the post processing algorithm numerically we can predict the flow parameters and to capture the images we can, we have camera.

Now we have CCD camera that is what I have discussed in the last class that is charged coupled device. If it is CMOS camera, complementary metal-oxide semiconductor camera it is also fine, and this both enable high speed imaging. Our objective is to ensure high-speed imaging and time between two successive laser pulses is very small and we need to ensure that the two different images at two different frames will be captured.

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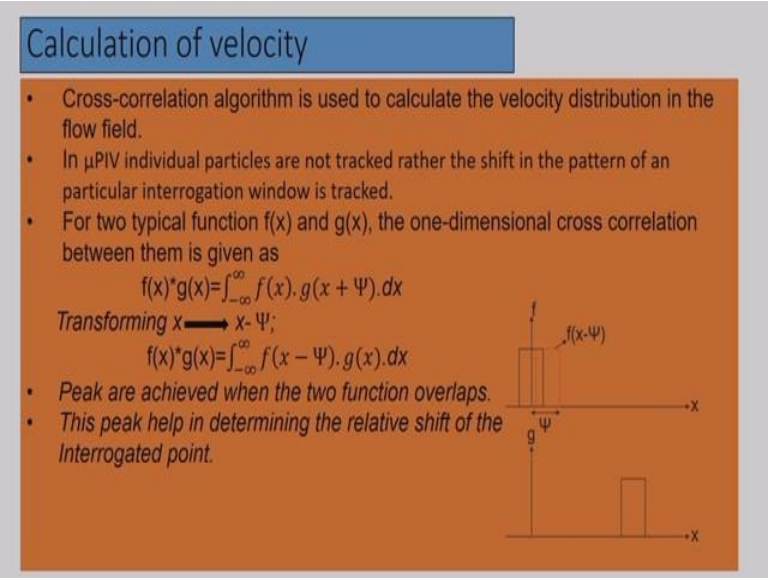

What I was discussing in the last lecture that velocity calculation using algorithm. I have discussed about the difference between auto correlation and cross correlation algorithm and from the discussion we have understood that the auto correlation algorithm is not desirable. Nowadays because if we use auto correlation algorithm, in one when we capture in this one frame we have one camera, then frame is advanced and the, in auto correlation both the initial and final position of the seeding particles are recorded in the same frame.

If we record in the same frame, then very difficult to identify which is in the, which was in the first and which was in the second and to avoid that the cross correlation algorithm is used. What is done is cross correlation algorithm that is what I have written in the last lecture.

If we try to recall what is done that flow field is illuminated, image is captured in the first frame. Camera frame is now advanced and the final positions are recorded in the second frame. So if the first frame, it is for the one dimension only for the understanding, for the ease in understanding this first example I have taken where the first frame which is say, only I would like to say this is only the function of x, so the particles are moving only in the x direction.

I have taken this example, again I am telling only to have our understanding in a effective way. So the first frame which is represented by a function f, which is function of x, one dimensional. Second frame, the image is represented by a function g, what is seen from the schematic.

What is done? In the cross correlation algorithm, particle seeding images which are divided into define zones those are known as interrogation windows that is what we have discussed in the last class. I am not going to discuss all those things again. But what is done? Seeding images in the flow field are recorded in the first frame of the camera that is represented by a function f in this plane, and camera frame is advanced and the final positions are recorded in the second frame and which is represented by g in this plane.

Now, these two images are post processed following the cross correlation algorithm essentially to measure the velocity. What is done? I have written in micro PIV individual particles are not tracked rather the shift in the pattern of a particular interrogation window is tracked. So for two typical function fx and gx, I mean one-dimensional cross-correlation between so we have captured the first frame f, there advanced there moved now by an amount psi.

So in the second frame it will have gx plus psi and transforming from x to x minus psi, that means, I have captured image in the first frame this is now advanced and another that is what the final positions, another image which is capturing the second frame that is g. Now we are advancing f and we are trying to find out rather we are trying to find out the particles which are there in the f whether where we can find out this particles in the g. So that is where we are advancing.

That is what is done in actual process. So f is now advancing, now when f will be in the g, that means when two function overlap, so that means f we have captured we are slowly advancing so particles are there in a space with time with flow, with time flow progresses, particles are moving.

We are capturing second image, that is what we did in the image and in the micro PIV technique. So we are trying to represent all these events in the numerical platform,

essentially to track the particles which are captured in the first frame and from there we are trying to calculate the velocity.

So the f which is captured and now advanced and trying to find out the f and g, and that means now when we are advancing f and when it is approaching to g and when these two overlaps, we will find p, we will find the peak and that is the cross-correlation algorithm. If we try to, when we ensure that there is a peak then from there we try to find out what is delta x.

