Measurement Technique in Multiphase Flows
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Lecture – 10
Capacitance Probe, Optical Fiber Probe and ECT

So, welcome back, last class what we were discussing is about the velocity measurement technique mainly RPT radioactive particle tracking technique.

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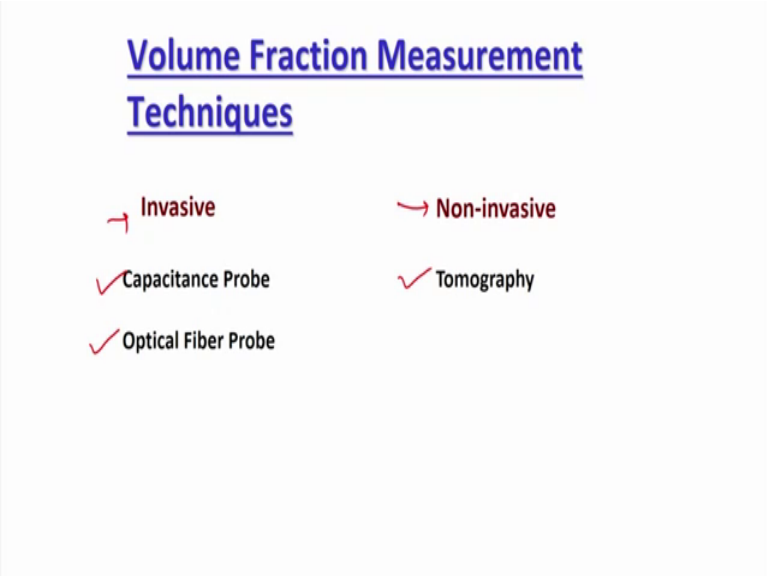

And what we have found that how the radiation can be used to measure the velocities. So, we have in the velocity measurement technique for non invasive, we have already discussed laser Doppler anemometry particle image velocimetry positron emission particle tracking and radioactive particle tracking. I have not covered the magnetic resonance imaging there, why because the same technique is also used to measure the volume fraction. So, what I am going to do that technique, I will cover together with the volume fraction measurement technique.

So, from now onward, we will move towards the volume fraction measurement techniques and we will discuss that what are the different technique used to measure the volume fraction; and as we have already discussed that to understand the behaviour of any multi phase flow reactor what you require? You require the understanding about how the local velocity; mean velocity and fluctuations are changing with the time and with

the position, and how the volume fraction local volume fraction, mean volume fraction and volume fraction fluctuation in the volume fraction if any is changing with the position and time.

So, that is the whole objective of the measurement techniques, and to understand that these two parameters. And what we have seen that in the velocity measurement no single technique can solve all your problem, and that is why still it is unresolved issues. So, what you need you need to take combine the techniques together, to get the complete spectrum of the information. And you should understand that; what is the limitation of each technique.

So, exactly following the same trail, we are going to discuss the volume fraction measurement technique, we will first discuss about the technique then we will discuss about the methodology of working principle of the technique, we will also see that what is the major advantage and drawbacks of each techniques or what is the major limitation of each techniques. So, that while apply these techniques for your application, you should know that what is the maximum accuracy you can achieve or what is the major limitation and whether you can use the technique in your case or in application or not.

So, with this background what we are going to do, we are going to discuss the volume fraction measurement technique and as for the velocity measurement technique again volume fraction measurement technique is divided in two parts, one is invasive and another one is non-invasive. So, invasive means you are intruding something inside the flow and you are measuring the parameter or you are measuring the volume fraction. The major advantage of invasive technique as I discussed earlier also is that it is a cheap it keep most of the time direct measurement and it is a very cheap. The major disadvantage is that the technique actually because you are intruding inside, you may change the flow field at the point of measurement itself. It means you may measure something which never exists in the true system ok.

So, the flow measurement can change at the point of measurement itself and that is the major disadvantage of invasive technique. Still there are several invasive technique is being use the major why we use the invasive technique even now, it is very very cost effective very very cheap compared to any non-invasive measurement techniques. And the non-invasive measurement technique for volume fraction measurement the major

classes actually tomography, we will discuss about it and what is non-invasive again to revise you are not disturbing the flow you are measuring the parameter from the outside without disturbing the flow. And that is the major advantage of this technique over the invasive technique, because you are not disturbing the flow, we are measuring the technique at actual conditions without disturbing any flow conditions. So, that is the major advantage of this technique.

The limitation is these techniques we will discuss this is very costly compared to the invasive techniques. So, it is not cost effective at all, and then the each technique has certain advance, certain advantage and certain disadvantages or certain limitations. So, one technique itself is not sufficient to probe or to fulfil all your requirement which means it cannot give you that how the volume fraction is changing with the time, and how the volume fraction is changing with the position with the similar accuracy.

So, somewhere you will get ma more accuracy in terms of the time, somewhere you will get more accuracy in terms of the spatial resolution. So, the temporal resolution and spatial resolution both are high for very very few techniques, and those techniques are very costly we will discuss about those techniques. So, and there are non-invasive technique, the major portion is actually covered by tomography techniques for volume fraction measurement and we will discuss about these techniques in detail.

So, what we are going to do? In invasive first we will discuss about the invasive techniques and then we will followed it with the non-invasive technique. So, invasive technique again there are several technique available even using the pitot tube, also you can measure even the pressure probe you can measure, but pressure probe I will keep it as a separate. So, basically there is majorly two technique is used to measure the volume fraction under the invasive umbrella, and that is one is capacitance probe and another one is optical fiber probe.

Now, these techniques are still being used popularly to measure the volume fraction and why the reason is they are very very cost effective. And we will try to see that how the you can improve the technique and what is the basic principle of working of each technique. So, let us begin with the capacitance probe.

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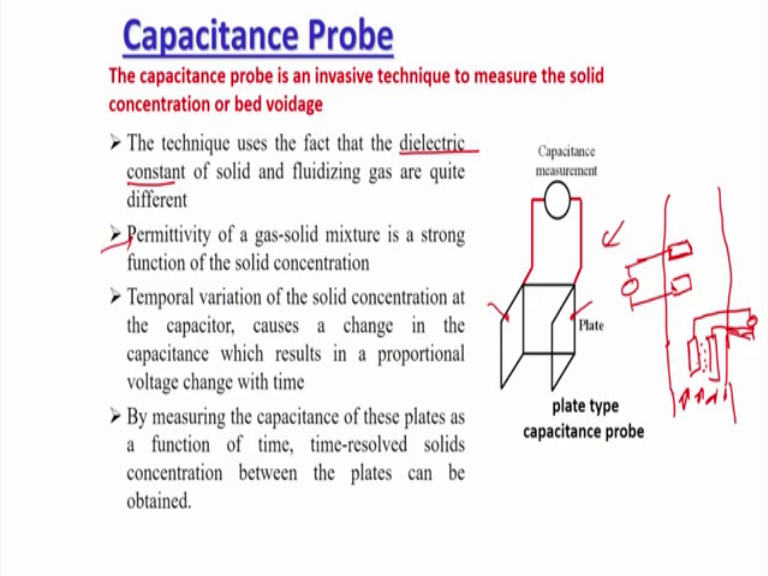

So, capacitance probe is actually is a invasive technique as I said to measure the solid concentration or bed voidage. So, suppose if you are talking about a gas solid fluidized bed and you want to find that what is the solid concentration or solid fraction or bed voidage, this technique is generally widely used. Particularly for the gas solid system this technique is widely used and particularly for circulating fluidized bed kind of application where the solid fraction is relatively lower. So, that it will not damage the plate or the probe which is being used to measure the volume fraction ok.

So, the major principle is that the fact the technique based on basically on the different dielectric constant for different phases. So, suppose if you are having a gas solid bed the dielectric constant for the gas and for the solid will be quite different. So, huge difference will be there between the dielectric constant of the gas and the solid. So, because of that dielectric constant, if suppose I put a capacitance in between if I take a capacitance, if there is only gas the overall voltage difference will be different, the overall voltage which will be you will get delta v will be different.

If there will be a solid you will see different voltage if there is a mixture of them you will get a different voltage. So, based on the capacitance which is being provided the dielectric constant of the medium, the capacitance will change and based on the capacitance overall voltage will change. So, what you can do? You can record the change in the voltage with the time and the to change in the voltage that the time, will be

actually the function of the dielectric constants of the phases which is present in the flow and that dielectric constant of the phases will be a function of the phase distribution which is available ok.

So, that is the basic principle which we used in the capacitance probe. So, what we do actually, we take that that we know that the dielectric constant for the solid or for the gas or for the different phases whose dielectric constants are quite different we can use this technique to measure the volume fraction. So, we know that the permit permittivity of a gas solid mixture will be the function because gas and solid will have a different dielectric constant.

So, the permittivity will be majorly the function of the solid, that how much it will permeate permittivity will be there then what you do? If suppose you put this kind of a capacitance probes. So, this is one typical example of capacitance probe, what you did you take in two plates. So, these are the two plates and you suspend these two plates under the system, which you are trying to investigate. So, suppose if I am having a gas solid fluidize bed, what I will do? I will just probe put this two plates here. I will just place these two plates here, and this will be connected with the flow. We can put it here or we can do it in this way that this is the plate. So, you will put the plate it in this way. So, that way you can put this plate.

Now, gas and solid will be flowing from the bottom say if I am talking about the fluidize bed the both gas and solid say is flowing from the bottom to the top, you will it will pass through this section. So, what will happen because of the different dielectric constant once only there is will be gas, the overall voltage recorded will be different or the overall capacitance which will be measured will be different we may make a device which can measure the capacitance. So, that will be different. If they will be completely solid the capacitance will be different and if there is a mixture of this both solid and gas your capacitance will be different.

So, based on that capacitance measurement, which is building the function of the solid distribution inside or solid present inside, you can find it out that what is the volume fraction. Now with the time if you recorded with the time continuously, what will happen? If the time there is any change in the solid concentration inside between these

two plates, your capacitance will change. Now that change in the capacitance can be calculated or can be recorded in terms of the change in the volume fraction.

