# Measurement Technique in Multiphase Flows

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## Lecture – 06
## Particle Image Velocimetry

So, welcome back now what we are going to do today; yesterday we have discussed about the laser of the anemometry, its basic working principle and we have done some mathematical will part to see that how the velocity has been calculated. So, we have done that for the single beam, we have done it for the two beam; now what we are going to do? We are going to see that today that how the signal processing should be done.

So, I will briefly cover those part; already I have covered the mathematical part and the something like in the signal processing; how to handle? Then we will see that what different type of a LDA's are available and then we will discuss the advantages and drawbacks or limitations of the laser of the anemometry.

So, please remember though I am giving most of the examples whatever we have covered, it is actually for the single phase, but it is equally hold for the multiphase flow two. The only thing is multiphase flow that you will track the phase of interest through which you want to map the velocity. So, the seed particles will be tracking the velocity orwill tracking the fluid for which you want to map the velocity field. So, that is the only difference will be there in the multiphase and then the limitation will try to understand that what are those difference and how this LDA behaviour will change or applicability will change in the multiphase flow?

So, what we have done? We have seen for the single beam and the single beam the problem was that you are getting that the f D value by subtracting the two bigger amounts; bigger frequency values. And therefore, the sensitivity of the f D calculations was less and that is the reason that mostly two beam LDA's are used. And in the two beam LDA; you calculate the f D which is the Doppler shift in the frequency by subtracting both the individual f D for each values; for each beam and then you get that.

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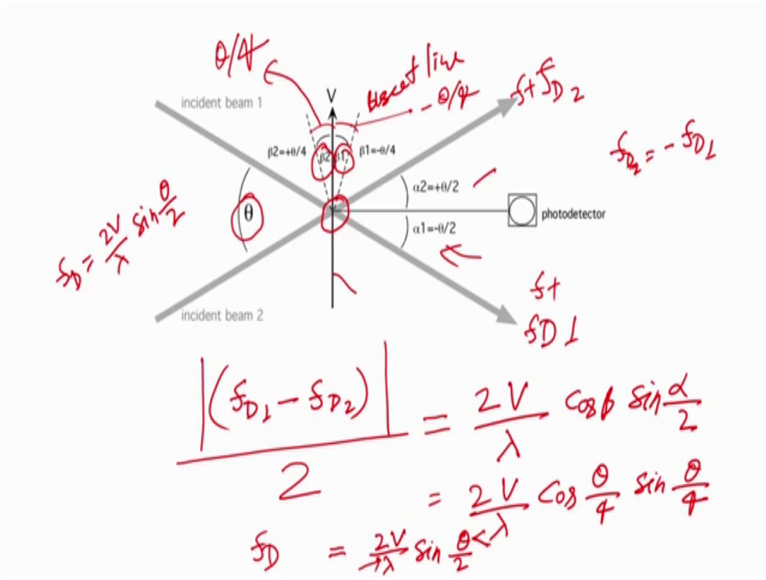


So, you know the f plus f D and plus f D which f is the frequency of the incident waves and f D is the Doppler shift up which you are kind of observing for beam 1 and beam 2. And we have found the formula where says that f D is equal to 2 V upon lambda into sin theta by 2; we have already calculated that. Now, what we have going to see? That how the signal processing should be done and in that way; it is a 2 beam things can also worked in the fringe mode. So, how the fringe mode is worked and how the signal processing is done that is what we are going to see.

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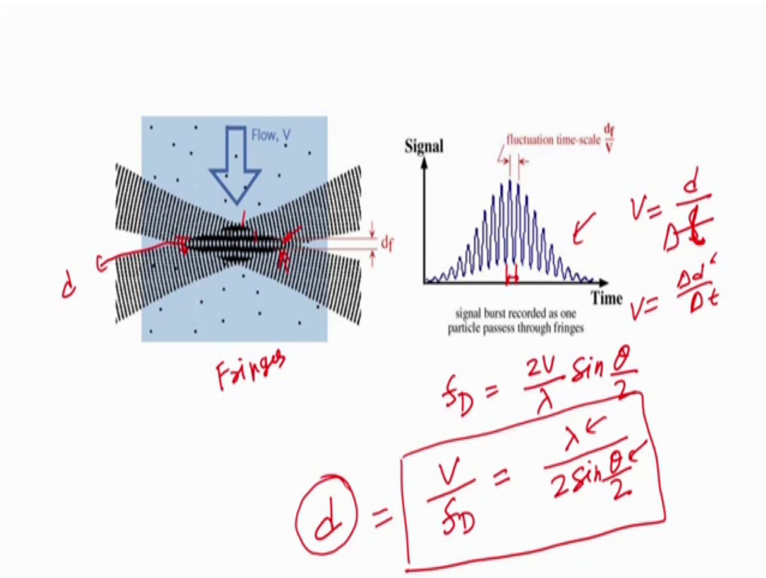

So, what we know that if we cut the two lights at a particular location or in the measurement volume you will see the fringes and that fringes will be made of some dark and bright fringes like these are the dark fringes and the others are the bright fringes. So, once you cut that, you will get the fringes structures if you go and see your basic light the courses based on the lights; you will get this that once you cut the two beams then that beams actually at the measurement point you will see some bright and some light fringes.

So, this is called the fringes now and this approach is that is why it is called fringes approach. So, you from actually bright fringes and light fringes; now any particle the seed particles once it pass through this fringes, what happens? It cut these lights and please remember that they are being recorded; the signal is being recorded by the photomultiplier tube. So, what will happen? Once it will cut the light signal will see the fluctuations in the current or fluctuation in the signal which will be observing at the photomultiplier tubes.

So, what you will see? You will see the signal fluctuations something like this that the seed particles I am assuming only one seed particles is cutting it right now, the seed particle will cut. Here the disturbance will be less; so signal disturbance will be less as it will move towards the centre; the disturbance will be higher and you we will see the higher frequency. So, you will get this kind of a signal by cutting the particles was it will cut the fringes and here also you can calculate the velocity by using the fringe method

So, how we are going to do? We are knowing that how much distance, how much time it took to travel from this fringe say to this fringe between this fringes how much time the particle is taking? So, velocity can be calculated this distance; say this distance is d, if I assume that the distance is d and if I know the time which will take to travel between these two fringes.

So, then the velocity can be calculated by d upon t; time. So, what we do? We record the signal with the time that how the time the signal is changing, if no particle will change; the signal with be flat. Once the particle will be cutting this, you will see this kind of a signal and that is why is called the fringe method; where you form of fringe you observed the signal; the change in the signal with the time.

So, once the particle will cut; it will be like this, we know the time it will take between these two travel between these two peaks. So, I know the time because this is the plot with the times, so I will know the time. If I know the distance between these two, I can easily calculate 8 by d upon t or d upon delta t or you can say that V equal to delta d upon delta t whatever the way you want to write.

So, d is nothing, but the distance between the two successive fringes. So, what you need to; this what we need to calculate, so if we know the d; we know the delta t by the measurements we can calculate the velocity. So, that is another way, but there is problem in this we will discuss that problem, but before that how to calculate this d? So, we have already discussed that f D is nothing, but 2 V upon lambda into sin theta by 2. So, what will be the d? If I know that what I need to find that what will be the d value; the difference between the two successive fringe location in the bright or dark.

So, there will be bright fringes, there will be dark fringes; the distance between the two successive bright fringes or two successive dark fringes that is what we need to find it out. So, what will do? You will use the same approach to find that. So, we know that if we want to find that d value then d value can be calculated based on what? This V upon f D will be what? IIt will be written as lambda upon 2 sin theta by 2. So, V upon f D we can write whatever the formula we have derived will be this.

Now if you are forming a fringes then what will happen? The velocity that fringes distance is what, it will be depending on the velocity and velocity it will be how this Doppler shifts if you will observe you will observe; once it will be cut this particles will cut this fringes.

So, how much time? How much distance they will cut? They will travel before cutting the two successive fringes two successive say bright fringes, it will be what velocity of the particle into the frequency out into the time it will required to travel from one bright fringe to another bright fringe and that is nothing, but the frequency. So, that is nothing, but the frequency of the Doppler shift.

