Multiphase Flows

Dr. Rajesh Kumar Upadhyay
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lecture - 17
Measurement Techniques: Velocity Measurement

Welcome back to this course. Now what we have discussed in the last class is about the different modelling technique, we have discussed about the algebraic slip model, we have discussed about the Aurelian Eulerian model, we have discussed about the Eulerian Lagrangian model.

And while presenting those models I always say that there is a limitation for each modelling method. And why there is a limitation because you assume something which may or may not valid, or we use some drag closure or some closure like a drag closure, which may or may not be applicable for the system you are investigating, or you are trying to understand.

And therefore, we I have shown you a slide where I said that there is a different techniques available, but each technique have their own limitation you are using some model, which is not scientifically developed which is developed based on certain assumption and therefore, it is important to validate experimentally your simulation data.

And for experimentally validation of the data what you need you need some measurement technique which can perform the or we can measure, the condition at the condition you want to do the measurement with, the accuracy or with the desired accuracy and the second thing, you need a technique which can be used at all the scales if possible with the equal accuracy.

And that will give you the luxury to do your numerical simulation at a smaller scale first, then you go for a higher scale you see that how your numerical simulation predictions are being done and, whether those predictions are matching with the experimental measurements or not.

So, what you need you have to do the first numerical simulation for the say laboratory scale system because that will be easy to simulate that will take less time to simulate, then you do the validation at numerical simulation numerical method technique at the laboratory scale at a smaller scale by using some experimental measurements. Now, you can use the same model which you have validated at laboratory scale, to do the scale up see the phenomenon at a larger scale, or say pilot plant scale, or even industrial scale do some measurement at that scale also to see that your scale up or your model which has been used to validated a laboratory scale, is working fine even at a larger scale. That need to be done and that exercise needed one thing, and that is called measurements of the flow parameters.

Now, as I said that already that in multiphase flow measurement, once I am talking about the measurements actually I talk about the 2 quantities, I want to understand the 2 quantities.

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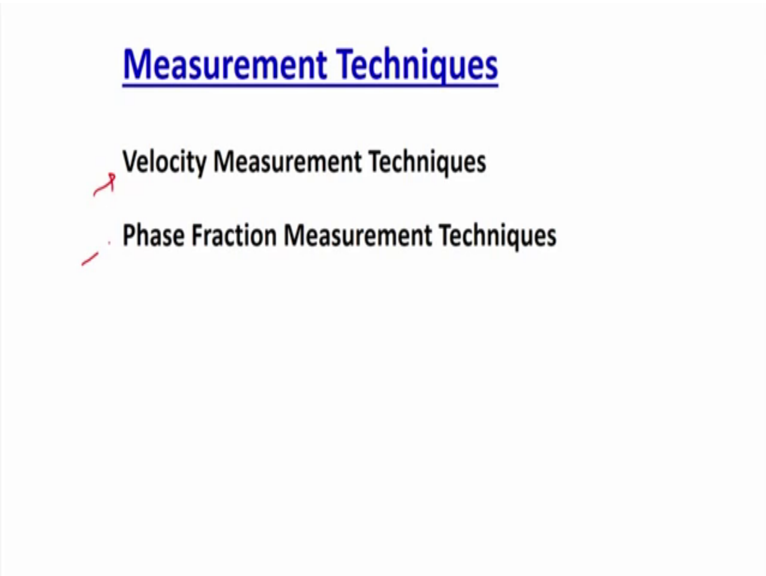

One is velocity, another one is the phase fraction and we have already discussed that these two parameters, whether it is a velocity or the phase faction in any multiphase flow reactors or process vessels, it is a function of position, it is the function of time it means you need to measure this parameters and you need to measure the parameter with the position and with the time.

And the thing require is that the measurements should be accurate it should give a higher spatial resolution it means with the position the accuracy is very high, it should have a very high temporal resolution it means with the time the accuracy should be higher and you need the technique which can be used at all the scale with equal accuracy. So, that is the requirement is there and that requirement will fulfil your job, if we want to validate your numerical simulations or numerical model which we have developed. And the validation is must because we are using several things or several closures or several equations which are empirically developed and because, they are empirically developed we need experimental validation.

Now, if you want experimental validation, then one need to understand that what are the methods you can use or what are the technique you can use to experimentally measure the parameter, what is the limitation of these techniques in the introduction classes, I have already said that why the multiphase flow is still as a major challenge as a field of research because, there is the region that there is no single numerical method available or numerical technique available which can do the prediction at all scale with the equal accuracy for all the system.

Similarly, there is no measurement techniques available, which can major the phenomenon at all the scale with the equal accuracy. And that creates the problem. So, what we are going to discuss in this part first is that what are the different measurement techniques available I will briefly cover them because, that itself is a big topic of research big topic of studies so, it will take huge times.

So, what I am going to do I am going to give you a glimpse of the different measurement techniques which can be used in the multiphase flow reactors, we will try to understand the capability the limitation of each technique and, the capability of each technique and, based on that on your system of choice the system you want to study the model, you have used and the parameter which you want to understand, you can use this technique you can choose one of the technique to validate your numerical simulation or to validate your numerical model.

So, therefore what I am going to do in this class, we are going to briefly discuss about the measurement techniques available for the multiphase flow reactors. Now the major challenge why you need a dedicated measurement techniques because, most of the single phase flow measurement techniques, suppose if I want to measure the velocity I want to measure the mass flow rate. So, most of the technique which is being used cannot be used here because of the multiphase flow nature of the flow.

So, suppose if you want to use rotameter, you want to use the rotameter of two phase flow you cannot do that because rotameter what you do you calculate the drag. Now once they will be a gas flow drag will be different, once they will be liquid flow the drag will be different because, they are you have a density of the continuous phase and that depends on the Reynolds number and again that will be going to be depend on the density and viscosity of the continuous phase.

So, therefore the based on that you cannot use the rotameter similar problem comes with the venture similar problems with the your orifice meter and all. So, you cannot measure that. Second thing in the numerical simulation whatever we are doing as I said that we are solving detailed equation. So, if you just validate it with the superficial velocity, it will be a very crude validation and, you cannot trust that the validation is correct or not your model has been rigorously validated or not.

So, the rigorous validation of the model is needed because, you are using those model to predict the flow phenomena inside the reactors. So, the measuring the global parameter and validating your model with the global parameters are superficial velocity is not a good idea, you will not able to conclude whether your model is working fine or it is not working fine.

So, what you need you need a local information you need a average information, but that should be inside the system and definitely, you need a validation for the mean velocities inside mean volume fraction inside, but you also need the validation for the local condition or the fluctuating velocity and fluctuating component of the volume fraction, that how the volume fraction is changing with the time. And, then only you can say that the model is able to predict the flow conditions with a high accuracy and therefore, the techniques should also have a capability to do so.

And to do that what we need we use some sophisticated technique to measure the flow parameter. And those measurement techniques actually we divide in two paths one is velocity measurement technique and, second one is the phase fraction measurement technique. So, these two technique you are going to discuss and we will briefly discuss this again I am saying I am not going in detail of this I will just give the overview. So, that based on your model based on the model which you have developed, the parameter you want to validate, you can use a suitable technique.

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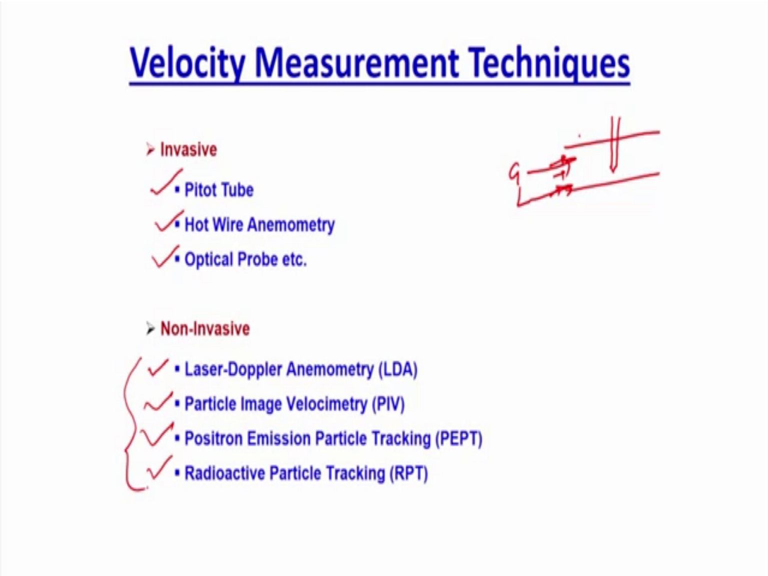

Let us start with the velocity measurement techniques here, velocity measurement technique or any measurement technique actually is divided in two path, one is called invasive, another one is called non-invasive. Now, what does the invasive means as the name suggest it means you are intruding something inside the flow.

So, suppose there is the pipeline where the fluid is flowing gas and liquid both are flowing so, gas and liquid both are flowing, you want to measure the velocity what you do you intrude some probe inside. And that is called intrusive once you intrude something inside some probe inside of the flow, to measure the velocity field or to measure the flow parameter that thing is called that technique is called intrusive measurement technique.

Now, this technique generally is very low cost technique it is cheap it give sometimes a direct measurement, but the major problem is because you are intruding something inside you may change the flow physics at the point of measurement itself. So, it means the flow dynamics of the system may change and, that to be at the point of measurement itself. And that is the major limitation of the intrusive technique, but still this techniques are widely used in industry in research mainly because, this techniques are very low-cost technique, you can easily use this technique, the this gives mostly direct measurement and therefore, it is relatively simpler to use this technique for the measurements.

So, if you are able to assure that your flow change, in the flow is not big you do not need that much accuracy and you are able to maintain in such a way that condition that it is not changing merge the dynamics is not changing the merge, you can use intrusive technique for the measurement of the flow quantities like velocity or volume fraction, but if you are not very sure about it you need a very high accuracy, the non-invasive technique are the option where, we used to measure from the outside we do not disturb the flow.