So, this is the basic principle of this technique how they measure. So, they took two this plates between that plate they connected it with the capacitive we major the capacitance between these two plates and depending upon if you are using the two phases, which have a different dielectric constant you can use this technique to measure of the phase fraction. And major advantages because you are working on the electrical signal, this technique is very fast the temporal resolution is very high. So, you can get that how the flux this fraction solid fraction or the phase fraction is changing with the time. So, that thing you can easily find it out ok.

The only disadvantage is, if you see this assembly that there is a two plates here and then it is connected to a capacitance measurement device. So, what will happen, this overall assembly will be big. So, you are having now two plates which we are inserting inside. So, you will have these two plates you will have connecting wires everything will be inserted inside. So, this is very bulky it makes the system very bulky. So, what will happen if the system is very bulky you are going to change the flow in the big amount, significantly you will disturb the flow and that is the major disadvantage of this capacitance probe particularly plate type of capacitance probe, which we are discussing here because your plate area will be quite big and you can change the flow significantly because of this whole bulky setup.

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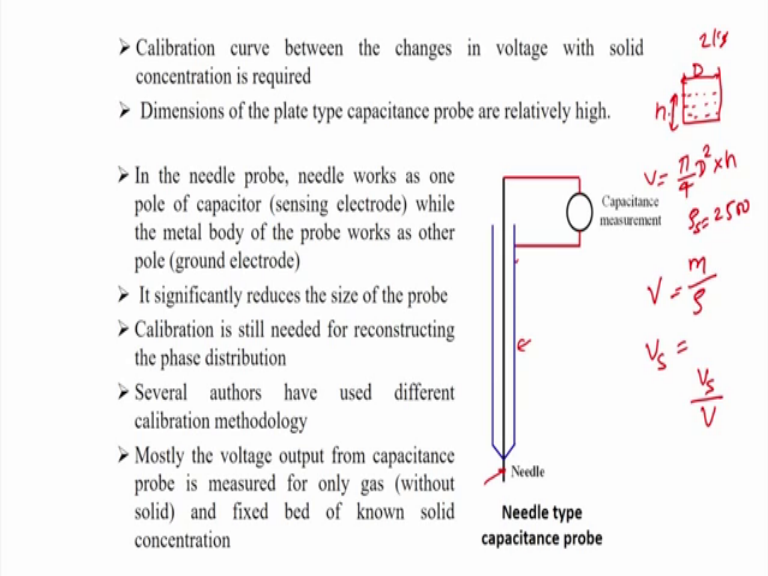

To overcome that a different type of capacitance probe has been developed and that is called needle type capacitance probe ok.

So, if you see here needle type capacitance probe what we need earlier, we need actually two plates among between which we will measure the capacitance. Now what we have done and because there is a two plates, your system is getting bulky. So, to if you want to minimize the size of the system what we can do? We can take luxury we can make it as a needle shape the whole one plate can be in the form of needle. So, you will have one connection and say that is the sensing electrode you will have. Now what you need you need a ground electrode between which you will measure the capacitance change.

So, what we can do? We can have this kind of a structure. So, this is the support the structure and this is the needle. So, what you can do? We can take make middle as one electrode which will be the sensing electrode, and the body of this probe the body of this probe can be act as a second pole of ground electrodes. So, this will be now acting as a two electrodes.

So, instead of the two plate I have put a small structure inside, which have a small needle at the center. Needle will work as one electrode and the body of the circuit this whole probe will work as a second electrode. So, needle will be the sensing electrode, body will be the ground electrode and you can measure that how the capacitance is change between these two electrodes depending upon which phase is touching my needle or which phase

is surrounding my needle. So, based on that you can measure the capacitance and that capacitance again will be the function of the phase which is present in the surrounding of the needles ok.

So, if the solid phase present the capacitance reading will be different if gas phase will be present capacitance reading will be different, if the mixture of the gas and solid will be present capacitance reading will be different. So, you can measure the volume fraction because the capacitance distribution will be directly proportional to the volume fraction distribution. Now what is the problem now if you feel that whatever I am saying what you are measuring you are not measuring directly the volume fraction. You are going to measure indirect measurement you are doing. So, you are measuring capacitance, and that capacitance distribution you are saying that it will be correlated with the volume fraction distribution. So, this is not a direct measurement, and the moment the measurement is not direct that calibration is required, as we have discussed earlier also in the velocity measurement techniques.

So, this is also not a direct measurement calibration is needed. Now if you need the calibration the problem starts why? The first thing your accuracy of the measurement will be limited to the accuracy of the calibration. And the problem is how you will do the calibration you have to measure the solid fraction and doing the in situ calibration for this kind of a system, with this probe is very very difficult. The way we were doing the in situ calibration in RPT, we cannot do it because we nee need now to need to measure the volume fraction of the capacitance. So, what we need to do? We need to depend on several some other method to measure the capacitance or to do the calibration.

So, what generally they do actually, they mostly author what they do they measure the capacitance of only gas. So, in the system they insert this probe whether its a plate type capacitance probe or needle type of capacitance probe, this system they inserted they just flow the gas first. So, you just flow the gas, what will happen at that velocity you will know that what is the capacitance of the gas, at that condition.

Now, what you can do? You can make a fixed bed of a known solid concentration. So, if I packed the bed we know that the solid fraction is going to be around 60 percent, if you do not know that you can measure it that how much amount of the solid you have poured, what is the height it achieved. So, you can find it out that what is the volume,

and you know that how much amount you have poured of the solid, if you know the density of the solid you can know the volume. So, you can find it out what is the solid volume fraction. So, suppose if you want to make a fixed bed, I say put two kg of the solids and two kg of the solid has achieved certain height in the bed.

Now, I know the diameter, I know the height. So, I can calculate that how much volume it has been occupied inside, and that will be nothing, but pi by 4 D square into h. Now I know the mass which I have provided say 2 kg of the solid, if suppose I am talking about the sand or glass beads. So, say glass bead density is 2500, say if rho of the solid is 2500 then what is the volume of the solid that will be your this two upon rho. So, mass upon rho that will be the volume. So, you can find it out that what is the volume of solid, you know the volume of the reactor, you can find it out the solid fraction V s upon V. So, this is v which has occupied inside.

So, we know that what is the solid fraction. So, you make a fixed bit of the known solid concentration or known solid fraction, you insert this probe inside and you measure that what is the your capacitance. So, based on that these two readings, you can find it out that you can calibrate that in between these two readings, and find it out the solid concentration that how the solid concentration is ready while doing the experiments. The problem is if you are doing only two point calibration, you know that the accuracy will be very very low because you are doing at the calibration at two streamates; one pure gas one most of the solids because pure solid is ruled out anyway. So, because you can pack maximum or to the packed bed concentration.

So, you are doing two stream conditions and you are trying to measure the complete distribution in between. So, what you need to do? Ideally you need to make a packed bed or a bed of known composition, different bed of known composition say 3 or 4 composition say 20 percent solid, 30 percent solid, 40 percent solids and so on and then you have to measure the concentration of this capacitance for those beds, those solid concentration and then you should calibrate the probe or you can make a calibration curve. But as we know that doing this that making a bit of a known concentration is very tough its very very difficult thing you do not depend on the other technique, you almost is negligible that you can do it and therefore, the calibration becomes a major point of stoppage point you can say a major restricting point for the needle type or any

capacitance probes. So, we need to think about the calibration and the calibration is very very critical ok.

So, that is there, and whether it is needle type or plate type the calibration is required you cannot go out of that. So, one way of the calibration I have already discussed, you measure on the stream its and with the based on those measurements you kind of do the use the calibration curve, on develop the calibration curve and measure the volume fraction.

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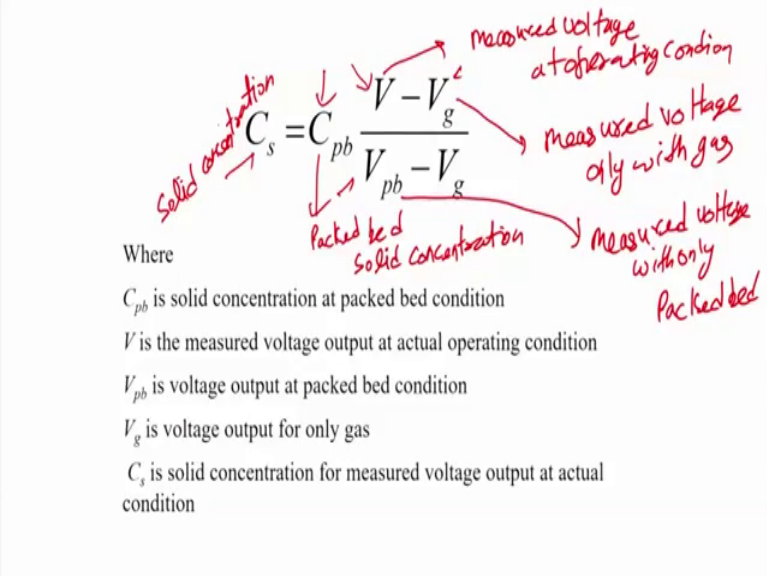

So, generally for the measuring the two stream its as I said that because that is very easy to do compared to the other whatever I said that, you should ideally make a solid of different solid concentration bed and you should measure the capacitance. But we know that practically doing that is very very difficult and second if you do it in that way the cost of calibration will be very high, because you need to dependent on some other technique.

So, researcher have tried to solve this problem several authors has tried to solve this problem, and based on the two point measurement that one is for the pure gas, one is for the packed bed they have tried to find it out the solid concentration formula. And then the solid concentration formula if you see has been given by this equation, where the C s is actually the solid concentration, this is the solid concentration this is solid concentration and this is the C p b is the pad bed concentration; bed solid concentration V is the

measured voltage, this is the measured voltage at operating condition and V g is the measure voltage once the gas was only flowing, measured voltage only with gas and V p b is measured voltage with only packed bed. So, based on that they have devise this formula that you can find the solid concentration at the operating condition based on this formula.