So, if I do V upon f D and f D is one upon f D is nothing, but the time. So, then V into t will be equal to the distance; so, this will be equal to d. So, d you can calculate this is the way the width between the two fringes is been calculated or distance between the two fringes, two successive white or two successive dark fringes have been calculated ok.

So, it means what if I know the lambda value; what is the wavelength of millage which I am using in my experiments. if I know the incident angle theta then I can calculate that what is going to be the d value. So, by choosing fixing the laser; by fixing the angle of intersection we can find it out that what will be the d value. Once you have the d value, with the signal recording what you can do? You can get the time that how much time it is taking place before it is coming from one bright fringes to two bright fringes so you can take this top distance or you can take this bottom distance there going to be the same.

And you will get that what is the time and d upon t will give you the velocity, that is also approach which is being used and widely used actually to find that what is the velocity of the seed particle or velocity of the fluid through which we want to measure this velocity by may tracking the seed particles.

So, you can get the seed particle velocity or in a way you can get the fluid velocity of phase of interest fluid for which you want to map the velocity field. That is what it can also be done and this is also an approach which is used to find that the velocity of the fluid or velocity of the seed particles; it has been done exactly same whatever the two beam this equations we have developed.

We have developed the same; we have used the same equation to calculate the d and d is the distance between the two successive bright or dark fringes; so we do that. Now the problem comes that suppose my particles sizes bigger and why we need the bigger particles? We will discuss. So, if suppose my particle size is bigger or mini particles are cutting the fringes; then what will happen, the signal will not be that much systematic and what you need to do in that case; you need to actually post process the signal before calculating this delta t.

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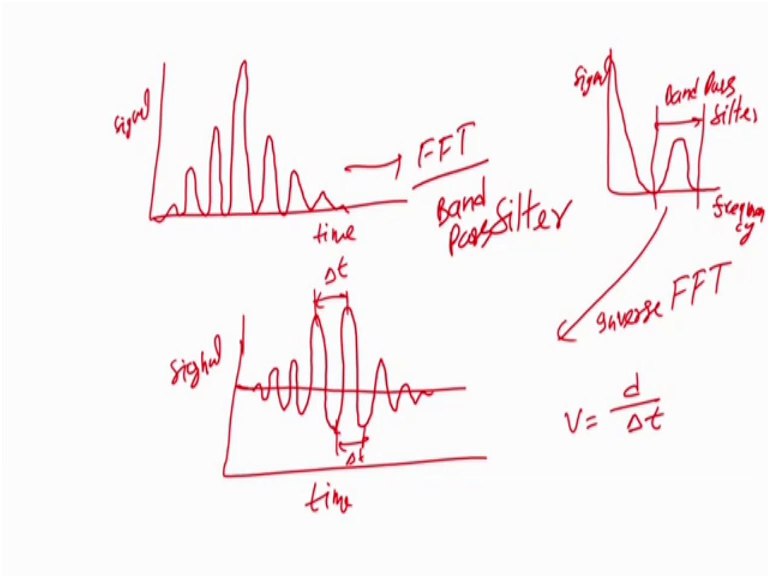


So, for doing that what we do? Suppose if there is a Doppler burst; the signal is going to be look like something like this the signal; will be something like this. Now because once; this is the signal and this is time, why the signal will look like this? Because once it will cut the fringes, you will not get any signal. Once it will go from the white fringes you will again the particle this photo multiplied will see the lights, it means light photon it will for supplies sum up the energy. So, you will get the signal, you will not get the signal; you will get the signal, you will not get the signal.

So, you will have this kind of a signal then what we do? We take the FFT of the signal and pass it through low band filter or band pass filter; I am not going in detail of this filter technique because it will be itself of course, but if you do the FFT it means if convert the time signal; time domain to the frequency domain and then you put a band pass filter and then you take a reverse FFT.

So, if you do that; if you put that you will get something like this curve and you are putting the band pass filter between this; this is a band pass filter actually you are putting; so if it takes FFT of this you will get something and then you put the band pass filter and then you take it a inverse FFT. If you do a inverse FFT for this, inverse FFT means now you are taking the inverse; you are again converting the frequency domain signal to the time domain, so this x axis will be actually frequency here, it is frequency it is signal.

Now, you again convert it to the signal versus time; so what you will get? The signal which you are actually getting 0 it is nothing, but the dark fringe. The signal which we are getting the light which actually the bright fringe; so now I once it will be cutting the dark fringe; it will be also cutting next right fringe; then it will be cutting the dark fringe then again bright fringe. So, the single will now come to a level and then you will see something like this.

You will get a this kind of a signal and then this signal the top or bottom, you can measure the distance between this whatever this and what is the time required at this place to travel from this; you can calculate the delta t either from the top or from the bottom that is going to be the same delta t. And then you know the distance between the two fringes, you can calculate the velocity; by using V is equal to d upon delta t; we can calculate the velocity. So, this is the method which is being widely used to process the velocity from this.

Now, the problem comes once you have a bigger particle and now why you need the bigger particle? Again I will come to that.

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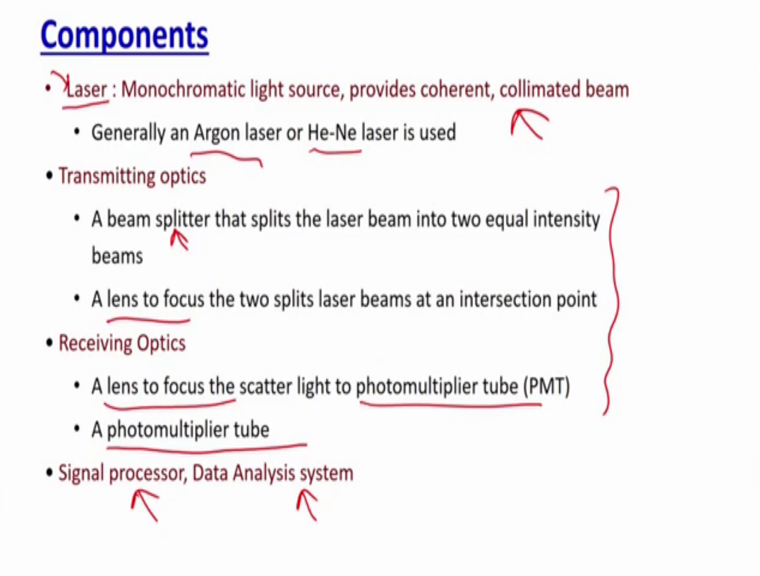


But before that I will just try to tell you that what are the components actually which we use in the LDA experiments. So, definitely the most important component is the laser; we use the monochromatic light source, which provide a collimated beam; generally

Argon or Helium Neon laser is being used for the experiment; there is different laser available, but these are the most commonly used this laser in the LDA experiments.

So, this is the most important part which is laser then you use a transmitting optics; now this transmitting optics is having a beam splitter; particularly if you want to have a 2 beam; this LDA. Then you have to split the beam in two parts; so you will have a beam splitter. You will use the lenses to actually focus that; you will use that lens to focus this two beam on the particular point. From both the beams you need a lenses so that it can be focus at the same point and there you can form a intersection point and that intersection point will actually forms of fringes.

So, you need that that is in the transmitting device then you have a receiving optics. In the receiving optics again you will have a lens which will be actually taking the signal from the intersection place or intersection zone or measurement volume. And then it will be again focusing that to the PMT photomultiplier tubes; so you need a lens which will be scattered light, it will collect the scatter light and it will again focus it to the photomultiplier tube and you definitely need of the photomultiplier tube.

The photomultiplier tube what it will do? It will actually generate the same amount of the current or proportional amount of the current as the number of photons falls on the photomultiplier tube.

So, it means you can find it out that how much shift will be there. If the shift is higher the larger number of photons will be incidenting on the photomultiplier tube, the current amount will also be high and that is what we are seeing that bigger signal. If the shift is lower, it means low number of photons are falling on the photomultiplier tube; it means low amount of the signal level you will see.