Now, the moment you do not disturb the flow what is you are going to do you are going to do, indirect measurement it means you measure something else and you will convert that in terms of the velocity. And therefore, there is always a problem. So, back reconstruction problems so, the reconstruction becomes an issue and kind of applicability of each technique, or the accuracy of each technique will be depending upon the position the reconstruction, algorithm will use and the method you used to measure the flow quantity, somewhere like to use camera, somewhere we use of laser, somewhere we use kind of radiation. So, depending upon what is you are using your accuracy of the system is going to be a get affected because of that.

In invasive technique velocity measurement technique, which is again I said that it is not that much accurate because, the flow can change at the point of measurement, but is still very low-cost and that is why it is still very attractive. And the accuracy can be maintained up to the desired limit, if you are able to understand the condition requirement and, you are able to maintain the flow condition between that.

So, invasive technique is divided in 3 parts of this is not only 3 there are many others, but they are mainly 3 technique which is widely used, one is pitot tube hot wire anemometry and optical fiber probe. Now pitot tube nowadays is not being used widely because, there are other measurement techniques is there, invasive measurement technique is there, but still I would like to say the pitot tube because most of you have already done the pitot tube under graduate studies or in your fluid flow courses.

So, I will trover the pitot tube I will try to give the brief difference between the pitot tube, whatever you have studied and how it is being used for the multiphase flow, then we look towards the hot wire anemometer and the optical fibre probe and, then we will discuss the non-invasive technique, under which I will mainly discuss about the PIV or LDA laser Doppler anemometer particle image velocimetry positron emission particle tracking and radioactive particle tracking. So, this technique I will be discussing briefly.

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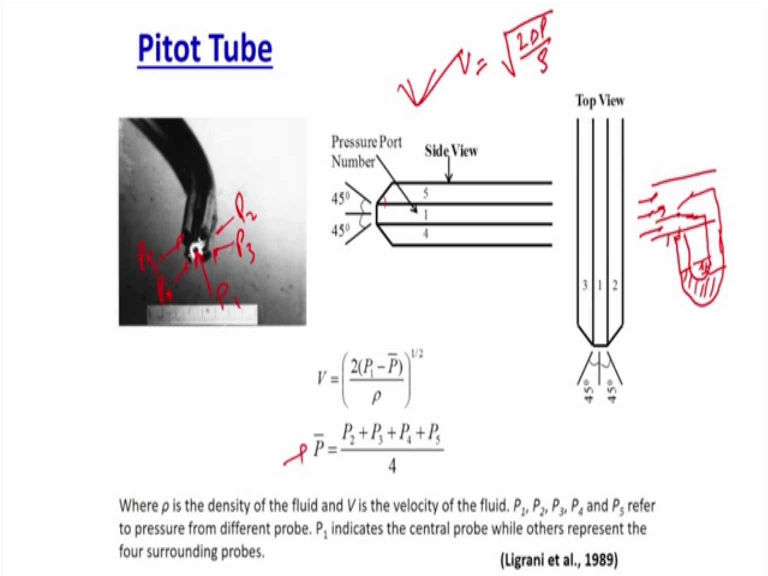

So, start with the pitot tube as we know that how the pitot tube work, there is a tube inside there is a flow suppose there is a pipeline you use a pitot tube which will be like this and, you connect this pitot tube with the YouTube nanometre to measure the pressure drop that, how it will be the pressure port will be there and how it is being measure that the streamline.

Suppose the fluid which will be coming here, once it will come and heat at this place it will achieve this stagnation pressure, once the it is achieved the stagnation pressure it means the velocity will goes to 0, the pressure will increase and because of that you will see that the selection in the manometer fluid. And this height change in the manometer fluid can be correlated with the velocity by using the Bernoulli equation. So, that is the basic principle of the pitot tube which you have already done and, that can be measure that velocity can the measure as V will be equal to under root 2 delta P upon rho.

So, that is the way you measure that this delta P will be the manometer reading and that can be calculated as rho of the fluid minus rho of manometer into to g into delta h. So, that is the way delta h can be delta P can be calculated, you can use the Bernoulli equation to calculate the velocity. So, that is the very basic principle of measuring the flow by using the pitot tube.

But the major problem with the pitot tube with this kind of a pitot tube is there is a multiphase flow reactors. So, what we measure that the delta P how we measure that we measure it at a wall tap, which is at the full condition you are somewhere at this location. And 1 pressure which we are measuring at the stagnation pressure.

But in multiphase flow actually we assume that this pressure whatever you are measuring is going to be the static at pressure and, that you can be kind of the constant everywhere, but in multiphase flow what will happen because the phase distributions are there they will be bubbles say gas liquid system they will be bubble, they will liquid phase flow. So, what you need this static the pressure should be measured near the stagnation pressure.

And to do that what we do we use 5 point probes or 6 point probes, we are we have a sensor probe where the velocity will be kind of a stagnation pressure will be achieved it will be measured and other probe we put other holes we put on the periphery of this probe this central hole like this, you can see that there are different holes here on the periphery of this and, they are actually 45 degree apart. So, this angle we have maintained at around 45 degree.

So, that they did not see the stagnation pressure directly and, the stagnation pressure affect will be there only at the central location. So, this pressure will be realized and this pressure combined will give you the average pressure around that central probe and, we measure the delta P by the average of this say there is a 4 hole you will measure P 2, P 3, P 4, P 5. So, say this is P 2, this is P 3, this is P 4 this is P 5 and this say is P P 1. You measure that pressure as we calculate the average pressure from all this probe, you calculate this P bar will be P 2 plus, P 3 plus, P 4 plus, P 5 upon 4 because the 4 probes and V will be equal to under root of 2 P 1 minus P bar upon rho and that way you calculate the velocity.

So, this is the method which we used in the pitot tube, to measure the velocity of the flow. The first problem it is a point measurement, it is measuring the velocity will be at 1 location. So, our dream to measure the flow phenomena with the position with the time will not be fulfil, you can measure with the time, but you cannot measure with the position. So, if you want to measure with the position what you need to do, you have to insert several pitot tube inside the flow or, you have to use the same pitot tube and we have to keep it at the different location for the different time.

So, if you put the several pitot tube inside the flow, definitely the intrusive nature will increase the disturbance will be very very high. And therefore, the error in the measurement will also be very high, if you use the same pitot tube and place it at different location then, you will not able to get a cross correlation or the correlation between the change in the flow at the centre of the column and the change in the flow near the wall at the same time. That luxury will be missing that information will be missing and therefore, this will not able to get the detailed information.

Second thing is that this probe because you are intruding inside cannot be used for the solid system, because what will happen the soluble go and choke all these holes they will go and sit inside all these holes. So, there will be problem will be created. Second we know that if the bubble coalescence take place, or bubble bursting take place, the bubble dead, or bubble generation both without bubble generation due to the coalescence, or bubble death due to the kind of bursting of the bubble.

What will happen, you will see a huge difference in the pressure and that huge difference in the pressure will be recorded by these 4 probes. And therefore, the delta P presenting itself will be very very difficult to measure and, that is put another challenge in the pitot tube. So, that is the limit the application of the pitot tube for the solid system or very dense system in the gas-liquid. And the dilute system you can still use it, where the bubble coalescence or bubble bursting phenomena can be minimised.

So, this is about the pitot tube is there, it is used a lot in the industry or for the measurement, particularly in the late eighties where people have use the pitot tube for the measurements in the multiphase flow reactors, but slowly the use of the pitot tube has been reduced in the multiphase flow reactors and it is limited mainly to the single phase flow, or a very mild conditions of the multiphase flow reactors like, measuring the velocity of the aeroplane and all you can still use the pitot tube.

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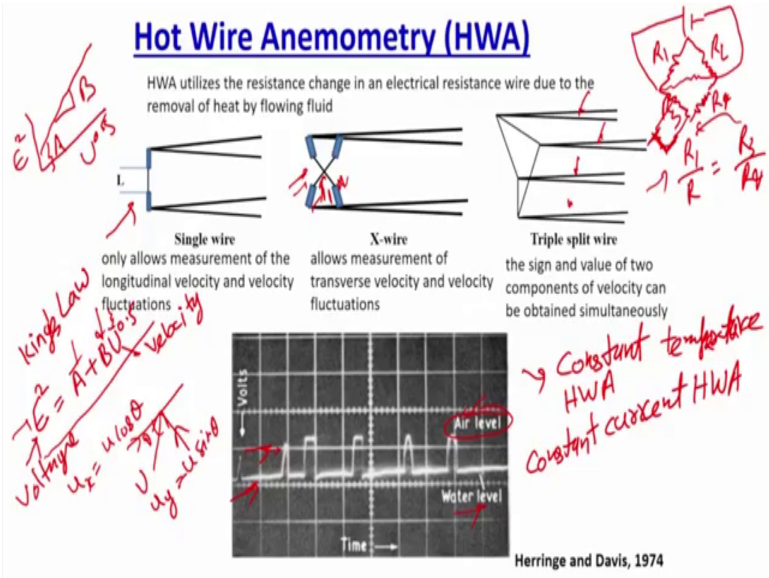

What we do there is a limitation in the pitot tube and therefore, a new technique has been invented and that is called hot wire anemometer. Now hot wire anemometer for single phase flow it is very very accurate and most of the turbulence analysis have been done this by using the hot wire anemometer, in the single phase flow and because it was very accurate for the single phase flow, the same technique has been tried to implement in the multiphase flow reactors to.

So, what we do here in the hot wire anemometer, we use a wire definitely as the name suggests there is wire which is maintained at a certain temperature or certain condition. Now, how it is being maintained or what condition it has been maintained this has been, there is a two type of hot wire anemometer one is constant temperature hot wire anemometer, another one is constant current hot wire anemometer. So, we say that constant temperature HWA and there is a constant current hot wire anemometer

So, based on how you are maintaining the condition of this wire, we have a constant temperature; we have a constant current hot wire anemometer. So, what we do there is wire which means sort inside and let us assume that we are using the constant temperature hot wire anemometer, this wire is a part of heat stone bridge circuit. So, we know that what is the Wheatstone bridge circuit so, suppose there is resistance. So, this is R 1, R 2, R 3, R 4. So, we know that R 1 upon R 2 will be equal to R 3 upon R 4.