So, you do the calibration at two different condition, you measure that what will be the voltage recorded because the capacitance change will be recorded in terms of the voltage, what will be the voltage recorded only if the gas is flowing between the plates or is flowing and needle is touching that gas. What will be the voltage recorded once you insert the probe in a packed bed, and what is the voltage recorded once you insert the probe at the operating condition, you want to measure the volume fraction ok.

So, you know this C p b based on your calibration, you know the V g you know the V p b on the calibration, V you know during the experiments you can calculate the solid concentration. So, this is the basics use to measure the solid concentration in capacitance probe.

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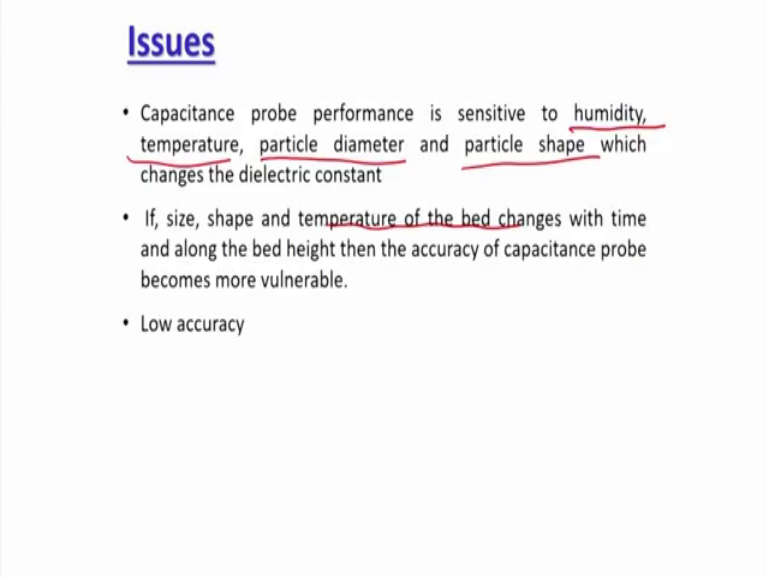

So, that is the way it has been measure. So, this is the technique is used and you see that if the technique and only other than the calibration part the technique is quite simple, it is very cheap you just need the two plates or one needle, which will be kind of grounded with the wall of the probe and you can measure the volume fraction.

The advantages again its very fast because it is going to be depend on the electrical signal, you can get up to ten kilohertz frequency you can operate easily, the spatial resolution wise it is not grad word because you are going to do a point measurement. So, that is the one of the major limitation. What you are going to measure is at a particular location you cannot measure the across the cross section or across the whole volume, how the volume fraction is changing with the time.

So, what you need to do, if you want to measure across the whole volume or across the whole cross section, either you have to use several probes and if you use several probes your intrusive nature will increase or you have to put the probe at the same probe at different locations, but at different time. So, it means first you perform say putting the probe at the center, then you move the probe say 1 centimeter far from the center or 2 centimeter far from the center depending upon what is the spatial resolution you want and you again perform the experiments.

So, this is the way you can do or you put a array of these probes across the cross section or across the whole volume to get that how the volume fraction is changing with the location, across the whole volume or across this cross section. So, that is the another limitation it is going to do the measurement volume is going to be very limited, and the next disadvantage is that though measurement volume is very limited, it is not fixed why? Particularly for the needle probe you are putting it a needle and trying to measure the capacitance across that needle. Now we know that capacitance is going to be the will change if you will have certain moisture in the bed ok.

So, if you have a moisture those capacitance value will change. So, this capacitance probe performance is very sensitive to humidity, temperature, particle diameter and particle shape which changes the dielectric constant. So, if you change any of this your capacitance probe are very very sensitive to this. So, you need to understand that what is the humidity, if the temperature changes during the operation again your capacitance values will change, particle diameter you should understand that what is the particle diameter, because that will all these things will change your measurement volume. So, that is the reason that why the capacitance probe is being used, but these are these are sensitive to this parameter and if you change any of these parameter your measurement volume will change ok.

So, that is the major thing and then if the size shape and temperature of the bed its changes with the time along the bed height or with the cross section, that capacitance probe use will be further limited. So, like in particularly fluidized bed what we see that either there is a chances of some agglomeration or particle attrition. So, if the particles shape type is changing, particle shape is changing or particle density is changing density will not play better role, but suppose the particle size and shape is changing or bed temperature is increasing or decreasing, what you are going to see that you cannot use actually the capacitance probe.

Because your capacitance probe, will the capacitance reading will modify and if the capacitance reading will be modify your voltage will modify, and you cannot use the calibration which you have done only for the pure solid, pure gas and in the packed bed condition that will no more valid. So, suppose if I am using in a boiler I want to measure that, that what is the volume fraction distribution of the coal in a coal fired boiler say fluidize bed coal fired boiler I want to find that how the coal concentration is changing with the time using the capacitance probe will be very challenging. Because your temperature will change first thing, coal will burn is particle size will also change and you will generate the as particle and maybe the shape will also change because of the uneven burning.

So, because of all this your overall accuracy of this kind of a measurement will be seriously hampered. So, that is the major issue one of the other major issue of the capacitance probe, anyway in general the accuracy is not very good why because you are doing only two point calibration. If you want improve the accuracy, the number of calibration point need to be improved. So, this is all about the capacitance probe, but still because this is very straightforward, very cheap, very the cost is very very low people is still used to major the solid concentration or the phase distribution by using the capacitance probe method.

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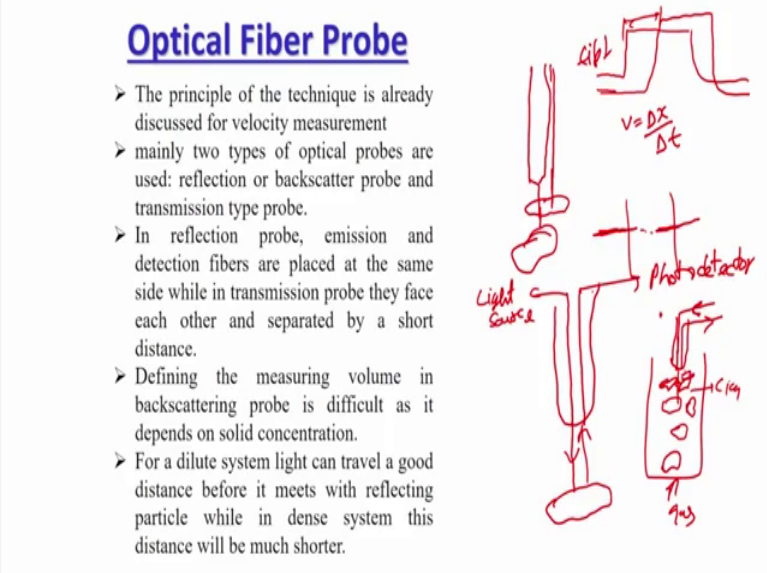

So, next is optical fiber probe; now we have already discussed the optical fiber probe in the velocity measurement technique, and the that time also I said that this technique can be used to measure the volume fraction I try to briefly explain it at that moment, but what we are going to discuss we are now going to see that how this technique will be used to measure the volume fraction.

So, the principle of the technique remains same as of the velocity measurement, whatever we have discussed in the velocity measurement. So, there will be one just two wires one wire will emit the light, and another wire will this particle the phase will reflect the light another wire will absorb that light or detect that light and based on that you measure the volume fraction. For the velocity measurement, what we do we actually both the wire actually when we take two probe or four probe both emits the light, the phase goes on the tip, the refractive index for each phases is different as we have already discussed in the velocity measurement, and based on that you can identify that which phase is touching the probe and how long it will take to move from one needle to another needle which is being placed at two different height, you can calculate the velocity by using delta x by delta t.

So, you will get a signal once the phase will touch the needle one, and you will get again a signal when the same phase will touch the needle two. So, in that way you can find delta x by delta t and you can calculate the velocity. So, exactly same principle of

refraction refractive index different refractive index for different phases, is being used in the optical fiber measurement probe and exactly same is being used even in the velocity measurement and volume fraction measurement both the measurements. So, we there also we have dependent how we have identified the phase, we have identified the phase based on the different refractive index of different material we are also going to do the same here. The only thing is there is little bit different in the way the optical fiber probe is used in the volume fraction measurement. So, there what we were you doing say in a simple way if I say we were taking a probe of two different lengths say, this is one probe this is the another probe and we take the length different.

And we say that if a bubble is coming once it will come here, it will touch here it will kind of give a peak we will identify that this is a bubble will record the voltage, once the bubble will come the voltage will change then on this probe and it will come constant and then again it will come to zero label say for tip one. For tip 2 what will happen again there is no bubble initially it will take this time, then it will increase and then it will decrease.

So, what will happen? We will know that how much delta t it has taken to travel from this location to this location once the bubble will move on this location. And that delta t we know the delta l already or we know the delta x already, you can calculate the velocity by using delta x upon delta t. So, that is the way we have done and to measure the diameter or measure the three dimensional velocity what we have said that, we use actually four point optical fiber probes. So, there is four probes is there which can measure the all the three directional velocity.

Now, in this case to measure the volume fraction, we use two methods once is the transmission method and another one is the backscatter or reflection method. Now what is transmission method? Transmission method means one probe is here one optical probe is here and the detection system is on the other side. So, suppose this is my measuring volume what I will do? I will put one probe here which will emit the light and another probe I will keep on the other side on this way. So, this probe will receive the light this probe will emit the light and based on that how much attenuation of the light will take place, we can calculate that what is the density distribution or the phase distribution inside. So, that is the transition mode, but the problem in the transition mode optical fiber probe is that, the alignment becomes very sensitive it means one probe now you have

two wires one wire is emitting the light another wire is absorbing the light. So, if they are not exactly aligned what will happen? You will not see the light properly; you will see that there will be some change in the intensity because of the alignment. And that change in the intensity actually we are going to calculate with the volume fraction distribution. So, if the change in the intensity comes because of the alignment all your measurement will be wrong.