So, that is the job of the photomultiplier tube which actually convert the light signal to the current signal or electrical signal. Then you need the signal processor where you have to use the software or you have to write your own code; where you can do the processing of the signal and then finally, you have to do the data analysis. So, whatever the velocity curve and all you get; you have to analyse the data.

So, these are the components of the LDA experiments and the major part is actually this and the optics; receiving and transmitting optics, but the laser should be very good very fine. Because if the laser is not very good then you will see lot of scattering problem in the laser and the data becomes very hazy. So, the laser should be such that it can penetrate through inside, it can go till long distance so that you can get a detailed information and that is required particularly for a close contact floor; if your laser energy is not correct then most of the time will be measuring only near the wall; it will not able to penetrate, it will not able to give you the depth. So, to get the depth you need to have a high energy lade with laser.

So, that is the main component and then the definitely the optics are very critical; if you are not able to do the focus properly through the lens, if you are not able to split the beam properly all these things will contribute in your noise and your data will be very hazy. So based on that; what kind of optics you should use there are two different type of LDA's are there and that is one is called backscattered LDA and one is called forward or side scatter LDA.

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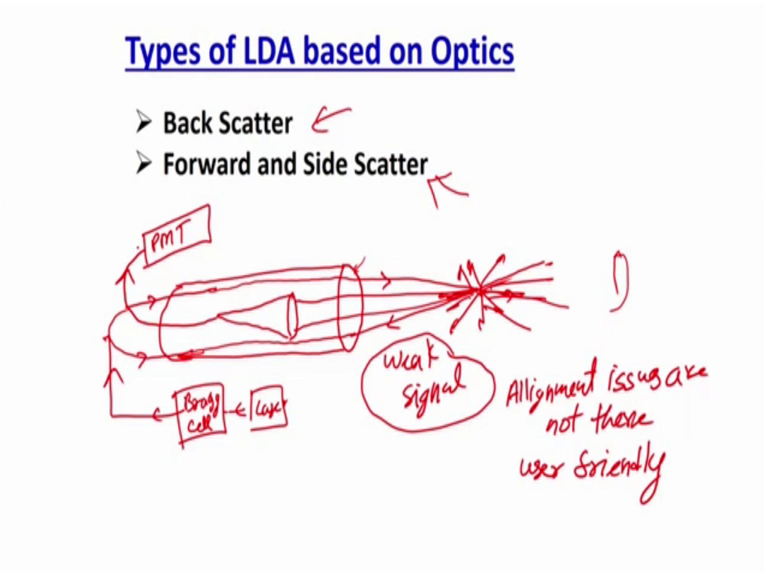


So, far we can operate this LDA both in the forward or in the side scatter and one is the backscatter. So, how they look like? The backscattered means this incident; your receiving and transmitting optics are placed at the same location.

So, how this will look like say I am just trying to draw a schematic. So, this is for the backscatter, it will be something like this and will be the lens inside; the beams will be coming out. so, this is the laser, you will have a laser, you will have a Bragg cell; it will split this laser in again two parts, they will be going here; this two laser lights. And then on this lens; this is again a lens it will be kind of focusing on a particular point which will be the measurement area; so, there will be measurement area.

Now, the scattered light always goes in all the direction. Now the light if the receiving signal is also being there and this is being connected say this receiving signal again is focusing at some place and that is being connected to the PMT. So, this is the line; this is the laser which is incident, the laser is divided into two parts; going it here. Then this some portion of this light is actually falling on this which is again convert into of PMT. So, in that way this kind of is called a backscattered because only the light which is being backscatter to the same point is being measured; so, this is called the backscattered approach.

Now, the problem in this approaches that the signal is weak because the light is being scatter more in the direction of where it has been kind of intersect. So, the scattering amount will be more in this direction compare to the backscattered amount; so, you get a very weak signal. So, that is the major drawback of this backscattered method because your signal is weak, you get a weak signal.

So, it means signal to noise ratio here is higher relatively. So, that is the major disadvantage of this, but the advantage which is the major advantage is that; the all aligned will the vibration effect can be minimised; alignment issues are not there. We will discuss that if you suppose have this you are receiving it in some place, you are working on the transmission resume or transmission way; then if suppose you have somewhere the detected the second lens here, then the problem is that these two things should be perfectly aligned; if they are not aligned then you will not receive the signal properly.

So, that is the major problem you have that the alignment issues and this case the alignment is not a problem at all because both are already aligned there at the same location. So, that is the major good thing is here and that is the major thing that it is very user friendly. In the other LDA, alignment takes lot of time it is something which you have to do properly; if you will not do it, your this is signal to noise ratio will increase, you will not able to get the signal properly; in this case that alignment issues are not there at all.

So, that is the major thing and even the front lens of the optics; this is the front lens of the optics serve as the focusing purpose. So, that is the only used as a focusing also; so, that is the kind of you are requiring the optics only from one side, not on the both side; the front laser, the front optics lens is actually used for the focusing. And then there in the back side lens which is used for the again focusing on the PMT.

So, you reduced the number of optics no additional collector or no additional lenses are required, no additional say 1 lens, 2 lens will do the job; you do not require the additional lenses, your alignment issues are gone. The only thing is the signal is very very weak because you are working on the backscattered; so, backscattered the signals are weak.

So, your signal to noise ratio is high; you have to actually do the processing, filtering properly neither you will generate the spurious signals. So, that is the only problem, but overall this is very user friendly backscattered, alignment issues are not there and that is make it very very user friendly and very effective. The other way is to forward and side scatter; so now forward and side scatter is actually something like this whatever we were discussing. Since till now; is that although we are discussing either the forward or we are discussing the backscattered.

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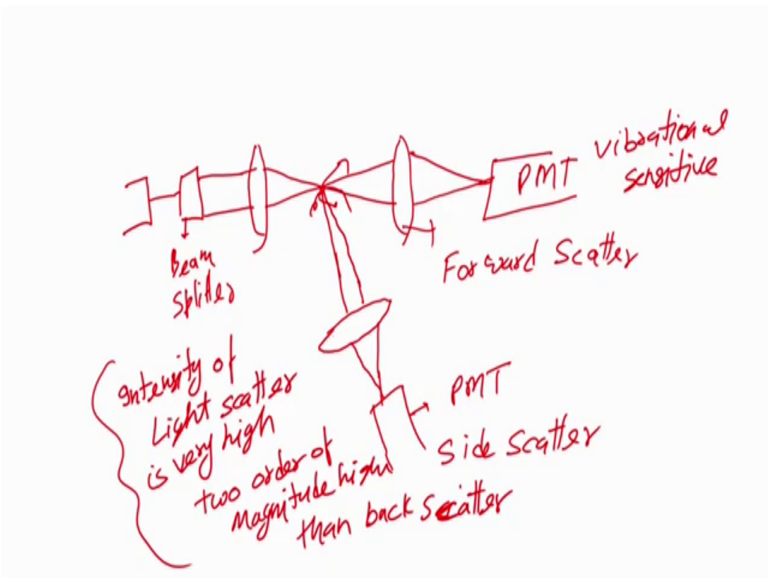


So, what we do? In that case we use the laser; laser seize the beam we put it in the beam splitter; split the beam, beam splitter and this is split the beam in this two part, you use a lens; you focus this to a particular place. Now again you use a lens and you focus it again on the PMT and that is PMT.

So, that is what is called forward; this is the forward a scatter and if you do it on the side if suppose you are doing it somewhere here the same thing, you are arranging the somewhere the lens in this way and then you are using the PMT somewhere here that is side; so say this is PMT; so this is called the side. Only good thing here is you have a better signal to noise ratio because the scatter is more in the forward direction; this goes more interest in this direction compared to the backscattered. So, that is the only thing advantage that you have a better signal to noise ratio, but the major problem comes with the alignment. So, you have to align these two lenses or these lenses exactly in the same way as this lens has been aligned.

So, alignment is a major problem these are very vibrational sensitive. So, if your system is vibrating; they are very vibrational sensitive; so if your system is vibrating. So, what will happen? Suppose if the system has little bit vibration, so what will happen? That you will see the signal which will be vibrating and this vibration will be kind of transmitting for this place.