So, the resistance will be an equilibrium and therefore, what will happen some current will be passed some current, if you connect to the voltmeter this will be there, or constant current will be maintained. Now, if you change there any of the resistance what will happen there will be change in the current and, that change in the current can be recorded in terms of the change in the voltage that is the basic principle is being used

Now, how the resistance will be changed. So, what we do we put 1 of the resistance edges of the resistance I extend it and. I put this resistance which is nothing, but a small wire in the flow. So, like this is the resistance 1; 1 resistance of the Wheatstone bridge and that is being suspended or that has been put in the flow condition.

Now, what will happen suppose if I give a initial voltage or reference current or reference voltage, then some current will pass through this wire and because, some current will pass through this wire there, will be certain energy or certain temperature will be maintained to the wire because, you know that the power will be equal to what I square R that will be the which will be supplied to the wire. Now, we are supplying some power we are supplying some current. So, the wire will be maintained at a certain temperature.

Now, the moment you put this wire into the flow, what will happen because of the flow the temperature will try to go down, there will be heat loss which will be taking place from the wire to the fluid. And because of that heat loss what will happen the wire temperature will change.

Now, we know that the temperature and the resistance is directly correlated. So, if you temperature will change your resistance will also change and therefore, the current pass this whole combination will be different. And because to maintain this condition what we need to do you have supply the extra current and that extra current supply can be recorded in terms of the change in the voltage which you need to do, to supply the extra current.

So, what you will get you will see that your voltage requirement will change. And the voltage the requirement change is correlated with the velocity by using the king's law where it is saying that E square, where E is the voltage output will be equal to A plus B into velocity raise to the power 0.5. So, you record the change in the voltage and that cost because of the change in the temperature which is taking place and, if you want to maintain the same temperature of the wire what you need to do you have to supply the extra current and to supply the extra current you have to give the extra voltage.

So, that change in the voltage you record and that change in the voltage is being correlated with the kings law kings law, which is says that E square is equal to A plus B into u raise to the power 0.5, where U is the velocity U is the velocity and E is the voltage, do this and you measure the voltage change and that voltage change is correlated with the velocity

Now, what we need to do here you see that we need a constant A and B, which is the constant this convective constant of the kings law equation and therefore, what you need you need a calibration. So, what you are doing is a indirect measurement you are not measuring the velocity, we are measuring the change in the voltage. And that change in the voltage. So, what you need to do you need to do the calibration? So, what we do we put hot wire anemometer in the flow and we operate it at a different known velocities.

So, what we have we know the U we give a reference current. So, we know that what is the temperature and, then based on the velocity the cooling will take place. And therefore, you increase to maintain the constant temperature this condition of constant HWA we need to supply extra voltage. And that voltage to U graph we measure, then we plot it because this plotted between the U square and U raise to the power 0.5.

Now, if you do this plot you will get a straight line which will intersect on the Y axis that intersect is A and the slope of this curve will be B. So, you get A and B values and based on that A and B value, you can find the constant. Now, you can insert this probe into the flow where you do not know the velocity, you will get the voltage output again and by using this constant which you have already found, by using the calibration you can calculate the velocity of the flow. So, that is the basic principle we use in hot wire anemometer, it can be operated whether you maintain the temperature constant, or you lead the change the temperature and you maintain the constant current.

So, in both the cases you can operate it there are different equations are available I am not going in detail of those application, if you are interested you can discuss with me or you can go through the books or literature, which is based on the hot wire anemometer, but that is the basic principle as I discuss of the hot wire anemometer to measure the flow rate.

Now, the major thing of the hot wire anemometer is that we are using only convective loss. Loss of the current or loss of the temperature because of the convection and, that to be the post-convection and therefore, this hot wire anemometer cannot be used for very low velocity, where the natural conviction may also dominate the conduction may also dominate, the radiation losses may also dominate.

So, we are neglected all these losses while using the kings law and, we have said that only the loss because of the post-convection is being counted. And because only the loss because of the post-convection has been accounted you cannot use the hot wire anemometer for a very low velocity system.

So, generally or typically what the velocity of more than 1 meter per second hot wire anemometer being used; So, if your flow is having a very low velocity HWA cannot be used, then this different HWA is available different type of HWA is available depending upon number of wires we use. So, suppose there is a single wire hot wire anemometer like this, what will happen you will get only 1 dimensional velocity, because there is only 1 wire you will get the average velocity of 1 dimensional the average velocity will get?

But if you want both X and Y velocity what you need you need 2 wires. So, 1 wire will be it is call X wires. So, there will be 1 flow in this direction, another will be say if the flow is in this direction say, what will happen for each wire it will form an angle say this is the flow this flow is coming at it in this direction, it will form an angle and this flow can be divided into the that this will be 1 component of the velocity say, it will be u sin theta and this will be the u cos theta, it use the velocity.

So, u sin theta is the X component of the velocity. So, you will Y component of the velocity it will be u y this is the u x. So, you will get both X and Y component of the velocity it means you will get both the directional velocity X and Y. If you will have only 1 wire you will get only 1 directional velocity.

So, to measure the 2 velocity we use X Y similarly if you want 3 directional velocity we use triple split wire, where there is a 3 wires there and you have this wires are aligned at a particular angle, you do this component wise analysis again and you get all the 3 component of the velocities. So, that is the way hot wire anemometer is used this is use. The similar way it is being used in the multiphase flow generally, whatever the way I told you it is being used in the single phase flow also the multiphase flow there is 1 more challenge and, that challenge is to identify the phase because both the phases are present inside.

So, what will happen the cooling of the wire will be happen because of both the phases. So, what you need to do your job has increased, which is in single phase flow you just measure the voltage change and, that voltage change we recorded in terms of the velocity or we calibrate in terms of the velocity.

Now, here two level calibration need to be done. And why the two level calibration need to be done because, we know that the thermal resistance or thermal property of each phase or each material is different. So, suppose in a gas liquid system if the gas is coming in contact of the wire, rate of cooling will be different if the liquid is coming in contact of the wire, rate of cooling will be different, why because the heat capacity the thermal conductivities are different.

And therefore, you need another level calibration to first need a calibration, you have to do the same calibration ENB for the air, you have to do the same calibration for the water, you need to see that for the velocity, how much for the same velocity change how much voltage change will be required, once the air comes into the contact what is the ground level voltage for the air, what is the ground level voltage for the water, and based on that voltage you do the phase discrimination.

So, like this is a typical example which is taken by the Herringe and Davis people of 1974 and they are try to so, that if you put the hot wire anemometer in 2 phase flow, you will get the voltage at two level, one is once the water comes into the contact another 1 is once air comes into the contacts. So, you will get the two different zone test level, you need to have the calibration for both the phases. You identify with the level that ok, if the voltage level at this scale at this range you are actually, you will have air if the voltage level comes to the ground state of this stage you are having water in contact.

So, it define the phase you find it out the phase here at which phase is coming into the contact, you use the kings law once the phases in contact, it depend on the that what is the voltage change required and, you do that calculate the velocity this is the basic principle is being used in hot wire anemometer, but the problem is your intruding the flow something inside which may change flow at the point of measurement.

Second thing is that if you use only 1 wire the intrusive nature will be less for sure, but you will get only 1 direction velocity or average velocity will not get the velocity with the all the 3 component of the velocity. If you intrude the triple split wire, then this support systems are very very big. So, they though the wire thickness is small the support which actually hold the wire that dimensions will be big. So, overall assembly size will increase and that which may change the flow at the point of measurement itself. So, that is the major problem.

Second thing is that the reverse flow condition is also create a problem because, the cooling will be the same whether the fluid is moving from bottom to the top at the same velocity, or it is coming from the top to the bottom at the same velocity. So, the reverse flow conditions you cannot actually measure it you cannot able to identify whether the flow is moving up or flow is coming down.

So, therefore, a condition where the reverse flow is possibility of the reverse flow is there, hot wire anemometer will not able to give you the direction of the flow. So, these are the major limitation further again the wire thickness is very small, if you are having solid present in the flow, the solid amount is very high then what will happen the wire will break because the solid will go and hit the wire.

So, it will erode the wire and because, the wire thickness is very very small it will immediately break. So, you cannot use the system for high solid hold-up system, for the gas liquid system you can use it, but the intrusive nature will increase if you use the triple split wire, for the solid anyway you cannot use it.

Of a any hostile medium say very acidic solution very corrosive liquid you cannot use it, why because a very scaling liquid which is very susceptible to scaling you cannot use it why because, if some layer will deposited or it will be eroded, then what will happen this calibration will change and therefore, you cannot use the same calibration for the measurement. So, that need to be careful and that limits the application of hot wire anemometer.

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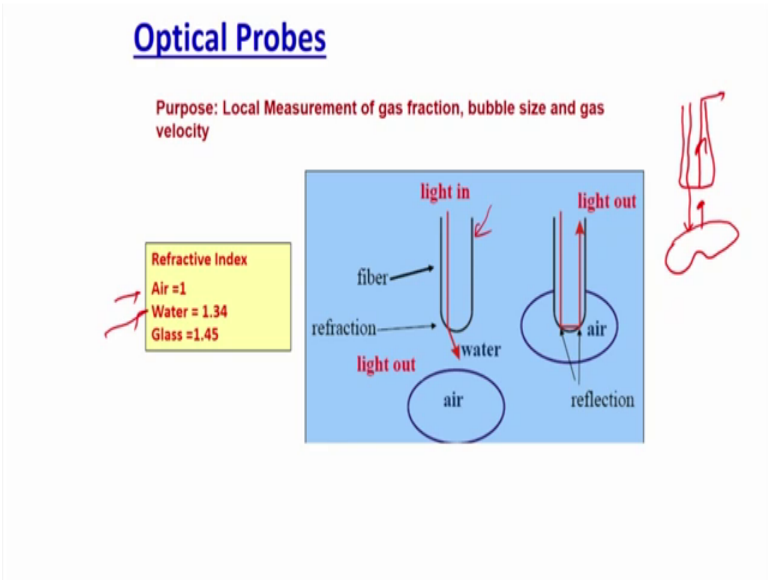

Next is optical fibre probe, now with the generation of optical fibre probe or development of the optical fibre probes, people have tried to use the same technique or same thing in the multiphase flow for the velocity measurement. Now what is the problem in hot wire anemometer, what I said that you will not able to get that whether the flow is reverse or not. You cannot use this system for a very hostile medium.