So, therefore, it is very important that both the probes should be exactly aligned, the wire which is being inserted or emitting the light and the detector or the wire which is actually detecting that light both should be perfectly aligned. So, in case of any vibration the alignment can change, and if the alignment will change all your reading will be wrong and that is the region that most of the time the backscattered optical fiber probe is preferred over the transmission optical fiber probe.

Now, what is the backscattered optical fiber probe? In that what we do we take. So, this is my optical fiber probe, these are two wire inside this is the body, one wire emit the light and that light will be reflected refracted by some of the system or the kind of in this system whatever the phase is present in the system, and that refraction whatever the light refraction will go back say this is the light which is coming in, this is the light which will be going in out. So, this will be say connected to a light source and this will be connected to the photo detector.

So, the light source will emit a light, it will go and touch with any medium whatever the phases will be present each phase have different refractive index. So, the refraction will be different or reflection will be different, and based on the reflection intensity we can identify that which phase is present there. And based on that how what page is presented how what is the frequency of that presence of that phase we can calculate the volume fraction.

So, we will discuss about how to calculate the volume fraction, but that is the main way that be spending upon the refractive index of each individual pages, different refractive index you kind of find it out that what is the distribution of it. And how you find you measure the current intensity that how the current intensity is changing, and change in the current intensity will be recorded in terms of the change in voltage again. So, you can

find the change in the voltage or change in the current, generally the change in the voltage is being preferred.

So, what we do in the reflection type just. So, most commonly backscattered type is being used why? Because in the backscattered type the probe good thing is that there is no alignment issues both the probes are aligned both the probes are in the same PC. So, the alignment issues are not there you can even the system is vibrating and most of the multi phase flow systems are vibrating in nature, because of the violent nature of the bed the this kind of alignment issue is not there and that is why the backscattered or reflection based optical fiber probes are more popularly used, compared to your this transmission type.

Now, the only problem in this case is that, your measurement volume is not fixed. So, if you see here the light is kind of emitting here, and when it will be get reflected when it will see some discrete phase or with any medium phase whatever it is there each phase have its own refractive index. So, if the discrete phase fraction is very very small light can travel to a very long distance. So, suppose if I inserting this in a bubble column and say only one bubble is present it is moving it in this way and I am inserting the optical fiber probe somewhere here.

So, this is emitting the light and this is taking the light. So, the incoming signal is for the light outgoing signal is for the signal which is being detected on the photo detector; what will happen the light will travel. Now if the medium is very lean the distance light will travel will be very high, and before it will get reflected back significant signal you will get neither it will be always say in the liquid, say its a gas liquid. So, it will always be in the liquid and this is the gas which we are exporting.

So, if the system is verily, the light can travel to a longer distance. If the system is very dense if you are operating at a very high volume high gas velocity, system will be very dense and light may not travel to that much distance it will get refracted completely. So, this measurement volume is not fixed and that is the major disadvantage of it, because you are using the straight tubes both the tubes are straight. So, it means we do not know that where we are measuring actually the volume fraction, we are getting the volume fraction we are getting the volume fraction how it is changing with the time, but we do not know where we are measuring; because depending upon the density system density

discrete phase fraction the light travel distance will be different. So, to overcome that what we can do we can design this probe in a different way and what is generally done.

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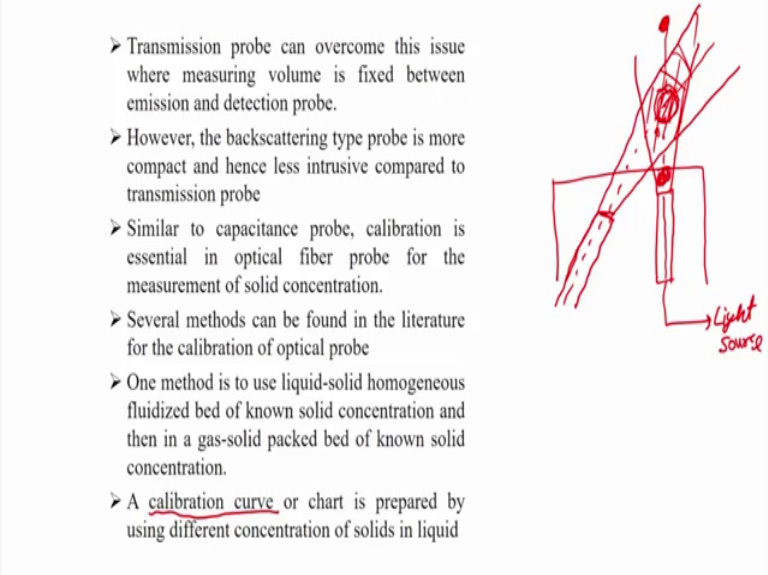

Suppose this is my casing I take one wire I am making the thickness of wire thickness something so, that I can make a volume which will be there. So, suppose this is the way the light will be emitted. So, I am connecting it with the light source, and I am taking another wire which is actually recording the signal I will put it at a certain angle I will put it at a certain angle.

So, what will happen? It will also have certain things certain view angle now my measurement volume is fixed. So, if I take a central portion of this lines. So, this is my central line of this light emitting, this is my central line of this. So, I know that what is the angle this angle, I already know that what is this angle we know that now what is the measurement volume only the point through which who will come on this line on this section will only that will only refraction refract the light and only that refraction will be measure.

If something is being refracted here at this location, my this detector which is actually of this probe or this wire which is actually receiving the light signal will not receive anything. So, in that case you will not be able to measure anything; similarly if the reflection of the light or refraction is happening at this location you will not able to measure anything. So, you will able to measure only in this zone; the zone looks here is

very big, but at real because the probe thickness is very very small this zone will be very very small. So, what you can do? You can fix the measurement volume by using this way.

So, generally this kind of optical fiber probe is being used, which one is aligned in angle one probe is aligned at a certain angle, one probe is aligned vertically. So, that actually solved the measurement volume problem, but the issue is that your probe becomes bulky because now you have to put the two probes which is under two different. So, what will happen? If you think about the length with the height what will happen your casing diameter will be bigger. So, what will happen? Your intrusive nature of the probe will increase.

So, that is the disadvantage it comes with when you are measuring it in this way. The another problem or another issue with this kind of a measurement is that calibration again what we are measuring? We are measuring the refractive index we are measuring the voltage and that should be converted in terms of the your volume fraction. So, what we are seeing we are seeing that how the voltage is changing with the time and that voltage change we know that because of the different phases have a different refractive index, the way the light amount of the light reflected or intensity of the light reflected will be different for the different phases.

And we know that the light which will be reflected that intensity of the light which will be reflected, will generate a volt. It will pass through a photo detector we have already discuss the working principle of the photo detector, what will happen the light will fall on this and once the light will fall on the photo detector, it will emit a photo electron that photo electron will travel to the cathode it will generate an electron, and electron will pass through the several diodes which will be placed in the PMP or photo detector backside of the photo detector and it will generate a corresponding current.

So, the current if you put a current resistance around it you will get the voltage. So, amount of the current generated will be proportional to the amount of the light falling on the detector or intensity of the light falling on the detector. So, what higher intensity higher amount of the current will be generated and you can convert it in in terms of the volt. So, in that way we recognize the phases, but we are not measuring the volume fraction, we are measuring the intensity of the light which is recorded or that is being

measured in terms of the voltage, and because that is being done what you need you again need a calibration curve to be prepared.

And this is again a problem, the moment you need a calibration curve the problem starts why is the same problem which we have discussed earlier in the capacitance probe. Now what you need you have to do the calibration for different solid concentration bed, it means you can do one calibration in the pure air, you can do one in the packed bed or say if it is a gas solid system if it is a liquid liquid system, a gas liquid system you should go for the pure air, pure liquid and for the different gas fraction. So, maintaining such condition the different gas fraction or different solid fraction itself is a challenge, and that is the major limitation which is for this optical fiber probe ok.

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$$\langle \varepsilon(x,t) \rangle = \frac{1}{T} \int_{t-\tau/2}^{t+\tau/2} M(x,t)dt$$

Where

$\langle \varepsilon(x,t) \rangle$ is time average volume fraction for a particular position

$M(x.t)$ is a discrete value 0 or 1 depending on the phase which is present around the probe tip

T is the total time

x is the position

So, we will discuss how to do the calibration, but before that how you measure actually the volume fraction the time averaged volume fraction, because you are measuring with the time. So, what we do? This is the quantity say m which is the discrete value and this is nothing it just identify the phase. So, we are in the measuring volume we are identifying that which phase is present. So, suppose the measuring volume we make very small. So, at a time we try that only one phase is present. So, if the gas phase is present this value will be say if I want gas phase volume fraction this value will be 1, if liquid phase is present this value will be 0 and we integrate it for the complete data acquisition time, say d t you are introducing this it, it is tau by 2 ok.

So, we are doing it from minus tau by 2 to plus tau by 2 or you can say from 0 to capital T we are integrating that with how many times that bubble is coming, how many times liquid is coming you take the integral of that you divide it by the total time and that is nothing, but the time average volume fraction. So, what we are doing we are recognizing the phase by using the optical fiber probe.