So, they may possible that you become of focus or actually the focus is; length is different; so you will see more noise. So, they are very vibrational sensitive; so that is why you need isolation table which actually reduces the vibration, but then those isolation tables are very costly. And your both transmitting optics and receiving optics should be placed on this isolation table, which can isolate the vibration. In the case of backscattered that is not needed because even if there is some vibration, both focusing and receiving of optics are vibrating at the same time with the same frequency; so you will not see much problem in that.

So, that is pretty much by this kind of vibrational sensitive is there, but the major advantage is that intensity of light scatter is very high. So, you get a better signal to noise ratio generally it is two order of magnitude higher; higher than backscattered and this is the major advantage of this and that is why it is still be things are used; particularly for a denser system, where the attenuations are very high; you will generally depend on the forward scatter or side scatter because your signal to noise ratio are very high; your forward scatter light signals are very good.

So, that is the way the optics is being used to find that what different type of optics are used to optimise the signal. So, we have discussed the signal processing, we have discuss the optics, we have discussed the methodology and working principle

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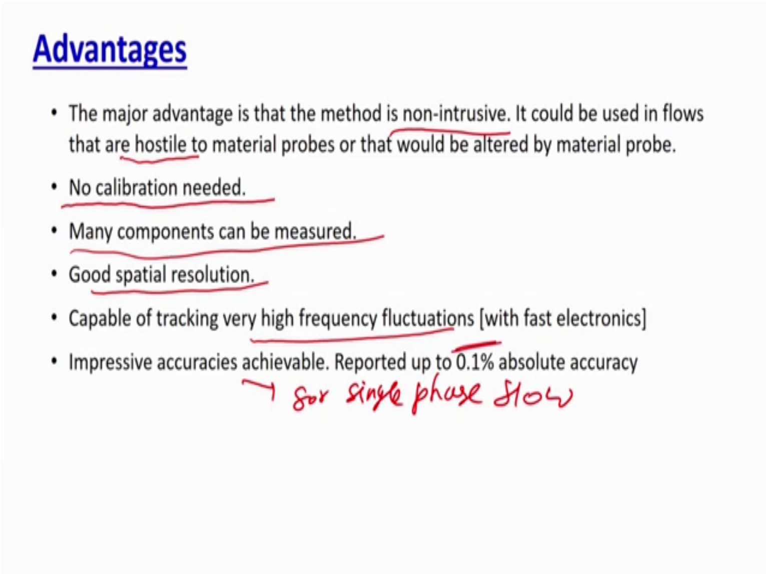


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Now, what are the advantage of LDA over the non intrusive? So, first thing is the major advantages that it is non intrusive technique compared to hot wire anemometer, optical fibre probes, LDA is non intrusive technique and that is the major advantage. And disadvantage actually give you the flexibility to use the LDA in hostile medium, where the material are such or where the fluid such which can damage your probe in case intrusive technique, you can use the LDA at that places so that because it is a non invasive. So that is the major advantage, you are not disturbing the flow; you can use in the hostile conditions on the kind of a fluid which is very corrosive or hot; we all skill in fluid where you cannot use your intrusive techniques.

So, that is the major advantage second major advantage and that is again a big advantage is that this no calibration needed; you do not need to do the calibration. Whatever we have seen in optical fibre probe or HWA, you need the calibration other than the pitot tube. So if you need the calibration, the problem is your accuracy will depend on the accuracy of the calibration. So, suppose if you are using HWA; you are using pitot tube for the calibration, the HWA measurement accuracy will be depending on the pitot tube.

Now, we know that in the multiphase flow; the pitot tube accuracy is very very low. So, if you are using HWA in multiphase flow or hot wire anemometry in multiphase flow, your accuracy will be limited to whatever the way pitot tube is presenting.

So, that is why some of the kind of companies what they do they use this non intrusive technique to calibrate the intrusive techniques. And that is why the cost of intrusive techniques are very very high because you are using the non intrusive technique for the calibration purpose. In this case LDA it is no calibration required and that is the major advantage, you do not need to do any intrusive calibration and all.

Then many components can be measured; so, you can actually measure one-dimensional velocity can measure, two-dimensional velocity, you can measure the three-dimensional velocity. All these things can be measured, it has a very good spatial resolution because you can see that if the fringes forms or what is the distance between that and you can localised even at that place even you can localised the optics by using the right lenses, you can localize the fringes wherever you want.

So, your spatial resolution is very high, your temporal resolution is very high which I have written the high frequency fluctuations can also be measured if you use a very good electronics, a very good light source and optics you can have a very good temporal resolution tools. So you have a high spatial resolution, you have a high temporal resolution and the accuracy for single phase flow is very high and that is generally reported to 0.1 percent.

So, it gives a very high accuracy, but that is valid only for single phase flow again I am mentioning that.

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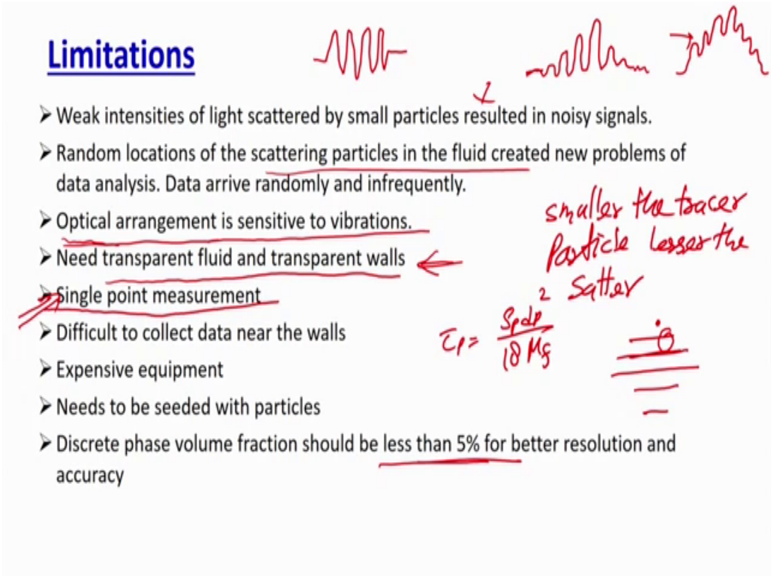


So, this is what is advantage of the LDA; the disadvantage is that weak intensity of light scattered by small particle. So, the tracer particle actually plays a very very critical role why? Because we know that if the tracer particle size is very small, then the light scattered by the tracer particle will also be very small. So, smaller the tracer particle; lesser the scatter, lesser the scatter later lesser the Doppler shifts or light intensity which will be recording on the PMT; so, the signal to noise ratio will be poor.

But the problem comes if use the bigger particles, if you use the bigger particles then what is the problem? That you may start; so suppose you make a fringes and making this as a dark fringes and where I am not drawing the light is suppose is a small fringe or this bright fringes. So, now, if a particle diameter if suppose the particle diameter is very small; it will cut one fringe at a time but what if the particle diameter is too big in that way? What will happen if we cut both the fringes at the same time and the signal which you are receiving in somewhere in this way that it is going in this way, it will start merging.

So, you will not get this kind of a signal; you will get some signal like this, then this, then this, then this, then this, you will get signal like this. Because you are cutting both the fringes at the same time; so before the signal is coming to the 0; you have again cut the same or next fringes.

So, you will get something like this fringes and then your post processing becomes typical you have to use lot of the filters to make the signal back to the same way as we have done after the Doppler bust that to make the signal it in this way, you have to do lot of processing. So, that is the reason that if your particle size is bigger; you actually cut mini fringes together and that will add on to the complications. So, what you need? You need a very fine particles; but if you go for very fine particles your light intensity is low.

So, you have to play between this, you have to optimise it in this way. Second thing we know that if you increase the particle size, the stokes number or you can say the particle response number of response time, you need to be very care with the particle response time which is nothing, but rho p; I think we have already discussed it is rho p; d p square upon 18 mu f.