Second thing is that the major problem of the hot wire anemometer is that if, suppose the density is very high, then discrete phase fraction solid particle we are using and solid discrete phase fraction is very high, then it will break the wire ok. So, hot optical fibre probe actually gives the better accuracy because it depends on the light ok.

So what we do? We use the 2 probes, one is the light emitting wire another wire is there inside which is light absorbing wire or light receiving wire. So, in 1 wire this is say optical fibre probe casing there is a 2 wire inside. So, this is say it work it in this way this is the casing, there is 1 wire and there is a second wire. So, what happen this wire actually emits the light.

Now, there will be a phase now each phase will have a different refractive index. So, the light emitted by the each phase will be different. So, that what will happen this suppose there is a gas liquid system once the bubble comes into the content of this light, the refractive index of the air say air water system I am talking about this refractive index of air is 1, what is 1.34.

So, now the reflection intensity will be changed and what will happen you will see the different reflection intensity this will the reflection will be different. So, the intensity recorded on this fibre or with the which is connected to the photo detectors will be different. So, what will happen again you will get the two level of the this voltage and, this intensity recorded on the photodetector is directly proportional to the current generated or current this generated by the photodetectors.

So, photodetector how it works once there is a photodetector in which there is a metal, which once the photon goes and interact with that material it eliminates some photoelectrons. That photoelectrons actually goes to the photocathode and generate electron, that electron is being actually passed through the several diodes. So, that the intensity that electron intensity can be amplifier, and then it least to the anode and produce a current.

So, the amount of current produce is proportional to or correlated with the amount of intensity recorded on the photodetectors. So, we know the phases we know the refractive index of the phases. So, we know that the reflection index that how much light will be reflected by a phase, we will find that how much current recorded on the photodetector how will be produced.

So, from their we can identify the phases. So, do the phase identification by this method, whether it is a air or it is a water and that phase identification once it is done we measure the velocity, and how we measure the velocity we measure the velocity by using either the 2 point optical fibre probe, or 4 point optical fibre probe.

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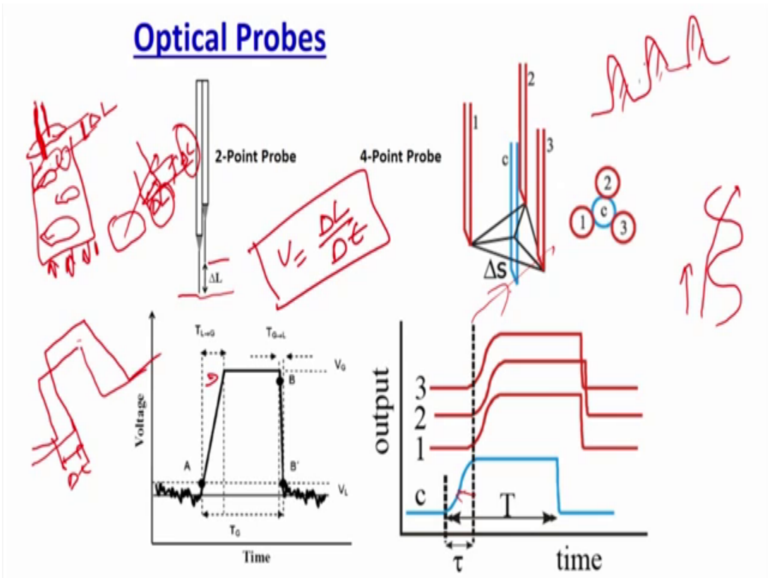

So, what happens in the optical fibre probe, this 2 point optical fibre probe, again we have the 2 probe. So, if you see there is a 2 needle and they are having distance this is the second needle, this is the first needle, there are delta l and distance we know that what is the delta l between that 2 needles.

So, what will happen you insert it in inside the flow? Now suppose there is a gas liquid system ok. So, there is a gas liquid system the gas has been completely continuously sparged it is forming some bubble. Now you insert say 2 pin probe I am just introducing the 2 pin probe. Now this is the pin the distance is delta l we know that.

What will happen now both the probes is emitting light emitting also light and absorbing also light both the probes are doing the same job. So, once a bubble will come in contact with this, what will happen you will see that in lout my the intensity recorded on the detector will change because, now the bubble is coming which have a different refractive index. So, we will see the similarly the change in the current.

Now, the change in the current or change in the voltage will be termed as which phase is coming in contact with that needle or that phase needle. Now, this bubble will pears through this needle because this needle thickness is very very small, it is in the range of 5 to 15 micrometer or even lower, now with the more development this that trying to reduce the needle diameter. So, this bubble will actually penetrate so, this needle or is to be spears through this needle and it will go to the second needle.

Now, again what will happen you will on the second needle, which was earlier in the water you are recording a different current or different voltage that voltage will change. And it will go or the output signals in terms of the voltage will change. So, earlier say it was going on this way it will increase and it will go to a new level. So, moment it will go to a new level we understand that, now the new phase comes into the contact with the other, needle also the same phase.

So, say if I am using 2 probe needle, I will get 2 such signal, one single will be like this for the probe 1, another signal will be like this for probe 2. So, what will happen we know the delta T that how much delta T, it is taken time taken from by the bubble to travel from this location of first needle to the second needle, we know that delta T we know that delta L the velocity can be calculated by delta L upon delta T. So, that will be the velocity calculation immediately, you can calculate the velocity.

Now, once you this way you can calculate, it the velocity can be calculated and the phase identification can be done based on the refractive index. Now, again the 2 point optical fibre probe, the problem is you can measure only 1 component of the velocity, you cannot measure the all the 3 component of the velocity.

And if the bubble is passing through certain angle suppose this is the 2 pen you have use and bubble is coming in this way in this direction, what will happen you will see the single you will record the signal, but now the delta L value is this, this is the delta l value not the this value. And because of this you are actually travelling more distance and we are considering the delta L instead of this delta L you are calculating this delta L. So, you will get the error in the velocity measurement.

And in the gas liquid system because of the left forces involved as we have already discussed, the bubble changes it is path it does not move vertically up it move somewhere it in this direction in this way, or maybe it is changing the path continuously it is going like a flow in this way, what will happen in this case you will have like error in the velocity measurement because, you are not measuring the direction through which the bubble is coming, we are assuming that it is using up vertically upward. So, that is the way the velocity error has been generated.

So, what we do we use 4 point optical fibre probe, where this is place like this. So, 1.1 needle is being at the they are being kind of put all this 4 needle on a equilateral triangle.

The first needle or the longer needle is placed on the centroid of that equilateral triangle, and there is other order on the 3 different points of the equilateral triangles like this the way it has been there. So, this is central needle 1 2 3 is the needle which is on the top.

Now, what will happen the bubble will come it will first see the central nozzle and, then it will move up. Now once it will move up if the bubble diameter is big enough it will touch all the 4 probes, if not it will touch only the 2 probes, we will get the delta t and we will get the velocity.

Now, because it is touching, this if suppose some bubble is moving it it in this way it will touch only these 2 you will get that component of the velocity, we know that if it is touching these 2 it will be coming in this direction. So, in this way you can calculate the all the 3 component of the velocity v x, g y, v z all the 3 component of the velocity, you can also calculate the diameter of the bubble and you can also calculate the volume fraction measurement.

How you can calculate the volume fraction measurement because, your identifying the phase and you can find it out the area under the curve for which the phase is coming in contact with that probe. So, which that area under the curve it means that the total the time the fraction of the time, if you are doing this if you take say you will always see this kind of a curve.

So, area under the curve of this where the bubble is coming into the contact and the total measurement time this will give you a time area under the curve, will give you a time total measurement time, and the area under the curve once the bubble comes into the contact these two the ratio of these two will give you the volume fraction.

So, that is the way to measure the volume fraction also it works also on the transmission network, we will discuss it once we will do the volume fraction measurement technique once we will discuss that technique. So, in this way it goes and then what happen you calculate the velocity ok. So, that is the good thing here that you can calculate all the 3 direction velocity because, optical fibre probe thickness is very less.

The equipment size or this probe size is very less compared to the hot wire anemometer hot wire anemometer is really big here, it comes you reduce the size drastically and therefore, the intrusive nature of the flow the disturbance in the flow can be minimised.

But there is a another problem and the problem is because of the piercing.

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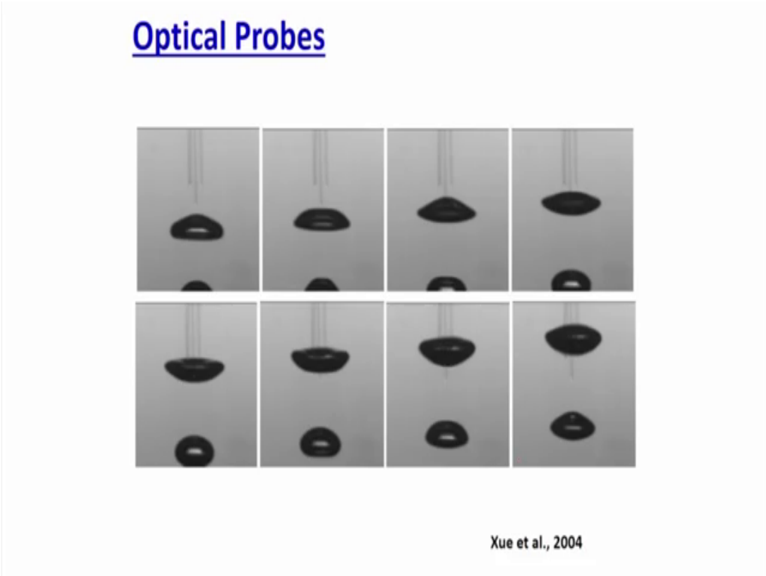

So, what happen let me show you the photograph which is taken from the Xue et al in 2004. If the bubble comes I do not know whether you are able to see, but if you see that there is a different pins, the fourth pin you are not able to see this is the 4 point optical fibre probe. So, this is the size which is there and it is zoom sizes.