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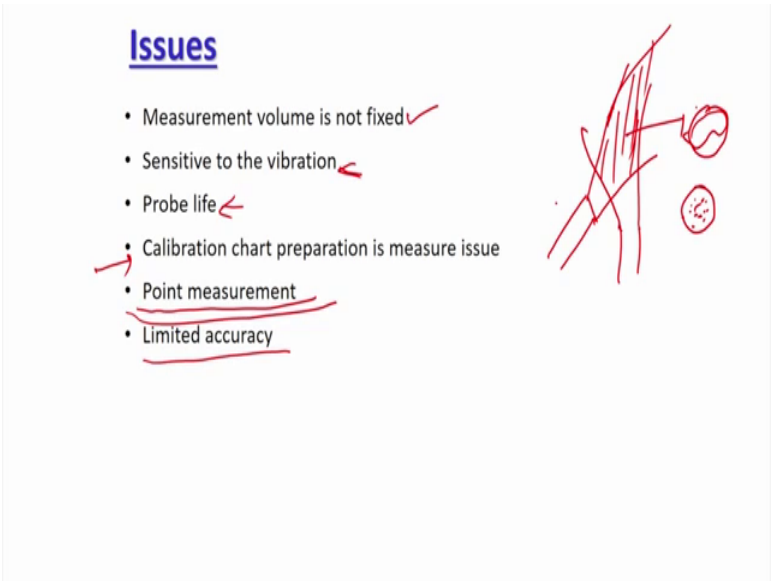

So, this is the way we calculate their silent, the problem remains same is the calibration that how to do the calibration. So, generally what we do? We do it in the two ways that first is you do either the gas and the solid packed bed condition in case of the gas solid or you do the pure gas and pure liquid in case of the bubble column, and you try to use the same similar formula which we have discuss in the capacitance probe, and major the solid concentration or discrete phase concentration or discrete phase volume fraction you identify the phase from that place or you can use the capacitance probe to do that.

So, generally some people also use particularly for the gas solid system, some people use the capacitance probe to identify the phases. Now why the gas solid system that is needed because suppose if its a gas liquid system or liquid liquid system, I can assume that the bubble size is so, big that it is occupying the whole measurement section or measurement volume. But in the gas solid system it is almost impossible, you will have definitely both gas and solid present in the measurement volume.

So, it means what I am saying, suppose if I fix the measurement volume. So, this is my one probe say this is there here in this way this is my this probe, it is going it is say in this way if I fix my measurement volume say this, those suppose this is very small. So, this much what will happen say if I bubble is there in such a way that one bubble is occupying the whole measurement volume, I can detect it this is bubble and that formula can be used with the pure gas and pure liquid calibration. But in case of the solid it will never be a pure bubble only bubble or it will never be a pure liquid or only liquid, it will be combination of the gas and liquid in this way; and that change in the gas concentration solid concentration there will change your intensity, which will be recorded on the detector photo detector.

So, therefore, you need to do multi point calibration, single point calibration or two point calibration will not work which we are doing in case of the velocity measurement because there you have to just identify the probe this phases. Here in the gas solid system the system becomes little bit complex, because you will have a distribution and depending on the solid concentration, different call it concentration will reflect the different amount of the light. So, it means what? You need to you will have different intensities. So, different voltage recording. So, what you need to do? You need to do the some multi point calibration particularly for the gas solid system and for that the gas solid system multi point calibration is being done mainly by using the capacitance probes.

So, the capacitance probe is used to do the calibration for your gas solid system particularly for the gas solid system for optical fiber probe, and capacitance probe calibration is being done by two point measurement. So, that makes the system very very complex. So, major advantage of optical fiber probe is now I want to conclude, I will say that it is again relatively cheaper compared to the non-invasive technique we are going to discuss here after first major advantage. Second it is very simple to use you have to just insert the probe and it will do the job you have to just record the voltage reading and the post processing is not that complex, and we will see that now whatever we will discuss in the non-invasive technique the post processing will be very complex and will be actually limiting your things.

So, that is the major advantage of this, the disadvantage is the major disadvantage if you use the vertical where the intrusiveness is less your measurement volume is not fixed. If

you use two probes which are aligned at two different angles your measurement volume is fixed, but the intrusive measure in increased. If you use transmission type of optical fiber probe again because you are now using two probes which both are inserted inside your intrusive nature of the optical probes, the disturbance in the flow will increase. They will be very sensitive to the vibration particularly for the angle one also, and the transmission also particularly the transmission will be very very sensitive to the vibration because if the alignment get disturbed you will not you will get the different data.

The probe life particularly for the gas solid system is a concern and that is why it is generally put a glass this a small glass layer or a small glass plate on top of the probe to make the to increase the solid life, but it actually again making it for a very long life is very very tough it will get damage. The hostile environment again you cannot use the major problem is the preparation of the calibration chart, you have to prepare the calibration chart then the another problem and the big problem is it also does only point measurement. So, if I want a cross sectional distribution of the volume fraction, how it is changing with the time then what I need to do, I have to put several probes in at the same time or I need to put the same probe at different location at different time.

So, the experimental hour if you are using one probe will be very high, you will not able to get the correlation that how the volume fraction change at the center of the column is affecting the fraction change near the wall is there any correlation or not. Those things we will be completely missing will be missing that if suppose you are injecting the gas bubble at the distri near the distribution, distributed how this gas bubble injection at the distributor is changing the fraction at certain height.

So, those correlation or cross correlation will be missing, your data information will be limited if you use one probe and put it at the several lo different locations. If you want those correlation you have to use multiple probes and that will increase the cost of the system, and it will also in intrude with the system behaviour it will change the flow field significantly and therefore, because the calibration is there the accuracy of these things is limited with the accuracy of the calibration and that is why we do not get a very high accuracy in this kind of a system.

So, these are the two major invasive technique which is being used to measure the volume fraction in the multi-phase flow, both the technique are still being used very

popular because they are relatively very simpler, they are relatively very very cheap very low cost and that makes these techniques very attractive even after being having several limitations. So, next way whatever we are going to discuss is about the non-invasive volume fraction measurement technique, and as I said the non-invasive volume fraction measurement technique is actually the class is called tomography.

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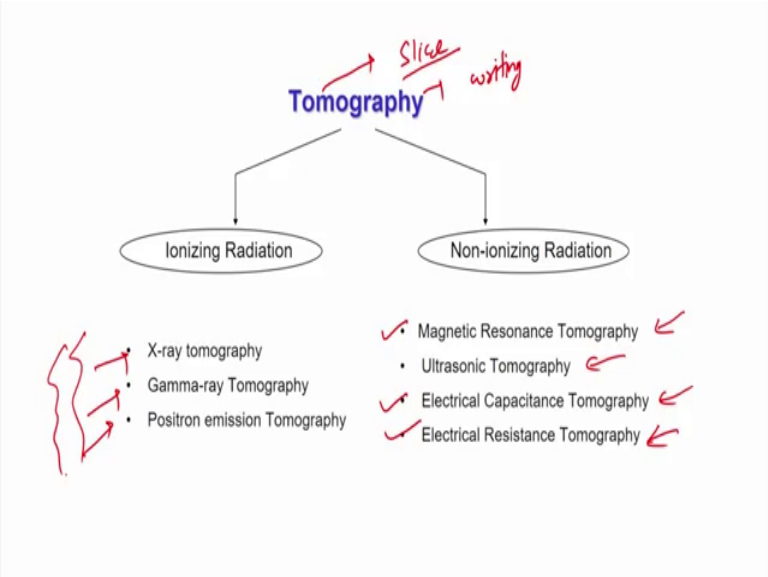

Now, what is tomography? Actually tomography is made of a Greek word which is being a tomo tomo means slice and graphy means writing. So, the tomography is made of a Greek word and this is actually made of tomo and graphy tomo means slice wise and graphy means writing. It means if you write the information in terms of the pieces in terms of the slices that is called tomography. Now there is major advantage of the tomography because what you can get here and we will see the non-invasive technique, that you can get two d or three d cross sectional average volume fraction not only cross section average you can get the 2 aD and 3D volume fraction I am not say the cross sectional average because some technique will give you the cross sectional average other technique will give you the information in the pixel wise it means you can find it across the cross section at the same time how the volume fraction is changing with the time or with the location, you can do also with the whole volume also.

So, that is the major advantage we will discuss about the technique and we will understand it more in more detail. But what is tomography means you are dividing the

whole volume in a small slices and then you are writing the information there that is called the tomography. iI is mainly divided in two part depending upon how you are measuring the volume fraction it is ionizing radiation and non-ionizing radiation. Because non-invasive technique we are not going to disturb the flow with nothing will be inside everything we are moving to put from the measuring from the outside.

So, based on that how you are measuring this how what principle you are using for the measurement what kind of waves you are using for the measurement of signal you are using for the measurement, its divided in two parts one is ionizing radiation and another one is non-ionizing radiation. So, mostly radiation based techniques are ionizing technique ionizing radiation base technique which includes x ray tomography, gamma ray tomography, positron emission tomography.

Now all these names we might have heard earlier, but not in the may be may not be in the reference of reactor diagnosis, but in the name or in the medical application. So, all these things are widely used in the medical applications, to diagnosis the problem in a human body. So, we are trying to use and all these techniques has been actually first developed for the medical application, and we have taken the inference and try to use the same technique or same principle to measure or to the volume fraction in the multi-phase flow technique or to diagnosis the multi-phase flow method this reactors or vessel.

So, these are ionizing non ionizing which is does not ionize the system, it is made of magnetic resonance imaging, now we will discuss here in including the tomography and velocity because they are very same in principle we will discuss it here ultrasonic tomography, electrical capacitance tomography electrical resistance tomography, electrical impedance tomography microwave tomography there is several class in this non ionizing. But major importance is all this that what is this three actually is the majorly important which is being used in the non-ionizing radiation technique, and have better accuracy in the ionizing these three are being used ok.

So, what we are going to do, now we will discuss about individually about these techniques that first we will discuss about the non-ionizing radiation, then we will discuss about the ionizing radiation again I am going to do the same we will discuss about the principle of operation, we will discuss about them how to reconstruct the things

and then what is the major advantage and disadvantage of each technique. So, that is what is tomography system and we are going to discuss.