You have to calculate this value if the particle response time is very high or it is stokes number; if goes more than 1, then what will happen? You see some motions which will be dominating by the particle the fluid if it. So, particle will take some time to respond any change in the flow. So, there are many studies has been done to find the optimal tracer particle size and that is very very critical in the LDA or any method we are use a seed particles.

So, if you are using a particle which is a very big size then what will happen? You will get a very good light scatter, but you will cut multiple fringes; at the same time there is a possibility that particle may not follow the path of the fluid; maybe it has his own (Refer Time: 31:51) so whatever you will get the velocity, it will be the combination of the velocity of the particles; seeding particle plus the fluid. And that definitely we do not want, if you use a very fine particle then the light scattered will be very very small; your signal to noise ratio will be improved. Further if you go for particle size which is really very small in the range of nanometre or even lower; then the problem comes that the particle will start it is Brownian motion.

So, again it will not follow the path of the fluid; it will have it is own motion and that will go in the Brownian regime. So, one need to be very careful before choosing the right size of the particle and that is the main critical parameters that you need to search that what type of particle should be used for tracking which type of fluid and that particle is going to change with the system, with the type of system, with the type of the fluid.

If you change that you particle will change; os that is the major problem in this to choose the right seeding particle. Then the random location of the scatter particle in the fluid create the problem in the data analysis; so, if suppose you are using lot of particles it will randomly placed and then they will be cutting the fringes at the same time. So, it will again create the problem in the data analysis. If you used too less number of the particle, your data acquisition time will be very very high.

So, then if you are using this forward scattered or side scattered then your system is very very sensitive to the vibration; isolation table is must to do this kind of experiments if you are using forward or side scattered way. You need a transparent fluid and transparent wall and that is the major problem. So, if your fluid is very muddy what will happen? The laser light will not able to penetrate inside; if your eyes cannot see definitely laser can also not see both falls in the visual range.

So, that is the problem your fluid need to be cleaned, you need a transparent wall; if you want to do it in the industrially scaled system where walls are made of the steel or made of the ss; you cannot use this system and that is the major drawback and that is the way the this applicability of LDA in multiphase flow is reduced. Why? Because as we discussed that in multiphase flow, even if suppose the wall is made of the glass is the transparent material, but if your discreet phase fraction is very high; your diffraction will increase and then what will happen?

You will see lot of is scattered because of these discreet phases and that will actually reduce the signal to noise ratio like anything and you will get only noise or you will get only whatever is happening at the wall; you cannot go inside because you will not able to penetrate inside through the laser. Even a very high intensity laser; why high energy leaser will not able to do that? And that is the way that why the application of LDA is being restricted in the multiphase flow.

Because you can do it only for a very small discreet phase volume fraction and that is generally less than 5 percent and those kind of a flows are very less or very kind of not commonly used in the industry particularly; for research people use this flows, but for industry we need high throughput, we need a high discreet phase fractions; so the applicability of this has reduced. Similarly, if you are using for the gas solid phase; if this solid fraction is not very low. So, less than 4 percent or 5 percent; you cannot use it because all these distraction or will be with very high because of the solid project.

So, again it is limits the use of this; if you want to use the LDA in the dense fluid, bubbling fluidized bed where the solid fraction is around 40 to 50 percent or 30 to 40 percent or 45 percent; you cannot use it; you will see only what is happening at the wall you cannot go at till the centre of the column.

So, these are the major limitations of the LDA particularly for the multiphase flow or even for the single phase flow where the system is either opaque or the fluids are very dirty; so where you are not able to penetrate. Then the major another problem which is the major problem again is the single point measurement. So, like optical fibre plot like HWA; like intrusive technique LDA is also do only single point measurement.

So, if you have to find a complete velocity fluid what you need to do? You have to do several measurements and that will increase the time of measurement, increase your effort. So, you can get the velocity only at a particular point; the complete velocity field fluid mapping cannot be done and that is another major setback for the LDA, for the industrial application where you want particularly for the close contact; where we want that how the flow is taking place near the wall, how the flow is taking place at the centre, how the flow is taking place near bends or near any internals which has been placed.

So, you cannot get the complete flow field fluid; you can get the velocity of flow field fluid at a particular point only and that is the one of the major disadvantage. And then again it is very difficult to collect the data near the wall; why? Because near the wall again the scattered because of the wall will be very high; the focusing of the light will be difficult. So, that is why taking the data very close to the wall is also difficult and again that is the reason that applicability of LDA in multiphase flow is limited, you can do it for a very small volume fraction system only.

Then again these are very very expensive compared to whatever the invasive technique we have discussed. These LDA are very expensive and that again limits the application of this, then the seed particles whatever I said right size of the seed particles is very very difficult or is very critical; I will not say difficult, they are lot of seed particles available in the market which you can buy for the LDA or PIV experiments which we will be discussing next.

But the size of those seed particles; what kind type and size seed particles should be used is very critical and affect the accuracy of the LDA experiment and it affect severely. So, that are the major limitation of the laser Doppler anemometer particularly for the multiphase flow, the major problem comes that you are using laser optics. And that is why you cannot use this system for high discreet phase fraction; where the discreet phase fraction is very high say in the order of 10, 15 percent; generally the accuracy is higher, if the discreet phase fraction whether the bubble fraction or the solid fraction is less than 5 percent.

So, this is all about the laser Doppler anemometer; now the next technique which is being developed after the laser Doppler anemometer is particle image velocimetry.

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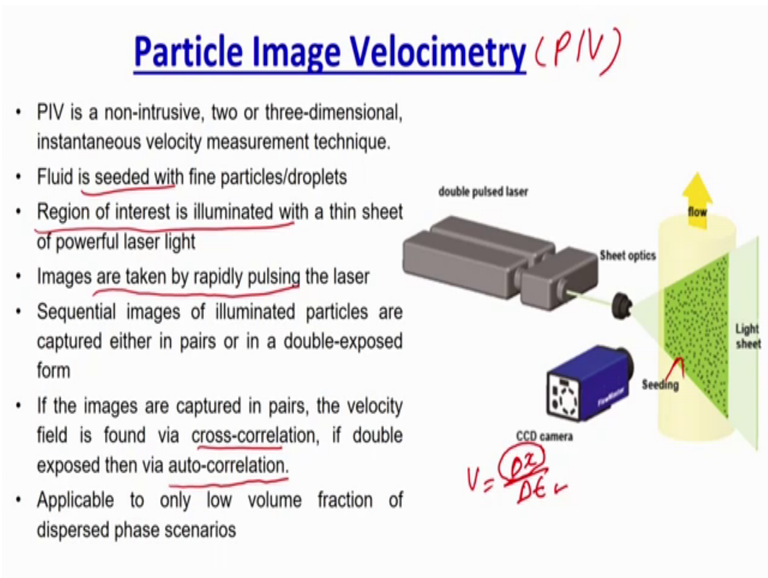


Now, this is the improvement; clear cut improvement of the LDA; from the LDA and one of the major improvement is done that in LDA where we are using only the point measurement which we will be using for point measurement only, here you can do the complete you can map the complete velocity field. So, you can measure the velocity at all the location; so complete flow field can be mapped and that is the major advantage of major improvement over the LDA.

So, basic principle remains same; it is also going to use the laser, it uses the laser, it uses the seed particles, but it is uses the camera. Now the camera we will talked about that it is camera can be very high speed camera, it can be a CCD camera; in which you can do the pulse generation and time between the two pulse are very very small.

So, all this kind of optics can be used to measure the flow fluid, but the major benefit over the LDA is it gives you a flow flied fluid for the entire domain or in the complete flow fluid map, you can get in one go what is happening near the wall, what is happening at the centre of the column; everything you can get.

So, you can get the complete flow fluid map compared to LDA where you are getting only a single point measurement. So what is particle image velocimetry; PIV particle image velocity metry we also say it PIV is a non intrusive technique like LDA, it gives you the two or three dimensional instantaneous velocity measurement in the same time and it gives the velocity measurement across the whole fluid. Again what you do? You do the same thing; you make a laser light seed instead of; you cut the laser light here there in LDA.