So, what will happen this bubble will come and it will pierce through the first needle, you can see that it has pierce actually through the first needle. Now, once it is pierce through the first needle, now it will move upward and it will pierce through the all the other needle the way it has been shown here and it will pass through.

So, what will happen you will see the signal, but what this problem it is not on a single you are going to see so, it is piercing through? So, it is been there for certain time it is being in touch with the needle for certain time. And, because of that instead of getting a off and on single like this, way instead of getting this you actually get a signal which is of this nature. So, you will see that then it will take certain time to rise to the voltage it will stay there for certain time and then it will come down.

So, the problem comes now if suppose you have this kind of a output, the problem comes where we should take the delta T. So, delta L is fixed, but what should be the delta T value and that create a problem why because this delta T value is going to be very very small in the order of microseconds or so. Now, small error in that delta T that delta T measurement will cost you a lot in the velocity why, because you are having using delta X by delta T.

So, the error in the velocity is very small error in the velocity will cost you heavily in terms of the velocity measurement and therefore, this creates a problem with the piercing also create a problem, different people do it in a different type the way to find the delta t value, but it has been proven by Mude et al that who is a professor in at tu delft; in his people who is which is published in this chemical engineering science, that if you do not do the measurement properly, or delta T measurement properly you can have a huge error, which can be in order of 100 to 200 percent that error you can generate and that is the limitation of the optical fibre probe.

Second limitation of the optical fibre probe is suppose if the discrete phase fraction is very high, it is a bubble density is very high, then what will happen multiple bubble may approach the probe at the same time, or before the first bubble pierce out the second bubble come in to the contact, what will happen you will not get the tuning signal and you will miss lot of things. So, that is the second problem.

Third problem is again the wire thickness the optical fibre probe thickness is very very small as I have shown you here, if the solid is present the solid fraction is very high they may is a possibility that you probe may get break. So, that is the another disadvantage of this thing this optical fibre probe. Otherwise the accuracy is higher it is relatively less costlier compared to whatever we are going to discuss in the non-invasive measurements.

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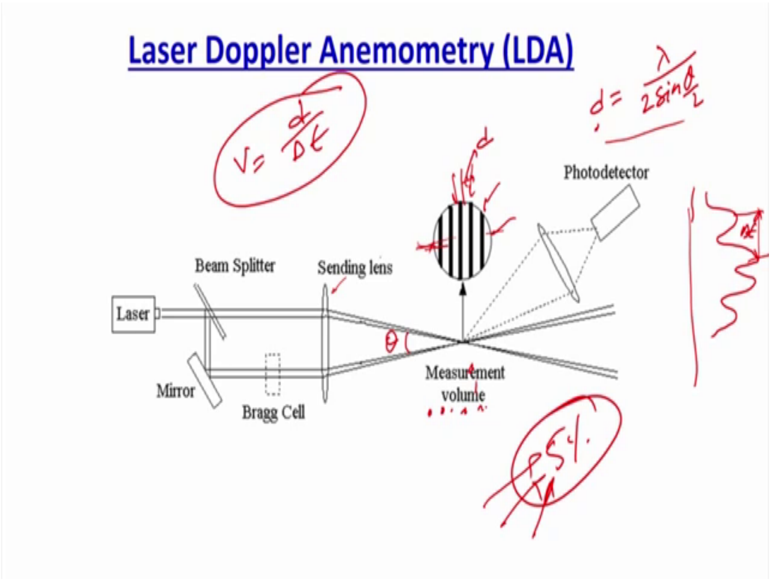

The non-invasive measurement is being preferred in that what is the major good point whatever I am keep on saying on all the measurements that your flow may change at the point of measurement itself, the intrusive nature will increase that can be reduced by using the non-invasive velocity measurement techniques.

So, what we do in the non-invasive velocity measurement technique, the first non-invasive velocity measurement technique which has been developed in the 1984, and all is the laser of Doppler anemometer. Now, again this is being developed initially for the single phase flow and, later on it has been utilised to investigate the multiphase flow reactors.

So, what is the principle of this measurement technique this is very simple, what you can do you use a laser light. And because the laser light is in the optical range and, it can go inside of the system what you do you use a laser light you use a beam splitter you break laser light to the two different with laser light. And that laser lights actually is being focused by using the sending lens or focal length at a measurement points.

So, then what we do we use a laser light we break it the laser light by using the beam splitter and, the mirror to the 2 laser light. We put we take a lens we focus these 2 lights on the lens and, then the lens what it does it converged it to the particular location. And that location is inside the flow of interest of the inside the region of interest where you want to measure the flow, it go to that point where the 2 laser light cuts, we know that once the 2 source laser light cuts or 2 optical light cuts or 2 lights cut, we form a fringes some bright fringes and dark fringes. So, by bright and dark fringes you get and the distance between the bright fringes and dark fringes can be exactly calculated, suppose if this angle is theta then the distance between the this bright fringes 2 successive bright fringes or dark fringes say d if this is the distance d can be calculated as lambda upon sin theta by 2,

See you can exactly find that what will be the distance between the 2 fringes. Now what we do we seed the flow with certain particles, which are literally bind the tray with void particles and have the ability to track the phase of interest. So, what we do? As we discuss in the multiphase flow if you are tracking the flow with the seed particles we have to see that the Stokes number is very very less than 1 a very low. So, that you can say that they can follow the path of the fluid.

So, we use a very small seed particles where stokes numbers are very very low; so, that they can follow the path of the flow. So, what will happen that seed particles will pass through it say these are the seeding I have done, and once this particle will pass through it this will cut this fringes? And there is another lens which is there which is again and there is a photodetectors which the light emitted from this measurement thing is again been focus to the photodetectors.

And the photodetector worked on the light intensity that, amount of the current generated by the photodetector, will be proportional to the intensity of the light which is recorded on the photodetector. So, that amount of the current can be converted in terms of the volt. So, you measure the volt generated by this.

Now, what happen once the particle will cut it, what will happen there is a velocity there will be some Doppler shift will take place. So, there is an intensity and that nothing is moving you will record certain frequency here. Once a moving particle will become what it will do, it will change the intensity of this reflection or this is scatter whatever it is being there. Now because of that the intensity of backward this is scatter will change and that change in the intensity or the shift in the intensity or shift in the frequency, will be depending on the velocity of this particle and that is the way the Doppler's effect comes into the picture.

So, if there is a light which is emitting, or wave which is emitting or emitting from a source and if you are having, if you are moving towards that wave what will happen you see the intensity recorded on your ear of that wave, or that sound frequency will keep on increasing, if you are moving towards the source and it will be decreasing if you are moving out of side of the source. And that shift in the frequency is called the Doppler shift.

So, similarly if the moving particle will go through this measurement area, it will cut this fringes and then what will happen the frequency recorded or intensity recorded of the light on this photodetector will has see a shift. And that shift in the frequency is nothing, but will be correlated with the velocity of the system ok. So, that is the way we measure the velocity or we measure the voltage change, if you do that there is 2 ways you measure the Doppler shift and you will can also measure that we know the distance between the 2 successive bright fringes and dark fringes which will be like this.

And we know that what is the that how the frequency shift will take place, or if suppose they will cut this bright fringes, there will be some change in the frequency some change in the intensity say the frequency shift will be there Doppler shift will take place and therefore, the intensity will change and the voltage output will change something like this. And the time required between these 2 change delta T can be recorded that is the time between the particle travel from 1 bright fringes to another bright fringes, you will get that delta T, you know this d you can calculate the velocity by using d upon delta T you can measure the velocity.

So, that is the way you measure the velocity in the laser Doppler anemometer, again it is nonintrusive. So, this is the major advantage that you can major the velocity with how disturbing the flow. And you can measure measuring the velocity again by using the Doppler shift and that Doppler shift is actually proportional to the velocity of the fluid or velocity of the particle. And that particle is the marker of the phase of interest whose velocity you want map. So, you can get the velocity of that particular phase ok. So, that is the way LDA measurement has been done, the problem if the LDA measurement is it is a point measurement you are cutting this thing at a particular point.

So, whatever the velocity you are measuring you are measuring velocity locally at that point ok, you are not measuring velocity at all the locations, you are not getting the area velocity or the how the velocity is changing with the position. If you want to do that you have to use several lasers or you need to focus on different places. So, you are experimental time will be very high.

Second thing the problem is this all are of lasers are under the optical range. So, because of the optical range frequency, they are if my eyes cannot see laser can also not see. So, what means if the system is opaque either the wall of the system is opaque which is true for most of the industry, then LDA cannot be used. Or if suppose even if I make the glass made this wall made of the glass, the system may be the wall is transparent, but if the system is opaque.

Once I say system is opaque means, if suppose the discrete phase in the gas liquid system the discrete phase bubble fraction is more than 10 percent or, 15 percent or, 20 percent, what will happen it will be completely dense bubble as I have shown you the pictures earlier also.

So, what will happen any light which will fall in will actually get reflected or diffracted. So, what you will able to measure you will able to measure only near the wall you cannot measure inside. So, that is the major problem with the LDA that if the discrete phase fraction goes anything above 5 percent, the use of LDA is limited, though it is very accurate for a single phase flow, but in the multiphase flow, this is the major limitation.