If I know the time between these two successive major pulses and to, between two defined images, now if I know the delta x that is peak is there and from by knowing the delta t I can obtain the u that is nothing but delta x by delta t. So this is the cross-correlation algorithm. That is what I have discussed in the last class, but today in the context of micro PIV that is I am discussing again.

Now, if we go to the next. So the peak are achieved when two function overlaps. This peaks help in determining the relative shift of the interrogated point. So that means our point, I mean the first frame we have divided into a small number of zones, interrogation windows.

We are now advancing the first frame and when the first frame is advancing, advancing and it is overlapping the second frame, we will find peak. By knowing the peak we will sure certain that there are the particles which are captured in the first frame and which are there in this frame. And from their peak we try to obtain the relative shift of the interrogation point.

If we now calculate, if we can predict the shift, from there we can calculate what will be the velocity? That is velocity is nothing but delta x by delta t.

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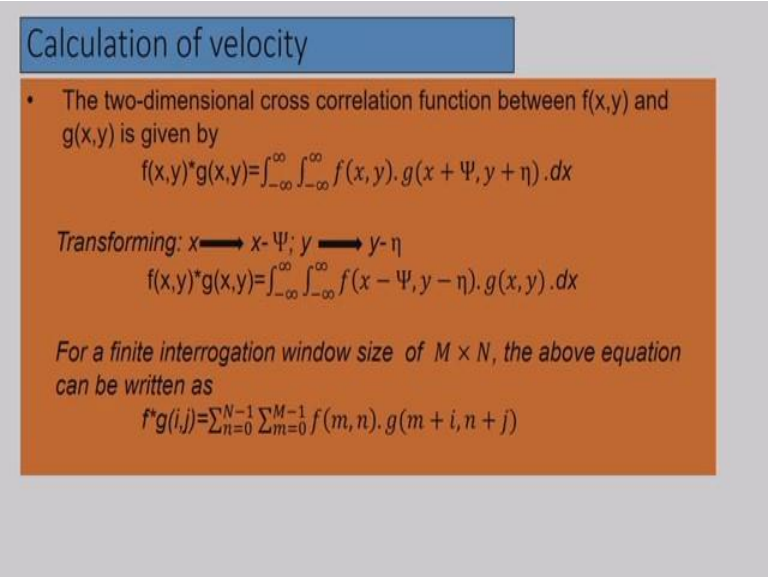

So this is again, in the first case I have taken one-dimensional case only for the ease in the understanding. This is again for the two-dimensional case, so instead of only x here the function is f, x and y and g, x and y, similarly transform x is equal to x minus psi and y to y minus eta and the same procedure is adopted in this case. And finally for a finite interrogation windows, we use this equation to track this delta x and delta y.

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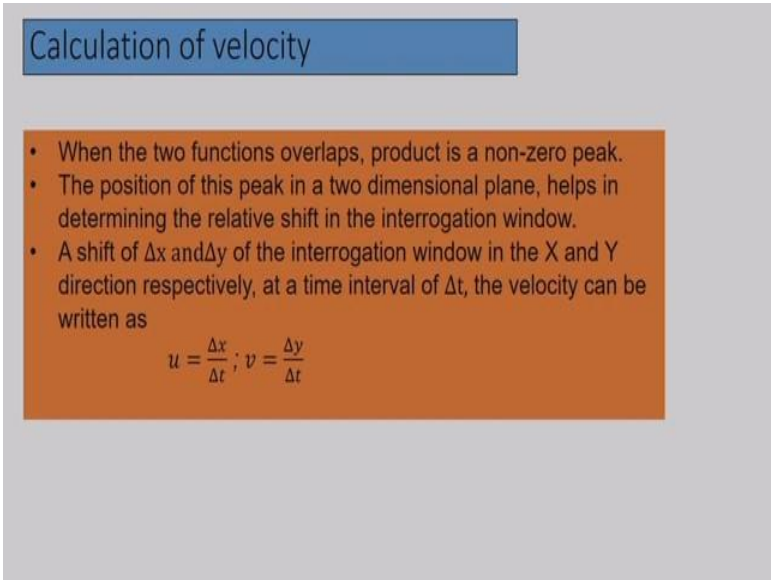