Whatever we are doing we are using the transmitting optics which you used mainly consists of lenses to cut the beams at a particular location; at the measurement point we make the fringes and by the fringes we see that how the particles are cutting the fringes and receiving the signals at the photo detectors or photo multiplier tube. Now in this case what we do? Instead of cutting the laser light, we make laser sheet.

So, you make a laser sheet like this; we use a just laser source again here also we use the sheet optics we say, we will discuss about this; we use a sheet optics, but sheet optics is nothing, but it makes laser sheet like this; it makes the coon form. So, what will happened because of this? It will eliminate the inside of the reactor volume and then we use a fluorescent particles; a seed particles which actually eliminates light ones they comes in the laser light field. And we use a high speed camera or a camera, I will say just the camera to take the photograph at a very high frequency.

So, what will happen you will capture the photograph; they will be seed particles which will be moving like this, there is a seed particles which are moving all around, you are taking the photographs, you are analysing the images; subsequent images and you are trying to find how the particles are moving. So that is the basic principle of the PIV that we use; so what we are going to use is a laser light to form a leaser sheet, we are to use seed particles which will eliminates the light in presence of the laser and then you capture the photograph.

So, now that will be eliminates the light what will happen? Those things you will see as a bright; the rest of the things you will see as a dark and you will see a cropper contrast, you can identify that where are your particles and how your particles a moving in a subsequent images. So, that is the basic principle we use; so we need a seed particles, the reason of interest is illuminated with a thin laser sheet. So, we illuminate that thing with the thin laser sheet, now we need a powerful laser because we need to penetrate through the system. So, the laser power should be higher; image are taken rapidly by pulsing the laser.

So, there is two way to take the image; one is you take camera which is continuously recording the images and you pulse the laser. So, if you pulse the laser what will happen? That initial pulse again the seed particles will emits the light, they will be (Refer Time: 42:27) recording then the next pulse again the seed particles will be eliminating.

So, we will know that how do seed particles has change the locations and then again by using the delta x by delta t you can do that or you can have a camera which can generate the pulse we can record the time this things; the photographs after certain times. So, we can pulse the light laser or you can use the pulse the camera; both options are available. In pulse camera you have to use a continuous laser or you can use a very high speed camera which is continuously recording.

So, this all the options are available and based on that you define actually different type of PIV. So, sequential images as I said that whatever has been recorded; the particles are capture they either moves in a pair or in a double exposure form and in the pair form what you do? You find what are the practical; you track the individual particle, in the double exposure form you actually use the two images which is being exposed at two different time which is the interval between this is very very low sometimes in the order of nanoseconds.

And then you kind of analyze those figures and then if the capture whatever is there you use either the cross correlation or autocorrelation in this kind of algorithms; to find the how the particles has been moved. And once you know that particle displacement, you can find it out delta x; you know the time between the two subsequent imaging or two subsequent laser pulsing, you can find it out delta x by delta t you can calculate the velocity.

So, you use simple formula V is equal to dealt x by delta t only problem is you know the delta t to find the delta x that how they have moved, how far they have moved. So, that depends that how you are capturing the image; you are capturing in the pairs or you are capturing in the double expose mode; we will discuss what is the pairs and double expose mode.

If you are using in that you use the suitable; this algorithms to find the delta x based on that which mode of operation you are doing and then you calculate the delta x delta t which gives you the velocity. For the two-dimensional flow what will happen you will get that how much is the radiant motion, how much is the axial motion, you will get the delta r by delta t; delta z by delta t, you will get the two dimensional velocity.

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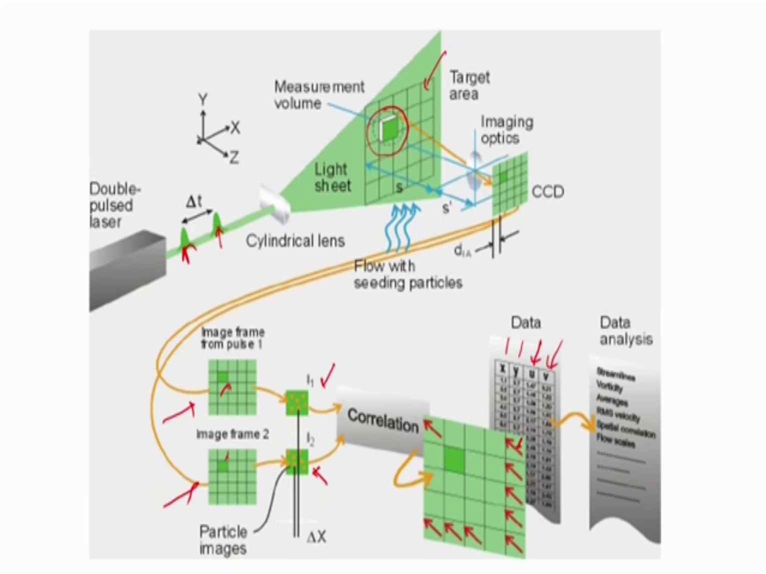


So, that is the basic of particle image velocimetry; this is what how it works we have taken it from the den take. So, what you do you use the laser and that is the double pulse laser. So, what does they do? The laser actually illuminate a particular section this is a measurement volume and the whole measurement volume; it divide into the small pixels is a virtual division you are doing it; it is a small pixels.

So, let us take I am talking about this one pixel and this is I have zoomed it; I will further divide it into the small pixels; the way we have done here and now what we do? We acquire the two images; so one image there is delta t difference between the two pulse. So, these are the pulse of the laser; so what I have done? I first sent a pulse and then after delta t times again I sent the pulse.

So, once the pulse will be there that with the laser sheet will form, it will eliminate the lights which are there in the measurement volume and you will record the image. Then again the pulse will get off, you will not get any image, you will not get any lights image. Then again the next pulse will come, it will always eliminate the whole section once it will eliminate the whole section you will again the seed particles will emit the light you will I can take the photographs.

So what will happen? You will have two photographs this is the photograph 1, this is the photograph 2. Now what we are going to do? We are going to take a particular cell in both the photographs this cell I am in the take and I will kind of see this two pixels and I will see that in these pixels, how many number of seed particles are there.

So, whatever the number of seed particles there we will do the cross correlation between these two images to find that how this seed particles has moved between the two images; between the two images which has been taken after interval of delta t. And we found the relative distance or total displacement of all the particles. So, displace that how the tota say if the 10 particles are there inside that cell, how those 10 particle has been displayed displacement has taken place.

So, how they displayed you calculate the overall average displacement and that is delta x for that cell and we divide it by the delta t, we get the velocity. So, similar things we do for all the cells and we calculate that how much displacement has taken place and that displacement we record actually x and y; we can did the displacement in the x direction, displacement in the y direction; we know the delta t you can calculate the velocity in the x direction and y direction.

Now, these can be used for the detailed data analysis; so you can plot the vector plot, you can see the some miss structures, some recirculation all those things you can see. So, this is the basic operating principle of particle image velocimetry PIV. So, this is what we do.

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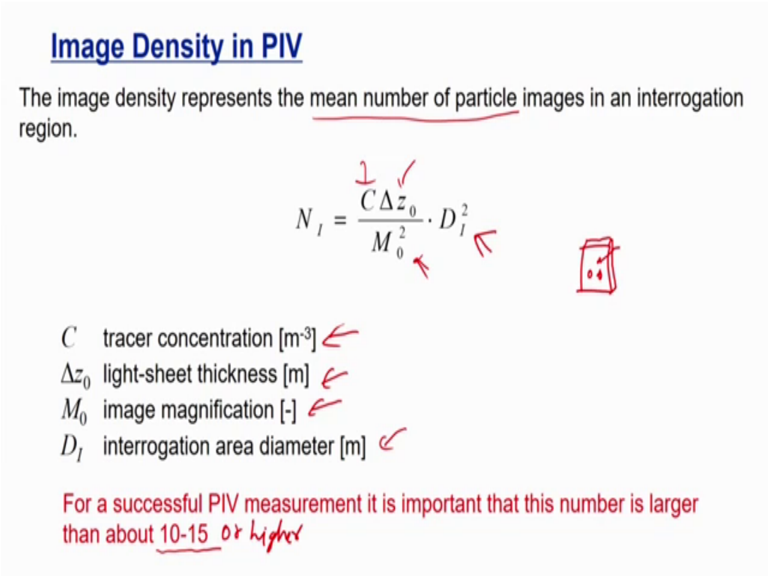


Now, we try see that what are the parameter which are critical in this PIV measurement. The most critical parameter is image density; now how the image density is defined? Truly speaking image density is nothing, but number of seed particles present in a particular cell. So, you are dividing it the complete domain in a small cells or we will say the small pixels; in each pixels, say this is one pixel in each pixel how many number of particles are there.