And most of the reactor will be use in industry is having a discrete phase fraction more than 5 percent. And therefore, it is being limited the application is being limited in the industry, for the gas solid flow the problem comes again, if the solid fraction is very high say you are using for the bubbling fluidized bed also, you all the light will be get refracted or diffracted and you will not able to any measurement.

So, these are the disadvantages of the LDA, they are issues with the post processing also, if suppose the size of the particles say in multiphase flow generally, if we use the bubble we use bubble itself as a seed particles ok. So, in that case if the size of the bubble is too big, which can cut the 2 fringes together your post processing becomes very typical ok.

So, that also generate some error inside so, this is the disadvantages of the LDA, but the advantage of the LDA is the spatial resolution is very very high, it goes in the order of say less than point 1 mm or even lower that is the spatial resolution very high, if you use a high speed laser you can even increase the temporal resolution of this.

So, this can gives you the phenomenon change, with the time how the velocity is changing, but the major problem is it gives the point measurement it cannot be used for high discrete phase concentration ok.

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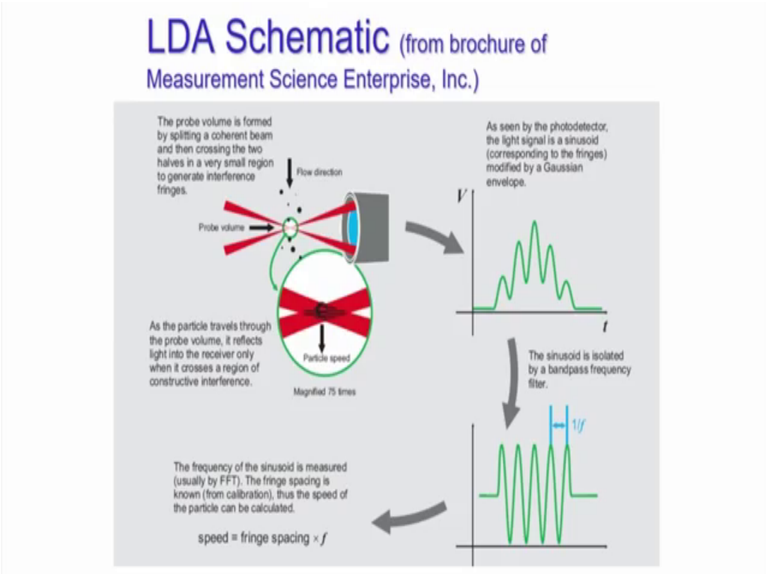

So, this is the post processing is keen which we have already discussed that what you do, you calculate the speed by the spacing between the fringes and, the time required of the frequency of this curve. So, what we do, we take this frequency we do the Fourier transform and we make this frequency we do the filtering of that with the putting the band pass filter and we can word that in terms of a proper waves. And that the frequency you will calculate that what is this f this is delta t.

So, delta t 1 upon delta T is f or you can say this is will be 1 upon f frequency can get, you can get the speed of this will be fringe spacing into the f, this is the slide which have been taken from the measurement science enterprise Inc, which supplies the LDA which of the also supplier of the LDA. So, we do it in this way and there we measure the velocity of the fluid.

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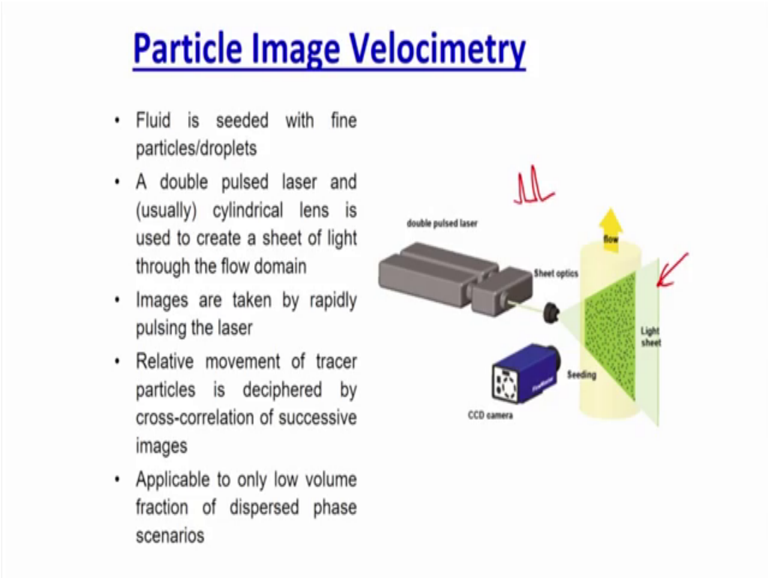

The only problem I said that is you do the point measurement. So, you get the position velocity change with the time, but you dendrite the velocity change with the position. So, that you do not did, second thing you cannot use it for the higher discrete phase fraction, now to remove the first part that you are doing only point measurement another technique is being introduced or being used and that is called particle image velocity material.

Now, what we do in particle image velocity material, we generate a laser seed instead of a cutting the 2 laser at a particular point, what we do we generate a laser seed say this is the laser seed, there is optics which is being used I am not going in detail of this, you can if you are interested you can go and see the optics, they are very interesting to understand all these optics. So, we use a laser source we use some optics where we generate the laser seeds. So, this is the laser seed is being generated, we use camera whether a high-speed camera or the CMOS camera, or this kind of a CCD camera which double pulse camera, we use that and we use the laser which is the double frequency laser.

Now, or this you the laser frequency can be generated in a small domain. So, what we do, we do a laser we put a laser seed we generate a laser seed inside the flow, we put some particle which actually eliminate lights in presence of the laser. So, we use double pulse laser we use a CCD camera in the older version of the PIV. Now what we do we use either the continuous laser and this is the high speed camera, or we use still the double pulsed laser and high-speed camera and we required the velocity kind of images with the time and we process it.

So, we will discuss about it, but what we do say the combinational of PIV technique, we use the double pulse laser. So, it is generate the 2 pulse in a very short duration, you eliminate you make a laser seed, you eliminate the whole flow field, we seed it with the transfer particle the way we are doing it in the LDA. Now again we are using the seed particles, it means the stokes number should be very low, you have to see that the seed particles exactly following the path of the fluid.

Now, once the seed particles will go inside in the presence of the laser light they will eliminate light we record the image, then you chip the laser and again after certain time you again kind of switch on the levels, you read the 2 pulses of the laser. Now once you read the pulse the light will be emitted photographs will be captured, another if the light will be emitted photographs will be captured. So, you will have 2 images, we cross correlate these 2 images and try to find it out the velocity.

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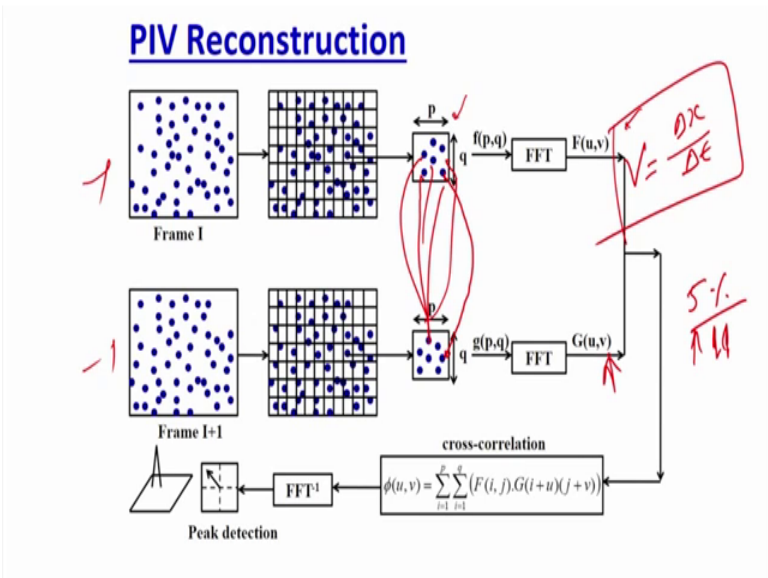

Now, how we do that cross correlation we have say image 1 at 1 pulse and image 2 at the second pulse. So, you understood how we are getting the image. So, lights are being emitted the laser light is there this particles are emitting the lights, under the laser light. So, what will happen once you take the photograph, those particles will come as a bright colour. Now or it will come as a this kind of a dark colour depending upon what is the particle property, whether it is eliminating the light or whether it is absorbing the light, both kind of things can be used.

Now, you will get the image you will get the particles ok, now what we need to do we need to find the velocity. So, this is suppose these 2 images and these are the seed particles we done lot seed particles so, that image density is very high. Now what we do we divide the whole picture this whole image into the small pixels ok.

So, this is 1 pixel I am talking about and, there are few number of particles is there then we take the FFT we do the kind of Fourier transform and, then the second m n image we take we do the FFT in the Fourier transform of this image. And then we cross correlate the Fourier transforms of these 2 images. If needed we do the filtering also again I am not going in detail of all those filters, but what you do not do suppose this is the Fourier if you do the Fourier transform you will get a function f which is u and v.

The second image again you will get a function G which is the function of u and v you cross correlate these 2 and, with the cross correlation what you do say you take 1 particle you try to cross correlate this particle in the second image with all these particles, or vice versa you take 1 particle in the first image and we will try to do the cross correlation with the all the other particles in the second image.

And with the cross correlation for each and then you do it for the second particle, third particle, 4 particle, whatever the particle available and you get a cross correlation index, you do the inverse FFT and you find that the displacement a specific displacement, for each particle or the combine displacement for the each particles.

So, each particle cross correlation you will get how well it is cross correlated. So, means suppose this is the particle I can cross correlating with all the particles, I will find that which is the particle which is having a better cross correlation coefficient with this particles in the second image, say this is the particle. So, earlier the image this distance was this, now the distance is this I will get a small displacement.

Similarly, I will do for all the particles, I will get the combined cross correlation index and that will give some peak, and with that the main cross correlation index what we did we will get the average displacement of all the particle. So, you get the displacement we get that the delta x from the cross correlation and delta t, we already know we know that what is the time of the double pulse. So, you know the delta t you can calculate the velocity that is the way the velocity is being calculated in the PIV experiments.