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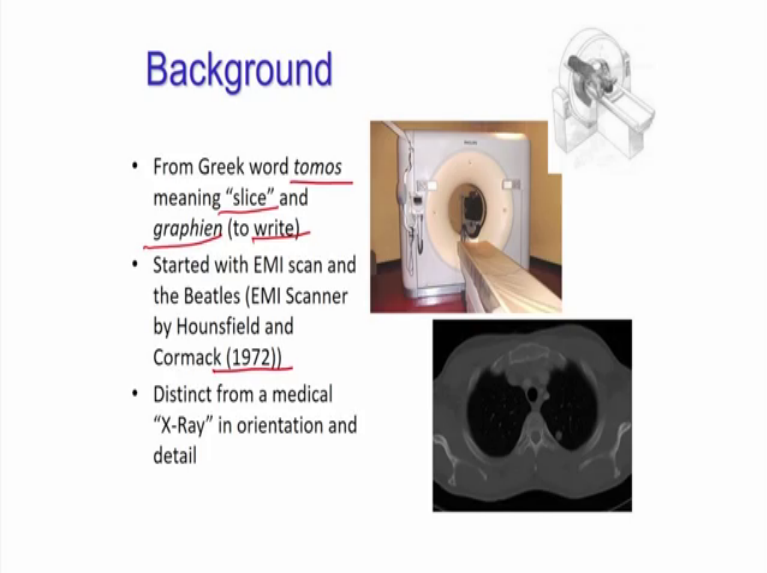

So, we will start with the electrical capacitance tomography. This is the background which I have covered the tomography is actually made of two words which means slice and graphic which means right. It means you write the information in terms of the slices it has been started with the EMI scanner, which has been devolved or kind of being commercialize in the year of 1972 near the 1972.

Now, the medical application most of these things as I said has been developed actually for the medical applications and later on we have taken the inference, and the things has been developed to diagnosis the reactor or multi-phase flow reactor or to investigate the multi-phase flow reactors.

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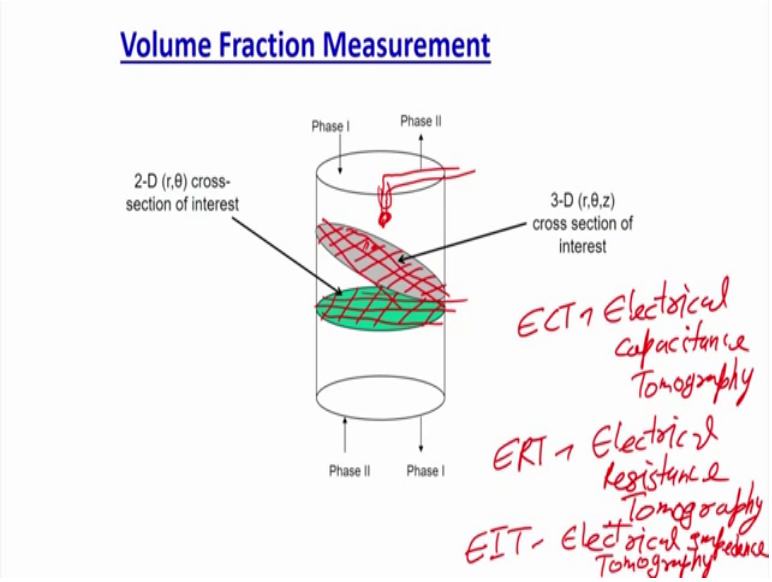

So, what we want ideally if you see that the invasive technique which I have discussed what was the major limitation for both non-invasive technique you are getting the fail you are getting the fraction at a particular location, it was doing a point measurement because you are intrusive a probe and because you are intrusive a probe you can get that how the volume fraction is changing at a particular location say at this location if I intrude the probe. So, if I intrude optical fiber probe, you can say optical fiber probe I will get that what is happening at a particular location.

Now, what is our interest? As I said that we want to measure the 2D cross sectional volume fraction or 3D cross sectional volume fraction depending upon the system. So, I want how the volume fraction is changing in this cross section with r and theta at a particular z or I want that how the volume fraction is changing in r theta and z in the 3D domain with r theta and z with the time how it is changing. So, that is my interest. So, I want to find epsilon volume fraction with the position with the time, in both across the cross section as well as across the volume if possible.

So, that is our interest and that can be done actually with the tomography, because you are going to scan the whole column we are going to cut down the information form of the slices. So, you will get that in the pixel wise how the volume fraction is increasing or decreasing. So, each pixel you will get the information each pixel, and that is the major advantage of this technique. So, this is phase one and phase two is moving they are

interacting with each other, we have to find that how that interaction is changing with the location with the time and that can be provided by using the tomography technique.

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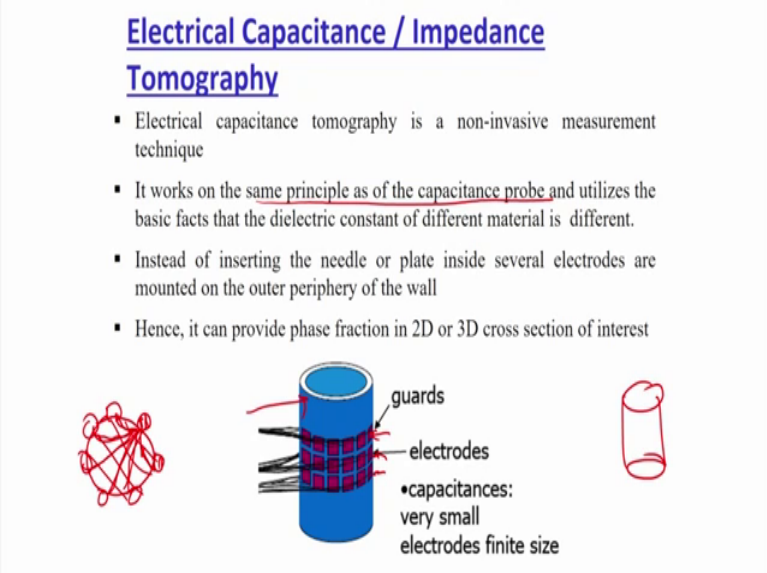

So, the first tomography technique is electrical capacitance tomography, it is also these they are actually three tomography method which uses approximately same principle only the measurement is difference. So, this is electrical capacitance tomography, we call it ECT I will write here. So, ECT electrical capacitance tomography, then this is ERT electrical resistance tomography and EIT electrical impedance tomography. This three method principle is exactly same electronics is also same only thing what you are measuring.

You are measuring capacitance, we are measuring impedance, we are measuring resistance. So, based on that whatever you are measuring and what you will measure depending upon what your phases are sensitive to what for the some phases maybe the capacitance this property will be different or dielectric constants will be different. So, your capacitance value will be different, impedance value will be different or some places the resistance value change will be very high may be the electrical conductivity and all those things will be different.

So, your resistance will be different. So, depending upon what you want to measure how what are the features present, one can use any of these three technique which can give you the better accuracy. And the electrical capacitance tomography the basic principle

remains exactly same as of the capacitance probe. So, what we are utilizing we are utilizing the basics that each material have a different dielectric constant. So, if you will have a different dielectric constant what will happen? It will have a different capacitance if there will be different capacitance the voltage pass between this these two plates or these two probes or electrodes will discuss will be different, and that can be actually constructed as per the volume fraction, that can be calibrated and it reconstructed in terms of the volume fraction.

So, its exactly going to be the same. So, it works exactly on the same principle as of the capacitance probe, the only thing is it is non-invasive we are measuring from the outside in the capacitance probe we are intruding the electrodes inside. Now what we are going to do we are putting the electrode outside. So, what we are doing an instead of any putting in insert a needle or plate inside, we are making the electrodes we are putting the electrodes on the outer periphery of the reactor or of the process vessel.

So, suppose you have this process vessel this is your process vessel or say there this is your process vessels, you put the different electrodes here some electrodes will be sensing electrodes some electrode will be the grounding electrodes. So, what will happen the current will pass between these two if they will connect the current will pass and depending upon how much current will pass, it will depend that what are the phases which is present in that side and now you are using the spectrum of the electrodes. So, suppose if I talk about a cross section I am using the different electrode suppose these all are my electrodes which I am putting outside, what will happen suppose I sensitize it will be passing through all I will get that what is the volume fraction for each line, I will get the volume fraction for each line clear.

Now, what I will do suppose I sensitize this probe, next time what I will do I will sensitize this probe. Now you will get the volume fraction for again all these lines and in similar way if you do it, you will get the volume fraction across all the pixel information you will get you for more complete pixel and you will get the information in the pixel wise. So, that is the way it works you use the electrode on the outside this guard electrodes also used to minimize the noise, neither it will be mainly two electrodes one is sensing and one is your grounding. So, that electrode a pair of electrode is being used and that the current recorded between that pair of the electrode is being recorded and been reconstructed in terms of the fro phase of each fraction present between the them.

So, what we do actually as I said. So, suppose this is my electrode this is my column and I put the electrode all around.

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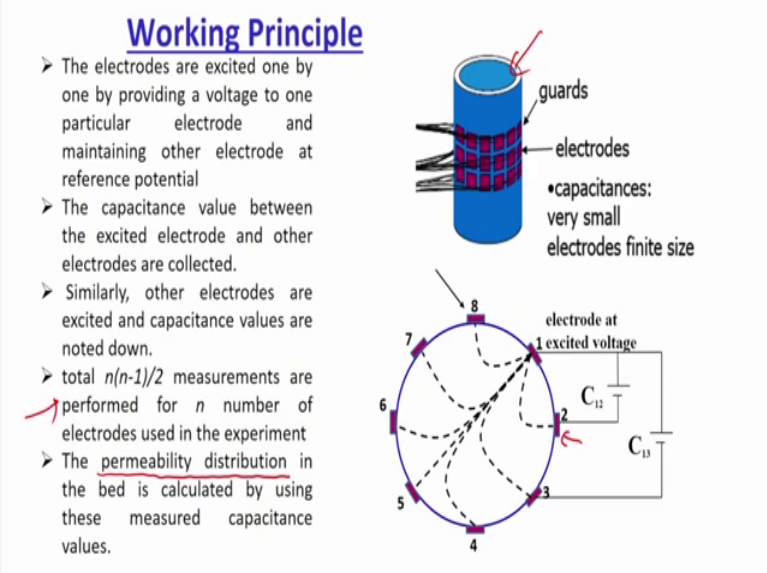

So, suppose these are my electrodes say I put 8 electrodes 1, 2, 3, 4, 5, 6, 7, 8. So, what I do actually I excite only one electrode. So, I tried only one electrode means I give a voltage provide a particular reference voltage to one electrode and rest of the other this electrodes are maintained on the reference potential. So, I excite one I give certain voltage to one electrode, others are maintained at a reference potential what will happen? This if this will be excited the capacitance value between these two electrodes say one and two will be recorded capacitance value between one and three will be recorded capacitance value 1 4, 1 5, 1 5, 1 6, 1 7, and 1 8 so, on will be recorded once I elect excited the electrode number one then the capacitance value will be recorded.