Higher the number of particles, higher the number density; lower the number of particle, lower the number density and this is a very very critical parameters. As I said that we calculate the mean displacement; so, in that cell suppose 10 particle is there; how those 10 particle has displayed from between the two subsequent images.

So, more the number of particles better the displacement you will get; mean displacement you will get and better the velocity production. So, we need to do once we doing the experiment we need to find it out what is the number density or image density of my PIV experiments. And the image density is actually as I said that it shows the mean number of particles which is available in the image in or in the integration region where we are doing the measurements. So, it has been defined as C into delta z naught upon M naught square into D I; where C is nothing, but the tracer concentration. So, any slop you seed with sometime number amount of the particle. So, that is what is the tracer concentration; number of tracer particle per unit volume.

So, how much is the concentration you have used that is the parameter this C. So, how much is the tracer volume, what is the thickness of the laser sheet. So, what is delta z because that will be the z direction of the sheet you are making a two-dimensional, the third direction is the thickness of the delta this laser sheet.

After that if the particle will suppose move say this is the small cell you are making actually you are making the cell in this way, where the particle if the particle will move on the other side; then it will be off focused. Once it will be off focused then it will not be considered in your number density or image density. So, that is why you need that what is your thickness of the laser sheet which you form; then image magnification they generally used lenses to focus this to magnify the image.

So, how much you have magnified the image, what is the image magnification factor you have used and then what is the integration or measurement area diameter. So, where you are doing the measurement; what is that area diameter that is the D I. So, that is depends on the N I; we called it as a image density and for a successful PIV experiments or for a good data; you will required that N I should be in the range of 10 to 15 or higher; I will see or higher.

But if it is to less your image processing will create several serious problem because you are doing the cross correlation between the two images. So, is required a good amount of particles which are being there; we will discuss that we will show you that if your number of particles are less how it is going to affect your accuracy.

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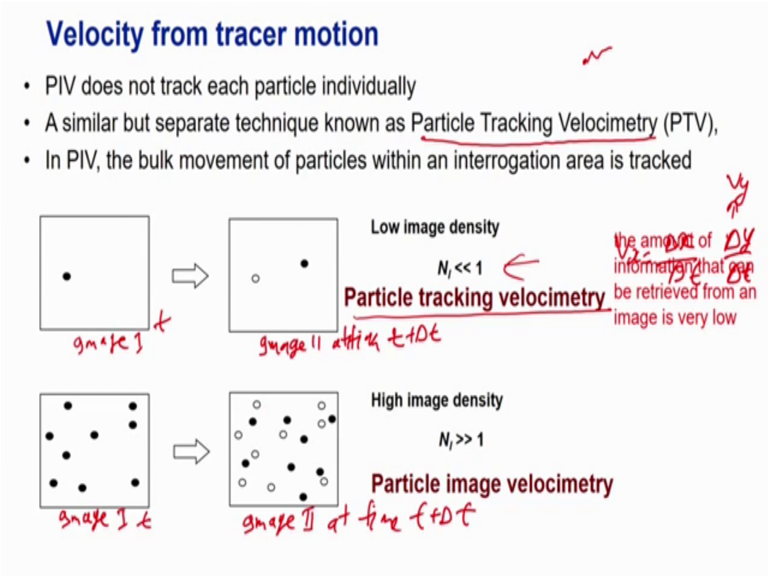


So, how you find the velocity from the tracer motion? That PIV actually there is a two ways you can do it; one you can track the individual particles. So, suppose there is one particle you can use and that individual particle motion you can track. Now if you do that in amount number of experiments will be very high because you are getting a very less data per cell.

So suppose you are using only one particle or if you are suspending you make the concentration so, low that in each cell only one or two particles are there and your tracking the motion of those one or two particles, you are tracking the particle motion each particle motion or each seed particles motion. So, then what will happen? Again the time; the information will be low, the time of experiments will be very high and those experiments are not called PIV experiments; those are PTV experiments Particle Tracking Velocimetry.

Because now you are tracking the particle, you are not tracking the image. In PIV what we do? We do not track the path of the individual particle, we will track the path of a group of particle, we track the whole image together. And we will see that two image we analyse, we do not analyse that how the individual particles are moving. So, what we do we analyse the bulk motion of the particle between the measurements area of between the pixels; so that is what is called PIV.

So, do not get confused because sometimes people get confused even if you are doing PTV experiments; they call it as a PIV experiments. So, particle tracking velocimetry in which you track the path of individual particles, but particle image velocimetry; you do not track the path of individual particles, you track the path of a bulk of the particle which is present in your measurement area or in your pixel where you are tracking the motion.

So, that is there; now in PTV what we do? As I said suppose you have this image 1, you have 1 particle; in image 2 the same particle this is image 1; say at time t, this is image 2; 2 at time t plus delta t. So, this particle originally at time t was here, it move at this place what is happened? The data processing is very simple, you will get that how much displacement has taken place; displacement in the x direction, displacement in the y direction you can use delta x upon delta t or delta Y upon delta t to calculate the V; V x or V y; so this is V y component of the velocity.

So, we can easily do that and that will do actually your this thing and you will able to calculate it. So, by V x and V y component you can calculate simply by measuring the displacement. So, this is called particle tracking velocimetry here the image density is very very low lower than 1, it means your number of seed particles are very very low your image density is very very low; so, you will be taking one or two particles seed particles in each pixel; so, that is PTV.

Now in PIV what we do? In PIV we actually have a image; in that image say I have few number of particles, which has been in the says; so this is image 1 and this is at time t, this is image 2 at time t plus delta t and you see that how the particles are moved.

Now, this movement if you see this is the original particle position which is not been darken, which is the hollow; this here a hollow circle with that this is darken is the new particle position. So, what we do? Now we see that how the whole displacement has taken place, we get the delta x, we will get delta y from that and we calculate the V x and U x component of the velocity.

Now this V x and U x component of the velocity in this case; if you do is actually it will be the mean displacement in the x direction, mean displacement in the y direction. And in this case, high image density is required and N I values are much greater than 1.

So, that is the way this has been PTV and PIV difference is there; the PTV the problem is that amount of information that can be the try for the velocity calculation is very low. So, the experimental time is very very high, which is not true for the PIV experiments.

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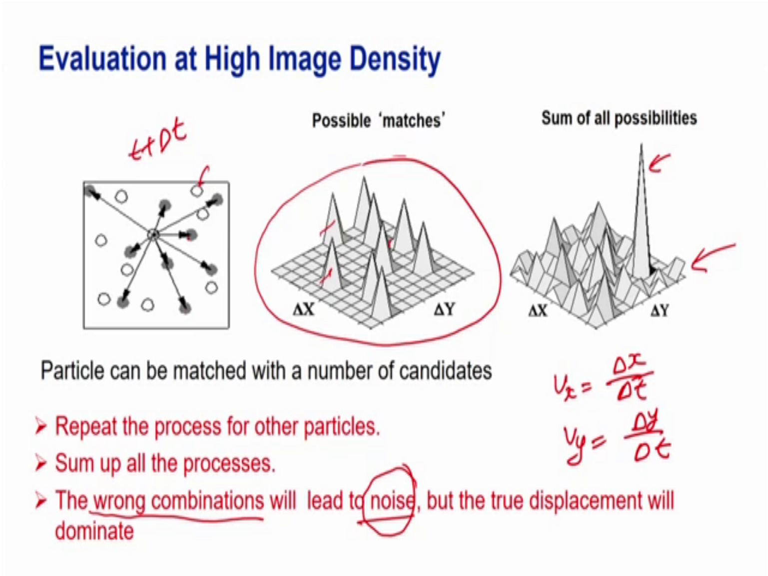


So, how we do that in PIV, how we do the velocity measurement, how we calculate the mean displacement? That is the major challenge. So, what we do? So suppose this is a image which is required time t plus delta t; the second image which I was talking about. So, what we do? These are the particles say hollow particles are there and I am seeing that the dark particles are the new position.