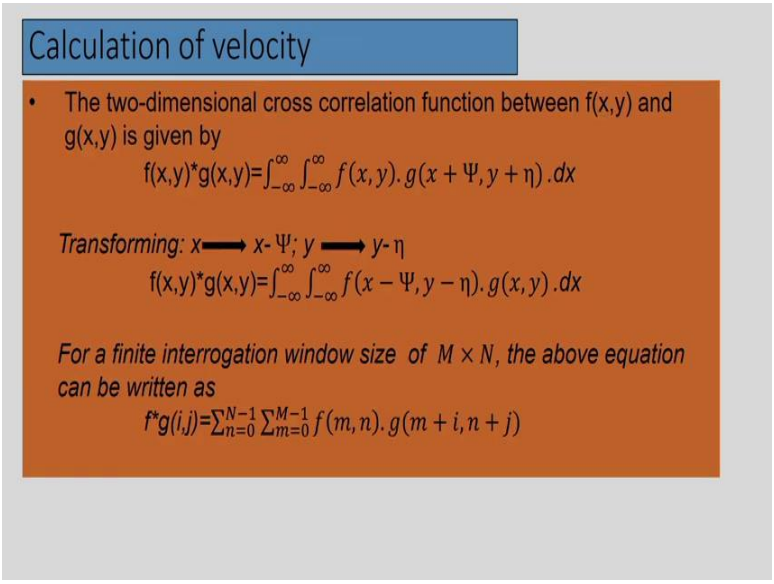

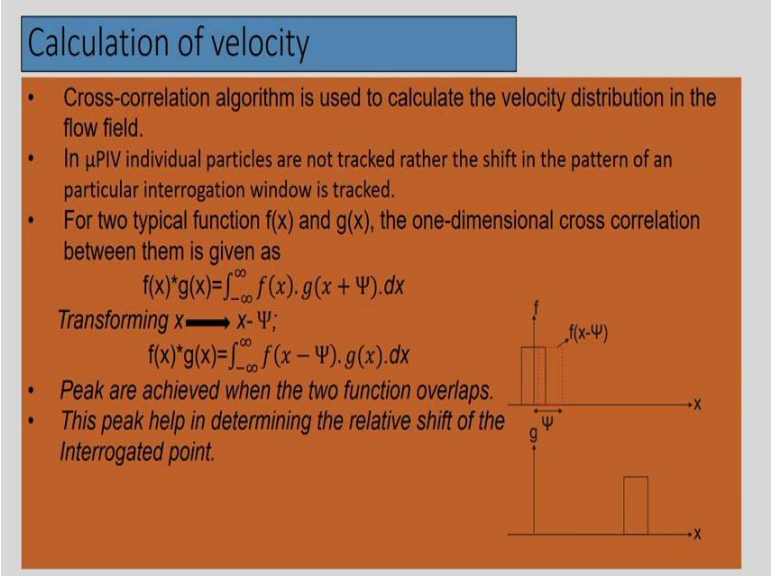

So when these two function overlap, so if it now consider this function, so initially we are considering f, x and y, camera frame is advanced. Second frame g, x and y, the first frame is now advanced and when it overlaps with the g, x, y, we will find the peak value, peak x and y, peak of x and y and if from the peak we can calculate, we can measure the shift in the interrogation point and the shift in delta x and delta y of the interrogation window in the x, y direction respectively at a time interval delta t and that is what we know.

Time interval delta t we know because the delta t is at time gap between two successive laser pulses or the gap between two images captured, we know that is we know from our experimental analysis. So knowing delta t are primary, we have calculated delta x and delta y, from there we can calculate u and v that is nothing but delta x by delta t and v is equal to delta y by delta t.

So to summarize today's discussion, our objective was to calculate the, to characterize the micro flows, to obtain the micro flow velocities. If it is two-dimensional, so all of it is three-dimensional. So starting from the basic process, basic mechanism of the PIV analysis, what are the different components present in the micro PIV system and also identifying their role, their objectives we have discussed today the PIV analysis, the process of the micro PIV analysis.

And we have tried to discuss the post processing algorithm which is used to predict the flow velocities from the captured images. And we have seen that for the one-dimensional as well as two-dimensional and this process, this method is equally applicable for the three-dimensional case as well. We can calculate the three-dimensional, velocity in three-dimensional as well in the micro fluidic confinement.

So from there we can quantify the micro flow velocities and also we can qualitatively estimate that is what we have seen from the schematic depiction from the figure that is what I shown in one of the slides in today's presentation. So, this micro PIV analysis is again, I am again telling that the micro PIV analysis is very important and sophisticated method in characterizing the micro flows to precise, measuring the micro flow velocities and for the prediction of the flow behavior, micro flow behavior both qualitatively as well as quantitatively.

So with this, I stop my discussion today and I will continue my discussion in the next class. Thank you.