Then similarly what I will do? Next time I will excite the electrode number two now the capacitance value again between 2 1, 2 3, 2 4, 2 5, 2 6, 2 7 and two eight will be recorded similarly I will keep on exciting the other probes. So, what will happen, the total number of measurement how will how much I will have? Say if I have n number of measurement n number of electrodes, then the total measurements amount of measurements I will perform it will be equal to n into n minus 1 divided by 2 why this because one electrode you are not using. So, for each electrode you are doing seven measurements. So, suppose you have 8 electrodes you are going to have 7 measurements. So, 8 into 7 this is 56, now

I am divided by two because for two electrodes that will be repeated say 1 2, 2 1, 2 3, 3 1. So, that a will be repeated, you will do the half.

So, in that way you will perform this much amount of the measurement, and for each path what you are going to get you are going to get that how the permeability distribution you will get for each path and that permeability distributed is actually the function of the volume fraction. So, the permeability distribution or capacitance distribution is going to be correlated directly with the volume fraction. So, that is the principle is being used it has been developed exactly based on same principle of the capacitance probes only thing is instead of intruding the probe inside, what we did we put the probe outside of the system and that did actually you make the invasive technique to non-imperfectly non-invasive technique.

So, how we calculate the volume fraction actually what we do? We calculate the permeability this permittivity distribution not permeability permittivity distribution and that is permittivity distribution is directly proportional to the phase distribution actually.

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$$\nabla \varepsilon(x,y) \nabla \varphi = 0$$

$$C_{ij} = \frac{1}{\Delta V_{ij}} \oint_A \varepsilon(x,y) \nabla \varphi \, dA$$

Where,

$\varepsilon(x, y)$ is the permittivity distribution in the measuring plane

φ is the electric potential field

C_{ij} is the measured capacitance between electrodes i and j

ΔV_{ij} is the applied voltage difference between the exited electrode and other electrode over the pair ij

A is the surface area of the electrode

The phase distribution is directly related with the permeability distribution.

So, that permittivity distribution can be said as the phase distribution, its directly proportional. So, what you do? You measure the electric potential across the each probe how its there, and that electric potential is actually the related with the del epsilon into del phi will be equal to 0.

So, how much will be the potential will be given, what is the permittivity distribution and the capacitance measured across the two electrodes say one and two indices i and j. So, in the electrode number say between the electrode i and electrode to j. So, suppose if I am measuring the one and two, it will be c one and two and that will be nothing, but what is the permittivity distribution between these two electrodes, what is the potential you have given dell phi what is the pote electrical potential you have given potential field you have provided, and what is the area of the electrodes.

So, area of the electrode will be different and what will happen this will be different the overall capacitance will also be different. So, that is there and that you keep on summing across because why I have done the curvature integral because the path will not be linear I have tried to. So, here also in this figure the path will not be linear it will be non-linear integral non-linear.

So, you have to do what, because this is a non-linear suppose this is one electrode, this is another electrode. So, it will be not a linear it will be something like say this it can pass something like this this is not linear, it is non-linear and because of that you have to do the area integral and delta V i j is the potential of voltage difference, which is being provided between the two electrodes. So, that whatever the voltage distribution has been given. So, in this way you can calculate the c i j that how what is the distribution of this and the C i j value you have already measured. So, you can find it out what is the epsilon x y and this epsilon x y is nothing, but volume fraction distribution.

So, in this way you can calculate that how the volume fraction will be measured in case of electrical capacitance tomography.

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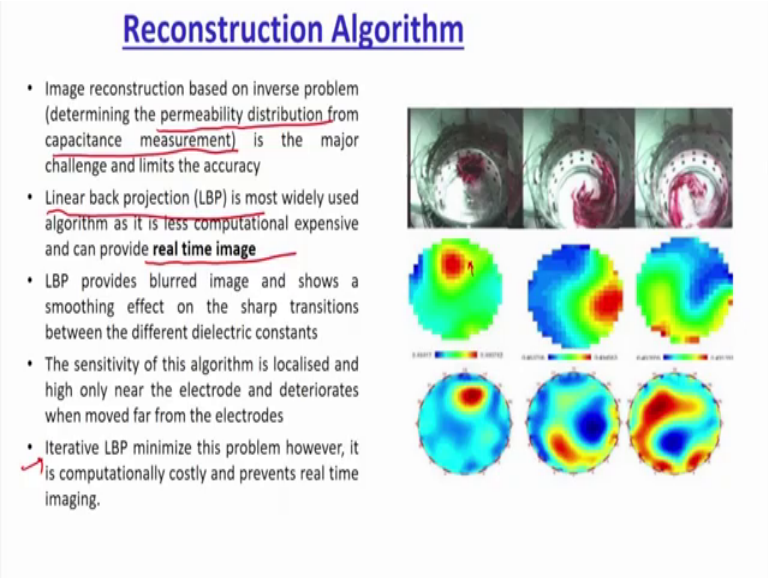

So this is again what is going to happen, this is a inverse problem what you are not doing the measurement directly, you are not even reconstructing the measurement directly, what you are doing you are measuring the permeability distribution and that permeability distribution from the capacitance measurement you are doing, and that is being converted in terms of the volume fraction measurement. So, this is the inverse problem this is not a linear problem, the permeability distribution is being fine with the capacitance measurement. So, its inverse problem is there. So, what you need to do you need a reconstruction algorithm you cannot do it directly ok.

So, what kind of algorithm is used? Generally the filtered back projection algebraic reconstruction algorithms are being used, but most commonly they are different algorithm I am not going in detail of that those algorithm, but different algorithm has been used by the different researcher, if you have more interest you can go through those algorithms and if you have any soon we can discuss over the forum. So, but most commonly linear back projection algorithm is being used and why it has been used? Because it is computationally very less expensive and as the name suggests you are doing linear back projection. So, non-linearity you are trying to remove, you are doing the linear back projection and because of that the speed of reconstruction is very very high it is very very computationally less expensive and it can give the major advantage to the ECT and that is real time imaging, it means whatever is happening inside you can exactly see it.

So, like this is the example I have taken from a literature, where a dye has been injected in the liquid a red colored dye and we are trying to see that how this dye is mixing in the liquid. So, this is following this path and it is trying to spread; and we can real time in the real time we can see that that how the dye was injected earlier here the red color concentration, and how it is spreading over the time. We can real time you can do the measuring and that is the major advantage what IBP bring it that it can do the real time this imaging, and that is why linear back projection method is being widely used in the ECT.

But because you are doing the linear this you are not using non-linear, the images are blurred you can see that you are not able to get a very clear image, this is you can see when small pixels here if I try to zoom it you will able to see some pixels here, but the images are blurred because you are using a linear assumption and why and if you see that it has been spread there are certain artefacts. So, wherever the liquid is there say red color is there, you see that there is certain artefacts this yellow color also.

So, why it is happening? Because if the images are blurred and at the interface it actually smoothen the effects its actually is smooth in will do this smoothly this whole algorithm. So, it means you will not get the cut exactly, that this is my say gas bubble column if I use gas liquid system this is my bubble this is my liquid you will see at the interface you will see some spread. So, that is the another disadvantage of this technique, it can be improved by using the non-linear algorithms or iterative IBP if I use the iterative LPT maybe it means iterative linear back projection methods we get a solution we again iterate it, we came of iterating till we are not getting a proper solution this condition will improve, but then you will lose the major benefit and that major benefit is the real time imaging. So, you will not able to do the real time imaging. So, that comes at the cost and that is why because we can do the real time imaging we can see what is happening inside my system in the real time mostly IBP is still being popularly used in for the ECT reconstruction.

So, this is about all about the ECT if any issues are there we can again discuss, there are several advantage of the ECT the first advantage is its non-invasive.

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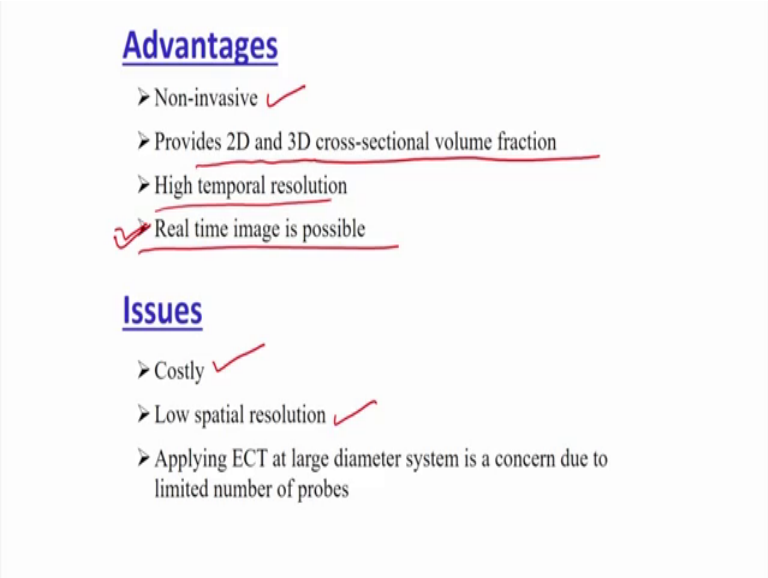

So it you improved over the capacitance probe now it is not invasive, it is measuring the volume fraction distribution from the outside, the major second disadvantage is you can do 2D 3D cross sectional volume fraction measurement, depending upon your requirement if you want to measure how the volume fraction is changing across the one cross section or with r theta z all three you can do that.