So, what I will do I will take one hollow particle which is the previous position and I will cross correlate this motion with all the particles; whatever the nuke in the new frame image the particles are there. So, first I will super in phase the original image or t plus delta t image with the t image; so I will get the both the particle positions.

Now, for each previous particle position; I will try to find it out that what is the probability of the displacement? So, I will do the cross correlation and I will find the cross correlation factor for each particles. Now similar thing I will do; so, I will get this kind of a peak. So, for this is delta x; delta y; I will get the peaks say for this; this is the displacement your cross correlation factor is this. If this is the displacement, your cross correlation factors this; if this particle is you will get a cross correlation. So, for each particle will get a cross correlation map like this.

Now, this is the way you will get for each particles; so, each particle is being correlated with everyone. Now what you do? You repeat the same thing for the other particle; so, now earlier I was doing for this, then I will do for this again. Again I will correlate with all the dark particles and again I will get this kind of a map. So, I will keep on doing it and then I will be summing up all the processes.

So, once we sum all the processes; you will get something like this and you will get a dominant peak because now you are summing up all the things, you will get one place which will be dominant; at that dominant peak actually shows the displacement delta x delta y which is the actually the average displacement of all the particles.

So, what will happen? If you will be having a wrong combination say if this is the one combination, you are making the combination for all the particles. If you are using have a now wrong combination, the sum up will actually least to the noise. If sum up all these, the wrong combination will least to the noise; it means this values will be reduced. The true combination will be a dominant; can this displacement it will shows the dominant displacement, you will get the delta x, you will get the delta y. Now the V x will be calculated as delta x by delta t; we know already delta t; V y will be calculated by delta Y delta t.

So, we can calculate these values and you can find it out the v x and v y component of the velocity.

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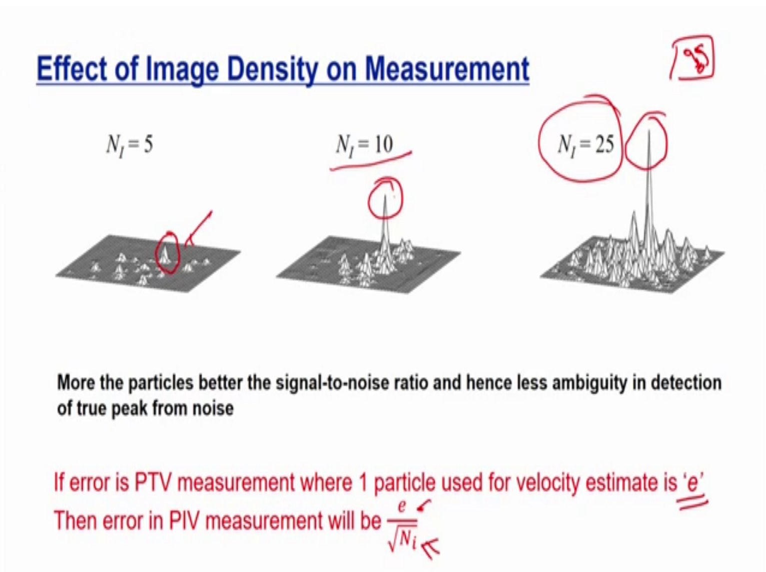

So, that is the way the PIV has been done and why the number density is important? More the number of particles, better this displacement peak you will get. So, suppose like this is the representative picture which I have taken from the literature. If suppose the N I is equal to 5, you will get this kind of a peaks; so the dominant though this is a dominant peak, but they are very close to the noise because your number of particles going to be in a particular cell will be less.

So, if they will be small error you will lose out the focus; you will not able to find that which one is the dominant peak. If you increase the number density or image density; then what will happen? That the peak dominance will be keep on increasing and the noise will be keep on reducing because you are now summing up everything. So, if you sum up for say 5 particles; if N I does not mean the number of particles so do not get confused.

But if suppose if you have a 5 particles you are doing the sum; the error will be higher because somewhere it is high; the response will be higher some for some it will be lower will sum up with you will get a very less; the dominant peak frequency will be very very less or height will be very very less. Keep on increasing, noise will be keep on reducing because you are doing the averaging; your noise will be keep on reducing and the signal strength will be keep on increasing.

So, that is the way that why we need the N I value very high and why the PIV experiments are better than the PTV experiments? The PTV experiments first thing the problem is the directional severity is not there. So, once you super impose the two figures; whether they come to this direction or this direction that is difficult. So, you should know that which direction the fluid display; PIV that is not there, the first thing.

Second thing because there you are tracking only one particle; you are in uncertainty in the measurement is very high. So, error is very high; so suppose in the PTV if you are getting a error which is e there is some number I am saying; if you do the PIV your error will be e upon under root N i and N i is the image density. So, even that also helps if your image density is high; you can reduce the error like anything compared to the PTV experiment and you can get a very good or accurate data.

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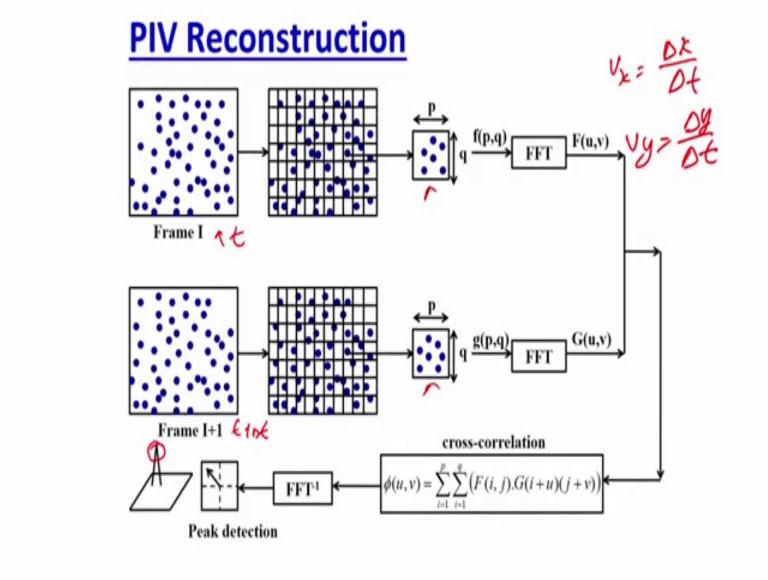


So, that is the PIV reconstruction; so if I summarise I can summarise it in this part that suppose this is the frame I; which is taken at time t, this is the frame II; which is taken at time t plus delta t. We divide it into the small pixels and we found that in each pixel how much number of particles are there. So, say if I zoom one pixel; say this is the pixel dimensions p and q, there are few number of particles here. In this image also the pixel p and q there are few numbers of particle here; we do the FFT here to reduce the noise again they go to the frequency domain from the time to the frequency; we take the FFT of both the image and then what we do? We do the cross correlation.

So, in the frequency domain we do the cross correlation; we find that whatever is the your displacement which one is cross correlating properly because the frequency domain cross correlation is much easier. And then you do the inverse FFT and you get the at displacement p that how much it will displace. So, you will get a vector that from original location how it has been displaced or you will get a displacement peak, you will get the delta x, you will get the delta Y; you can calculate that your V x is delta x upon delta t, your V y is the delta Y upon delta t.

So, you can calculate all these values and you can do the reconstruction. So, this is the way you can do the measurement, you can calculate the delta x by delta t values, you can do the measurement, you can calculate the velocity in the x direction, in the y direction with the more advancement; you can even do the three dimensional velocity calculation.

Now we will discuss about optics, we will discuss about the limitation and advantage of this technique over LDA and the major limitation of this techniques in the next class.

Thank you.