The problem in the traditional PIV experiment is if you are not using a high speed camera, you will not get a time resolved picture, your spatial resolution will be very high, but your temporal resolution will be low. And therefore, now a time resolved PIV experiments of PIV measurement techniques have been developed, where we use a high speed camera, we eliminate the flow with the laser, we use whether the continuous laser and keep on observing or the keep on recording the images with the time.

Now, it is a high speed camera which record the image that different ways and, now you correlated between these 2 images and you get the time resolved the PIV that how with the time the flow is changing. So, you have a continuous image now ok. So, that is the time resolved PIV experiments.

Now, advantage of the PIV is; obviously, it is in it has given the luxury to analyse the company flow field at 1 shot at least the region of interest complete region of interest, you can analyse at 1 shot you do not need to do multiple experiments like LDA. So, this gives you the complete information of the flow field that is the major advantages over the LDA technique.

The kind of the accuracy is higher the temporal resolution can be improved a lot by using the high-speed camera, but the major limitation remains same that if the system is opaque, of wall of the system is opaque or the system itself is opaque though the wall is transparent, but because of the higher discrete phase fraction, or higher solid concentration the system is opaque, you will not able to get anything because the camera will not able to see if your eyes are not able to see.

So, if you are not able to see till the centre of the column, you will not able to the camera will also not able to see and your information will be limited only near the wall. And that poses the major problem or you can say the major issue with this technique. So, you can use it for the dilute phase or even the discrete phase fraction is less than 5 percent, but if the discrete phase fraction is more than that ideally you cannot use this technique and that poses the major limitation.

And therefore, the optical phase techniques are used in the multiphase flow reactors a lot, but cannot be used at all this case, cannot be used at industry or cannot be used when the discrete phase fraction is really high though their accuracy is better. And therefore, radiation based technique is being developed.

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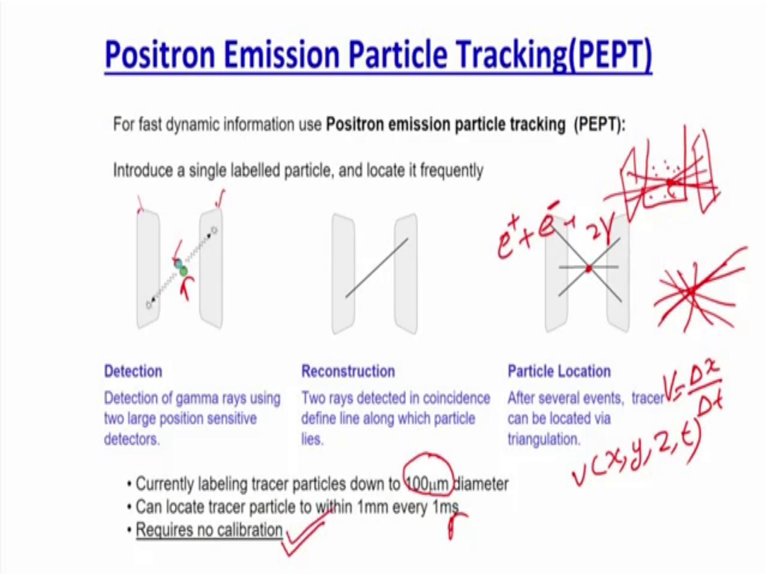

And in the radiation based technique the first technique is positron emission particle tracking.

Now, what we do in the positron emission particle tracking, we track the motion we seed the particle, or we seed the flow with the positron source and we track the motion of that particle. So, what we do suppose this is the gas solid system, we take a positron source say we take a positron particle source which can emit the positron particle and, we match the size shape and density of this tracer particle, exactly as of the other solids present in the flow. And if suppose you want to track the motion of the liquid, you will match the density of this particle exactly as the density of the fluid you want to track ok.

Now, what we do there are certain detectors which are placed around and, you track the motion of the particle. Now, how you track the motion of the particle? We know that 1 positron emission source will actually emit a positron and, electrons are available in huge amount around the system ok. So, bulk of the electrons are available so, the moment a positron is emitted it annihilates with the electron.

So, what happen there is a positron it means e plus it annihilates, or it combine with electron once the comes together, they generate 2 gamma rays ok. And this gamma rays are 180 degree apart back to back, it means 1 gamma suppose this is the positron this is positron this is electron, they analyte each other and they generate 2 back to back gamma rays, which would be 180 degree apart and back to back they will move.

We put a complex detector system around, the vessel of interest say we put some detector system complex this detector systems are really complex, which can detect simultaneously these 2 gamma rays, which is being emitted from the source. And only those detection which is simultaneous on both the detectors is considered as a event. So, you get that this line that how the simultaneous detection is there.

Now, depending upon this certain this source intensity gamma ray kind of beta, this positron emission will be number of positron emitted per unit time will be huge. So, what will happen you will see that several such lines ok. And this lines way where they will cut each other that will be the location of the particle.

So, what we do say this is an illusion, this 1 is the electron, 1 is the positron, once the annihilate they produce to back to back gamma rays. Now because there gamma rays they can travel in any medium, they will go and detected on the system this detector system. So, say this is my detector assembly, they will be detected and their detection will be simultaneous

If suppose some gamma rays got scattered, or attenuated that detection will not be counted, if suppose the gamma ray is detected only on 1 detector that will not be counted. Only the simultaneous detection of the gamma rays on both the detector will be counted. So, what it will give, it will give you a line. So, you will be knowing that my particle is within this line.

Now, several such interactions will take place depending upon intensity of the source, now it means each interaction is going to give me a line. So, you will get these kind of a line I am showing only 3 lines because, only 3 line is needed to calculate the position of the particle, but in reality you will get several such lines, you will get several such line where the particles will be detected. So, what you will get out of all these events you need only 3 events which will be cutting each other to get the particle positions. So, I will say that this is my particle position.

Now, particle will be free to move inside and therefore, you will able to get the particle position with the time you know the particle position with the time by using delta x upon delta t you can calculate the velocity of the particle. Now, the particle will move in all the 3 directions. So, you will get the displacement in x y and z.

So, what you will get you can get the v as a function of x y and z with the time and you will get all the component of the V, it means you will get the V x, you will get the V y, you will get the V z all the component of the v you will get and how it is changing with the time. So, that is the major advantage of the PEPT and because you are using gamma rays, what you are going to get you can use it even for the opaque system ok.

The only thing is that here the kind of the size the this the only problem here is that you are using gamma rays. So, the safety requirement is there and, the detection system is very very complex, they are very complex detector detection system. Second thing is that the diameter of the particle labelling particle is generally is in the range of 100 micrometer, it means around 0.1 mm it cannot be lower than that.

So, any structure which will be lower than that you will not able to track it and then kind of the time of acquisition is generally limited at around 1 millisecond. So, that is the kind of the limitation in terms of the spatial resolution and temporal resolution.

But the one of the major advantage is that you do not need any calibration, you do not need to put the particle inside the way I have said for the invasive technique, you do not need any calibration here because, you know you are solving it with the triangulation theory. So, that is the major advantage.

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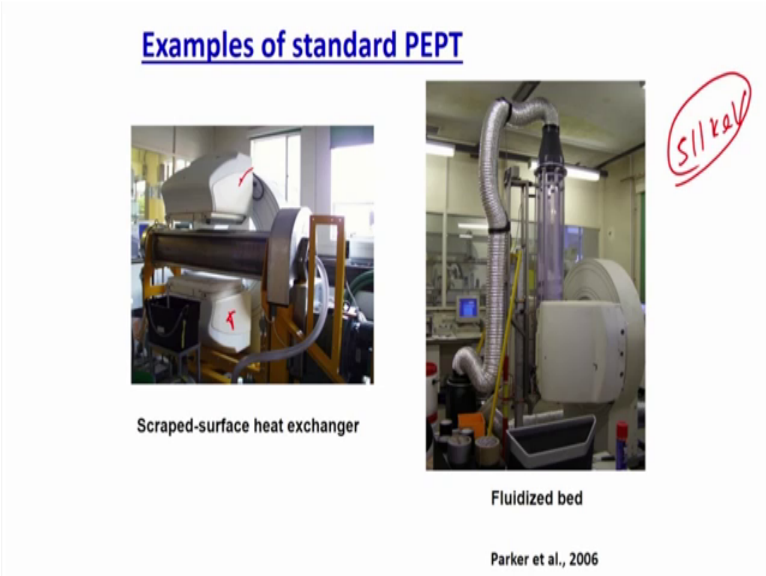

Second advantage is you can because it is a gamma ray system you can use it for the opaque system also, but the major disadvantage is that the detection systems are very complex, this is the paperwork has been done by Parker et al which they have investigated the flow profile inside the rotary clean and a bubbling fluidized bed, but you can see that the detector systems are very very complex very bulky system and, they are very complex as you require simultaneous detection of the gamma rays.

And that is why the cost of this technique is enormously high and therefore, the use is very limited and only the parker probe which is the industry of Birmingham will place an industry of Birmingham has this technique available because this is very costly ok.