Temporal resolution is very high you are using the electric currents, based on the current signal current temporal resolution is very high up to 10 kilohertz you can go and real imaging this is the major major goes that you can have a real time imaging. You can see what is happening inside and temporal resolution is very high. So, suppose if you want to see how the two phases are mixing with each other say its a liquid liquid system you want to find how they are mixing with each other I hope this is the technique, we should use to find that mixing; the way I have showed you that how the dye is mixing.

So, that is the major advantage the issues with it is costly compared to any technique it is very very costly, it has a poor spatial resolution I have already shown you that the images are blurred. So, you will have a very poor spatial resolution and the another disadvantage is the number of electrodes are fixed, and you have to fix that electrodes at the time of purchase itself, and that too also you cannot use a very high number of electrodes. So, your number of electrodes are fixed if you go for a very high diameter a large diameter your spatial resolution will further go down. Because now the distance between the two

probes will be very high. So, if that will be the case, your special resolution will further go down it will kill you further. So, that are the major issue with the electrical capacitance tomography.

So, to overcome this issues what we do, we actually go for gum ionization tomography I will discuss MRI, but later on. So, we go for ionizing kind of system ionizing radiation system and the big advantage of the ionizing radiation system you are using radiation, if you change the intensity of the radiation you can use it for any diameter system without disturbing the flow. So, that is the major boost in the gamma ray tomography or x ray tomography that you can do the system diameter is not a limiting, you can increase the diameter of the system only what you need to do you have to increase the source strength and that is in your hand you can use the kind of you can use higher activity of the source.

So, that is the obvious development comes from the ECT or you can see that move from the ECT that comes because you can use it for its a non-ionizing system, you can use it for the larger diameter system and you can also improve the spatial resolution, but it comes at certain cost, but before that what I am going to do I am going to discuss that what is the basic concept of gamma ray transmission tomography.

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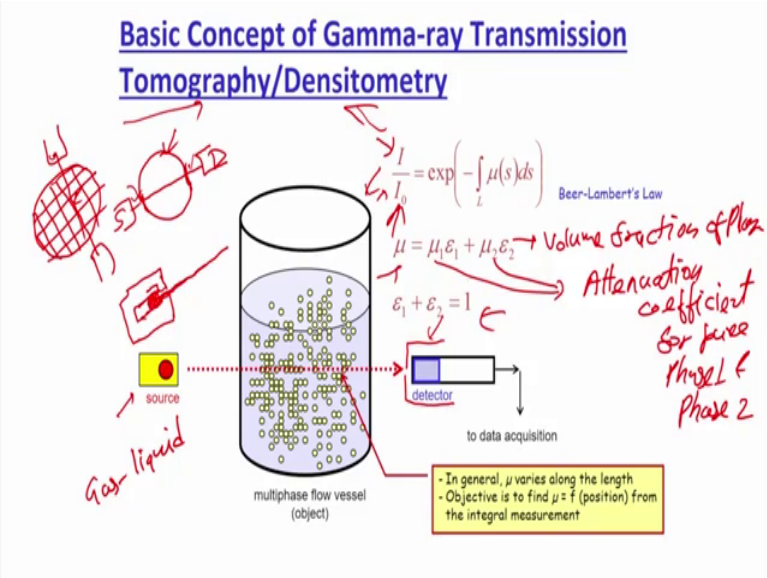

Now this is all transmission tomography. Now I have written both tomography and densitometry. So, actually densitometry is nothing, but the first generation tomography in densitometry what we do, we measure the chordal average we do not get the information

on the pixel wise, we get the line information line average information or we say chordal average information it means suppose if this is my column just stop you, and you are putting a source on this side and detector on this side, you will get that what is the attenuation or what is the fraction along this line, you will not get the pixel wise information. In tomography as it says that its information based on the slices, you will get the information based on the pixels that each pixel how the volume fraction is decreased how it is being done we will discuss.

So, what happened in the gamma ray transformation, tomography or densitometry lets first discuss densitometry and will then discuss the tomography in densitometry what we do? We use your radioactive source we use the scintillation detectors. Now this scintillation detector is exactly same as we have used in the radioactive particle tracking technique I have already discussed about the working principle of that this scintillation detector, if you want more detail you can go and just revise that if you still raise problem you can write back to me.

So, we use the source we use a detector and as I said it is based on the transmission tomography method transmission principle, both the source and detector will be 180 degree apart which will be facing each other not apart they will be facing each other and the system of interest will be placed in between. So, suppose this is my system of interest this is my source and this my detector both are facing each other and system of interest is placed in between.

This gamma ray source these collimated; collimated means you make a led sheet you put this is the way we make it generally and we put a radioactive source inside, say we make a radioactive source this is my radioactive source this alright this is my radioactive source inside and what we do we make a small hole here sorry. So, we do it, it in this way let me draw it again this and what we do we put the radioactive particle here in this. So, what this radioactive particle is going to do it is going to emit the gamma ray in a single line this collimation is very very fine. So, you just emit in a single line or a very small fan beam will form we will discuss about the fan beam for the sake of simplicity let us assume that it is emitting the gamma ray in single line.

So, this line this collimation we use the detector and we collimate the detector also. So, this do the same thing we put a let source here on the detector. So, what will happen

these two collimation should be perfectly aligned. If they will be aligned then only you will get the signal either you will not get any signal that is why we why we are using led material which have a very high attenuation coefficient and can absorb all the gamma rays.

So, the thickness need to be designed it in such a way that any radiation should not come from the top or any other place, only the radiation which is directly coming from the source should be recorded on the detector. So, you are recording on a single line. So, what we do? We place the system of the interest in between and we do the line measurement. So, two measurement what we do? We first scan the column at empty condition suppose in the gas liquid system if I have a gas liquid I kind of imaging the column or a measure the column or measure the intensity at the empty column it means, I am measuring it only with the pure gas. So, I do that I measure the I naught what is the intensity recorded if there is only gas. So, I naught it is being measured.

Then what we do? We operate the column it in situ condition it means in the gas liquid system now what will happen? Because of the liquid attenuation will change, and you will see that the change in the intensity recorded on the detector, that is being also recorded that is called I. So, these two intensity is being recorded and as per beer lamberts law we know that I upon I naught is equal to e raise to power minus mu l. So, that mu is what is the attenuation coefficient or mass attenuation coefficient in this chord line between this length.

So, we integrate it equal on the length. So, this is the d s we do the line integral of the mu s this s s d s and we know that along the line because there can be different phases involved, we do this mu line integral of the mu and we found that how the attenue what is the attenuation coefficient for this line the complete line, and that is being transferred in terms of the volume fraction why? Because suppose if I imaging this is my source, this is my detector some places there is gas, if you can see this yellow bubble yellow kind of circle as a gas and the blue is saying liquid, some places in the same line you are seeing that it is covered with the yellow, some places is covered with the blue. So, what will happen this line attenuation whatever you are getting it will be the function of it will be the combination of both the phases or it will be the because of both of the phases and that will be mu will be the overall line attenuation whatever you are seeing here will be equal to mu 1 epsilon one epsilon 1 is the volume fraction of the phase 1 plus mu 2 into epsilon

2, epsilon 2 is the volume fraction of phase 2 and mu 1 and mu 2 is the attenuation coefficient for pure phase 1 and phase 2.

So, what we do? With major first attenuation coefficient for the pure phases we know the mu 1 and mu 2 value we measure at in situ condition first scan the empty column the measure at in situ condition we know I and I naught we calculate the mu we get this equation we know that mu equal to mu 1 plus mu epsilon one plus mu 2 epsilon 2, we know the mu 1 mu 2 value we get a equation of epsilon 1 and epsilon 2 and we know that for two phase system the summation of epsilon 1 plus epsilon 2 will be equal to 1.

So, we use this we solve these equations simultaneously and what you will get, you will get that on the line what will be the distribution of the phases. So, in this line you will immediately get say this is the cross section top view again this is source this is say detector this is source, this is detected, in this line you will be immediately getting in that in this line in this circle, what is the phase distribution of gas phase and liquid phase say in case of the gas liquid system. For the gas solid system again you can get what is the phase what is the fraction of the gas present in that line, what is the fraction of solid present in that line.

So, this is called densitometry, gamma ray densitometry where you get the line abreast. Why I am saying that you are getting here because this will be in here and we know that air has almost no attenuation coefficient. So, you can easily neglect that that attenuation because of the air. So, whatever you are getting is only because of the system and wall effective are neglecting because once you are scanning the empty column, whatever the attenuation cause because of the wall thickness is already be the part of I naught.

So, whatever you are getting is the attenuation change, which is within the system with the change in the flow. So, with the flow what will happen the epsilon will change and that is what you can record. So, you will get the line average. So, that is the about the gamma ray densitometry for the tomography what you need to do? We need a pixel wise information how we can get this we will discuss. But before that the major disadvantage of this technique is it cannot give you the temporal variation of the volume fraction, that is the major disadvantage of this technique, it cannot give you the tempolor temporal variation of the volume fraction why? Because you need to wait sufficient time this is the

multi-phase flow where the bubble fraction or the solid fraction will be changing with the time.

So, if you record the attenuation for a very short time you will not able to see the difference. So, you get a sufficient statistics, you need to wait till you are getting a sufficiently statistics on this detector sufficient counts on this detector and for that you need to wait for the longer time sometimes 1 minute or 2 minutes or 3 minutes depending upon the fluctuation in the system. So, you cannot get the epsilon with the time you can get epsilon with the position.

So, the spatial resolution is very high because you can move the source and detector as per your choice, even whatever the smallest distance we want 1 mm, 0.5 mm you can move that, but temporal resolution is going to be very very poor. So, that is the major limitation of this technique, major advantage of the technique any column diameter, any system gas liquid, gas solid, gas liquid solid you can do it.

So, what we have discussed is the densitometry now what we are going to discuss is the tomo will discuss the tomography in the next class. And we will see that how from the line average we can get the pixel wise information.

Thank you.