Second disadvantage is the annihilation generate or gamma ray energy of 511 keV that will be the energy you will generate. And it means you cannot use the system this energy is limited. So, if the system diameter is very big, you cannot use it. So, suppose if you want to use it at industrialist scale fluidized bed, or boiler say diameter may be of several meters, you cannot use this technique because the gamma ray will be the scattered, or attenuated inside the system itself. And that is the disadvantage of PEPT ok

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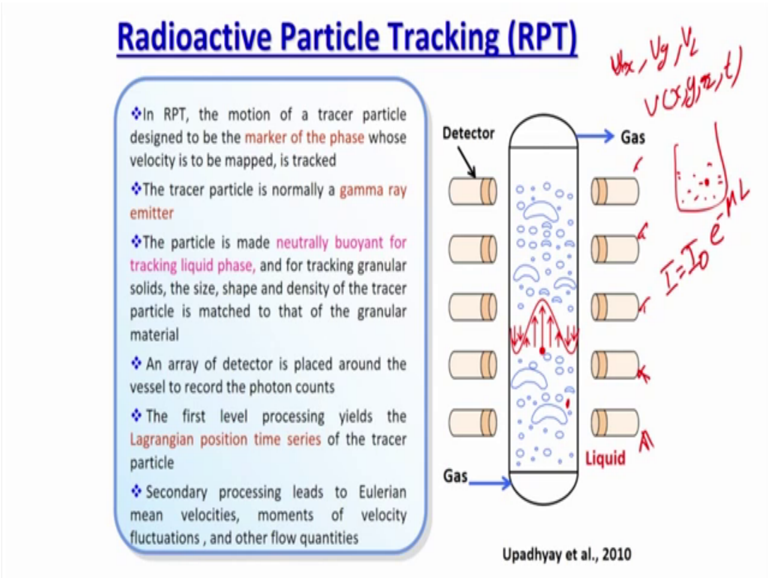

And therefore, another technique has been developed which is called radioactive particle tracking technique, in this technique what we do, we again use the same concept as in the PEPT instead of now positron emission positron particle, we use a gamma ray particle directly. Now using the gamma ray particle directly gives you a luxury that, you can use any intensity of your choice you can use any energy of your choice.

So, it gives you the flexibility to use the technique for any diameter system, for any volume fraction or phase fraction system, for the opaque system also. So, whether you made wall is made of wall or anything, the diameter of the system is very high discrete phase fractions are very high, you are using with the solids or bubbling fluidized bed of 40 percent solid you can use it ok.

So, that is the major advantage of this technique, it gives you lot of flexibility and that why this technique is very versatile and, can be used at every scale for the different type of the system. And what we do in this technique we use a marker of we use a single radioactive particle, which is marker of the phase of interest whose velocity you want map.

So, suppose in a gas solid fluidized bed, suppose there is a solid, you want to map the position or motion of the solid you make one of the particle as the radioactive, or you make use a radioactive particle which size, shape, and density is exactly same as of the particle present in the flow. And you track the motion of this particle, in case of the liquid what you do this is like a picture of the bubble column, where gas liquid flow is there you make the liquid or neutral this particle neutrally buoyant to the liquid.

So, what will happen? It will follow the path of the fluid. Now the size of the particles should be smaller. So, that the strokes number of the particle is low and it is following the path of the fluid exactly, and you track the motion of this particle. And how we track the motion of the particle?

Now, during because this is a gamma ray source during, it is part it will emit the gamma rays we put some scintillation detectors, which are being made to absorb those gamma rays or count those photos which emitted by the particles and, we place this scintillation detectors strategically around the vessel of interest. So, that you can cover the entire zone of interest, or zone of investigation, we place it properly so, that we get the proper resolution and resistivity and, the count emitted by this gamma ray is being recorded on these detectors.

Now, by using the b lamberts law, we know that the intensity recorded on the detector will be the function of the distance and the attenuation coefficient. So, I equal to I dot into E raised to the power minus mu l. And therefore, because it will be going to the attenuation coefficient, you need that we know that if the particle is closer to the detector, you will get higher counts on the detector, if the particle is far you will get the lower counts.

So, by using the suitable reconstruction algorithm, we reconstruction the position of the particle by measuring the counts on the each detector so, each detector acquired the counts at the same time, we get again the same principle distance from each detector and that distance from each detector will concise to a particular location of the particle. So, we get the location of the particle.

So, what we get is that how the particle position is changing with the time, from there again by using delta x by delta t we calculate the velocity. And then again we can calculate the all the 3 components say V x V y V z of the particle and, we can find it out that how the velocity is changing with the position and with the time, that all you can do the calculation.

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Now, how reconstruct and what we do? Suppose this is a experimental setup photograph, this is the gas solid column, these are the scintillation detectors, which are being used to edge of the count and we put a say solid particle inside. Now, this particle will move inside feeling and you will see this kind of a count.

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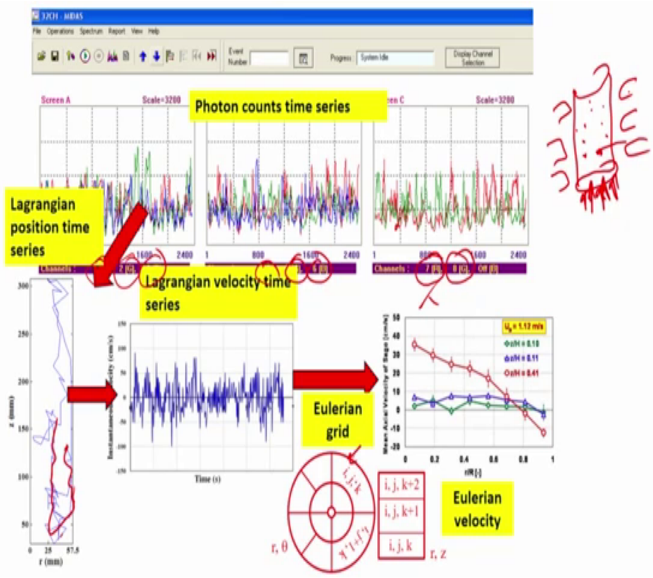

So, y axis is a count and x axis is a time. So, we will see that how the counts on each detector is changing, in this experiment we have used 8 detectors. So, you can see that there is a 3 detector 1, 2 and 3 on this graph 4, 5 and 6 on this graph which is combined with the red blue and green colour, and red and green on these 2 so, 8 detectors how the counts on all the eight detectors are changing.

Now, you do the calibration that is the major disadvantage of this. So, what we do initially we put the particle at several known location for in situ condition, we find that how the counts on each detector will change, once you will put the particle at a particular location for the given operating condition.

So, we know that how the count, will change for a particular location of the particle in the calibration stage in the real experiment stage, we know that how the count on the detector is changing we match this 2 counts we get the position. So, understood we do that say this is my column, what we do initially at operating conditions at in situ condition it may the condition at which you want to do the measurement, we first place the particle say anyhow at a certain location. And we record that how much is the count is being recorded by all this detectors.

Then we change the location we do to it the same thing at the several location. Now we generated the scale count map for all the particles, all the detectors, for each location of the particle you all this detector will record some count. So, we generate we note it down, we generate a this scale count map for all this detector, for the known location of the particle, we know the particle location, we know the detector, we know the distance and then we record the count for the in situ condition.

In the real experiment particle is free to move inside, wherever it wants to go. Now the particle what we do we record the counts on the detector with the time. So, in the calibration, with the position, how the count is being recorded on each detector in real experiment with the time how the count is recorded on each detector.

Now, we compared these two and, once you compare these two what you will get you will get that how the position of the particle is changing with the time. So, you will get this that suppose this particle has start it in this place, how it is changing it is position, how it is changing it is position with the time you get that.

Now, by using the delta x by delta t you get the velocity, that is the Lagrangian velocity time series, earlier you get the Lagrangian position time series that how the position of the particle is changing with the time. Now, we got the Lagrangian velocity time series with delta x by delta t you will get the V x how the V x component is changing, with the time how is V y component is changing with the time, how is Vz component is changing with the time.

Now, to get how the velocity changing with the position we do the Eulerian we form Eulerian grid, we discretise the column in a virtual the small grid virtually, and we see that in each grid how many times the particle is coming. So, say in each grid in each cell if the particle say during the whole time of experiment say 8 or 10 hours, if you are acquiring the data if the particle comes 100 times we take a average and we say that is the position velocity at this cell.

Similarly, we do it for all the location and we found that how the particle velocity is changing with the position. And we get the mean velocity. Now, once we have a mean velocity I already have the local velocity I can get the fluctuations. So, I can get that how the fluctuation is changing with the time, how the fluctuation of the particle is changing with the position, all the things we can calculate.

And that is why this gives this technique gives you a rich database to do the detailed analysis of the flow. The only disadvantage of this technique is the spatial resolution and the temporal resolution is lower, it is much lower compared to the LDA and PIV it is in the order of 0.1 mm or 1 mm in between the 0.1 mm to 1 mm depending upon, how many number of detectors you are using what is your transfer particle size.

Now, the that is the disadvantage another disadvantage is this is the radiation based techniques. So, required lot of safety gadgets, you need to take a proper approval before installing this technique in your laboratory, or before using this technique in your industry. So, that is the disadvantage the major advantages, it is very versatile technique, it is kind of it can be implemented at all this scales with the equal accuracy.

The another disadvantage of this technique, is our limitation by this technique, is a major you can say the limitation of this technique is the calibration required. So, what you need to do? You need to do the calibration at in situ condition and therefore, in the medium is very versatile say, it is a very high temperature high pressure reactor, do the calibration at in situ condition may be difficult and, which limits the application of this technique.

Neither otherwise this technique is very versatile, for any solid fraction for any kind of a condition say wall is opaque, or it is a transparent, solid, fraction is smaller higher, it is a smaller equipment laboratory scale equipment, or it is industrial scale equipment, you can implement it everywhere.

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So, that gives the versatility. So, with this is a typical photograph of this technique.

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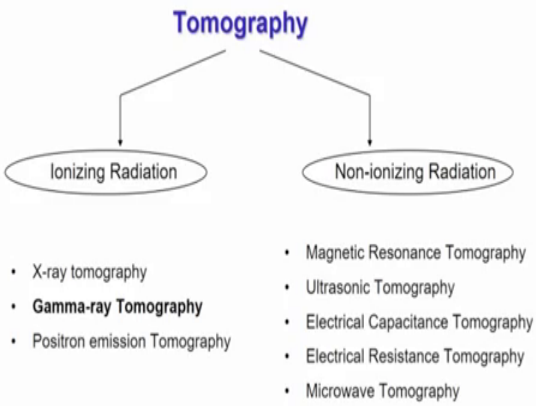

With this your velocity measurement technique is over and, in next class we will briefly discuss about the phase fraction measurement technique.

Thank you.